The Potential Use of Bio-ultracarbofluids in a Standard Diesel Engine

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Doctor of Philosophy

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Summary

The replacement of diesel fuel by ultra-carbofluids was perceived to offer the potential to decrease the emissions of environmental pollutants such as carbon dioxide, carbon monoxide, hydrocarbons (HC's) and smoke. Such ultracarbofluids consist of a suspension of coal in fuel oil and water generally in the ratio of 5: 3: 2 plus a small amount of stabilising additive.

The literature relating to the economics of coal and fuel oil production, and the production and properties of charcoal and vegetable oils have been critically reviewed. The potential use of charcoal and vegetable oils as replacements for coal and fuel oil are discussed.

An experimental investigation was undertaken using novel bio-ultracarbofluid formulations. These differed from an ultracarbofluid by having bio-renewable charcoal and vegetable oil in place of coal and fuel oil. Tests were made with a Lister-Petter 600cc 2-cylinder, 4-stroke diesel engine fitted with a Heenan-Froude DPX 1 water brake dynamometer to measure brake power output, and Mexa-321E and Mexa-211E analysers to measure exhaust pollutants. Measurements were made of engine brake power output, carbon dioxide, carbon monoxide, hydrocarbons and smoke emissions over the speed range 1000 to 3000 rpm at 200 rpm intervals. The results were compared with those obtained with a standard diesel reference fuel.

All the bio-ultracarbofluid formulations produced lower brake power outputs (i.e. 5.6% to 20.7% less brake power) but substantially improved exhaust emissions of CO_2, CO, HC's and smoke. The major factor in the formulation was found to be the type and amount of charcoal; charcoal with a high volatile content (27.2%) and present at 30% by mass yielded the best results, i.e. only slightly lower brake power output and significantly lower exhaust pollutants.

Bio-ultracarbofluids are concluded to show great potential for use as a diesel fuel replacement, since harmful exhaust emissions are significantly lower than those from standard diesel fuel. The results provide an initial basis for the specification of a bio-ultracarbofluid to give optimum performance. Areas for further useful research, and possible engine modifications, are identified. However, long term tests are required in order to measure the effects of bio-ultracarbofluids on engine components. Current economics are unfavourable but depend upon both crude oil price fluctuations and political considerations e.g. EU economic and environmental policies.

Keywords: Bio-ultracarbofluids, diesel fuel replacement.

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INTRODUCTION

Chapter 1

'In the short term, energy conservation must be the cornerstone of our policy; the potential for savings is immense.... it is now certain that if we do not change our ways while there is still time our society will risk dislocation and eventual collapse.'

Roy Jenkins as President of the E.E.C.
VI EEC Energy Conference, Brussels 7th July 1979.

1.0 INTRODUCTION

1.1 Energy Resources

During the 1970's it became clear that the world's non-renewable energy resources were decreasing rapidly and might be exhausted within the foreseeable future. In response to this disturbing prospect, added to concern over the emission of harmful gases from vehicle exhausts and power stations (particularly the greenhouse gases e.g. CO_2, and acid rain gases NO_x and SO_2) into the environment, the technologically-advanced countries began to focus attention on renewable energy resources. As a result there have been significant advances in the technology, if not in its application, in such areas as solar heating and cooling, photovoltaics, wind power, biomass and ocean wave energy.

The impetus for the replacement of petroleum-derived diesel fuels, whether wholly or partially, arises from the need to conserve a non-renewable energy resource and because of the significant pollutants generated by their combustion. However the use of bio-mass derived fuels, namely bio-ultracarbofluids, may also offer strategic and economic advantages.

The majority of the world's energy resources occur in nature as solids e.g. coal and various biomass and waste materials. Bio-fuels such as wood, charcoal and agricultural residues are a major source of energy in many of the developing countries providing as much as 14% of the current world energy requirements. This is equivalent to some 25 million barrels of oil per day, and equal to OPEC's current production[1]. World-wide there is substantial arable land potentially available for growing energy crops. However, most modern transportation is based upon the use of liquid fuels. This dependence on liquid fuels has arisen partly from the ample availability of petroleum which, because it is a mixture of hydrocarbon liquids, can easily be recovered from nature, transported and converted to a variety of liquid fuels. However, liquid and gaseous fuels do have the added advantages of easy distribution within an engine and freedom from routine ash generation.

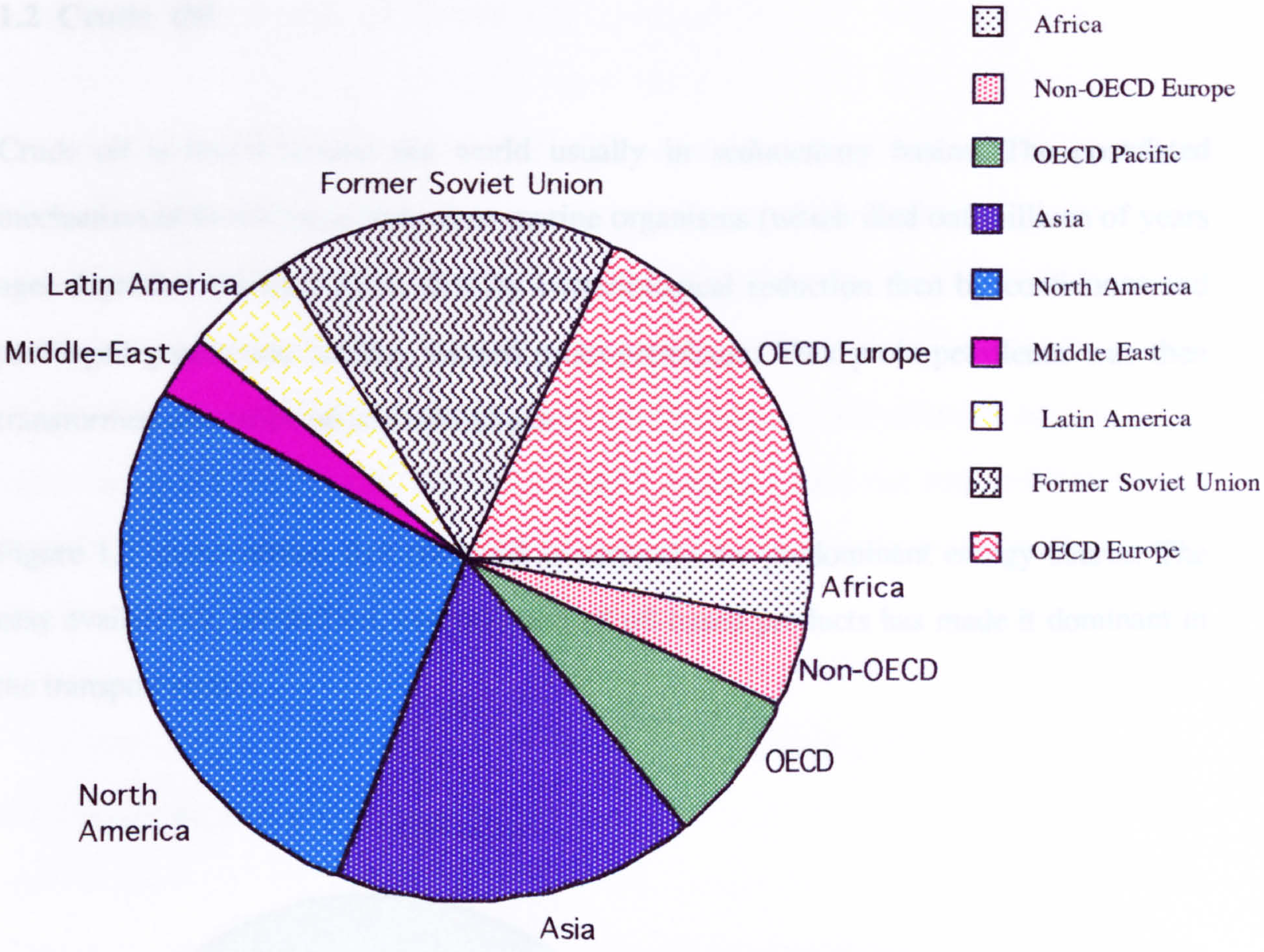
Every year the world population consumes an amount of energy equivalent to that generated from 80 billion tonnes of oil. In practice only two-fifths of this energy is obtained by burning oil itself; the balance comes mainly from coal, natural gas and nuclear energy. Indeed, closer examination shows that over 90% of our energy comes from fossil deposits, the reserves of which are finite and will eventually be depleted.

The world population depends upon energy for heating, generating electricity and for transport. Latest estimates suggest that there are 400 million passenger cars registered around the world and this number has doubled in the last 20 years. In North America there are 50 cars per 100 people, in Europe 40 cars per 100 people and in Japan 30 cars per 100 people. The world-wide average is 10 cars per 100 people. In countries like India and China there are less than 1 car per 100 people. Cars, especially, need a liquid fuel that can power their engines; most run on petrol but an increasing number are fuelled by diesel. The question therefore arises as to whether a significant proportion of these could be fuelled from renewable sources. Obviously, it would also be beneficial to the environment if the exhaust gases produced had a lower potential to cause pollution, a complex function of mass and composition, than those from existing fuels. [The overall environmental impact clearly however has to be assessed by including the resource generation process, the conversion processes and the energy utilisation process—including any liquid or solid wastes to be disposed of].

So far the discovery of fossil fuel reserves has more than kept pace with the demand. Known resources now exceed one trillion (10^{12}) tonnes in total compared with just over half this amount 20 years ago. Natural gas and oil consist mainly of hydrocarbons, which make excellent fuels. The main components of natural gas are methane (CH_4) the simplest hydrocarbon, and small quantities of ethane (C_2H_6). Propane (C_3H_8) and butane (C_4H_{10}) gases which can be produced from oil are also widely used in the form of liquid petroleum gases. With increasing molecular weight the hydrocarbons become less volatile albeit easier to handle safely. Petrol contains carbon chain lengths of C_7's and C_8's, whilst diesel contains C_{9-11}'s, and paraffin (i.e. kerosine) contains carbon chain lengths of C_{12-16}. These heavier fractions make excellent liquid fuels for cars, lorries and aircraft respectively. Clearly, therefore alternatives will need to be identified before reserves of these fossil fuels run out.

1.1.1 World Energy Demand

From 1982 to 1992 the world energy demand grew by 25% from approximately 6,000 mtoe (million tonnes of oil equivalent) to 8,000 mtoe. The demand in the US and Organisation of Economic Co-operation and Development (OECD) countries rose steadily during this period. In Asia, with rapid growth in population and industrial production, the rise in energy demand has been at three to four times the rate in the developed countries in the West. In Eastern Europe and Russia the energy demand has at present stabilised as a result of political and economic changes and uncertainties. The pattern of world primary energy consumption as at 1991 is illustrated in Figure 1.1. The energy utilisation from various sources is shown in Figure 1.2.



Africa	3%
Non-OECD Europe	4%
OECD Pacific	7%
Asia	17%
North America	27%
Middle East	3%
Latin America	5%
Former Soviet Union	16%
OECD Europe	18%

Figure 1.1 The World Primary Energy Consumption (as a percentage)

1.2 Crude Oil

Crude oil is found around the world usually in sedimentary basins. The postulated mechanism of formation is that when marine organisms (which died out millions of years ago) degraded, the fatty acids, first by bacteriological reduction then by continuous and prolonged geothermal heating, formed proto-petroleum. This proto-petroleum was then transformed into crude oil and natural gas.

Figure 1.2, demonstrates that crude oil is currently the predominant energy source. The easy availability, production, and transport of oil-based products has made it dominant in the transport sector.

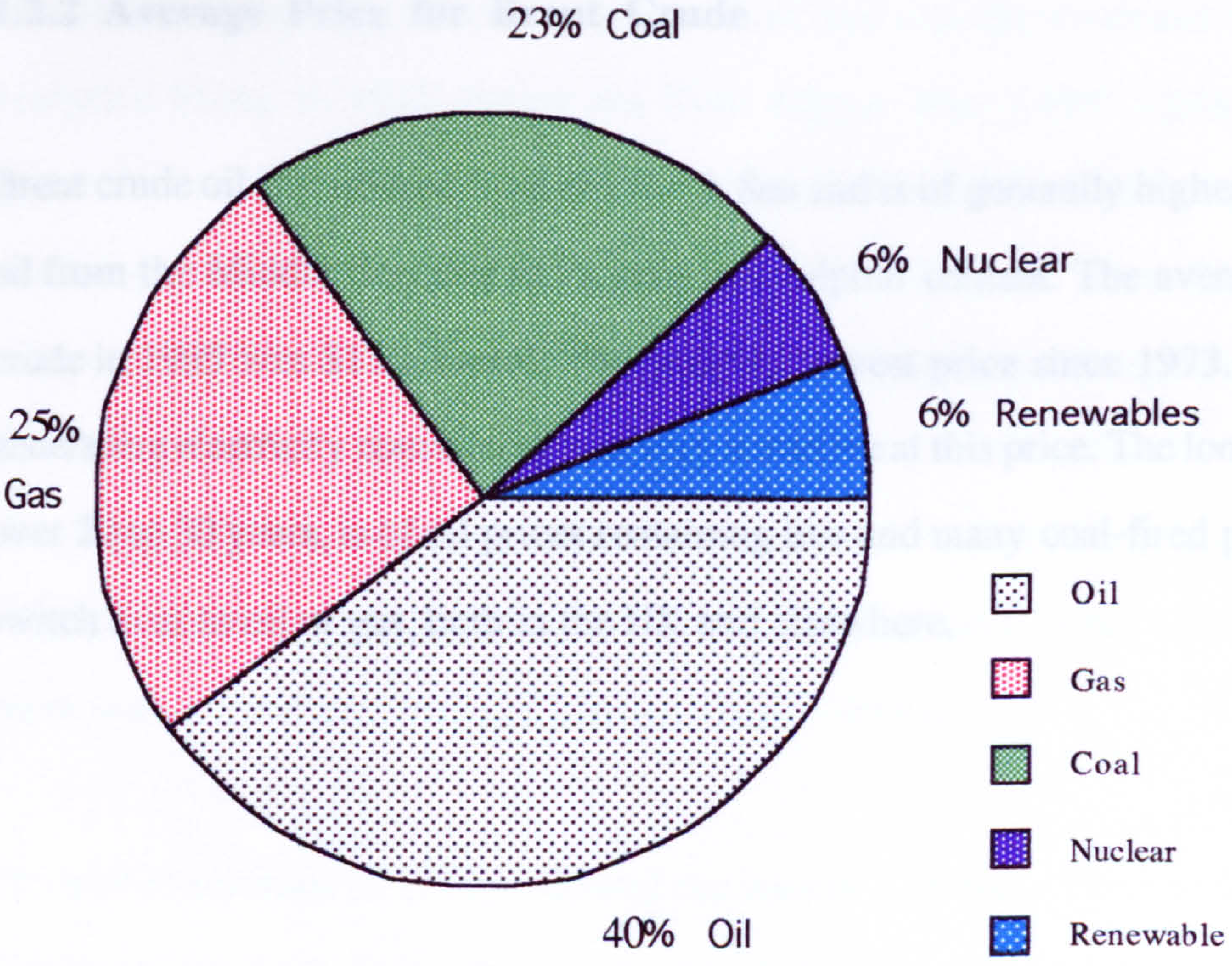


Figure 1.2 Current World Energy Sources Utilised (as a percentage)

1.2.1 Proven Reserves of Crude Oil

Proven reserves of crude oil stand at 1000 billion barrels; at the current rate of usage these will last another 40 years[2]. Most of these proven reserves are in the Middle East with 62%; other OPEC members' reserves are 13% and the Organisation of Economic Co-operation and Development (OECD) 6%. The remaining reserves are in countries such as Russia and Khazakstan. Actually, however the 'availability' improves with advances in technology e.g. in the North Sea accurate drilling even horizontally, means that more reserves can be tapped. The viability of such technology is however determined by prevailing energy prices.

1.2.2 Average Price for Brent Crude

Brent crude oil is produced from the North Sea and is of generally higher quality than crude oil from the Middle East due to its very low sulphur content. The average price for Brent crude in 1995 was $17 a barrel. This was the lowest price since 1973. The use of oil for generating electricity commercially is very attractive at this price. The long-term outlook i.e. over 20 to 30 years, is of oil prices remaining low and many coal-fired power stations may switch over to oil or gas, both in the UK and elsewhere.

1.2.3 The Strategic Importance of Oil

Current world reserves of oil are shown in Figure 1.3. The vital importance of a constant oil supply was broughy home to the developed world as early as 1956 via the Suez crisis. Although the United States was the biggest oil producer at that time, it still needed to import oil from the Middle East to sustain its vast demand. In the 1960's the U.S.A introduced oil-import controls, limiting the import of foreign oil to 12%; the remaining 88% has to be obtained from domestic sources. At about this time, the oil-exporting countries began to realise that their oil reserves were being depleted and perceived that they were being exploited. These countries therefore formed the Organisation of Petroleum Exporting Countries (OPEC) in 1960 to improve their bargaining power and control the level of oil production.

In 1967 the Six Days War between Israel and Egypt again resulted in a world shortage of oil. OPEC successfully raised the price of oil and also demonstrated its potential power overprice fixing. In 1973, during the Yom Kippur War, OPEC again demonstrated this power by using oil as a political weapon. The OPEC Chairman, Sheikh Yamani, pressurised the world powers to force Israel to withdraw from the territories it had occupied. OPEC reduced its output and deliveries and stopped supplying nations such as Holland and U.S.A . As a result the price of oil increased fourfold by the following year. The United States and many other countries had to introduce temporary emergency measures, such as speed limits on motorways (still in force in the United States), limiting petrol station opening-times and bans on Sunday driving.

The second oil crisis in 1979, followed the Iranian revolution because the new regime cut exports by one half. Again the oil prices rose from an official OPEC ceiling of $23.50 in June 1979 to $32 by January 1981. Although countries such as Japan and Israel had taken seriously the 1973 oil crisis and implemented conservation measures, some like the United States still had a consumption of energy per capita twice that in Europe.

After 1979, most countries began to formulate energy policies and to reduce their dependence on oil. Conservation of energy was seen as a necessary and potentially inexpensive way of stretching the fossil fuel reserves.

The Iraqi Invasion of Kuwait in 1989 again highlighted the inherent instability in the Middle East region. However, the steps taken after the 1973 and 1979 crises ensured that this political crisis had a minimal effect on oil supply and price. The wider base of fossil fuels (e.g. greater use of natural gas instead of oil), and the greater storage capacity introduced by the major oil companies, also ensured more stability and confidence in the ability to withstand the effects of any political crisis.

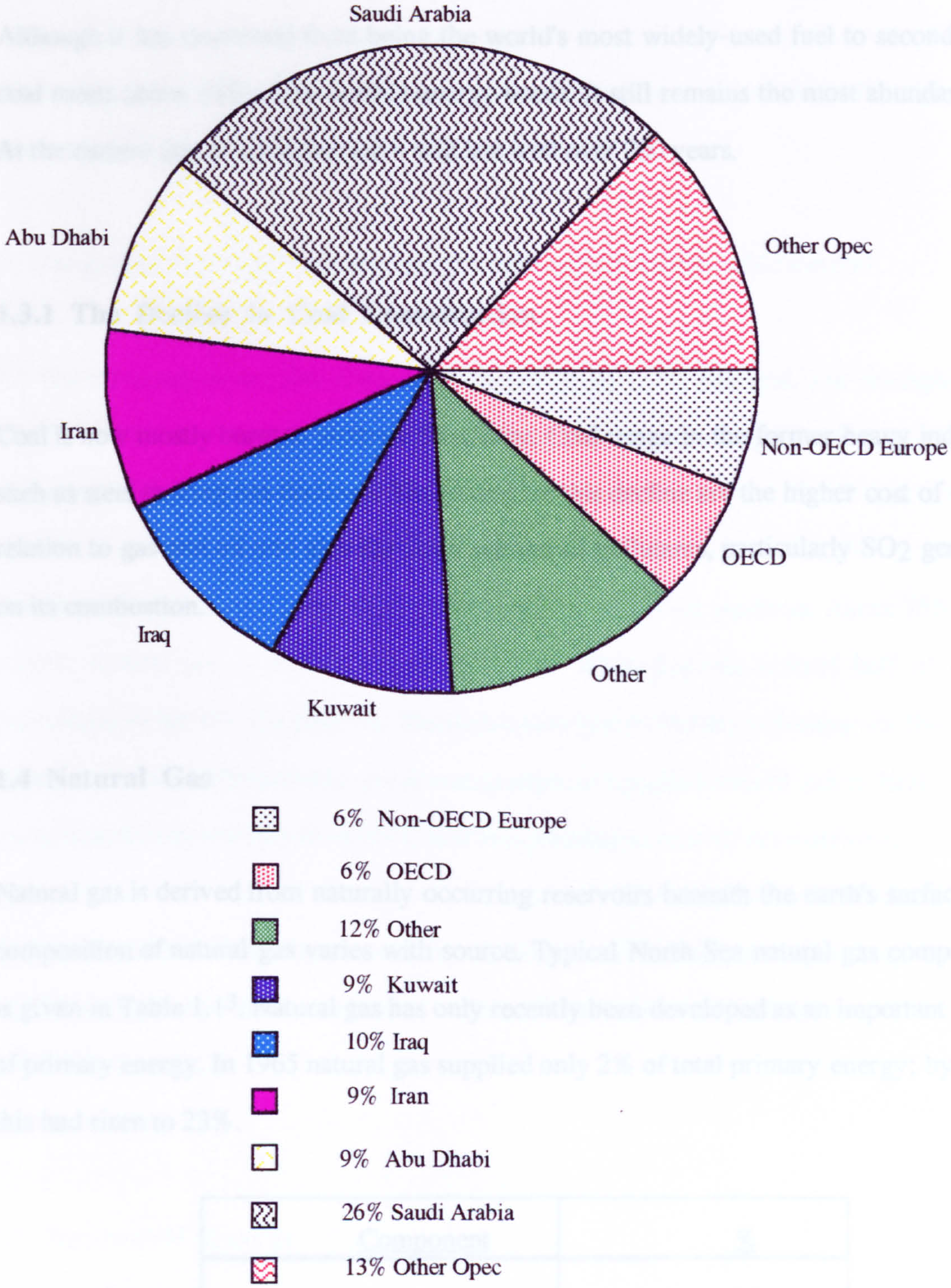


Figure 1.3 Location of Current Reserves of Oil (as a percentage).

1.3 Coal

Although it has decreased from being the world's most widely-used fuel to second place, coal meets about 25% of the world's energy needs. It still remains the most abundant fuel. At the current rate of consumption it will last well over 200 years.

1.3.1 The Decline in Coal Consumption

Coal is now mostly burnt to generate electricity. Coal usage in the former heavy industries such as steel making has declined. The reason for this decline are the higher cost of coal in relation to gas and oil and also the large amount of pollutants, particularly SO_2 generated on its combustion.

1.4 Natural Gas

Natural gas is derived from naturally occurring reservoirs beneath the earth's surface. The composition of natural gas varies with source. Typical North Sea natural gas composition is given in Table 1.1[3]. Natural gas has only recently been developed as an important source of primary energy. In 1965 natural gas supplied only 2% of total primary energy; by 1993, this had risen to 23%.

Component	%
methane	83
ethane	16
propane	<1

Table 1.1 Typical Composition of North Sea Natural Gas

1.4.1 Increase in Use of Natural Gas

The increase in the use of natural gas can be attributed to many factors. The four major factors are;

(i) The proven natural gas reserves estimates exceed 120 trillion cubic metres[4].

(ii) The extremely favourable costs of gas as compared to oil and coal. For example in the UK as of 1995 it was cheaper by 15% to produce electricity using natural gas, and 11% cheaper using oil, than using coal[5].

(iii) Improvement in the technology for the transport of gas via pipelines. About 75% of the world's natural gas is distributed via pipelines. Thus, Canada exports half of its gas production to the US via pipeline. Russia exports gas to Western Europe via the Trans-Siberian pipeline. Alternatively, gas is transported as liquefied natural gas (LNG). Natural gas is liquefied by cooling to -82.5°C and compressing to over 45 atmospheres.

(iv) To diversify their energy sources Japan, Korea and Taiwan now import large quantities of LNG in specially-constructed super tankers. These have capacities of upto 125,000 m^3 of LNG[6].

1.5 Renewable Energy

Over the years, research has been carried out into new and renewable energy resources. Renewable energy is that which occurs naturally and repeatedly in the environment and which can be harnessed for human benefit. The ultimate sources are the sun, the earth's rotation and internal temperature and gravity. The main carriers of energy are the wind, oceans, and crops, the fall of water from lakes and rivers, and both animal and human waste. Renewables contribute to energy needs in a sustainable way, and also have the potential to reduce the emissions of pollutant gases. Research has been carried out on biofuels, solar energy, wind, hydro and fuel cells.

1.6 Sustainable Developments

The UK Sustainable Development Strategy, which met a commitment entered into after the United Nations Conference on the Environment held in Rio de Janeiro in 1992, emphasised that the use of energy is a key issue for sustainable development. Today's energy use is based mainly on the combustion of non-renewable fuels.

The concept of sustainable development does not imply that all non-renewable resources must be preserved for all time, but rather that suitable replacements must be found. Despite the economic growth of the last few decades and the greater use of energy it has involved, the world's stocks of all primary fuels, measured in terms of proven reserves, are now larger than ever before, and there are more to be discovered. There is no reason to believe that the availability of resources will itself impose constraints on the process of economic development in the foreseeable future.

However the environmental and security issues related to energy production and use have to be resolved[7]. These include climate change, regional air quality issues, concerns relating to the extraction, conversion, and transmission of fuels, and transport-related impacts. One means of ensuring that energy use is kept on a sustainable path is to supply energy in ways which have less environmental impact. Another means is to encourage consumers to meet their needs with less energy inputs, through increased energy efficiency. A third way is to ensure that prices charged for the different kinds of energy reflect the full cost of the resources consumed, including the environmental and social costs of their extraction, generation or refinement, distribution, and use.

Environmental issues feature prominently on today's international energy agenda, and provide the basis for action at international level. The UK has already reported on its progress towards Sustainable Development and its programme on Climate Change[8]. There are initiatives which are directed in the European Union and the United Nations Economic Commission for Europe (UNECE) towards reducing acid emissions from industrial plant and transport. Other initiatives are directed towards controlling emissions of volatile organic compounds (VOCs), which can damage plant and animal life by contributing to the formation of extra ozone at ground level. There are also plans to assist the countries of Central and Eastern Europe and the Former Soviet Union (FSU) to reduce the perceived risks associated with Soviet-designed nuclear reactors. The UK also funds a large number of projects in the developing countries to improve the efficiency with which energy is supplied, distributed, and used.

1.7 Energy and the Environment

Industrial pollution underwent a step-change with the industrial revolution. One of the first laws passed to limit industrial pollution was the 1906 UK Alkali Works Regulation Act. Another major UK law was the Clean Air Act of 1956.

The problem of pollution of the environment by motor vehicles, first began to taken seriously in the 1970's[9]. In California 'smog', mostly attributable to the huge increase in automobile traffic, became a constant irritant. As well as the inconvenience, the environmental damage began to be assessed and solutions were sought by both politicians and scientists.

Improvements were sought by measures including the introduction of more efficient automobile engines, fitting of catalyst converters as standard on all cars to reduce harmful exhaust gases, and an increase in fuel prices. Other schemes are also being tested. In California and some other states, these include encouraging the public to share a ride to work; company buses picking-up and dropping-off people to and from work; and educating companies e.g. haulage contractors, and the general public about the need to protect the environment. Recent radical plans in California include calling upon all car manufacturers (petrol and diesel) to build zero emission vehicles (ZEV's). ZEV sales are required to be 5% of the car manufacturers' sales by the year 2000, and 10% of sales by the year 2010. [In January 1996 this requirement was suspended for 10 years because the three big car manufacturers in the United State; Ford, Chrysler and General Motors, convinced California State government that the availability of ZEV's was not feasible in the above timetable. This is a characteristic example of the conflicts which arise between desirable pollution control measures and the perceived needs of industry.]

The activities of the energy industries have the potential to affect the environment in a variety of ways e.g. through particulate or toxic gas emissions, and synergistic processes which under the influence of U.V. radiation produce 'smog'. Therefore, in practice, regulations and other environmental policies serve to limit the damage. But the major potential causes of concern relating to energy generation are emissions of greenhouse gases, acid gases and other pollutants listed below.

1.7.1 Greenhouse Gaseous Emissions

Carbon dioxide () emissions contributed most of the direct increase in the greenhouse effect in 1990. Fossil fuel burning probably accounts for almost all of this. The second most significant greenhouse effect contributor is methane. Oil-gas production, distribution and use account for about a quarter of current CO_2 emissions.

1.7.2 Acid Emissions

Man-made sulphur dioxide (SO_2) and oxides of nitrogen (NO_x) emissions add to the natural acidity of rain. Virtually all UK SO_2 emissions are energy-related and currently about 70% are estimated to come from power stations. Road and other transport contributes about half of NO_x emissions in the UK, and other fossil fuel burning the remainder, with power stations contributing 25%.

1.7.3 Ambient Air Quality

Local air quality is affected by emissions of SO_2, NO_x, VOC's (volatile organic compounds), and particulate matter. Nearly 40% of estimated VOC's emissions are from industrial use, and about 13% from the extraction and distribution of fossil fuels.

1.7.4 Water Pollution

Power plants, industrial cooling systems, abandoned mines, and onshore oil wells all have the potential to contribute to water pollution. Water run-off and leachates pose the biggest problems.

1.7.5 Maritime Pollution

Accidental oil seepages and spills may foul beaches and kill seabirds and other marine life. The relatively slow rate of biodegradation of heavy residues, left behind after evapoartion, is one factor in this.

1.7.6 Land Use

The processes of electricity generation and distribution may call for the use of scarce or sensitive land and countryside. The impacts are associated with both old and new forms of generation. Coal mining can also have adverse effects on the land, due in particular to the familiar spoil heaps created.

1.7.7 Solid Waste Disposal

The use of scrubber systems to clean sulphur emissions from coal fired power stations creates a potentially large source of solid waste in the form of gypsum. In practice, much of the gypsum is used to make wallboards and other plaster products. Similarly, much of the furnace bottom ash from coal-powered stations is used in building materials. Other solid residues are land-filled wherever possible as part of reclamation schemes. Some colliery spoil can be disposed of in a similar manner.

1.8 Advantages and Disadvantages of Nuclear Fuel

Although virtually free from greenhouse and acid gases, nuclear energy inevitably produces radioactive wastes. Disposal of these, and decommissioning of redundant facilities, requires careful supervision. Nuclear and hydro power can both be considered as renewable fuels. The majority of the remaining electricity generating fuels are non-renewable fossil fuels, which at the current rate of consumption are rapidly being depleted.

Nuclear fuel has a clear advantage over other energy producing fuels in that it produces no pollutants such as; carbon dioxide, sulphur dioxide, NO_x, hydrocarbons or soot etc. Hence, it is more 'environmentally-friendly' than fossil fuels. Total consumption of nuclear energy was equivalent 532 mtoe of oil in 1992[10] and this use extends the life of fossil fuel reserves. However, accidents such as those at Brown's Ferry (1978), Three Mile Island (1979)[11] and Chernobyl have exacerbated concerns over the safety of nuclear power stations and thus raised doubts over their long term future. The generation of nuclear electricity, was promoted as a cheap alternative source. In the event, electricity generated from nuclear power is actually more expensive than that from coal, gas or oil, when all the real costs such as construction, operation, disposing of toxic waste and decommissioning the plants are considered. Zaleski[12] states that nuclear generated power will decrease from the peak of 3500 GW in the 1970's to about 700 GW world-wide by the year 2000.

In summary it appears that at sometime in the future, energy generation will require a significant contribution from other sources. Basic engine fuel will continue to be liquid. Therefore it is pertinent to review some aspects of the sources of energy crops and the economics associated with their growth, recovery, processing and utilisation and also how their development is influenced by economics e.g. government subsidies.

CHAPTER 2

LITERATURE REVIEW OF ALTERNATIVE FUELS

Chapter 2

> *'One of Nature's Laws, publicised by Parkinson, is that demand always rises to meet supply. Unfortunately he failed to state what happens when supply fails to meet demand*.'

HRH The Duke of Edinburgh
World Energy Conservation Month, Oct.1979.

2.0 Literature Review of Alternative Fuels

Although the considerations and conflicts vary with the fuel type and method/scale of utilisation, it is worthwhile to briefly review current energy considerations-environmental protection issues, since these impact upon the future viability of both alternative fuels and diesel engines.

It is now recognised that the fossil fuel resources of the world are depleting. Hence, conserving petroleum-use by developing alternative fuels and new energy resources is of prime importance.

2.1 Possible Alternative Fuels

Over the years many researchers have sought to develop an alternative to petroleum fuels for automobiles. Four promising potential alternatives viz alcohols, hydrogen, battery-powered cars and vegetable oils, are reviewed below.

2.1.1 Alcohol Fuels

Alcohol fuels have been researched very extensively in many countries. The alcohol fuels, methanol and ethanol, are of special interest in countries like Brazil and other Third World countries, such as Zimbabwe where economic benefits are of more importance than political or environmental pressures. Already in Brazil research into alcohol fuels has paid dividends and many cars are running on 100% neat alcohol (ethanol), reducing the need for oil imports and helping the country's trade balance.

As early as 1945, Brooks and others[13] demonstrated the feasibility of alcohol as a petrol engine fuel. More recently Menrad[14] in the United States and many other researchers are continuing work into the viability of alcohol as fuel.

Alcohol fuels, both methanol and ethanol, offer both short-term and long-term potential contributions to the automobile fuel supply. In the short term they offer both the potential for fuel extension (e.g. gasohols which are 80% petrol and 20% alcohols) to expand the motor fuel supply and to assist octane enhancement for better performance of petrol engines. The octane enhancement capability is particularly crucial for the manufacture of low octane base fuel. This is important for refining and production of unleaded fuel. In the longer term alcohol fuels in neat form (100%) offer the opportunity to displace petroleum products in the fuel market.

In the testing of alcohol fuels in internal combustion (I.C.) engines, particular attention has been given to their performance and degree of compatibility with the fuel system[15,16] Much work has involved improving alcohol blend quality (i.e. minimising water separation), improving alcohol engine cold-start properties, decreasing vapour lock, overcoming corrosion and improving driving performance. Among the major benefits of alcohol engines is the superior kilometres/kJ performance of alcohol fuels and reduced emissions in contrast with conventional fuels.

Of the alcohol fuels, ethanol and methanol are the principal renewable contenders. However, the major disadvantages of using alcohol as a fuel are currently the higher cost, 5 to 10 per cent above that of petrol and the limited production capacity; e.g. in the UK only one tenth of the 115 billion gallons of alcohol fuel which would be required per year to meet demand can be currently produced (1982)[17].

2.1.1.1. Ethanol

In Brazil some petrol-engined cars were converted to run on ethanol produced from sugar cane. In the United States ethanol used to fuel vehicles is usually manufactured from surplus grain.

The hope in Brazil was that ethanol would ease their growing need to import oil. In the late 1970's crude oil doubled in price to $40 a barrel (159 litres), equivalent to about $65 at today's prices. Weight for weight ethanol does not release as much energy as petrol or diesel, but in terms of volume, the fuels almost match. Ethanol releases about 2300 kJ/ litre compared to 2500 kJ/ litre for petrol. In 1990, Brazil grew 25 million tonnes of sugar cane a year on 4 million hectares (8 per cent of their cultivated land) and converted three-quarters of this into 12 billion litres of ethanol.

Today, Brazil has four million cars running on ethanol, and another one million which run on a gasohol mixture of 20% ethanol and 80% petrol by volume. One quarter of Brazilian transportation fuel is ethanol. It was predicted that in the near future all Brazilian cars would run on ethanol, but with oil now much cheaper at approximately $18 per barrel (December 1995), this seems unlikely. In terms of cost ethanol can no longer compete with petrol, even when the State generates electricity by burning sugar cane residues. One of the benefits of using clean-burning ethanol, is that the atmosphere in Sao Paulo, Brazil is relatively clean in comparison to many similar South American cities where conventional fuels are used.

2.1.1.2. Methanol

Methanol, termed wood alcohol, was once produced by distillation from wood chips. Today it is made from synthesis gas, which is converted into methanol using a catalyst of zinc oxide and chromium,

$$CO + 2H_2 \text{ ----------> } CH_3OH$$

Methanol is a volatile liquid which boils at 65°C. It is 'clean burning' and, since it is less volatile than petrol, the fire hazards following a vehicle collision or accident are reduced. Most unleaded petrol contains a derivative of methanol, methyl tertiary butyl ether (MTBE) as an anti-knock additive. World demand for methanol now exceeds 20 million tonnes per year. Problems with methanol are corrosion of the fuel delivery system, toxicity and high price.

2.2 Hydrogen

Considerable research has been carried out into the potential of hydrogen as an alternative fuel[18]. One gram of hydrogen yields more energy than the same amount of conventional fuels. However a major problem with hydrogen is that one tonne occupies 11 million litres at atmospheric pressure, which is about the size of a sports hall. Hydrogen is considerably less dense than methane, and it requires three times the volume to yield the same amount of energy.

For commercial use hydrogen is usually shipped at 2000 psi at 21°C. By condensing hydrogen to a liquid at -253°C the volume of a tonne reduces to a manageable 14,000 litres. This is how large quantities of hydrogen are transported and stored for rocket power. There are however major safety problems associated with the use of hydrogen, namely its wide flammable range i.e., 4% to 75% by volume in air, low energy for ignition (and an A.I.T. of 587°C in air at atmospheric pressure) and the possibility of ignition on leakage due to the Joule-Thompson effect (hydrogen being an exception in that it warms on expansion at room temperature). These risks are exacerbated by storage under high pressure.

Therefore, schemes may be based upon the use of hydrides to generate hydrogen in-situ. There are two natural sources of hydrogen:

(i) Water

Electrolysis of water releases hydrogen. Such generators work with 90% efficiency. The electrolysis of steam inside porous electrodes of zirconium oxide produces hydrogen even more efficiently. However, even this process would not make a hydrogen economy viable, since it is cheaper to produce electricity than to produce hydrogen. Economies could be advanced by utilising the surplus electricity produced by a nuclear power station at night to electrolyse water to hydrogen.

(ii) Hydrocarbons such as methane.

Methane can be oxidised to produce hydrogen and carbon monoxide. The reaction is normally carried out at 850^{o}C using Ni catalyst.

It has been predicted that, by the year 2015, most cars will still be powered by conventional petrol or diesel engines, with battery-powered cars and alternative fuels relegated to the "politically correct fringe "[19].

2.2.1 Hydrogen Fuelled Cars

The 'Power to Petrol' report[20] takes a strongly pessimistic view of the prospects for hydrogen-powered cars, upon which several leading manufacturers are working as one of the most promising alternatives to battery vehicles in the search for environmentally "clean" private transport.

The study appears to reinforce the arguments of the US "big three" car makers, General Motors, Chrysler and Ford, that electric vehicle technology is not sufficiently advanced for viable battery cars to go on sale in California in 1998 in line with the State environment legislation.

2.3 Alternative Engines

A battery-powered car would be cheap to run, especially if its power cell were recharged at night at low tariff. It would be quiet and non-polluting and smooth to drive. Environmentalists have said this would be the ideal solution; however there are still many problems.

One problem is that the electric battery is not the source of the energy but merely a convenient means of packaging and storing electrical energy generated elsewhere, that is usually in a coal, oil or gas-fired power station which adds to pollution of the atmosphere with SO_2 and CO_2 from its flue gases. As noted earlier CO_2 contributes to the greenhouse effect and SO_2 towards acid rain. Also only approximately 30% of the energy contained in the coal is turned into electricity.

The automotive industry world-wide is spending more than £5 billion a year on research into, and development of, electric vehicles. BMW has spent about £330 million developing sodium-sulphur batteries. They have better performance, but cost £16,000 per car and have to be recharged every 140 km. The weight of the batteries is a major disadvantage because a kilogram of petrol contains 300 times as much energy as a one kg lead-acid battery.

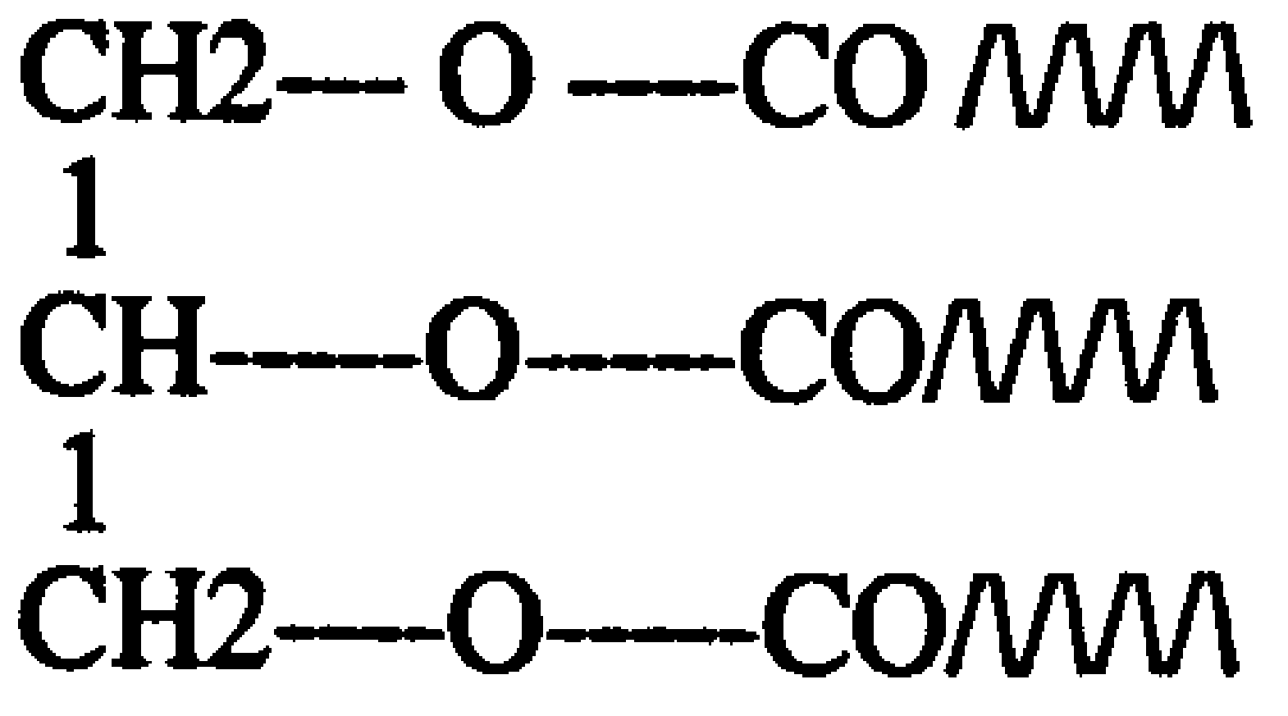
So far, few practical commercial vehicles have appeared apart from early prototypes by General Motors (GM) and electric vans that have been produced in limited numbers by Peugeot and Citroen since 1989. GM has just finished building a fleet of 30 models based on the Impact, a prototype unveiled about three years ago. The fleet is starting trials under programme PrEView in Los Angeles and will be evaluated along with prototype systems for recharging the vehicles by 1000 drivers of widely varying types and needs over the next two years. Peugeot has been producing a limited number of electric 205 models. These have a range of 60 miles before recharging is required. Although fuel cost is a fraction of the petrol car, the batteries need changing every four years at a cost of £1000 and since the original battery car costs twice as much as an ordinary petrol/diesel car the economic benefits are low. (Solar charged power cells exist, but for an average family car, the size and weight of these give rise to problems and they are not yet therefore a serious viable alternative). Despite this it has been stated that "GM wants electric vehicles to be a market-place success. The PrEview drivers will help us understand the potential electric vehicle (EV) customers and help take us one step closer to making EV's a reality"[21].

It has been claimed that the production, recycling and disposal of large numbers of car batteries would release dangerous levels of lead into the environment[22]. The mining and smelting required to manufacture their batteries also produce lead emissions. However, modern manufacturing and pollution control technology could be expected to cope with such problems in compliance with stricter legislative controls[23].

2.4 Vegetable Oil Derivatives as Fuels

Rudolph Diesel the engine inventor envisaged and first used vegetable oil as fuel in 1899. However cheap and abundant petroleum-derived fuel quickly overtook vegetable fuel to became the major source.

All vegetable oils and animal fats are made up of molecules of tri-acylglycerides, which consist of three long fatty acids connected to a molecule of glycerol:



$$\begin{array}{l} \mathrm{CH_2{-}O{-}CO}\wedge\!\vee\!\wedge\!\vee\!\wedge \\ | \\ \mathrm{CH{-}O{-}CO}\wedge\!\vee\!\wedge\!\vee\!\wedge \\ | \\ \mathrm{CH_2{-}O{-}CO}\wedge\!\vee\!\wedge\!\vee\!\wedge \end{array}$$

Plants and animals synthesise oils and fats because the long chains of CH_2 units provide an efficient mechanism for energy storage. Vegetable oils without further processing/ modification cannot be used as fuel in the direct injection diesel engine, and can be used only with difficulty in pre-chamber diesel engines, since they cause severe engine deposits, ring sticking, injector coking and degradation of lubricants. Coking is the accumulation of hard carbon deposits around the injector orifices and other surfaces in the combustion chamber, which can eventually disrupt the spray emitted from the orifices and prevent valve seating, causing ring sticking and engine failure. To reduce these problems the fatty acids are liberated from the glycerols by using alkali in a process of trans-esterification. The resulting acid is treated with methanol (CH_3OH) which converts it to methyl ester.

$$\mathrm{CH_3{-}O{-}CO}\diagup\diagdown\diagup\diagdown\diagup\diagdown$$

These esters are more volatile and are hence more suitable for use in the diesel engines.

Vegetable oils have been tested as alternative diesel fuels. They have heat contents of approximately 90% those of diesel fuels. However, an unmodified vegetable oil has a very high viscosity (e.g. rape seed oil has a viscosity of 37.0 cST at 38^{o}C) as compared to diesel oil (e.g. 2.7 cST at 38^{o}C).

Use of vegetable oil methyl esters avoids the formation of carbon deposits. But here also, problems arise such as lubricating oil dilution and sludge formation. Strong efforts are being made to eliminate these problems. The use of vegetable oil can be of great benefit in some special fields such as fuelling farm machinery and canal boats in Holland were they are required to use vegetable fuel and lubricant, which are more readily biodegradable to protect the sensitive marine environment.

2.5 Rape Seed Oil

Rape has yellow flowers, from which can be extracted amber oil (a "green" fuel). The advantages of rape seed oil are that, in theory, it could replace fossil fuels in both diesel and petrol engines and it is much 'cleaner' than most fuels resulting in a reduction of sulphur dioxide emissions by 98% and of soot particles by 50%. Rape seed oil is also an edible oil.

In Austria this oil can already be purchased at filling-stations and in Italy it is sold as Bio-diesel. It could also offer a solution to the 'over-production' by EC farmers. Under set-aside land policy, farmers are paid not to produce edible crops; if rapeseed oil were grown for fuel it would offer a bonus for farmers in giving them a real use for land which they are now being paid not to use.

The disadvantage of rape seed oil is that one acre of rape yields only 80-90 gallons of bio-diesel. Furthermore one gallon of bio-diesel contains 5 per cent less energy than standard diesel oil. The tens of million £'s subsidies spent on growing it in Europe indicate that the real cost is high and encourages highly intensive agriculture[24].

Suda[25] investigated the effects of potential vegetable oil fuels in diesel engines. Vegetable oils have heat contents of approximately 90% those of diesel fuels. However, one undesirable property of unmodified vegetable oils is that they have a very high viscosity upto 10 times greater than ordinary diesel oil.

Diesel engines are sensitive to viscosity changes. High viscosity leads to poor atomisation of the fuel, incomplete combustion, coking of fuel injectors, ring carbonisation and accumulation of fuel in the lubricating oil. A further problem with unsaturated vegetable oils is that, following mixing with engine oil, they undergo polymerisation; this results in increased viscosity of engine oil, which may cause engine damage. Hence more frequent engine oil changes are needed.

Different methods of dilution, micro-emulsification and transesterification have been tried to overcome the viscosity problem.

2.5.1 Dilution

Dilution of 25 volume parts of unmodified sunflower oil with 75 parts of diesel fuel has been carried out by Ziejewski and et al.[26]. The viscosity of the mixture was 4.88cSt at 40°C, slightly greater than the 4.0cSt at 40°C maximum recommended as the ASTM value. Furthermore Ziejewski et al. recommended that the 25/75 blend should not be used as a long term solution as it will have a detrimental effect on the piston rings, engine wear and injector components. Clearly this is not a practical solution.

Unmodified[27] high oleic safflower oil was also mixed in a formulation at 25 volume parts of safflower with 75 parts of diesel fuel. Again the viscosity was high (4.92 cSt at 40°C) compared to the recommended maximum value, even though it passed the EMA (American Engine Manufacturers Association)[28] test.

Another formulation tested by Goering[29] used 50 volume parts of soya bean oil with 50 volume parts of Stoddard solvent (48% paraffins and 52% naphthenes) from Union Oil Co. This formulation also passed the EMA[30] test. However Goering reported heavy carbon deposits on the tulips of the intake values and considerable top ring wear. The problem of elevated viscosity still remains; for this fuel viscosity was 5.12 cSt at 38°C.

2.5.2 Microemulsions

The viscosity of vegetable oils can be reduced by microemulsion with short-chain alcohols such as methanol or ethanol. A microemulsion is defined as a colloidal equilibrium dispersion of optically isotropic fluid microstructures, with dimensions generally in the 1 to 50 nm range, formed spontaneously from two normally immiscible liquids and one or more amphilphiles. These are miceller systems that may be formed as ionic or non-ionic amphiphiles. Schwab and Pride[31] demonstrated amphiphiles in the miceller stabilisation of methanol in triolein and soya bean oil.

Methanol has an economic advantage over ethanol, and can be derived from a large variety of base stocks including biomass, municipal waste, natural gas and coal. By microemulsion formation it is possible to prepare alternative diesel fuels completely free of petroleum. The 200 hr Engine Manufacturers Association (EMA) test was passed by one such fuel (soya bean oil, methanol, 2-octanol and cetane improver in the ratios 52.7: 13.3: 33:3 : 1.0)[32]. Because of their alcohol contents microemulsions have lower heating values than diesel fuels, but alcohols have high latent heats of vaporisation and tend to cool the combustion chamber which would reduce nozzle coking.

2.5.3 Transesterification

The process of converting neat vegetable oils into esters is termed 'transesterification'. It is essentially the process of reacting a triglyceride (of the vegetable oil or animal fat), with an alcohol in the presence of a catalyst to produce glycerol and fatty acids esters. The molecular weight of the resulting ester is roughly one third that of the unmodified vegetable oil. For rape seed and methanol the equation is, Rapeseed oil + Methanol------> Diester+ Glycerol

(1t) (0.1t) (1t) (0.1t)

Previously in the production of methyl esters, washing was an important process in the fuel preparation. Washing (termed 'sweetening' in the petroleum industry) of methyl esters required a large amount of water to remove unreacted tricglycerides (Figure 2.2) and derivatives, excess methanol, salts, and unreacted catalyst. To yield methyl esters, almost 5,000 litres of wash water was used to produce 100 litres of ester in order to remove corrosive unreacted catalyst which was found to be present at only 0.03% in the unwashed ester.

A superior method of producing ethyl esters at the same output as the previous methyl ester production process has been reported[33]. In contrast to the routine method of preparing esters, the new method operates at ambient temperature and washing the final ester (an important washing step requiring extensive amounts of water) is eliminated. In addition the production capacity of ester is reported to increase five times, from 760 litre of methyl ester to 3,800 litres production of ethyl ester. The increase is due to time saved in washing (10 hours) plus at least 48 hours of settling plus separation.

Ester	Heat content MJ/kg	Cetane No.	Cloud point ^oC	Viscosity cSt at 38^oC
Me soyate	39.8	46	2	4.1
Et soyate	40.0	48	1	4.4
Bu soyate	40.7	52	-3	5.2
Me sun	39.8	47	0	4.2
Me rape	40.5	54	-2	6.7
Me peanut	-	54	5	4.9
Me palm	-	62	13	5.7
Diesel	45.2	46	-19	2.4

Table 2.1 Fuel Properties of Vegetable Oil Esters.

Table 2.1 summarises relevant fuel properties of vegetable oils. Methyl, ethyl, butyl soyate have similar properties to those of reference diesel fuel. The gross heating value of ester soyate is approximately 10% less than that of the reference diesel[34].

The biodiesel fuel has a lower calorific value (LCV), 7% less than reference diesel oil[35], but the slight power loss that may be expected is compensated for by an appreciable improvement in combustion as a result of the oxygenation of the diesel fuel proportion by the addition of the esterified oil. Thus thermal efficiencies have been shown to be higher than energy calculations predict. It should be noted that the power reduction can only be detected when the proportion of biodiesel in the diesel exceeds 30%.

The energy yield from the bio-diesel is invariably greater than that expended during production (more than twice as much on average)[36]. Better results can be expected with more productive hybrid rapeseed and more efficient and economical cropping.

Environmentally, biodiesel is a relatively low-toxicity product and more than 98% biodegradable. Combustion produces less sulphur dioxide, smoke, particulates, hydrocarbons and carbon monoxide. Biodiesel has a positive CO_2 balance and does not contribute to global warming. Above all biodiesel is renewable, hence saving valuable natural resources.

The most recent large-scale industrialised use of vegetable oil is in the area of alternative fuels for diesel (compression ignition) engines. Preliminary results indicate that such fuels result in lower nitrogen oxides and particulates production, as well as meeting oxygenated fuel restrictions in the U.S.[36]. In the US. soya beans are more available, hence biodiesel is made from soya. In Europe rapeseed is a primary crop produced for edible consumption.

Also, the longer carbon chain length of oils, such as rapeseeds, results in longer storage stability and improved lubricity when used as biodiesel.

Vegetable oils are obtained from a variety of crops, such as soyabean, peanut, sunflower, safflower, cottonseed, rape, canola and coconut crops. Linseed and castor are also used to a large extent. Figure 2.3 shows the flow chart for biodiesel production. Neat vegetable oils differ from diesel fuel in that the latter is composed of saturated hydrocarbons; the vegetable oils listed are triglycerides consisting of glycerol esters of fatty acids. Table 2.2 summarises fatty acid compositions of representative oils. The high molecular weights, high oxygen content and high unsaturation means that some vegetable oil properties differ significantly from those of ordinary conventional fuel.

Vegetable species that contain low or no linolenic acid (18:3) and large amounts of stearic (18:1) and oleic acids (18:2) are favoured because they give less trouble in the engine (Figure 2.1).

	Fatty acid Composition										
Vegetable Oil	14:0	16:0	18:0	20:0	22:0	24:0	18:1	18:1*	22:1	18:2	18:3
Castor	0	1	3	0	0	0	5	90	0	1	0
Cottonseed	0	28	1	0	0	0	13	0	0	58	0
Crambe	0	2	1	2	1	1	19	0	59	9	7
Linseed	0	5	2	0	0	0	20	0	0	18	55
Peanut	0	11	2	1	2	1	48	0	0	32	1
Rapeseed	0	3	1	0	0	0	64	0	0	22	8
Safflower	0	9	2	0	0	0	12	0	0	78	0
‡H.O Safflower	tr.	5	2	tr.	0	0	79	0	0	13	0
Sesame	0	13	4	0	0	0	53	0	0	30	0
Soybean	0	12	3	0	0	0	23	0	0	55	6
Sunflower	0	6	3	0	0	0	17	0	0	74	0

tr. = trace

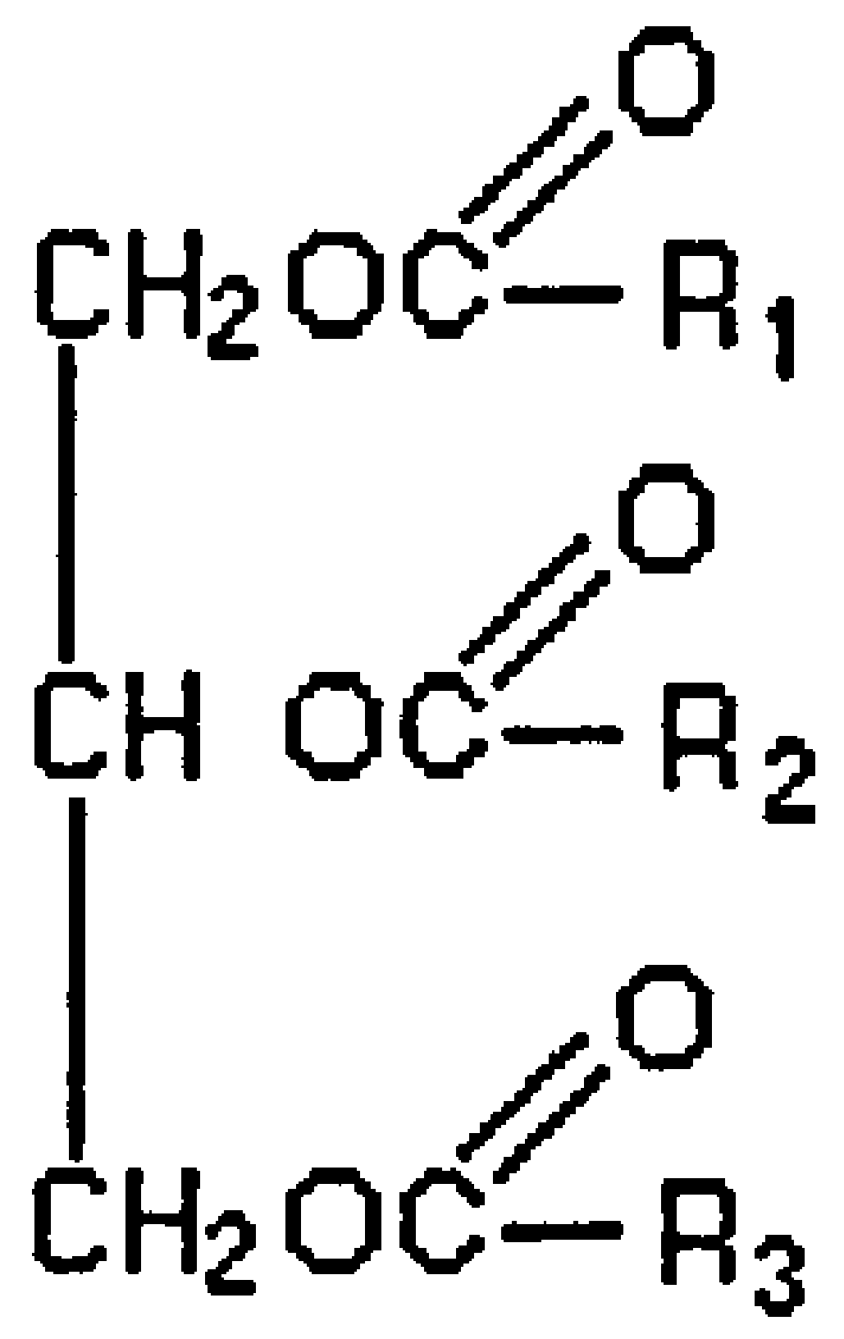
‡ High oleic Safflower

* Ricinoleic acid, 12-hydroxy cis-9-octadecenoic acid

Table 2.2 Chemical Composition of Vegetable Oils

$CH_3(CH_2)_{16}COOH$	stearic acid
$CH_3(CH_2)_7CH=CH(CH_2)_7COOH$	oleic acid
$CH_3(CH_2)_4CH=CHCH_2CH=CH(CH_2)_7COOH$	linoleic acid

Figure 2.1 Fatty Acid Structures



(where R= similar or different hydrocarbon chain leng

Fats (triglycerides of fatty acids)

Figure 2.2 Fats (triglycerides of fatty acids)

The oilseed crops listed in Table 2.2 are traditional crops which have been grown over hundreds, if not thousands, of years. The appliance of bio-technology, fertilisers and new modern production techniques should improve the current yields. For example, in the US improvement in wheat yield from 1945 to 1976 was 87% [37].

From Table 2.2 only peanut yields 50% oil content, whilst soya bean produces only 18%. The US. Department of Agriculture (USDA) has examined over 8,000 different species for oil production[38]. From their search they have isolated several hundred species which give over 40% oil content and 50 species which give 60% or more of oil. Some of these species e.g. Apocynaeceae Thevetia ovata (60% oil), and Theaceae Chrysophyllum (68% oil), may be developed for possible fuel crops[39].

2.5.4 Properties of Vegetable Oils

The properties of diesel oil and various vegetable oils were compared by Goering et al[40] and the data are summarised in Table 2.3 .

oil	Viscosity cST (38°C)	Cetane Number (ASTM D 613)	Gross Heating Value MJ/kg	Cloud Point °C	Pour point °C	Flash Point °C	Density kg/litre
Corn	34.9	37.6	39.50	-1.1	-40.0	277	0.91
Cottonseed	33.5	41.8	39.47	1.7	-15.0	234	0.92
Peanut	39.6	41.8	39.78	12.8	-6.7	271	0.90
Rapeseed	37.0	37.6	39.70	-3.9	-31.7	246	0.91
Soybean	32.6	37.9	39.62	-3.9	-12.2	254	0.91
Sunflower	33.9	37.1	39.58	7.2	-15.0	274	0.92
Diesel	2.7	47	45.34	-15.0	-33.0	52	0.84

Table 2.3 <u>Fuel Properties of Vegetable and Diesel Oils</u>

The data show that the viscosities of neat vegetable oils are on average 13 times greater than of diesel oils. This high viscosity severely handicaps the use of vegetable oils as substitutes for fuel in automotive engines. Several different methods are used to lower the viscosity as described in sections 2.5.1, 2.5.2 and 2.5.3 .

The Gross Heat of combustion for vegetable oils is fairly constant and equivalent to about 90% that of diesel fuel. However tests have shown that, due to the presence of extra oxygen in the vegetable oils, the total energy release is nearly the same as for diesel fuel[41].

The cloud points of the vegetable oils in Table 2.3 are in the range -3.9°C to 12.8°C. These are high compared to diesel fuel, -9 to -22°C. The pour points of vegetable oils apart from corn (-40°C) and rapeseed (-31.7°C), are also higher and range from (-6.7°C to -15°C), whereas, the diesel pour points range from -23 to -42°C. Therefore, because of their high pour and cloud points, vegetable oils would introduce severe problems in very cold weather depending on the type used. Vegetable oils are much safer to handle because of their very much higher flash points, but then diesel oil itself is a conventional flammable, not highly-flammable, liquid for the purpose of storage and transportation.

2.5.5 Properties of Vegetable Oil Esters

Low molecular weight alcohol fatty acid esters have viscosities and volatilities much closer to those of diesel fuel. Consequently they have been extensively tested as alternative diesel fuels; generally they show great promise. As an example, it was recently reported that a Massey Ferguson tractor running on sunflower ethyl ester successfully completed a 1500-hour field trial[42]. Inspection of the engine showed that it was in exceptionally good condition after the test.

Fuel properties of several vegetable oils are summarised in Table 2.3. Heat contents of the esters are fairly uniform which indicate that differences in their chemical structures have only a slight effect. The gross heats of combustion, Hg, of esters are slightly higher than those of the respective vegetable oils[43]. The Cetane Numbers of the esters are greater than those of either vegetable oils or diesel fuel. However the cloud point still remains high presenting problems such as cold weather starting. The viscosities of esters are much lower than those of neat vegetable oils (Table 2.3) and no problems are forseen during passage through the injectors.

Long term engine tests with the methyl ester of winter rape seed oil have shown that engine performance, wear criteria and injector coking criteria are favourable compared with the reference fuel[44]. A small amount of oil dilution has been observed. However this does not have serious consequences, because the viscosity-temperature characteristics and lubricity of rapeseed oil are similar to those of lubricating oil. The lubricating oil of a normal car diesel engine has to be changed more often as a result, every 6000 miles instead of the usual 9000 miles.

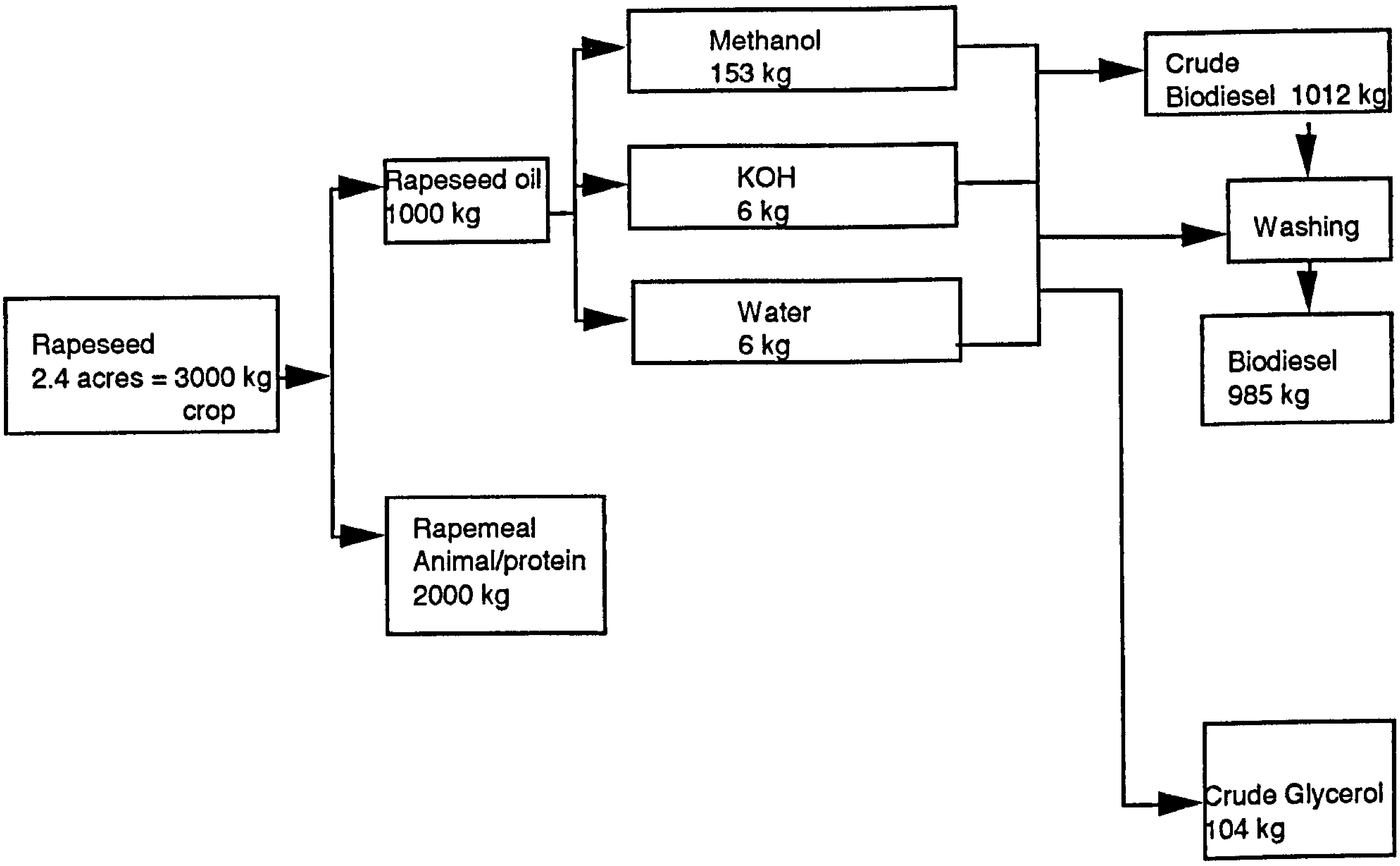


Figure 2.3 Biodiesel Production from Rapeseed Oil-Flow Chart

CHAPTER 3

PETROLEUM COMBUSTION CHEMISTRY

Chapter 3

3.0 PETROLEUM COMBUSTION CHEMISTRY

3.1.1 Mixture Formation and the Combustion Process in a Spark-Ignition Engine

The spark-ignition engine is a piston engine with homogeneous external, or internal, air-fuel mixture formation and spark ignition. In a spark-ignition engine, the homogeneous air-fuel mixture is compressed to approximately 15 to 25 bar during the compression stroke. The final compression temperature of 400^oC to 500^oC thus generated lies below the auto ignition threshold of the mixture; therefore it must be ignited by an ignition spark shortly before TDC (Top Dead Centre). Subsequent combustion, and hence the economy and power, are influenced primarily by the achievable flame velocity and hence the duration of combustion.

Spark-ignition engines must inevitably use a more volatile fuel than diesel engines, and mixture formation up to the point at which combustion begins takes longer than in diesel engines. Spark-ignition engines thus achieve a more homogeneous mixture than diesel engines.

Spark-ignition engines operate in the range of stoichiometric fuel-air mixture ratio. Diesel engines always operate with excess air (Λ>1). Operation with insufficient excess air leads to an increase in soot, CO and HC emissions.

3.1.2 Mixture Formation in a Spark-Ignition Engine

The function of the mixture formation system in the spark-ignition engine is to produce a combustible, suitably homogeneous, air-fuel mixture. However, homogeneity can only be achieved with gas or gas/vapour mixtures , i.e. all of the fuel must be vaporised before ignition is initiated. If the fuel cannot be completely vaporised, e.g. during cold starting, because the temperature is too low, additional fuel must be supplied such that the amount of fuel vaporised is sufficient to form a combustible air-fuel ratio (cold-start enrichment). The unburned fuel is then emitted in the exhaust and detected as unburned hydrocarbons and white smoke particulates.

In addition to the formation of an homogeneous mixture, the mixture formation system must also provide engine load control. Homogenous air-fuel mixtures only burn "clean" within a narrow range of air-fuel ratio (Λ= 0.8 to1.2), and therefore load control must be accomplished by controlling the amount of mixture which enters the cylinder (quantity control). This is achieved by throttling the amount of the fuel entering the working cylinders under part-load operating conditions (throttle control). The air-fuel mixture must also be formed in a manner which minimises deviations in the air-fuel ratio from cylinder to cylinder and from working cycle to working cycle.

The degree to which this requirement is fulfilled varies between carburettor and fuel-injected engines. Although the position of the throttle valve in the lower load range causes uneven air distribution, and thus uneven cylinder filling, in the case of a single-point carburettor mixture-formation system, intake manifold pressure, which drops as the load decreases, causes the amount of fuel vapour to increase.

In both types of mixture formation system, changes in the air-fuel vapour ratio (real Λ) must be corrected by means of enrichment during cold starting and during the warm-up phase. This is done by increasing the petrol concentration during cold start in the spark-ignition engine and in the diesel engine by starting aids such as glow plugs which increase the temperature inside the combustion chamber resulting in easier combustion of diesel fuel.

3.1.3 Ignition in a S.I Engine

The ignition system is required to ignite the compressed mixture at a predetermined time, even under dynamic operating conditions which cause fluctuations in mixture movement and in air-fuel ratio. Combustion reliability, especially within the lean range ($\Lambda > 1$) and under extreme conditions, can be improved by positioning the spark plug in an area which provides good accessibility to the mixture and which also ensures orderly mixture movement. The ignition energy required is a function of the air-fuel mixture composition. An ignition energy of 0.2 mJ is required for petrol/air mixtures in the stoichiometric range. Rich or lean mixtures require up to 3 mJ per ignition.

3.1.4 Combustion Process in a S.I Engine

The initial thermal reaction which occurs between the addition of the ignition energy by the ignition spark and the exothermic reaction of the air-fuel mixture is termed the flame development phase. The rate is roughly constant over time, and depends solely upon the mixture composition. Hence, in relation to piston movement there is an ignition lag which increases and varies as the air-fuel ratio changes.

The course of heat release depends primarily upon the shape of the combustion chamber and the location where ignition occurs, and combustion time is primarily a function of the speed at which the flame propagates (combustion speed). The combustion speed is greatest at approximately 10% air deficiency i.e. an air fuel ratio $\Lambda=0.9$ and flame speed is 20 to 40 m/s.

Low fuel consumption and high efficiency are both promoted by short combustion times i.e. high combustion speeds, and by heat releases at the proper location with respect to the piston movement. The greatest heat release should occur shortly, (approximately 5^0 to 10^0 crankshaft) after top dead centre. If the majority of the heat is released too early, wall heat losses and mechanical losses (high peak pressure) are increased. If energy releases occur too late, the heat is used inefficiently and the exhaust gas temperature increases. The correct position for heat release must therefore be ensured for maximum efficiency.

The number of motor cars sold (both diesel and petrol) in the UK is predicted to rise as shown in Figure 3.1. From this figure it can be seen that the number of cars predicted to be sold in the year 2025 will be double the present (1995) number, resulting in increased congestion and pollution emissions. Therefore the use of alternative fuels, producing less harmful pollutants will be beneficial to the environment.

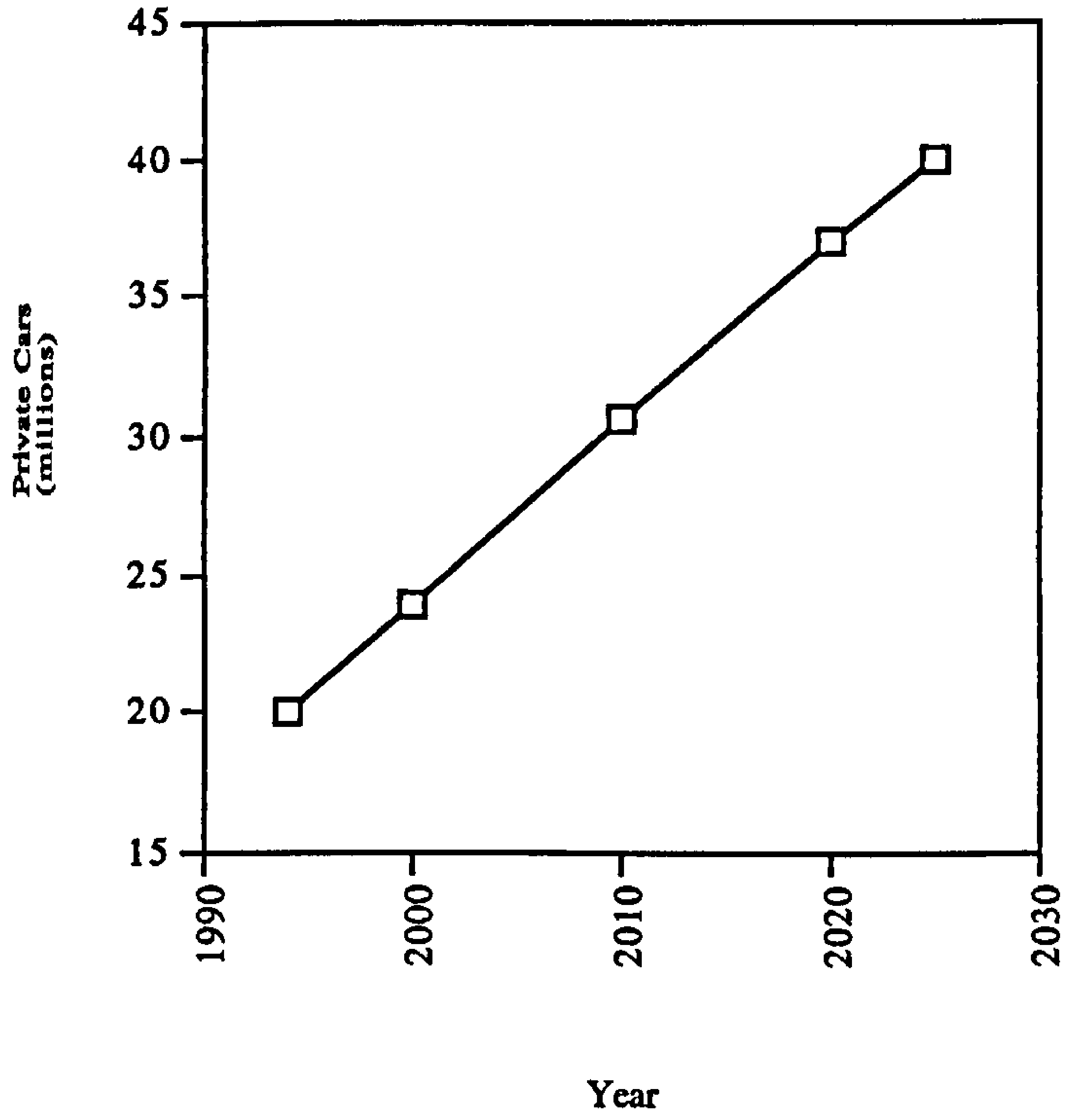


Figure 3.1 The Predicted Rise in the Number of Private Cars to be Sold in the U.K.

3.2 Diesel Engines

Diesel engines are perceived as an 'environmentally-friendly' alternative to petrol engines because they produce less carbon dioxide, fewer hydrocarbons and less nitrogen oxides. Diesel engines also provide more vehicle-miles per gallon. The sales of diesel engines have risen rapidly in the last 16 years as exemplified in Fig 3.2 [46].

In general the main advantages of diesel engines are:

1. The engines burn a wider variety of fuel (C_9-C_{11}).
2. Due to the higher temperatures (700°C-900°C) and pressures (35-55 bar) generated during combustion the engines are built to be much more durable.
3. Lower harmful NO_x and HC emissions[47].
4. Simpler design and maintenance i.e. a new diesel saloon car requires a service every 9000 miles as compared to an equivalent petrol engine car's service at 6000 miles.
5. Life of the engine is much longer as a consequence of 2 and 4 .

The main disadvantages of diesel engines are:

1. Higher original price than comparable petrol engine (diesel cars on average cost 10% more than equivalent petrol engine cars).
2. Noise at low speeds, i.e. at 1000 rpm, due to diesel knock.
3. High bulk and weight (1.5 times greater than a comparable petrol engine).
4. Problems of starting in cold weather, especially below 0°C.
5. Price of glowplugs.
6. Higher PM_{10} emissions.
7. More frequent oil change.

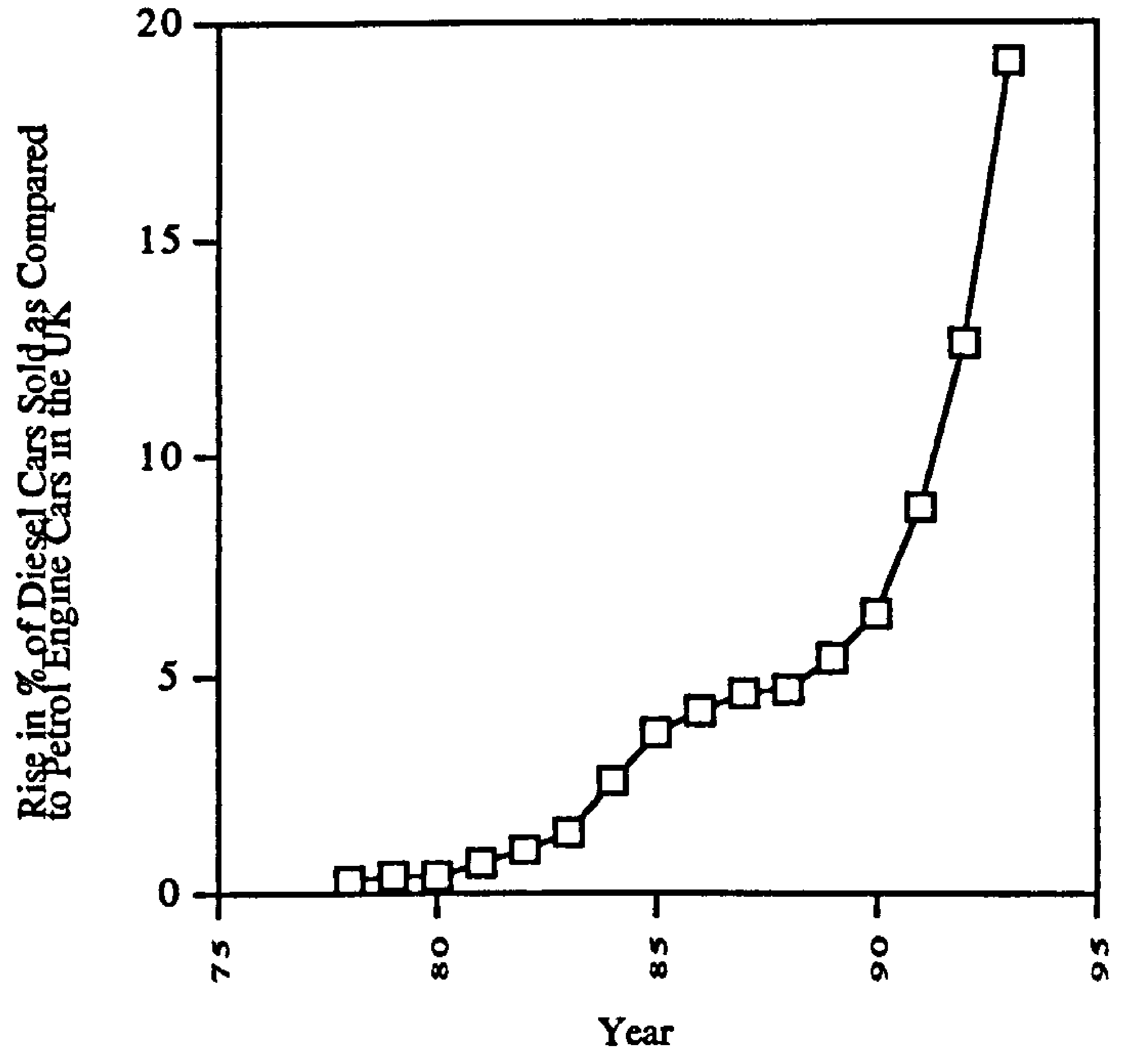


Figure 3.2 Rising Sales of Diesel Cars (as a percentage) Compared to Petrol Engined Cars in the U.K.

A diesel engine is a reciprocating-piston engine with internal air-fuel mixture formation and auto ignition. During the compression stroke, intake air is compressed to 35 to 55 bar, and its temperature is thereby increased to between 700°C and 900°C. This temperature is sufficient to cause auto-ignition of the fuel which is injected into the cylinders shortly before the end of the compression stroke and very near piston top dead centre. Subsequent combustion and utilisation of the induced combustion air, and thus the attainable mean effective pressure, depend to a great extent on mixture formation in the heterogeneous processes.

3.2.1 Mixture Formation in Diesel Engines

In heterogeneous mixtures, the air-fuel ratio (Λ) covers the area of pure air in the spray periphery ($\Lambda = \infty$) inward to pure fuel in the spray core ($\Lambda=0$). Because this zone occurs for every drop of injected mixture, load-control can be achieved via the amount of fuel introduced at mixture formation. This is termed mixture quality control.

As in the case of homogeneous mixtures, combustion takes place in the relatively narrow range of $0.3<\Lambda>1.5$. The mass transport necessary in order to generate these combustible mixtures takes place via diffusion and turbulence, and is brought about by the mixture formation energy sources described below and by the combustion process itself.

3.2.2 Kinetic Energy and Fuel Spray

The kinetic energy of the fuel spray is a function of the pressure drop at the nozzle orifice and, together with the spray cone determined by the nozzle geometry and the resulting fuel velocity, determines the air-fuel interaction areas and the droplet size range within this space. The spray energy is influenced by the delivery rate of the fuel injection pump and the flow cross-sections of the injection nozzle.

During the injection period, the injection conditions such as injection pressure, nozzle orifice area and injection rate may vary. Consequently the droplet size distribution at a given location in the spray may also change with time during the injection period. In addition, since the characteristics of the atomisation process differ between the spray core and the spray edge, and the trajectories of individual drops depend on their size, initial velocity, and location in the spray, the drop size distribution will vary with position within the spray.

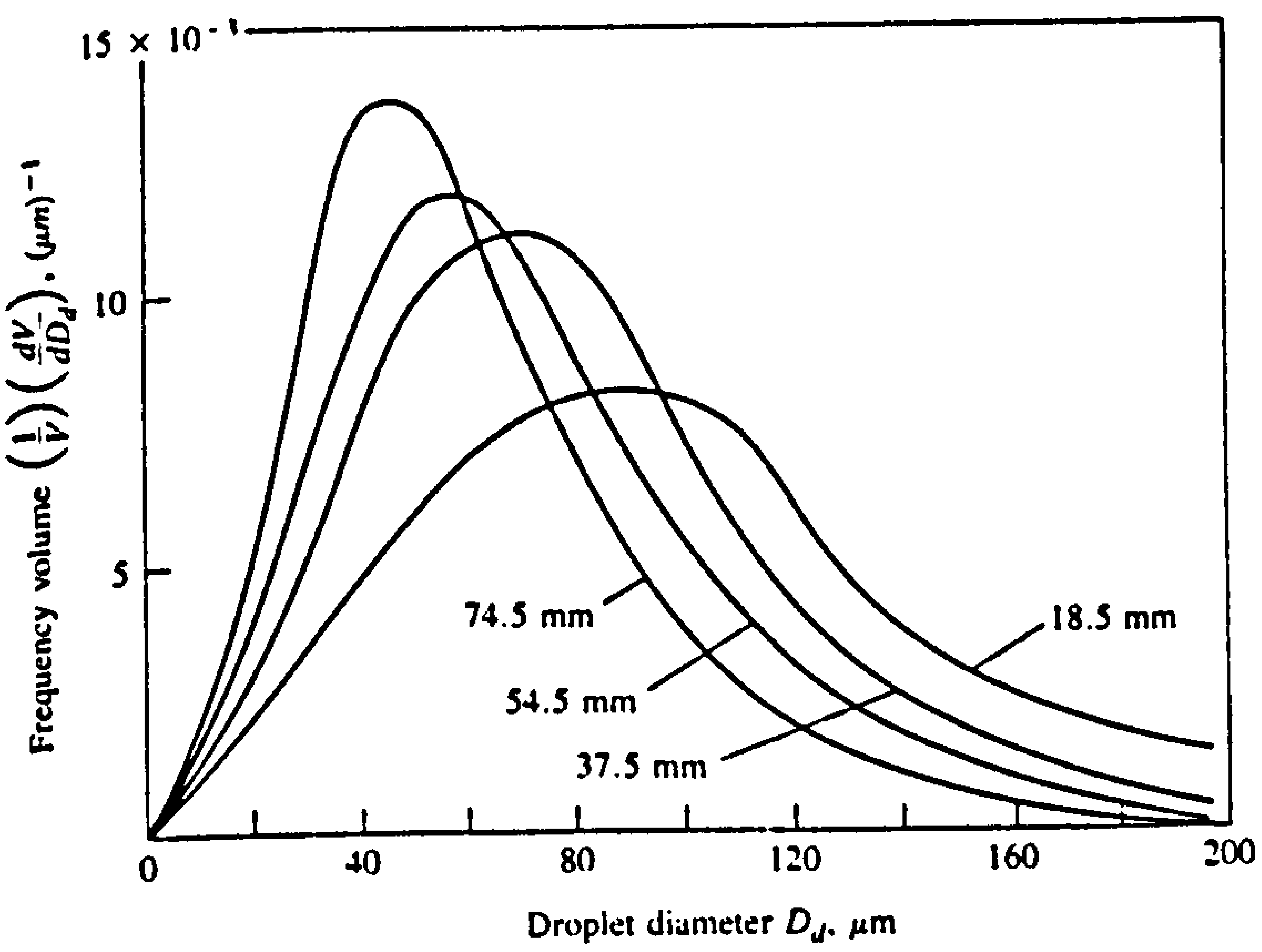


Figure 3.3 Droplet Size Distribution of Diesel Fuel at Given Radial Distances from Spray Axis

Figure 3.3 shows the droplet size distribution of a diesel fuel spray injected through a throttling pintle nozzle into quiescent room-temperature air at 11 atm. Nozzle opening pressure was 9.9 MPa and pump speed 500 rpm. Droplets were sampled at given radial distances from the spray axis[48].

3.2.3 Heat Energy

The heat energy generated by the combustion chamber walls and compressed air promotes the vaporisation of the injected fuel in the form of film vaporisation and in the form of drop vaporisation. Hence it is important in efficient fuel combustion.

3.2.4 Combustion Chamber Shape

The combustion chamber shape together with the piston movement can be used to generate turbulence (squish). Squish generated gas motion results from using compact combustion chamber geometry and occurs at the end of the compression stroke. The squish motion is used to enhance movement of the air-fuel mixture to improve combustion performance.

3.2.5 Orderly Air Movement (swirling action)

A movement imposed on the combustion air inside the combustion chamber, usually in the form of solid-body rotating flow, promotes the flow of air towards the fuel stream, and removes the combusted gases from the stream, if the direction of the fuel flow is roughly perpendicular to the direction of the swirling air and if the drops of fuel are in the process of being vaporised.

In the case of wall-film vaporisation the swirling motion of the air removes the vaporised layer from the wall and induces thermal separation of combustion gas. The micro-turbulence superimposed on the solid-body rotating flow causes rapid mixing of the fuel and air. The orderly "solid-body rotating flow" of the air is generated either by the special shape of the inlet port or by transferring a portion of the cylinder charge to a swirl chamber.

3.2.6 Direct injection (DI)

Direct injection refers to all processes in which the combustion chamber is not divided. Direct injection (DI) chambers in diesel engines can be further divided into three main types:

(i) Quiescent injection process.

(ii) Partial combustion in a swirl chamber.

(iii) MAN M system single-hole nozzle combustion process.

The above types of chamber are shown in Figures 3.4.1, 3.4.2 and 3.4.3 .

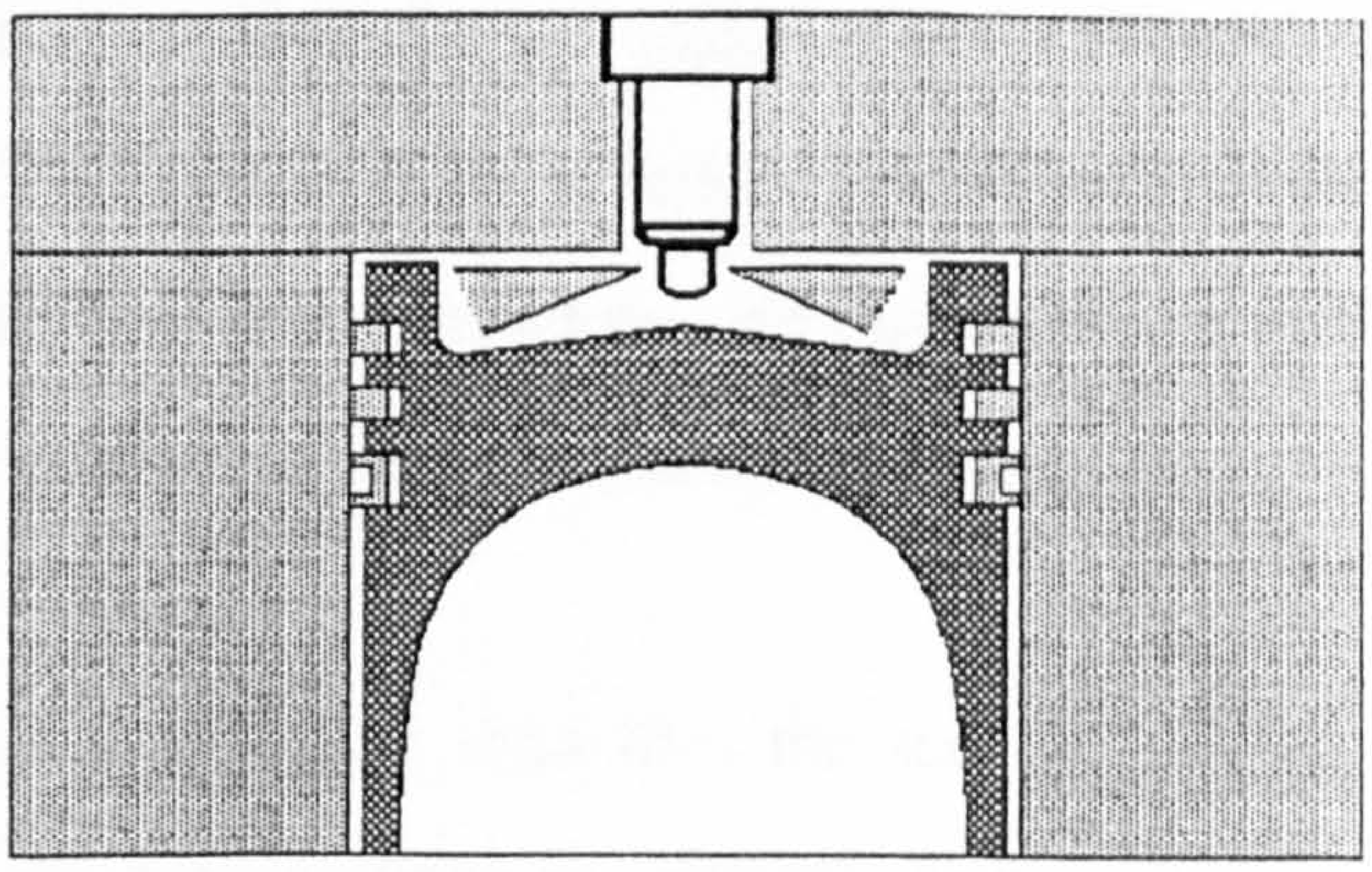


Figure 3.3.1 Quiescent injection process

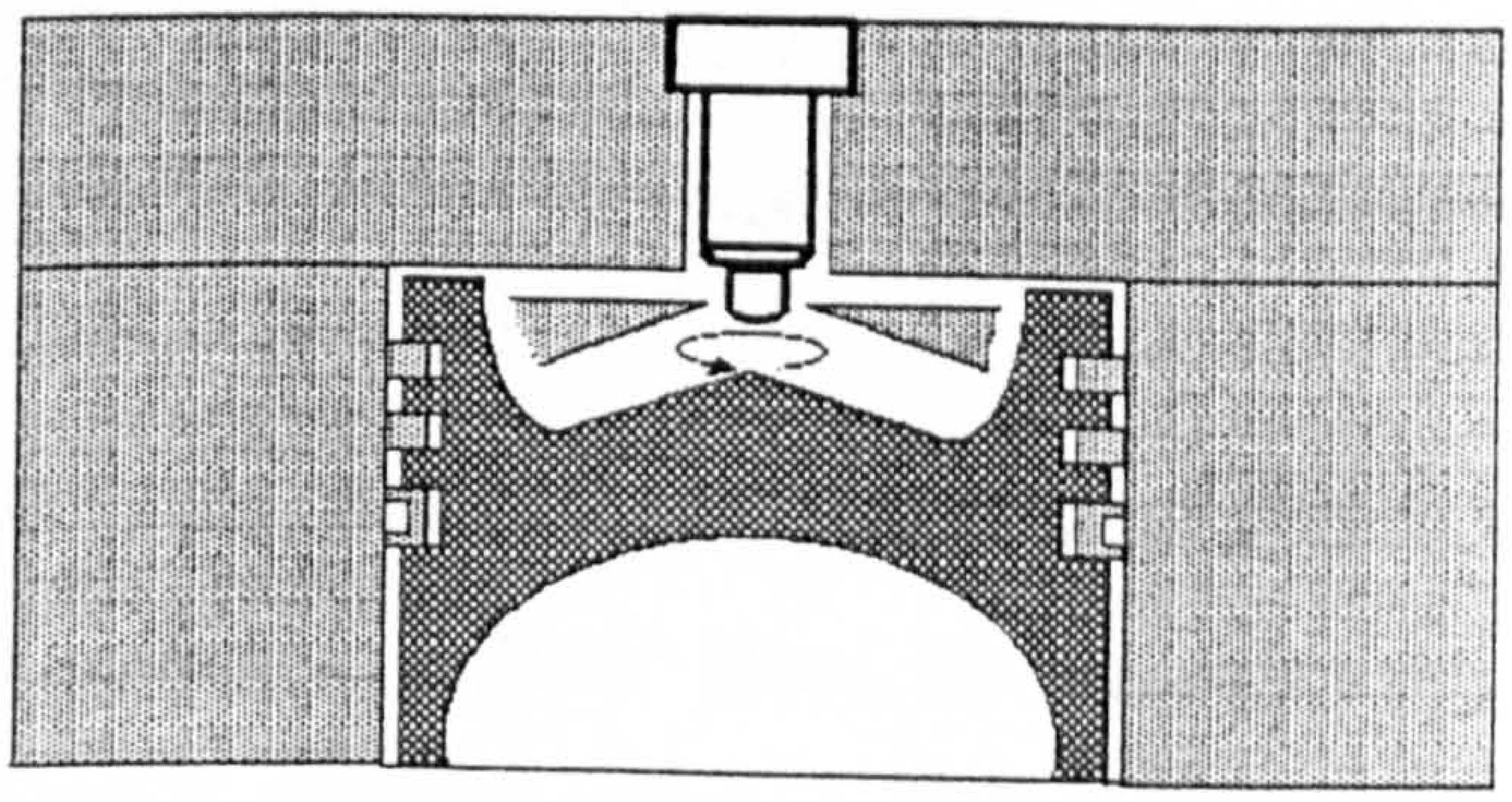


Figure 3.3.2 Partial combustion in a swirl chamber

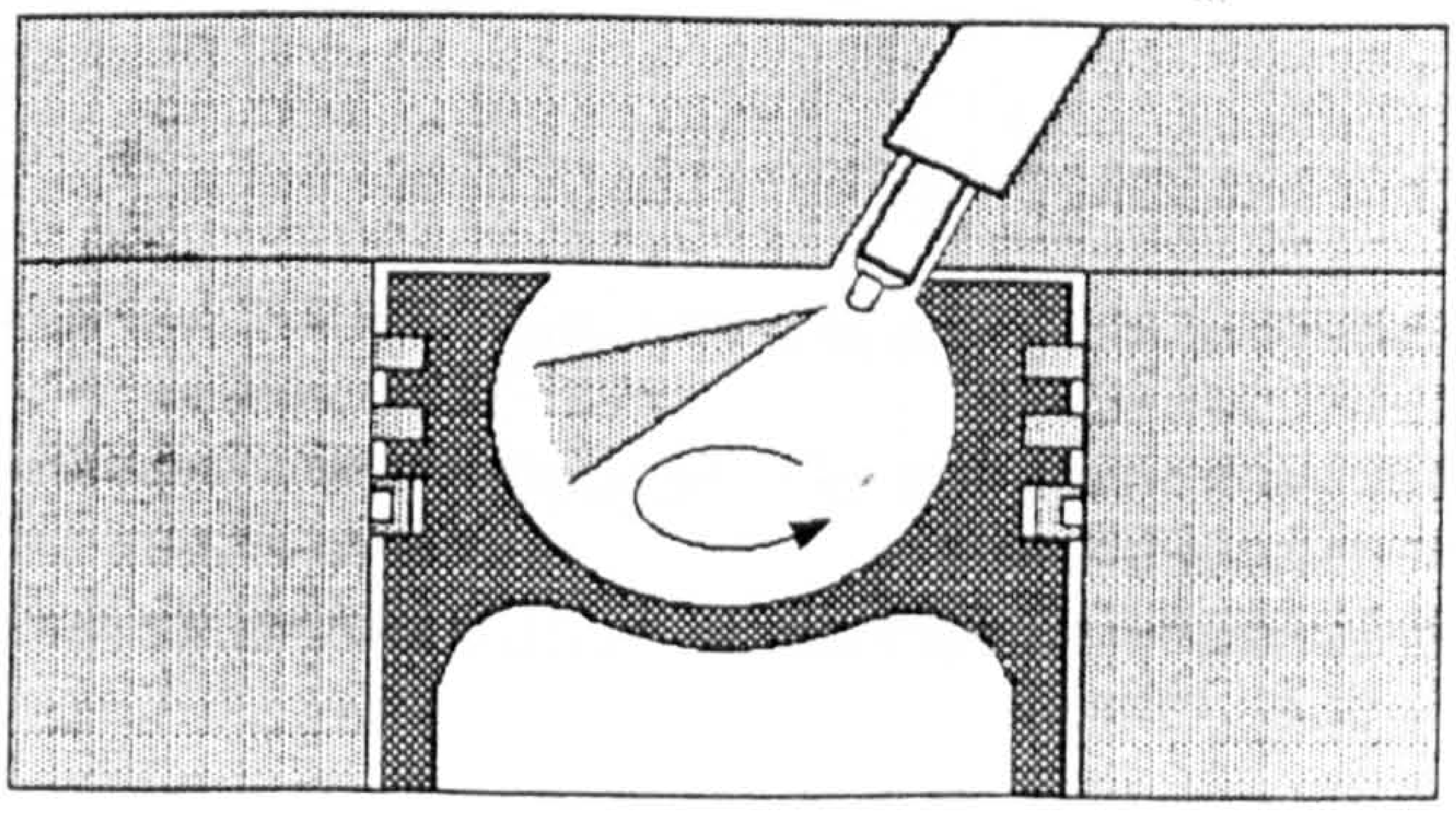


Figure 3.3.3 MAN M system single-hole nozzle combustion process

3.3 Combustion Process in Diesel Engines

In a diesel engine, the fuel is burned in a controlled manner, not explosively as in the petrol engine. In a petrol engine combustion is virtually instantaneous. In a diesel engine, ignition does not take place immediately the fuel is injected into the combustion chamber. There is an interval between the fuel injection and self-ignition; this is termed the ignition delay period. The ignition delay affects the performance of the engine. The engine is hard to start if the ignition delay is too long and this results in diesel knock. The shorter the ignition delay the smoother the performance of the engine.

The start of injection (and thus the start of mixture formation) and the start of the exothermic reaction (start of ignition) are separated by a certain period of time, called the ignition lag. This lag depends upon the ignition quality of the fuel (Cetane number in diesel fuels), the compression ratio and thus the final temperature, the type of the fuel management selected and the load condition of the engine .

The combustion which begins with the start of ignition, can be subdivided into two phases. In the first "premixed flame" phase, the fuel injected prior to the start of the ignition and mixed with air, combusts. The fuel which is injected after the start of ignition combusts in a "diffusion flame".

That portion of the combusted fuel which burns as a very rapid premixed flame is primarily responsible for the pressure increase, and thus is the primary cause of combustion and the generation of oxides of nitrogen. The slower burning diffusion flame is the primary source of soot and, since combustion is incomplete, of unburned hydrocarbons.

The release of heat in a diesel combustion process is thus a direct function of the type of mixture formation, and can be varied over a wide range by changing the above-mentioned parameters.

The two-stage combustion cycle, which is characteristic of the auxiliary chamber process allows the combustion process to be additionally controlled via the selection of the appropriate cross-sections in the connection throats between the auxiliary chamber and the main combustion chamber.

These processes differ from one another primarily with regard to the initial combustion phase. The high conversion peak of the air-distributed direct fuel injection process at the start of the combustion can be reduced by applying the fuel to the wall of the chamber, and even more greatly reduced via two-stage combustion in the auxiliary chamber process; combustion efficiency is however reduced.

3.4 Combustion Problems and Limits

Because the fuel injected into a diesel engine ignites spontaneously, the ignition quality of the fuel must be high; i.e. it must have a Cetane Number in the range of 45 to 50 . In spite of a high compression ratio, ignition problems can occur during starting, particularly when starting from cold, because at the low cranking speed of the engine, compression does not begin until significantly after BDC (Bottom Dead Centre), when the intake valves close. The effective compression ratio, and thus the compression temperature, are therefore greatly reduced. In addition cold engine components promote the flow of heat out of the compressed air (polytropic exponent : $1.1 < n > 1.2$). Mixture formation is additionally unsatisfactory at low speed engines (large fuel drops), and air movement is low.

A longer vaporisation time (i.e. earlier injection) and an increased fuel quantity which is significantly greater than the full-load quantity (i.e. supply of a greater quantity of low boiling fuel) can only partially solve the starting problem, because the higher-boiling fuel constituents leave the engine in the form of white or black smoke. Starting aids which increase the temperature, such as the glow plugs or flame starting systems, are therefore necessary, especially in the case of small engines .

Because a significant portion of the mixture formation process occurs during combustion in heterogeneous processes, local concentrations of over-rich mixture occur in the diffusion flame, thereby leading to an increase in the emission of black smoke, to a certain extent even with moderate excess air. The optimum air-fuel ratio is one which leads to smoke emissions which border on the legal limit . Divided chamber engines which emit smoke at the legal limit operate with excess air of 10 to 25%, whereas this value is 40 to 50% in direct-injection diesel engines. It should be noted that large-volume diesel engines must also run with a significant amount of excess air, usually 15 to 30 %, for reasons of thermal component load.

A soot-free diesel engine cannot be designed because heterogeneous combustion always produces soot. Work is therefore proceeding on the development of regenerative soot filters which collect the soot for subsequent combustion.

Auto-ignition processes are, because the vaporised fuel mixed with the air burns abruptly, characterised by noisy combustion with less combustion emissions. The emissions of noise can be reduced by decreasing the ignition lag (e.g. by heating of the intake air, supercharging, or increasing the compression) and/or by reducing the amount of fuel supplied to the engine during the ignition lag (throttling pintle nozzle).

A characteristic of diesel engines is, the so called "diesel knock" which is different from noisy combustion. Diesel knock is generated in the middle lower regions of the diesel engine map, and is caused by problems in the mixture formation system, such as chattering or carbon-encrusted injection nozzles, and is audible as a pulsating, metallic noise.

Because of the high compression required in a diesel engine for starting and for noise reduction purposes, and the high peak pressures caused by auto ignition, the diesel engine needs to be a comparatively strong power plant. Because heterogeneous processes must also occur with excess air at full load, diesel engines in general have a low power density.

In the case of the spark ignition (SI) engine, the fuel (gasoline) is vaporised in advance, between the carburettor and the combustion chamber, where it forms a gaseous mixture with air in the appropriate ratio (expressed by air-fuel weight ratio). This gaseous mixture is induced into the combustion chamber where it is ignited by an electric spark. Conversely, with the compression ignition (CI) engine, fuel is injected into the combustion chamber in the form of fine droplets. These droplets subsequently evaporate from the surfaces in the hot atmosphere inside the combustion chamber to form a combustible fuel-air gas mixture that ignites automatically. With either type of internal combustion engine, the liquid fuel must vaporise before it can ignite. Hence correct volatility is one critical property of the fuel.

3.5 Composition of Petroleum

Any petroleum product, whether it is crude oil, petrol, lubricating oil, or fuel oil, is essentially composed of only two elements, carbon and hydrogen plus small amounts of undesirable inorganic elements such as sulphur, nitrogen and oxygen. Minute impurities such as aluminium, calcium, nickel, sodium and vanadium may also be present in amounts between 0.015% to 0.05%. The hydrocarbons are sub-divided into four main classes; paraffinic, aromatic, naphthenic and olefinic as shown in Table 3.1.

Paraffinic hydrocarbons	Chemical Formula
ethane	C_2H_6
propane	C_3H_8
pentane	C_5H_{12}
undecane	$C_{11}H_{24}$
ceryl	$C_{30}H_{62}$
Aromatic hydrocarbons	
benzene	C_6H_6
xylene	C_8H_8
toluol	C_7H_8
cymol	$C_{10}H_{14}$
Naphthenic hydrocarbons	
cyclobutane	C_4H_8
cyclohexane	C_6H_{12}
Olefinic hydrocarbons	
ethylene	C_2H_4
propylene	C_3H_6
butylene	C_4H_8
melene	$C_{30}H_{60}$

Table 3.1 Components of Petroleum

3.5.1 Basic Refining of Crude Oil

Basic refining of crude oil results in typical fractions as shown in Table 3.2 .The energy output of different fuels is shown in Table 3.3.

Fraction	No. of carbon atoms
Gas	1-5
Petrol	6-10
Kerosine	11-16
Light distillate	13-17
Heavy distillate	18-32
Residual	28-70

Table 3.2 Typical Fractions Produced from Refining of Crude Oil.

Fuel	Chemical Formula	Lower Calorific value kJ/kg
Petrol	C_8H_{17}	43710
Gas Oil	C_9-C_{11} H_{20-24}	42410
Light Fuel Oil	$C_{12}H_{26}$	40590
Medium Fuel Oil	$C_{13}H_{28}$	39920
Heavy Fuel Oil	$C_{14}H_{30}$	39690
Methane	CH_4	49350
Propane	C_3H_8	45760
Butane	C_4H_{10}	45130
Natural Gas	C_2H_6(16%) CH_4(83%)	50090

Table 3.3 Typical Energy Output of Different Fuels

Any replacement fuel must burn to give a similar energy release per unit mass combusted in air. Diesel fuel contains hydrocarbons as shown in Table 3.4 .

Saturates	81.1%
Olefins	0.0%
Aromatics	18.9%

Table 3.4 Typical Hydrocarbon Type Constituents of Diesel Fuels

The earliest processes for the fractionation of crude oil were simple and inefficient. They involved heating crude oil and condensing the vapour from various levels of a fractionating tower. Table 3.2 shows the typical fractions produced from refining crude oil. The cylindrical tower was usually 1.2 to 1.8 m tall and provided with bubble trays. The lightest material condensed at the top, the heaviest at the bottom.

This 'straight-run' method is referred to as topping or skimming. Modern refinery processes are much more efficient and complex. The initial distillation process is followed by further refining by any of four most important methods, depending upon the end product required. These comprise thermal cracking, catalytic cracking, distillation or visbreaking as shown in Figure 3.5 .

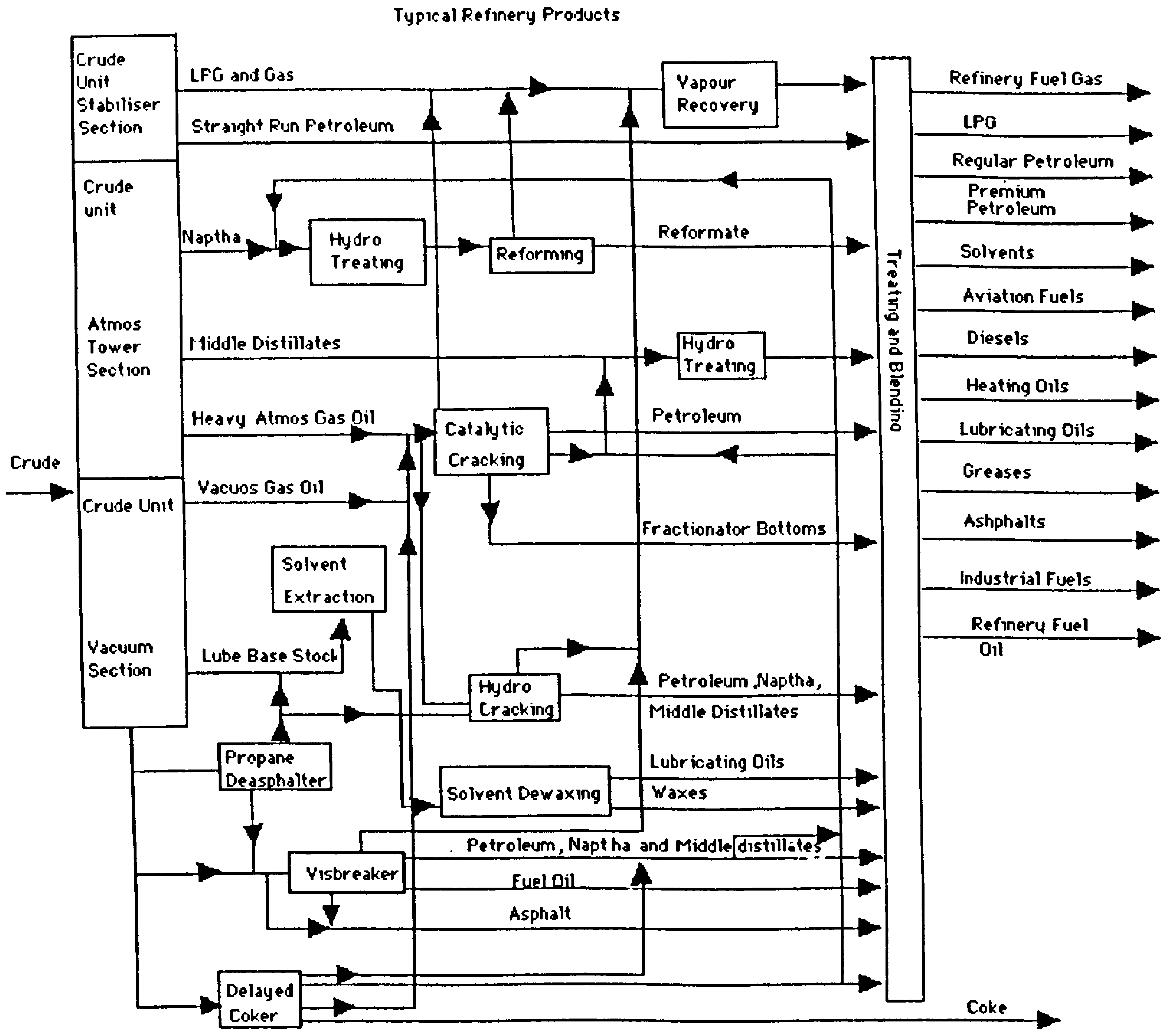


Figure 3.5 Typical Poduct-Outputs of a Modern Oil Refinery

3.5.2 Thermal Cracking

Thermal cracking is essentially the same as the straight run refining process, except that higher temperatures and pressures are used. The thermal cracking process can e.g. be divided into two types, liquid phase cracking and vapour phase cracking, and the major products usually obtained are petrol, diesel and residual fuel.

3.5.3 Catalytic Cracking Process

After the first step in refining, crude oil can be passed through the catalytic cracking process. The catalysts are contained in the reactor (e.g. sulphuric acid, hydrofluoric acid, anhydrous aluminium chloride and oxides of metals such as vanadium, nickel, aluminium). Depending upon the initial oil feed, the catalyst used, and the operating conditions the products may be either petrol or diesel and slurry oil.

3.5.4 Vacuum Distillation Process

After the straight run oil process, the oil is passed through a vacuum distillation at high temperature. This enables the heavy distillate to be recovered from the crude oil. This distillate is usually used as the stock for a catalytic cracking process.

3.5.5 Visbreaking Process

The visbreaking process uses the feed stock from the vacuum distillation process. The reaction is similar to that in thermal cracking but the lower temperatures and pressures result in high quality, and higher proportions of petrol, jet fuel and diesel fuel.

3.6 Viscosity of Liquids

The viscosity of a liquid is a measure of its resistance to flow, or a measure of the liquid's, internal friction. It is a complex function of temperature, shear rate, pressure and time. Viscosity can be envisaged as that physical property of a fluid that offers resistance to relative motions of adjacent planes, i.e. it corresponds to an internal fluid friction produced by the molecules of a lubricant as they flow past one another. The greater the motion the greater is the internal resistance offered by the lubricant.

Viscosity can be defined as the ratio of the stress required to shear the liquid to the rate at which it is sheared. The viscosity of an ideal, or Newtonian, fluid shows a linear function of shear rate with shear stress as in Figure 3.6 .

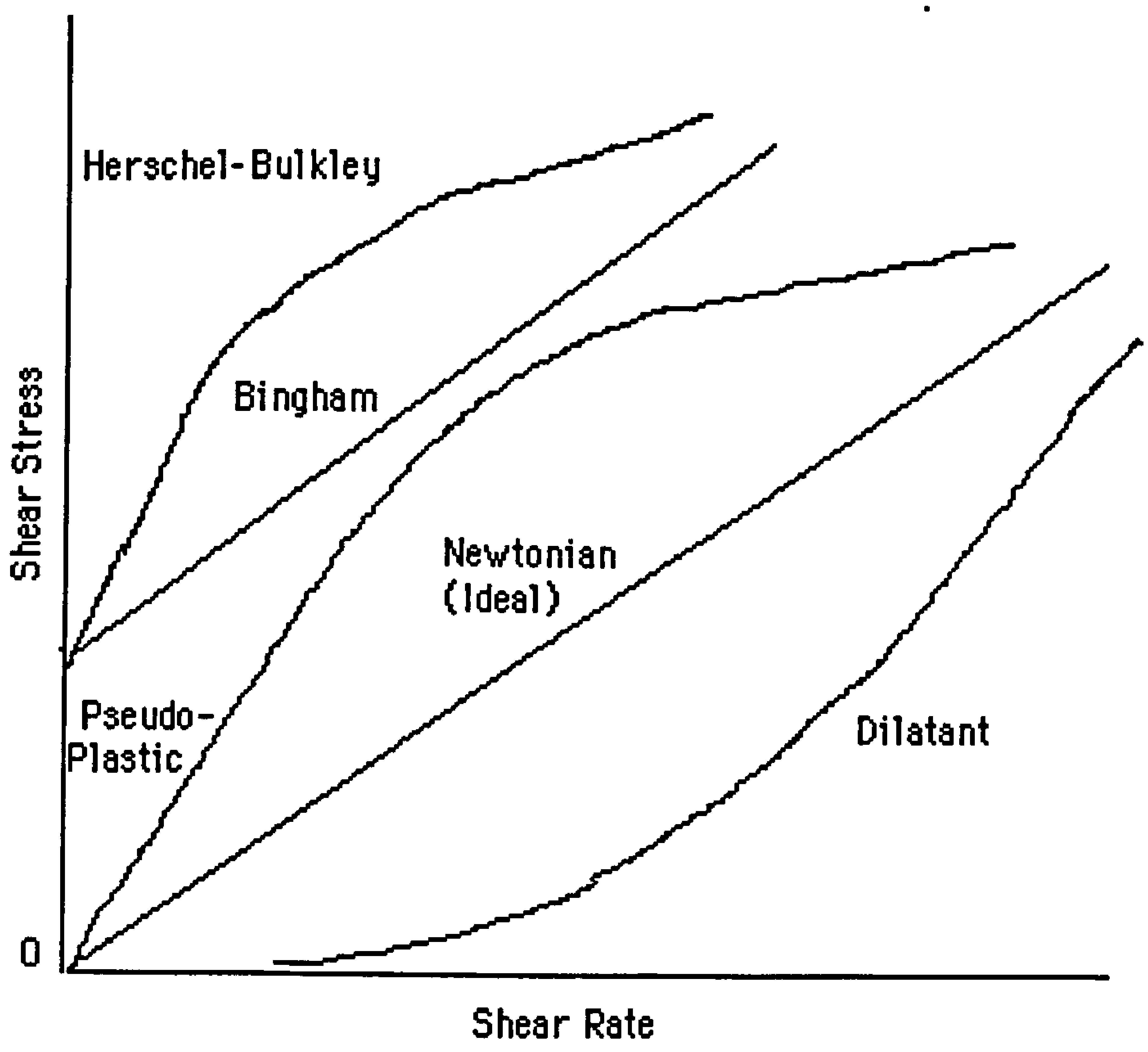


Figure 3.6 Generalised Fluid Flow Behaviour

Fluids that become less viscous the more rapidly they are sheared are termed thinning or pseudoplastic fluids[49]. Most polymers behave as pseudoplastics. The shear rate at which the viscosity is measured must be quoted. Other materials, e.g. sewage, that become stiffer the faster they are sheared are termed dilatant fluids. Materials filled with fibres exhibit a very high viscosity at low shear rates, and a certain minimum value of shear stress is needed before the material will move. The initial stress is termed the yield stress. If, after the yielding, the material behaves as pseudoplastic, it is known as a Herschel Bulkeley fluid. If the material flows in a Newtonian manner after yielding, it is termed a Bingham fluid.

The viscosity of most petroleum oils and vegetable oils follows Newtonian (ideal) behaviour. Viscosity is dependent upon temperature and pressure. When an oil is heated, the viscosity naturally decreases. Low viscosities enable easier flow and pumping of oil from fuel or storage tank and in utililisation. Control is obviously required however where lubricity is a factor.

3.7 Heat of Combustion of Fuel Oil

The heat of combustion of a fuel oil is determined using an oxygen bomb calorimeter. The bomb comprises a metallic cylinder, approximately 17.8 cm high and 8.9 cm in diameter. A known amount of fuel is completely burned in the presence of oxygen. The heat generated by combustion is absorbed by a known volume of water in which the bomb is immersed. The amount of heat is obtained by determining the temperature rise of the water and converting this to MJ/kg.

3.7.1 Flammable Range

A concentration of a flammable vapour in air (or a lower concentration in oxygen) below which a flame will not propagate. This concentration is termed the Lower Flammable Limit. Conversely the vapour concentration can be made so rich that there is insufficient oxygen to support combustion; this corresponds to the Upper Flammable Limit. Between the two limits comprises the flammable range within which any mixture of the specific vapour will burn when ignited in air (or oxygen). Flammable limits of hydrocarbon fuels in air are determined by a specific test method.

3.7.2 Flash Point of Hydrocarbon Fuels

When a liquid fuel vaporises to form a uniform gaseous mixture with air, the concentration of the fuel mixture increases with an increase in the liquid temperature, and finally reaches the lower flammable limit. The temperature at this point is termed the flash point. The flash point maybe determined in a closed-cup, ASTM D-93 58T test method, or an open-cup, ASTM D93- IP34 test method. It is taken as the temperature at which a flash of flame of specific size occurs, in repeat tests, when a pilot flame is inserted into the vapour above the liquid surface in a standard apparatus. To maintain burning, the fuel must be further heated to the fire point, generally a few degrees higher.

3.7.3 Autoignition Temperature

Autoignition is the term used for a rapid combustion reaction which is not initiated by any external ignition source. The autoignition of a gaseous fuel-air mixture occurs when the energy released by the reaction as heat is larger than the heat lost to the surroundings; as a result the temperature of the mixture increases, thereby rapidly accelerating, due to their exponential temperature dependence, the rates of reaction involved. The autoignition process is complex, i.e. the reaction is not a single- or even a multi-step process; the actual chemical mechanism consists of a large number of simultaneous, interdependent chain reactions[50].

3.7.4 Sulphur in Fuels

A high sulphur content in diesel fuel is likely to increase corrosion and engine wear, and to promote formation of tarnish on piston areas as well as sludge in the crankcase. Sulphur content can be determined by the classical bomb method. The test is done using ASTM D-129, in which the sample is burned under pressure in oxygen and the sulphur content recovered as barium sulphate for weighing.

3.7.5 Cetane Number of Fuels

The Cetane Number is used to express the ignition quality of a diesel fuel. The readiness of a diesel fuel to ignite is measured by determining the cetane number, analogous to the octane number of petrol, using test ASTM D-613. The cetane rating is the most important specification in the evaluation of the diesel fuel oil.

The cetane number scale is defined by blends of two pure hydrocarbon reference fuels. Cetane (*n*- hexadecane, $C_{16}H_{34}$), a hydrocarbon with high ignition quality, represents the top of the scale with a cetane number of 100. An isocetane, heptamethylnonane (HMN), which has a very low ignition quality, represents the bottom of the scale with a cetane number of 15 (In the original procedure [α]-methyl naphthalene with a cetane number of zero represented the bottom of the scale. Heptamethylnonane (HMN), a more stable compound has replaced it), thus cetane number (CN) is given by

$$\text{CN} = \text{percent } n\text{-cetane} + 0.15 \times \text{percent HMN}$$

The engine used in cetane number determination is a standardised single-cylinder, variable compression ratio engine with special loading and accessory equipment and instrumentation. The engine, the operating conditions, and the test procedure are specified by ASTM Method D613. With the engine operating under ASTM Method D613 with the fuel, whose cetane number has to be determined, the compression ratio is varied until combustion starts at TDC: i.e., an ignition delay period of 13^o (2.4 ms at 900 rpm) is produced. The above procedure is then repeated with reference fuel blends. Each time a reference fuel is tried, the compression ratio is adjusted to give the same 13^o ignition delay. When the compression ratio required by the actual fuel is bracketed by the values required by two reference blends differing by less than five cetane numbers, the cetane number of the fuel is determined by interpolation between the compression ratios required by the two reference blends.

The ignition quality of a diesel fuel is improved by a higher content of normal paraffins. Because combustion is self-initiated in the diesel engine, the quality most required for a diesel fuel oil is good ignitability or a high cetane number. The cetane number of the hydrocarbons decreases in the order n-paraffin > naphthene ~ olefins > i-paraffins > aromatics.

3.7.6 Heating Values of Fuels

The heating values of fuels can be calculated from the values of the heats of formation and heats of vaporisation tabulated in the literature. For a fuel of formula C_mH_n. the higher heating value (HHV) is calculated from the combustion equation as follows:

$$C_mH_n\,(g) + (m+1/2\,n)\,O_2\,(g) \text{----->}\, mCO_2\,(g) + 1/2n\,H_2O\,(l)$$

$$-\Delta H = \Delta H' \text{ --- } 393.4m - 142.8n \quad kJ/g\ mol$$

where ΔH of the fuels is HHV, ΔH' is the heat of formation of the reactants, and the contents of heats of formation of the products.

The mechanisms of combustion reactions of hydrocarbon fuels are very complex and are affected by many different factors. Although different fossil fuels (i.e. petrol, diesel and aviation fuel) are used in internal combustion engines, the fuels decompose before the combustion starts and the oxidation occurs through some basic forms. The basic substances are hydrogen, carbon monoxide, gaseous hydrocarbons, and solid carbon. Each of these is called a basic fuel of combustion.

3.8 Basic Fuels of Combustion

The combustion routes of the four basic fuels are also very complicated and many unknown factors remain to be identified. The probable, and most simplified, reaction mechanisms are shown below.

3.8.1 Hydrogen Basic Fuel Combustion

For the hydrogen basic fuel, hydrogen radicals are formed on combustion either by thermal dissociation of H_2 as shown in Equation 3.1 or through reaction of oxygen as shown in Equation 3.2.

$$H_2 \text{------>} 2H\cdot \qquad \text{Eqn. 3.1}$$

$$H_2 + O_2 \text{----->} HO_2\cdot + H\cdot \qquad \text{Eqn. 3.2}$$

The H· then reacts with O_2 to form OH·; the reaction advances to Equations 3.3, 3.4, and 3.5.

$$H\cdot + O_2 \text{---->} HO_2\cdot \qquad \text{Eqn. 3.3}$$

$$HO_2\cdot + H_2 \text{----->} H_2O + OH\cdot \qquad \text{Eqn. 3.4}$$

$$OH\cdot + H_2 \text{---->} H_2O + H\cdot \qquad \text{Eqn. 3.5}$$

The H· radical in Equation 3.5 becomes available for use as in Equation 3.3 and continues the chain reaction. Once all the fuel is consumed, the radicals react with each other and terminate.

3.8.2 Carbon Monoxide Basic Fuel Combustion

Because it does not itself form radicals, the combustion of carbon monoxide basic fuel, requires the presence of radical forming materials. When water is present the reaction route is as shown in Equations 3.6, 3.7, and 3. 8.

H_2O ------> $H\cdot + OH\cdot$ Eqn. 3.6

$CO + OH\cdot$ -----> $CO_2 + H\cdot$ Eqn. 3.7

The $H\cdot$ reacts with oxygen to form $HO_2\cdot$ in eq. 3.3, which then reacts with CO as

$HO_2\cdot + CO$ ----> $CO_2 + OH\cdot$ Eqn. 3.8

The $OH\cdot$ in Equation 3.8 returns to eq. 3.7 and repeats the chain reaction. When all the CO has been consumed, the reverse of Equation 3.6 occurs in which the radicals disappear completing the reaction.

3.8.3 Hydrocarbon Basic Fuel Combustion

Combustion of hydrocarbons occurs when they are thermally decomposed to become gaseous hydrocarbons. The simplified first step with basic fuel methane is as shown in eq. 3.9. Because the carbon-hydrogen bond of methane has a greater dissociation energy than the carbon-carbon bond, the first step in methane combustion is postulated to be cleavage of H from CH_4 to form products as shown in Equation 3.9 and 3.10.

$CH_4 + O_2$ ---------> $CH_3\cdot + HO_2\cdot$ Eqn. 3.9

$CH_3\cdot + O_2$ -------> $CH_2O + OH\cdot$ Eqn. 3.10

Because of its high activation energy, the formaldehyde is thought to form CO_2 and H_2O via Equations 3.10 and 3.11.

$CH_2O + HO_2\cdot$ ------> $CHO\cdot + H_2O_2$ Eqn. 3.11

The CHO decomposes to become CO and H·;

$CHO\cdot$ ----> $CO + H\cdot$ Eqn. 3.12

This CO then reacts with $OH\cdot$ in Equation 3.7 to form CO_2 and $H\cdot$. The $H\cdot$ radical reacts with oxygen to become $HO_2\cdot$ which reacts as in Equation 3.11, or with H_2O_2 as in Equation 3.13 .

$H\cdot + H_2O_2$ -------> $H_2O + OH\cdot$ Eqn. 3.13

The $OH\cdot$ produced as in Eqn. 3.13 again reacts with the initial methane reactant to yield $CH_3\cdot$ and continues the chain reaction:

$CH_4 + OH\cdot$ -------> $CH_3\cdot + H_2O$ ....Eqn. 3. 14

3.8.4 Carbon Basic Fuel Combustion

A simplified route of carbon combustion is that oxygen is first adsorbed onto the surface of the solid carbon to form CO; this CO further reacts with oxygen to form CO_2 which is desorbed. Some CO is also desorbed; this reacts with oxygen as before to give CO_2. The processes of adsorption and desorption are repeated, until one of the reactants is exhausted. As a consequence amorphous carbon with a large surface area per unit mass such as charcoal burns well, whilst crystallised carbon such as graphite does not easily adsorb oxygen or burn well.

In the intake process of the diesel engine, only air is inducted and then adiabatically compressed, using a high compression ratio (CR) in the range of 13-22. Into this compressed air at temperatures as high as 500-650°C and high pressures (35-42 atm), the fuel (diesel fuel oil) with an ignition point of 300-400°C is atomised, giving rise to constant-pressure combustion from self-ignition. During this time work is done by expansion, as combustion occurs slower than in SI engines because it is constrained by the rate of injection of the fuel. The objectives to be achieved from an internal combustion engine are ideally high power and low fuel consumption with low levels of emission of pollutants.

Work done by the engine during one cycle is the product of the chemical energy released by the combustion of the fuel and the thermal efficiency of the engine. Engines are at most only 35% efficient and most of the chemical energy is lost as heat, friction and resistance; the larger these quantities are, and the higher the rotative engine speed, the more power the engine loses.

At the same CR, the higher the air-fuel ratio and the more air-rich and fuel-lean the combustion, the higher the thermal efficiency becomes. However in the case of an SI engine, a slightly higher fuel-rich condition than the stoichiometric mixture (the minimum air-fuel weight ratio required for complete combustion of the fuel) enables the chemical energy to be effectively utilised to the maximum and brings about maximum power. However, the quantity of the pollutants discharged from the engine is considerably affected by the air-fuel ratio. Although a fuel-rich mixture maximises power, the engine is generally operated under the conditions of air-rich and fuel-lean combustion, especially to prevent incomplete combustion, which reduces efficiency and increases pollutant emissions.

As the CR of the SI engine increases, various abnormal combustion conditions are expected to occur and decrease the thermal efficiency of the engine. Knocking is a typical abnormal combustion condition; it varies considerably with the composition of the fuel. In the CI engine, the ignition quality of the fuel is quite contrary to that for an SI engine. Thus a fuel of higher cetane number is required, but which has a low octane number, and is readily ignitable.

Diesel knock is one type of abnormal combustion behaviour which arises when the speed of the CI engine is increased to gain power. In a low speed engine following the typical diesel cycle, ignition occurs almost concurrently with the atomisation of the fuel and leads to constant-pressure combustion. In a high speed diesel engine however, because the ignition delay (7-30 ms) becomes considerable, a large amount of fuel ignites at the same time. This accounts for diesel knock which is produced by high irregular pressure.

Ignition delay is basically influenced by the ignitibility of the fuel. This is related to various phenomena such as fuel atomisation and vaporisation which occur during the few milliseconds, and to self-ignition and combustion. The oxidation reactivity is important as well as physical properties such as viscosity, heat of vaporisation and surface tension of the fuel.

3.9 Diesel Engine Exhaust Gases

Complete combustion of hydrocarbons with oxygen in the air, will produce only carbon dioxide and water. However in an internal combustion engine (I.C.) incomplete combustion of hydrocarbon fuel occurs, even if excess air is supplied. Hence, soot, incomplete oxides of hydrocarbons, aldehydes, carbon monoxide and carbon dioxide also form as well as oxides of nitrogen and sulphur. For example SO_2 and SO_3 result from the combustion reactions of sulphur compounds present in the fuel. The oxides of nitrogen, NO and NO_2 are generated because the nitrogen present in the air reacts with oxygen at high temperatures in the engine.

3.9.1 Combustion Chamber

The design of the combustion chamber has a critical effect upon the level of emission of exhaust gases.

Engines which have divided combustion chambers emit smaller amounts of oxides of nitrogen than do engines with direct fuel injection. However, engines with direct fuel injection, are more fuel-efficient. Careful control of air movement in the combustion chamber with respect to fuel sprays promotes the mixing of fuel and air, thereby increasing the efficiency of fuel combustion. A sufficiently high temperature is required to reliably ignite the mixture, generally in the range of 500 to 650^{o}C.

3.9.2 Fuel injection

Start of injection, injection-sequence characteristics and fuel atomisation have an effect on toxic emissions of oxides of nitrogen. Over-retarded injection increases the emissions of hydrocarbons. Deviation of the start of injection from the nominal value by 1' of crankshaft angle can increase the emissions of NO_X or HC by upto 15%[51]. This very high sensitivity requires that the start of the injection process be precisely set.

Fuel injected into the combustion chamber after the combustion phase may reach the exhaust system unburned, and hence increase the hydrocarbon emissions. Post-injection must therefore be prevented. Finely- atomised fuel promotes the mixing of fuel and air, and reduces the emissions of hydrocarbons and soot (particulates). Fine atomisation i.e. generating droplets in the range 20 μm to 110 μm is achieved by high injection pressure and the spray orifice geometry.

3.9.3 Products of Combustion

Complete combustion produces carbon dioxide and water. Incomplete combustion produces unburned hydrocarbons: C_nH_m (paraffins, olefins, aromatic hydrocarbons) and also partially-burned hydrocarbons such as $C_nH_m.CHO$ (aldehydes), $C_nH_m.CO$ (ketones), $C_nH_m.COOH$ (carboxylic acids) and CO (carbon monoxide). It also produces thermally-cracked products and derivative products such as; C_2H_2, C_2H_4, H_2 (acetylene, ethylene, hydrogen etc.), C(soot) and polycyclic hydrocarbons.

3.9.4 Main Pollutant Gases from Diesel Engine Exhaust

The main pollutant gases from the exhaust are; hydrocarbons (uncombusted), incomplete oxides of hydrocarbons, CO_2, CO, soot and NO_x as by-products of combustion

3.9.4.1 Hydrocarbons (Uncombusted)

Uncombusted hydrocarbon fuels and low molecular weight hydrocarbons are formed by thermal decomposition of fuel. The influence of hydrocarbons on the body depends upon their type. Saturated hydrocarbons are not harmful to the human body (although, by depressing the oxygen concentration in inhaled-air, they may cause physical asphyxiation), but hydrocarbons of low molecular weight may have an anaesthetic effect. This anaesthetic effect increases with molecular weight. It has also been reported that long paraffinic hydrocarbons as well as aliphatic acids, may promote the formation of cancer. The waste gas also contains ethylene ($CH_2=CH_2$), which is a factor in photochemical smog formation because of its high photochemical reactivity .

3.9.4.2 Incomplete Oxides of Hydrocarbons

The toxicity of the aldehydes and CO, the incomplete oxides of hydrocarbons, are very considerable. Aldehydes in the range of 10-100 ppm are contained in the exhaust gas; they are composed of formaldehyde (HCHO), acetaldehyde (CH_3CHO), acrolein (CH_2=CHCHO), and others.

Formaldehyde irritates the mucous membranes of the eyes in very low concentrations; it is also a respiratory sensitiser causing asthma. The skin and mucous membranes are irritated by CH_3CHO, and it increases heart activity. When a quantity of the vapour is inhaled, asphyxiation occurs temporarily. If the vapour in inhaled for a long time, the number of erythrocytes (red blood cells) and leucocytes (white blood cells) decrease. In a concentration of 50 ppm, the eyes are slightly irritated. The toxicity is very low compared with HCHO.

Acrolein is considered to be very hazardous. When the vapours of CH_2=CHCHO at concentrations of 0.5 ppm and 1 ppm were inhaled in controlled experiments for 2-3 minutes respectively, eyes and the mucous membranes of the nose were strongly irritated[52].

3.9.4.3 Carbon Dioxide

The effects of various CO_2 concentrations on humans are summarised in Table 3.5 . However, as with all chemical exposures, there is a variation in response between exposed persons. Whether the person is at rest or physically-exerted is also a factor.

CO_2 concentration (ppm)	CO_2 %	outcome
5000	0.5	Can be tolerated for 8 hr exposure with no symptoms and no permanent damage.
15000	1.5	Can be tolerated for 10 minutes.
20,000	2.0	Breathing rate increased by 50%.
30,000	3.0	Breathing rate increased by 100%
50,000	5.0	After 30 minutes, vomiting, dizziness and disorientation.
80,000	8.0	After short exposure, headaches, dizziness, vomiting and breathing difficulties.
100,000	10.0	Headaches, dizziness, vomiting, unconsciousness and death after few minutes.

Table 3.5 Reactions of Typical Person to Different CO_2 Concentrations in Air

The levels of carbon dioxide in the atmosphere have been increasing particularly since the industrial revolution in the Eighteenth Century. The US. Department of Energy's study estimated that from 1850 to 1950 about 60 Gigatonnes (Gt) of carbon dioxide were emitted to the atmosphere by burning fossil fuels, and approximately double this amount by burning waste and forest clearings. The study showed that by 1981, 5 Gt of CO_2 were released annually by burning fossil fuels and the rate of fossil fuel usage was increasing at approximately 4% per annum world-wide. At this rate the amount of CO_2 released annually will double by the year 2030. The increasing quantities of CO_2 in the earth's atmosphere are contributing to the 'greenhouse effect', which seems likely to increase the Earth's temperature in the Northern Hemisphere. This raises the prospects of polar ice melting, hence flooding of major cities near coastal areas especially when heavy unseasonal rains occur. Global Warming was demonstrated in March 1995 when parts of Holland had to have mass evacuation for fear of unprecedented flooding occurring near the coastal areas. Other parts of Europe were also affected including Belgium and Germany. Many other regions of the world have suffered from rain shortages due to climatic changes, as a result of global warming.

The world's informed governments recognised that the greenhouse effect could represent a major concern to the well-being of the planet and hence, in 1991 the United Nations organised a world convention on Climate Change in Rio de Janeiro to address this problem. The ultimate aim was "to achieve stabilisation of the greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system"[53]. Governments of 153 countries agreed to take action to reduce the emissions of carbon dioxide to their 1990 levels by the year 2000. Developed nations agreed to help with resources and technology transfer to help developing countries to meet their Convention commitments.

3.9.4.4 Carbon Monoxide (CO)

Carbon monoxide is a colourless, odourless and tasteless gas. Inhalation of 0.3% by volume can cause death within 30 minutes. At idle, the exhaust gas from the spark-ignition engines has a high CO content and, in the absence of adequate ventilation e.g. in a typical garage, the concentration can build upto >0.3% within 15 minutes. Hence an engine should not be started, or run in a confined space. The reactions of a typical person to different levels of CO concentration are given in Table 3.6 .

CO Concentration (ppm)	Outcome
50	Maximum Exposure Limit.
200	Headache after about 7 hr if resting or 2 hr exertion.
400	Headache with discomfort with possibility of collapse after 2 hr at rest or 45 minutes exertion
1200	Palpitations after 30 minutes at rest or 10 min exertion
2000	Unconscious after 30 minutes at rest or 10 minutes exertion

Table 3.6 Reactions of Typical Person to Different CO Concentrations in Air

Carbon monoxide is one of the most toxic substances found in exhaust gas. Because it does not irritate the skin and mucous membranes, its existence cannot be perceived. The binding strength of CO and haemoglobin (Hb) in the blood is 210 times stronger than that of oxygen (O_2). If CO binds to Hb, the function of Hb-carrying oxygen in the body decreases. If the linkage between CO and Hb becomes 20%, headaches, dizziness, and other toxic symptoms appear and a linkage of 50% leads to unconsciousness. A linkage of 70% leads to certain death.

3.9.4.5 Particulates (Soot)

The amount of exhaust soot, i.e. as particulate matter, usually includes all substances which under normal conditions are present as solids (ash, carbon) or liquids in the exhaust gas. The amount is very small in SI engines, but becomes relatively large (typically 0.2 to 0.6 grams/km) in light-duty CI engines. The toxicity of soot is due largely to the presence of condensed polycyclic hydrocarbons with high carcinogenic potential e.g. benzo(α)pyrene. Exposure to such carcinogenic substances may cause lung cancer because their condensates are suspended particles, about 8 µm in diameter with a high permeability into the lungs. American studies[54] suggest that emissions of particulate matter, especially that under 10 microns in diameter, from diesel engines are causing 10,000 deaths a year in Britain. The victims are mainly those with heart conditions, and breathing disorders.

Maximum fuel quantity must be limited per stroke according to intake-air quantity such that the engine produces minimum soot. This requires an excess-air factor of 10 to 20% (Λ=1.1 to 1.2).

3.9.4.6 Nitrogen Oxides

Oxides of nitrogen comprise mainly nitrous oxide (N_2O), nitric monoxide (NO), nitrogen dioxide (NO_2), dinitrogen tetroxide (N_2O_4) and dinitrogen pentoxide (N_2O_5). N_2O_5 is a low melting solid which rapidly decomposes in air to NO_2/N_2O_4. The main nitrogenous component of air in the waste gas of a diesel engine is nitrous oxide (N_2O), but immediately the gas is exhausted, NO is oxidised into nitrogen dioxide (NO_2).

Nitrogen monoxide NO is a colourless, odourless and tasteless gas. It is rapidly converted in air to nitrogen dioxide NO_2, a reddish-brown, toxic gas with a penetrating odour which in high concentrations can destroy lung tissue. There is no question however of such concentrations being reached, even in a confined space such as a garage. Both NO and NO_2 are referred to as nitrogen oxides NO_x, or 'nitrous fumes'.

Although NO is not an irritant, it binds to Hb in the blood. The binding strength is about 100 times greater than that of CO, which is itself substantial, and is about 3 times stronger than that of NO_2. By the oxidation of NO-Hb in the blood, metheglobin forms, and its increase leads to lack of oxygen in the blood and ultimately to damage to the central nervous system. In general, the concentration of NO in the air is less than one-tenth that of CO, and the normal levels of it and CO in the human body cause no adverse health effects.

The gas NO_2 strongly irritates mucous membranes, is toxic to the bronchi and lungs, and influences the formation of metheglobin. The general symptoms of NO_2 poisoning are insomnia, coughing, fast breathing, and corrosion of the mucous membranes. If NO_2 is absorbed into the blood, in serious cases, blood appears in the saliva and after a few days, death follows through edema of the lungs. A concentration of 100 ppm NO_2 quickly leads to toxic symptoms after a short time, and a concentration of 200 ppm quickly becomes a danger to life. Reactions of a 'typical person' to different concentrations of NO_x are summarised in Table 3.7 .

Concentration of NO_x (ppm in air)	Outcome
<60	No effect
60-150	Can cause irritation and burning in nose and throat
100-150	Dangerous within 30-60 minutes
200-700	Can be fatal within 1 hr

Table 3.7 Reactions of a Typical Person to different Concentrations of NO_x in Air

3.9.4.7 Sulphur Oxides and Trace Metals

Sulphur dioxide and SO_3 are produced from combustion reactions of the sulphur compounds present in the initial fuel used. Although the majority of the sulpur dioxide in the atmosphere is produced by coal-fired power stations, the remainder is produced by vehicle exhaust emissions. Pollution from sulphur dioxide emissions is said to be responsible for more than 1,200 deaths a year costing millions of pounds per year[55]. Very small quantities of metals which are present in lubricants, or from fuel additives e.g. lead oxides, lead halogenides are also emitted as pollutants.

3.9.4.8 Oxidants

Many different types of hydrocarbons are present in the exhaust gas. In the presence of nitrogen oxides and sunlight, they react to form oxidants which irritate the mucous membranes. When the emissions come into contact with sunlight, this acts on exhaust-gas constituents to produce, organic peroxides, ozone and peroxyacetyl-nitrates.

3.9.4.9 Benzene in the Exhaust Gas

Benzene has been known to be a chronically toxic chemical for at least 20 years, but opinions differ sharply over whether the levels produced in the air due to motor vehicle emissions represent a serious health risk. Wolff[56] believes that benzene causes childhood leukaemia, and that regional variations of the disease can be accounted for by different levels of motor vehicle pollution. However Seaton[57], states that benzene levels in British air present an exceedingly small risk to health.

Benzene and other aromatics are added to petrol to replace lead, itself the subject of health concern. A campaign was started in the early 1980's to remove lead. It was believed to be a cumulative poison that could damage the health and intelligence of children, although the evidence was largely circumstantial. Perry[58] considered it a mistake to introduce unleaded petrol before catalytic converters were in wider use to remove benzene.

Benzene and other aromatics, toluene and xylene, are added to petrol to make it burn more smoothly, preventing knocking effects. More of these compounds, are required in unleaded petrol, so the effects of the trend towards increased unleaded petrol has been to increase the amount discharged. Unleaded petrol generally contains between 3 to 4 percent benzene, compared with 2.5 per cent in leaded fuel.

Benzene reaches the air through the exhaust pipe, and also by evaporation from fuel in the garage and the fuel tank itself. Recent research has found levels inside cars much higher than those on the street.

When unleaded petrol was introduced in America in 1973, the US Environmental Agency was concerned that the effects would be to increase benzene levels. Most of the medical evidence against benzene comes from exposure in the workplace. A group of more than 1,100 workers exposed to high levels of benzene in a Goodyear plant for 25 years showed nine extra deaths from leukaemia[59].

An Expert Panel[60] on air quality standards concluded that the risks were not perceptible in workers exposed to less than 500 parts per billion of benzene in the air. The annual average level of benzene in London is less one-hundredth of this level; hence if the assumption is correct even assuming that exposure is for a time period some three-times longer, then the risk is negligible.

As with occupational exposures to air pollutants, it is important to realise that vehicle emissions comprise a mixture of the chemicals discussed. Their effects may be additive, e.g. in the case of respiratory irritants, or synergistic. Moreover addition, or reaction, with pollutants from other sources-and photochemical action-may exacerbate the damage-producing potential on the environment.

CHAPTER 4

ENERGY CROPS

Chapter 4

4.0 ENERGY CROPS

There has been increasing interest in the development of crops for use as 'energy crops' in the developed world. In the European Community (EC) apart from the traditional crops, some of which have been researched extensively and show good potential[61], new and exotic species (Miscanthus Sinensis, Napier Grass etc.) are being studied. These show even greater promise than existing crops (e.g. maize, sugar beet and cereals). However, the potential for such novel crop production, and the economic potential of energy crops in the EC, is crucially dependent upon the EC Common Agricultural Policy (CAP).

4.1 EC Common Agricultural Policy (CAP)

The EC CAP policy was introduced in 1988 to curb excessive food production by farmers which resulted in the fiascos of 'butter mountains' and 'excess food mountains' which subsequently had to be destroyed or sold cheaply abroad, e.g. to Russia, in order to maintain stable market prices in Europe. The policy involved not growing edible crops on upto 15% of agricultural land and is known as the Set-Aside Scheme. In the United Kingdom in the 1991/92 season 167,000 ha, equivalent to about 5% of the total cereal area, was in the Set Aside-Scheme[62]. In 1993/94, 14% of the United Kingdom total cereal area was in the Set-Aside Scheme. Buckwell[63] stated that in 1992/93 overall in the EC countries 3.73 million ha of arable land were set aside across EC states.

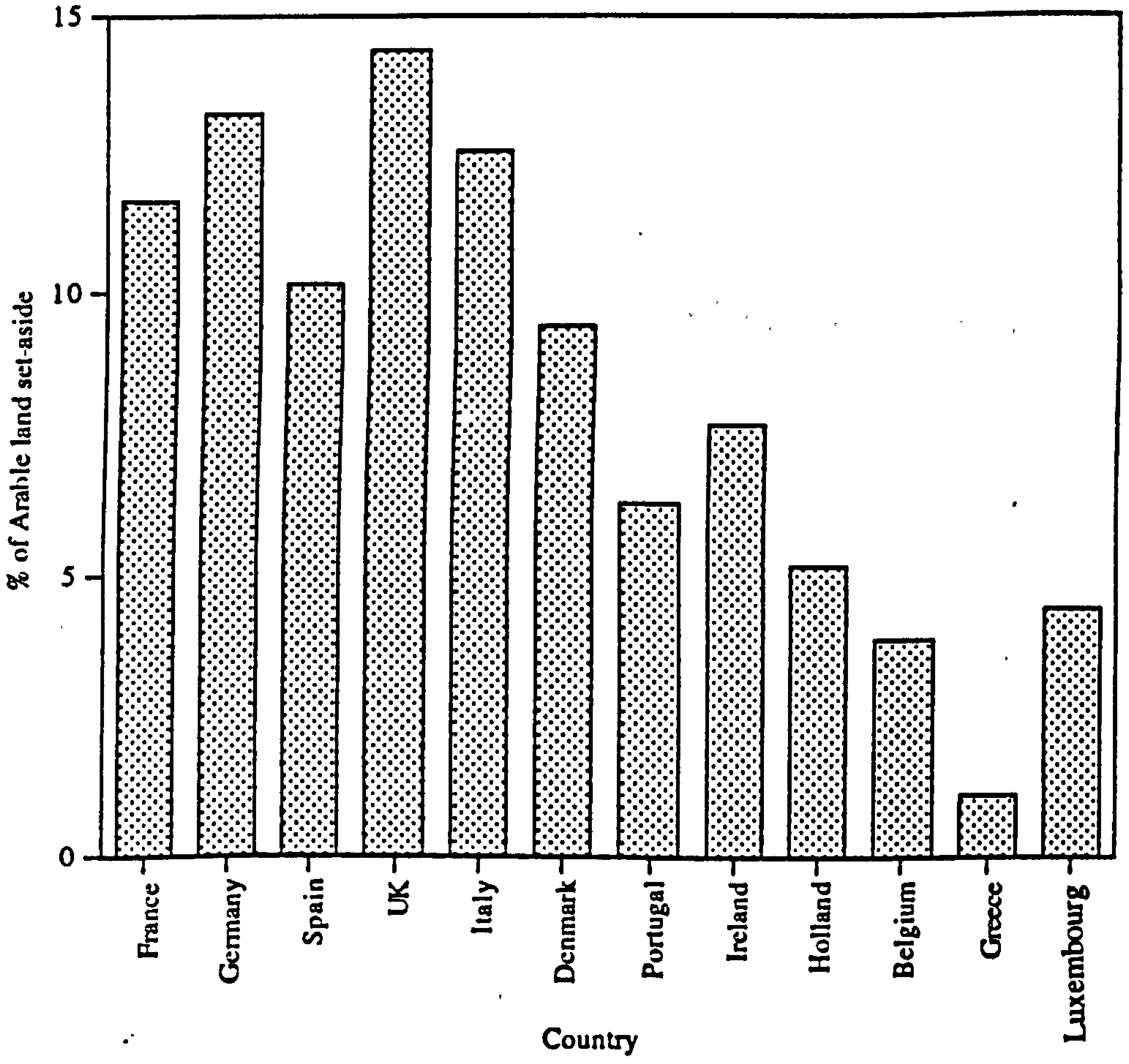
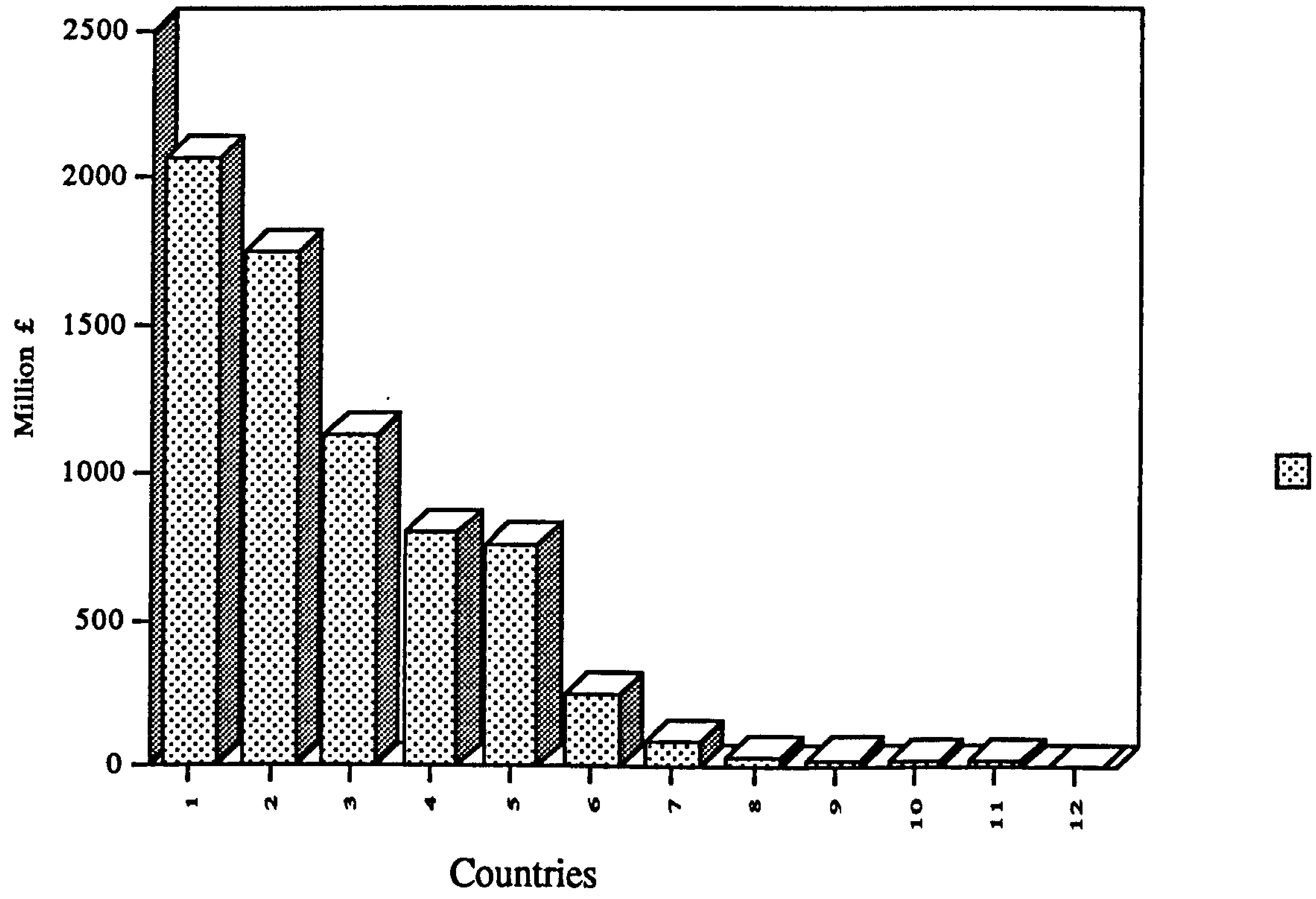


Figure 4.1 Percentage of Arable Land Set-Aside by EC Countries (1991/92 season)



1= France
2= Germany
3= Spain
4= United Kingdom
5= Italy
6= Denmark
7= Portugal
8= Ireland
9= Holland
10= Belgium
11= Greece
12= Luxembourg

Figure 4.2 <u>Amount of Payment Received by Each Country in the EC For Set-Aside Land Scheme</u>

Figure 4.1 shows the percentage of arable land set-aside in the EC by member States. In 1994, 4.7 million ha (11.6 million acres) of arable land in the EC were set aside. Overall in the EC 30-40 million ha of land may be available for non-food production. In the near future with the admission of three new countries into the EC (Switzerland, Sweden and Austria) and possible entrance of further new members (Turkey, Hungary, Poland, and Slovakia) the total land surplus may well be 50-80 million ha[64]. Current thinking within the EC is to use this surplus land for possible energy production crops to avoid surplus food production. Figure 4.2 shows the range of payments received in total over the last 6 years by each country for Set-Aside Land Scheme.

4.2 Crop Yield Potential

Biomass is defined as any organic material composed primarily of carbohydrates and lignin in addition to small amounts of oils, proteins and other constituents. It has of course been used as an energy source for centuries. Wood and charcoal were principally used. Wood, grasses, grains and waste paper are examples of biomass which give bio-energy. Bio-energy is defined as the production, conversion and the use of material which is directly or indirectly produced by photosynthesis (including organic waste) to manufacture fuels and substitutes for petrochemical and other energy intensive products.

Photosynthesis enables solar energy to be utilised by plants to perform a chemical reaction using carbon dioxide and water to form carbohydrates.

$$n\,CO_2 + n\,H_2O \xrightarrow[\text{chlorophyll}]{\text{solar radiation}} (CH_2O)n + n\,O_2$$

To determine which plants are suitable for possible cultivation as energy crops, the efficiency of conversion of solar energy into stored chemical energy is considered. The efficiency of photosynthesis in general is very low, typically 0.8% (maize, potato and rice in Europe and U.S.A) upto a maximum of 2.4 % for Napier grass variety in El Salvador[65].

Only a fraction of this solar energy is utilised because 94% is lost through reflection or dissipation as heat. Hall[66] states that plants can also only use radiation in the visible part of the solar spectrum, between wavelengths 0.4 and 0.7 microns, termed the photosynthetically active radiation (PAR) region. Half of the total available solar energy is lost for the above reason, and the rest through reflection, and respiration requirements, 8 quanta of light being needed to fix the CO_2. Other losses of efficiency arise because of inadequate water supply and competition with weeds. From Hall's calculation only 5.5-6.7% of available light remains for photosynthesis.

To achieve the highest possible energy crop yield, the most efficient plants are those which capture the solar energy all year round i.e. perennial plants, and plants free of disease, drought or water shortage. The potential dry matter yield from certain plants (i.e. disease-free, with ideal soil/water and sun conditions) can in theory be 50-60t ha/yr[67]. The photosynthesis reaction in plants can be carried out in two main ways termed C3 and C4 pathways. The mechanism of metabolism of plants plays an important role in the final yield of the crop. Plants with a C4 pathway (e.g. maize) offer a higher yield potential than plants with a C3 pathway (e.g. wheat, sugarbeet, rape, potato). 'C4' refers to plants which have an additional pathway for the transport of carbon dioxide in the process of photosynthesis as compared to C3. C4 plants are more efficient than C3 plants at higher light intensity and temperature.

The Ideal Energy Fuel Crop Requirements are as follows[68]

1) Dry harvested material for efficient use.
2) Perennial growth to minimise growing costs and lengthen the growing season.
3) Good disease resistance such as exhibited by *Gramineae*.
4) Efficient conversion of solar radiation to biomass energy; therefore crops with a prolonged leaf canopy and the C4 photosynthetic pathway[69].
5) Efficient use of nitrogen fertiliser and water such as exhibited by perennials and C4 pathways species[70].
6) Yield close to the theoretical maximum of 55-60t/ha/year dry matter for C4 and 33t/ha/year dry for C3 species.

Although of the current crops only maize utilises the C4 pathway, the yield is constrained by the short growing season. Cereals currently grown have shown an annual yield of 20t/ha/year dry matter, including grain and straw, with a high input of fertiliser and pesticides. More realistically a dry matter yield of 14/ha/yr can be expected in less favourable conditions.

4.3 Miscanthus Sinensis

Miscanthus sinensis is a woody, perennial grass related to the sugar cane; it possesses the C4 pathway of metabolism. It produces annual shoots which grow to about 4m tall and about 100mm in diameter and which appear similar to thin bamboo canes. The foliage dies at the end of the growing season and is suitable for the harvest at a high dry matter content in the late winter period (February-March). Fresh shoots appear from the rhizome networks in April. Following the establishment (using rhizome cuttings or micro-propagated plants) at a plant density of 1 to 4 plants per m^2, the rhizomes spread until full crop cover is reached. Full yield potential is achieved in the third or fourth year. Miscanthus fulfilled all five characteristics of the 'The Ideal Energy Fuel Crop Requirements'; the sixth, the yield was reported to be fulfilled according to data obtained from Denmark[71].

4.3.1 Reported Yields

The reliable reported yields of miscanthus grown in Europe have shown that 11.7 to 25.3t/ha/year dry matter have been achieved[72/73] and in Denmark as high as 44t/ha/ year dry matter[74]. Recent work in Germany has shown miscanthus yields of 18t/ha/yr dry matter and yield in the fourth year is expected to be in excess of 25t/ha/year[75].

One disadvantage of miscanthus is the cost associated with its initial establishment. It may be planted by rhizome cuttings or by utilising micro-propagation. Both these systems are expensive and can cost from £6,000 to £10,000 per ha. A proposed method of reducing the cost is to develop genotypes that produce fertile seeds.

The market for fuel crops has been stimulated particularly by the EC policy of set-aside. Artificially-favourable prices are also available under the NFFO (Non-Fossil Fuel Obligation) for energy generated from non-fossil fuel. From present research, energy produced from energy crops will always be more expensive in relation to current energy produced from fossil fuels. However, taking other factors into account such as balance of payments, creation of employment and environmental pollution the option of energy from crops appears more attractive .

4.4 Conversion Of Biomass Crops To Energy Fuels

Different processes are used in order to convert biomass crops to useful energy fuels . These processes are shown in Figures 4.4 and 4.5

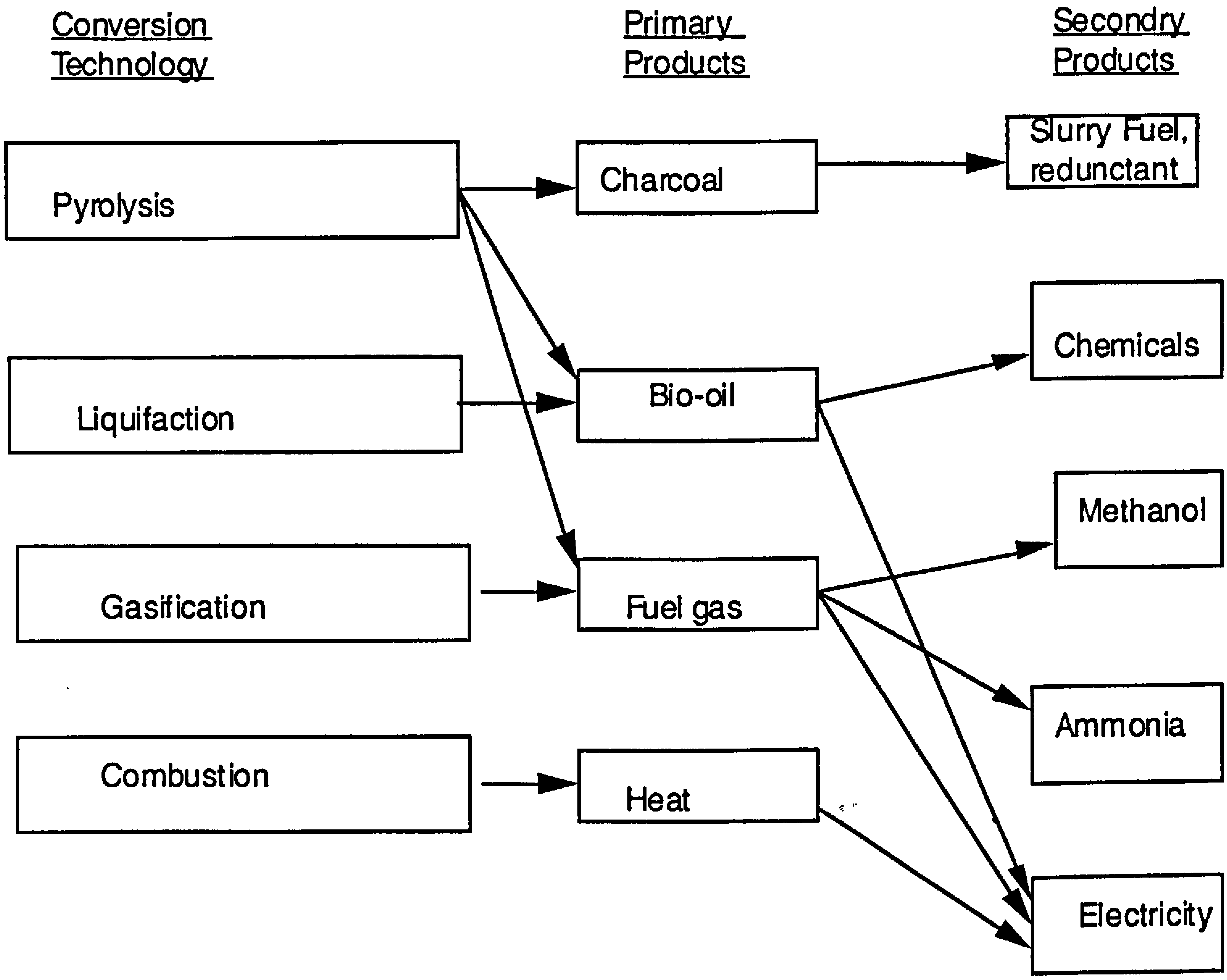


Figure 4.4 Thermochemical Conversion, Products and Uses of Biomass

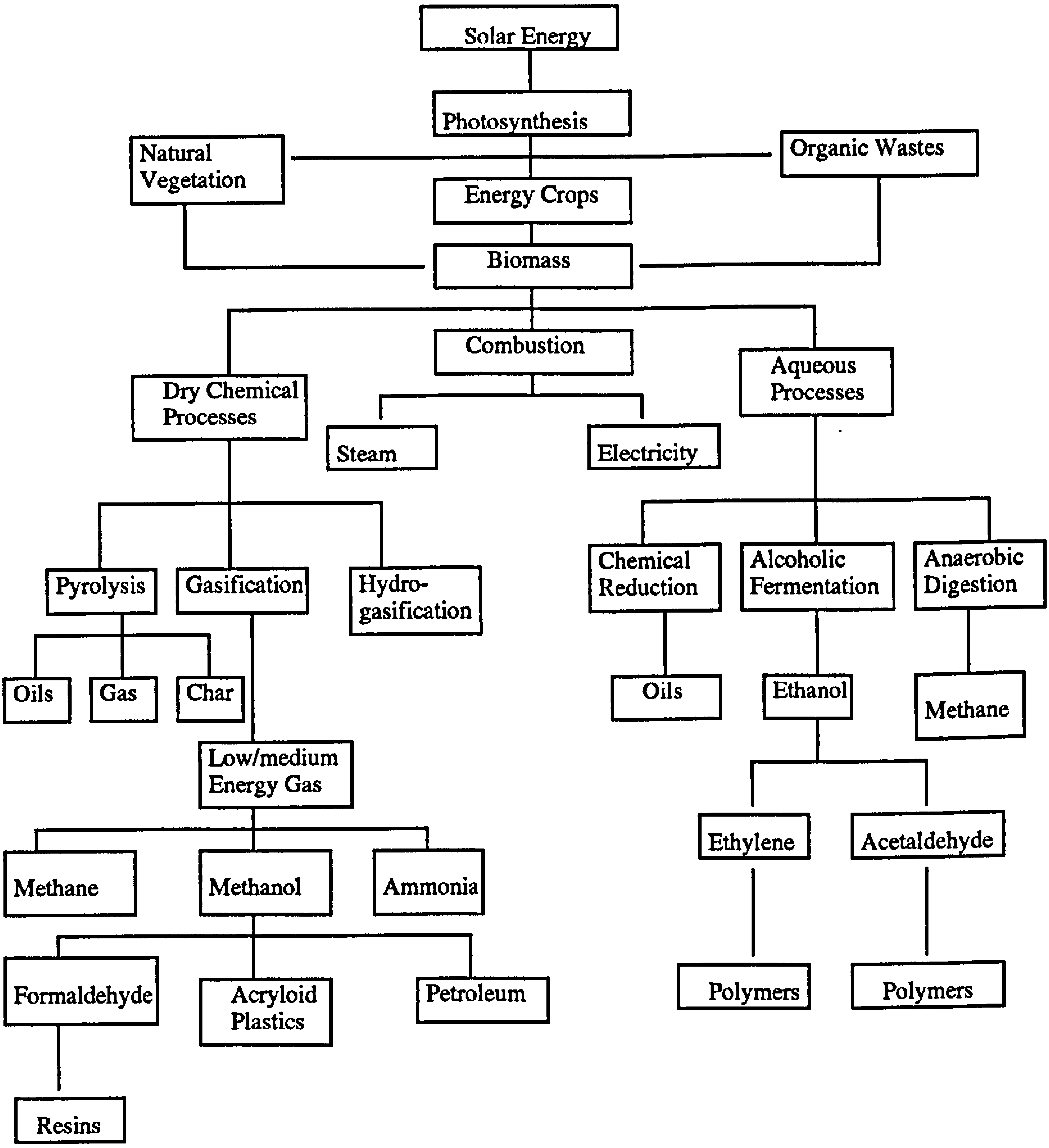


Figure 4.5 Biomass Production Route from Solar Energy

4.5 Wood as an Energy Resource

It has been recorded that some 720,000 tons of charcoal (85% made from wood) were produced in 1976 in the U.S; this was used primarily in residential applications[76]. There are many different wood fuels. Figure 4.4 illustrates thermochemical conversion, products and uses of biomass e.g. wood. Charcoal is, the premier wood fuel. It is followed, in descending order by dry softwood material (e.g., pellets, planer shavings), air dried hardwood, as-received hog-fuel, spent liquor where the energy rich lignin is concentrated, and ultimately as-received bark. In the fuels listed above, heat content varies from 20416 kJ/kg for charcoal (with 1.5% moisture content) to 6960 kJ/kg for bark (with 67% moisture content). Sulphur and ash in the fuels range from negligible to very significant.

4.5.1 Wood as a Combustible Fuel

Wood fuels vary by tree species and wood material (e.g., cell walls or bark), but these are not an important parameter in determining the energy value of wood materials. The chemical composition is of critical importance. Wood is a composite of three basic polymers: cellulose ($C_6H_{10}O_5$), lignin ($C_9H_{10}O_3(OCH_3)_{0.9-1.7}$), and the hemicelluloses such as xylan ($C_5H_8O_4$). Added to these materials are extractives and minerals ash.

4.5.2 Calorific Value of Wood

Two ways are used to express the calorific value. The gross calorific value, also known as the higher heating value (HHV), measures the heat given off to the surroundings plus the heat absorbed to vaporise the water produced. Most species of wood have a gross calorific value of 20 MJ/kg for oven dry wood[§]. The net heating value, also known as lower heating value (LHV), is the total amount of heat released during combustion, excluding that which vaporises the water. The net calorific value of oven dry wood is usually taken as 18.8 MJ/kg.

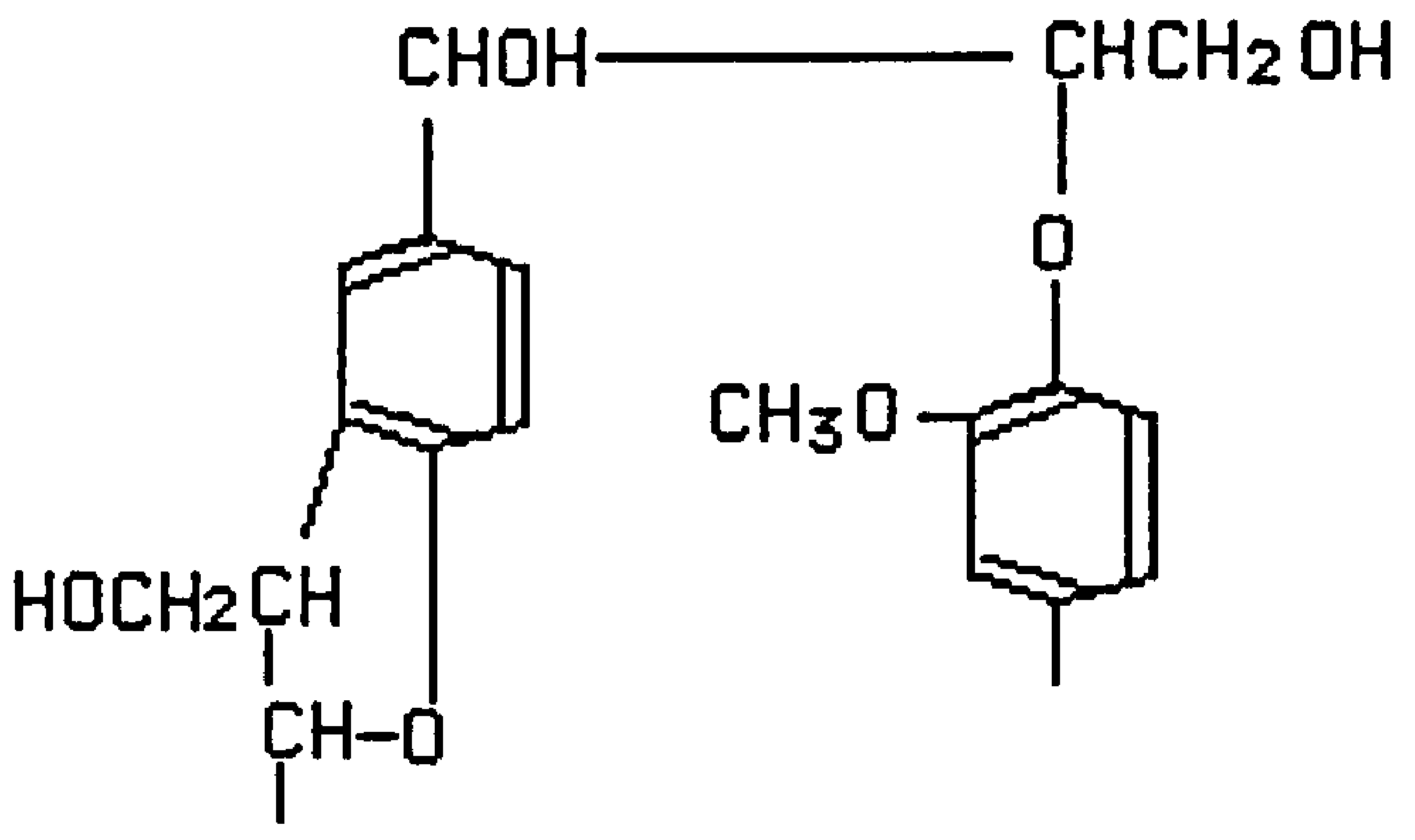
4.5.3 Wood Composition and Heating Value

In general, hardwoods contain about 43% cellulose, 22% lignin, and 35% hemicelluloses. Softwoods (such as poplar and eucalyptus) contain about 43% cellulose, 29% lignin and 28% hemicellulose[77]. The specific compositions of seven species of the North American woods, and their energy contents, are presented in Table 4.1 . As species vary in composition, so do parts of the tree itself. Further, residues such as bark, sawdust, planer shavings and spent pulp liquor, vary in energy value and chemical composition.

The different chemical compositions result in varying heat contents for various wood fuels. Holocellulose (cellulose and hemicellulose) and lignin offer significantly different heats of combustion; 17560kJ/kg for holocellulose and 26632kJ/kg for Douglas fir lignin[78]. The extractives also contain high energy contents, sometimes approaching 34800 kJ/kg. As shown in Table 4.1 , there is some association between the lignin (Figure 4.6) content and the energy value. This association is to be expected and supports the general statement that as the lignin and extractives content of wood species rise, so does the higher heating value of the fuel produced.

§ The following terms are generally accepted for various moisture content of biomass;

Bone-dry = 0% moisture.
Oven-dry = 8% moisture
Dry (air-dry) = 20% moisture.
Green = around 50% moisture



Lignin (small section of polymeric molecule)

Figure 4.6 Structure of Lignin Molecule

Tree Species	Cellulose(%)	Lignin(%)	Hemicellulose (%)	Energy kJ/kg
Beech	45.2	22.1	32.7	19620
White birch	44.5	18.9	36.6	19335
Red maple	44.8	24.0	31.2	19488
Eastern white cedar	48.9	30.7	20.4	19488
Eastern hemlock	45.2	32.5	22.3	20613
Jack pine	45.0	28.6	26.4	20718
White spruce	48.5	27.1	21.4	20625

Table 4.1 Association of Lignin Content And Energy of Seven Species of North American Woods[79]

The composition of wood determines both its heat content and the mechanisms via which useful energy is released from it. All wood combustion and conversion begins with pyrolysis. In pyrolysis holocellulose principally promotes the release of volatiles while lignin, which also releases volatiles, primarily promotes char formation. The volatiles produced burn directly in flaming combustion or provide wood gas. The char oxidises in glowing combustion, is used as charcoal, or is gasified.

A more traditional approach to the evaluation of combustible fuels employs the ultimate analyses of the candidate material. These analyses may or may not include ash: they may or may not include moisture content. Ultimate analysis can be employed to evaluate charcoal fuels as well as wood material per se.

Table 4.2 presents the ultimate analyses of numerous wood fuels on a dry weight basis. The energy/mass values presented are higher heating values. These data demonstrate generally that wood is a highly-oxygenated fuel with about two-thirds the energy content of coal. Softwoods generally contain more energy than hardwoods on a dry-weight basis due to higher lignin (hence carbon) content plus the presence of more resins in the extractions.

The ultimate analyses shown in Table 4.2 suggests some correlation between carbon content and higher heating value. This has been demonstrated by Shafizadeh[80], who concluded that for such solid fuels a mutual cancellation minimises, or eliminates, the influence of hydrogen and oxygen. In general, then, the higher heating value of wood (on an oven-dry basis) is approximately 20880 kJ/kg. Variations in this value result from the lignin content and to a lesser extent extractives content, or the carbon content of the fuel.

4.5.4 Comparison of the Heating Value of Wood to other Combustible Fuels

The previous discussion presented a general analysis of the heating value of wood. However, to make further conclusive statements concerning the position of wood within the class of combustible fuels requires a comparative evaluation to be carried out. It is here that the comparison of biomass energy with fossil energy becomes important. It is also in this process that the ultimate analyses of fuel becomes critical.

Table 4.2 also presents 15 ultimate analyses of fuels from dried sludge to Utah bituminous coal. In higher heating value (dry weight basis) they range from 4735kJ/kg to 33447 kJ/kg). Ash contents vary from 1.0 to 71.4% and oxygen contents range from 4.9 to 51.2%. All analyses were obtained from literature cited[81].

Bagasse and municipal waste are employed as waste fuels. Among the wastes now combusted for energy purposes, they are the most frequently used materials other than wood. From Table 4.2 it is clear that wood is the transition material between wastes and fossil fuels. However, there is more similarity between wood and the wastes than between wood and coal.

It should be noted that the values for wood and coal presented in Tables 4.2 and 4.3 can be anticipated from an investigation of the process of coal formation. An insight into the decomposition of holocellulose and lignin, at different rates, and the subsequent formation of charcoal is offered by Gore[82].

	Ultimate Analysis (Dry weight basis)						
Fuel Material	C (%)	H (%)	O (%)	N (%)	S (%)	Ash (%)	Energy kJ/kg
Utah coal	77.9	6.0	9.9	1.5	0.6	4.1	32890
Pittsburg coal No1	75.5	5.0	4.9	1.2	3.1	10.3	31683
Pittsburg coal No 2	73.3	5.3	10.2	0.7	2.8	7.6	30399
Wyoming coal	70.0	4.3	20.2	0.7	1.0	13.8	33447
Douglas fir bark	56.2	5.9	36.7	0.0	0.0	1.2	22050
Wood	52.0	6.3	40.5	0.1	0.0	1.0	20890
Pine bark	52.3	5.8	38.8	0.2	0.0	2.9	20379
Bagasse	47.3	6.1	35.3	0.0	0.0	11.3	21215
Raw sewage	45.5	6.8	25.8	2.4	0.5	19.0	16433
Bovine Waste	42.7	5.5	31.3	2.4	0.3	17.8	17129
Rice hulls	38.5	5.7	39.8	0.5	0.0	15.5	15342
Rice Straw	39.2	5.1	35.8	0.6	0.1	19.2	15180
Municiple Solid Waste	33.9	4.6	22.2	0.7	0.4	38.0	13102
Paper mill sludge	30.9	7.2	51.2	0.5	0.2	10.2	12418
Sewage sludge	14.2	2.1	10.5	1.1	0.7	71.4	4735

Table 4.2 Ultimate Analysis of 15 Biomass Fuels

Fuel	Density kg/m^3	Energy/Volume kJ/m^3
Bituminous coal	833.04	25431
Charcoal	244.31	7377
Hogged fuel	288.36	6036
Bark	384.48	8187
Bagasse	80.1	1676
Municipal Waste	160.2	2103

Table 4.3 Heating Value for Selected Fuels (Dry weight basis)

4.5.4.1 Other Elements and Compounds

While energy/m^3 provides one approach to rating the affinity of transition fuels to waste or primary fuels, a discussion of the other elements and compounds contained in each fuel provides more conclusive results. The materials considered here are those which either cause pollution or directly impair the heating value of fuel. These include not only the traditional pollutants considered in the discussion on fossil fuels but also, separately, moisture. Water reduces the heating value and can contribute to pollution control problems.

4.5.4.2 Potential Pollutants Analysis

Traditionally, sulphur and ash comprise the principal impurities in combustible fuels. The sulphur on combustion forms SO_2 which is a pollutant in its own right. It can also combine with rain to form sulphurous acid, or transform in the atmosphere into other potentially dangerous compounds. On a fixed installation the ash results in the release of particulates via the stack. These pollutants can be controlled by devices such as stack scrubbers. All such installations, however, reduce the efficiency of given energy utilisation operations (e.g., a power plant).

The ultimate analyses presented in Table 4.4 show wood to be very low in sulphur and ash. For the eight selected fuels presented, wood fuels have virtually no sulphur content and also have very low ash content . These values demonstrate that wood combustion is essentially pollution free in relation to SO_2, although some particulate control measures are needed.The ultimate analyses in Table 4.4 show other solid combustible fuels to be in a less favourable position.

Coal, for example, can have sulphur contents ranging from 0.6% to 3.1%; Illinois coal can have 5%+ sulphur, creating significant SO_2 control problems. From earlier Table 4.2 the ash content of different coals varies from 4.1 to 13.8% . Lignite coals from North Dakota and Texas are even higher in ash content. Also in Table 4.2 the waste based fuels are low in sulphur. Ash content is a serious problem, as all waste fuels usually contain in excess of 10% inorganic matter. Table 4.2 shows municipal waste has 38.0% ash and sewage sludge 71.4% ash hence they present the most severe problems.

From the point of view of controlling formation of SO_2 and limiting the release of particulate matter, wood is more desirable than any of the other solid fuels. In a time of environmental consciousness, this advantage is a compelling attraction for the premium biomass energy source.

4.5.4.3 Moisture analysis

Wood does suffer from the disadvantage of the presence of moisture in significant quantities. Fresh wood may contain upward of 22% to 55% H_2O (weight %, total material basis). Moisture, more than any other single variable, segregates the class of wood fuels into the distinct and separate types identified in the introduction. Moisture content significantly influences the net heating value of wood fuels. The influence of water on ignition is as serious as its influence on net energy content.

Shafizadeh[83] has given possibly the best explanation of the influence of moisture on heat release and heat of pre-ignition. Because the influence of water is so significant, it is essential to determine the average moisture content of wood fuels.

The problem of high moisture content is common to all biomass fuels in which it ranges from 20% to 50% or greater among municipal waste, crop waste, feedlot waste categories[84,85] . Thus wood is in a disadvantageous position with respect to coal. Further, it has no particular advantage when compared to other biomass fuels. This stands in stark contrast to the previous analysis of carbon content (dry weight basis) and pollutant content. It is perhaps the dominant factor explaining the proximity of wood to wastes, as opposed to coal, in total energy value.

The inclusion of moisture content into the ultimate analysis data is very useful. It highlights critical comparisons which must be made when determining the relative positions of the numerous wood fuels in the total family of fuels. Wood fuels, such as charcoal and, to some extent, pellets are virtually equal in energy content to solid fuel such as coal . Other wood fuels, as received by those who would use them directly, are less desirable than coal but far more useful than waste materials. They are less concentrated than coal, and the presence of oxygen and water in them significantly reduces their carbon content whilst presenting operational problems. However these fuels are, except bark, generally higher in carbon content than other biomass fuels and pose less problems for the user. Thus, they hold a position in the middle of the fuel spectrum, between coal wastes and coal. Depending upon the degree of processing, they may show proximity to either competitor.

Constituent mass %	Bituminous coal[b]	Charcoal (Techair)	Dried sawdust pellets	Maple wood[c]	Douglas fir bark[d]	Bagasse	Municipal waste	Feedlot manure
C	73.2	75.3	47.20	34.0	18.7	30.8	27.5	21.4
H	4.9	3.8	6.49	9.1	2.0	4.0	6.0	2.7
O	4.7	15.2	45.34	28.1	12.2	22.9	36.4	15.6
N	1.2	0.8	0.0	0.2	0.0	0.0	0.5	1.2
S	3.0	0.0	0.0	0.0	trace	0.0	0.3	0.2
Ash	10.0	3.4	0.97	0.9	0.5	7.3	29.3	8.9
Moisture	3.0	1.5	2.62	32.8	66.6	35.0	20.5	50.0
Energy kJ/kg	30,753	28,060	20,457	15,087	6,963	11,210	10,607	7,172

Table 4.4 Analysis of Selected Fuels[a] (Total weight as received)

[a] Sources[86]

[b] Because of the wide variation in coals, Pittsburgh seam bituminous coal is used as a representative for coal

[c] Recognising the similar variation in wood fuels, maple was chosen as representative for cord-wood fuels. [d] This is bark as obtained directly from a wet debarking system.

4.6 Combustion of Wood

Recovering the energy value from wood usually involves either direct combustion or conversion to gaseous or solid fuels followed by combustion of those energy products as illustrated in Figure 4.5 . In either case the process begins with pyrolysis, which drives off the volatiles from the wood which, when reacted with oxygen, burn in flaming combustion. In conversion, a pyrolysis reactor is possibly followed by more conversion systems and then by combustors.

Three basic approaches exist for complete combustion of wood: (i) the Dutch oven, (ii) the spreader-stoker, and (iii) the fluidized bed combuster. Each system seeks to achieve complete oxidation of volatiles plus the fixed carbon in the wood fuels. The reactions detailed in Table 4.5 are used to oxidise the char. When reaction (2) occurs, it is followed by reaction (3) to convert the carbon monoxide into carbon dioxide and complete the oxidation process.

Reaction	Molecular heat of reaction (kJ/mol)
(1) $C + O_2 \longrightarrow CO_2$	97.65
(2) $2C + O_2 \longrightarrow 2CO$	58.80
(3) $2CO + O_2 \longrightarrow 2CO_2$	136.40

Table 4.5 Combustion Reactions of Wood Fuels

The three combustion systems seek to maximise the oxidation processes whilst providing (i) flexibility of furnace operations, (ii) wet fuels handling, and (iii) pollution control of stack gas emissions.

4.6.1 Combustion Efficiency of Wood Fuels

A standard combustion efficiency for pulverised coal is quoted as 80-85%. A similar range can be cited for natural gas and fuel oil. The combustion efficiency range cited for wood is 67-72%. A comparable steam-raising efficiency for municipal waste combustion (incineration with heat recovery) is about 55% (52-58%)[87]. For many of the low carbon content wastes (e.g. sewage sludge at 20% solids) the heat released by combustion about equals the energy required to vaporise the water content[88]. Thus wood, which is normally combusted at 67-72% efficiency, is a highly useful fuel.

In the past, wood was burned directly, converted into charcoal, or converted into producer gas. With the advent of cheap petroleum and natural gas however, such systems fell into disfavour and were ultimately abandoned. Today there is a rediscovery of this approach to recovering the energy values from wood. A new conversion industry is in its infancy in order to meet the needs for a broader supply of fuels.

There are several generic approaches to conversion (See Figure 4.4 and Figure 4.5): pyrolysis, gasification, hydrogenation, enzymatic hydrolysis followed by fermentation, and anaerobic digestion. Pyrolysis yields several products in solid, liquid, and gaseous form. By the process of pyrolysis of wood, charcoal is most commonly obtained. This is discussed in more detail in Chapter 5.

4.7 Biomass Forestry

The earth has a surface land area of 133 million km^2. Obviously, not all of this land is suitable for growing of crops[89] and currently land usage is approximately as shown in Table 4.6 .

Land use Pattern	Area (x10^6 km^2)
Agriculture:	
Cultivation (crops/residues)	15
Pasture/Grazing	40
Forestry:	
Closed Forests	29
Open Woodlands	11
Totals	95

Table 4.6 Global Land Utilisation

Many different biomass options are under consideration for future potential development benefits. Amongst these are forest wastes, and energy plantations of new or genetically-improved plant species. Another development is the use of marine and freshwater cultivation of various algae on a large scale, the algae then becoming available for use as biomass albeit with a relatively high initial moisture content.

Over the years planting of crops for energy has been attempted in many different countries. One of the earliest experiments was the six hundred eucalyptus plantations which supplied wood to the 200 mile Paulista Railroad built to serve Sao Paulo in Brazil. The tree plantations supplied wood to fuel the steam locomotives from 1903 to 1958, when the engines were replaced by diesel[90].

4.7.1 Short Rotation Forestry (SRF)

Short Rotation Forestry (SRF) has been proposed, in order to maximise the yield and growing times, and minimise the labour costs, of growing energy crops. In ordinary forests the normal forest cycles can be 30 to 80 years. However trees that grow very fast in the first five years, can be cropped every two to four year cycles. Tree crops such as poplar, sycamore, alder and eucalyptus can sprout from their stumps, hence saving considerable amounts in replanting costs. Biomass crops can be used in a variety of ways, as shown in Figure 4.5. Charcoal can be made using kiln types as in Table 5.1.

The general advantages of Short Rotation Forestry (SRF) are;

1) The products will be largely be sulphur-free.

2) The feedstock is renewable.

3) The production of raw material will not drastically disturb the land.

4) The crop production and use will not adversely affect the global thermal or carbon dioxide balance.

5) The products are relatively non-polluting.

6) The residues are recyclable.

The advantages of Short Rotation Forestry (SRF) in particular are:
Higher yields per unit of land,
Quicker return on investment,
Improved harvesting efficiency through mechanisation and
Higher labour productivity.

The disadvantages of Short Rotation Forestry (SRF) are;

High establishment management costs in the first year.
Because the plants are monocultures disease and infestation are higher.
Large areas of land needed.

4.7.1.1 Yields of Short Rotation Forestry (SRF)

In order for SRF (Short Rotation Forestry) to be economically attractive, the maximum yields of present species need to be obtained.

Tree type	Location	Yield (dt/ha/yr)
Amer. sycamore	Georgia	10-25
Red alder	British Colombia	37
Hybrid poplar	Pennsylvania	10-22
Hybrid poplar	Wisconsin	17

Table 4.7 Typical Yields from Potential SRF Tree Types (North America)[88]

Factors affecting species yield include climate, and the availability of water and nutrients. Calculations show that a 150 MW thermal power station in continuous generation, with a conversion rate of 35% producing 20,000 kWh will require 65,000 ha at 10 dry tonnes per ha per year.

For SRF to be worthwhile, the energy obtained from the products of SRF must be significantly greater than that put in. Siren[91] (1976) calculated that for Swedish conditions an energy input balance of 3 or 4:1 is required.

Management factors	Energy input per ha/yr in kW/hr
Production of cuttings 40,000/ha	400
Transport	2000
Drainage, soil preparation, establishment	16000
Fertiliser and application	700
Application/control of water	700
Harvesting operations	400
Processing and drying of crops	2000
Energy loss due to production failure	2200
Total	24400

Table 4.8 SRF Plantation in Sweden. Energy Input Equivalents

From Table 4.8 the input energy consumed per ha per year is 24,400 kWh/ha/yr which is equivalent to 12 m^3 of dry wood; with an average density of 0.4t/m^3 this equals 4.8 dt weight. Therefore, to gain any energy, more than 4.8 dt/ha/yr[92] have to be produced with a practical yield of 15-18 dt/ha/yr. Ratios must hence be 3 or 4:1. To further improve the ratios, energy inputs have to be lowered and/or higher yields obtained.

Kemp and Szego[93] state that the total energy requirements of the United States could be met by energy plantations covering some 65 million ha converting solar energy at 0.4 percent efficiency. This land is available as unmanaged forestry, range and scrubland currently not used.

In Europe, Sweden and Ireland are prime candidates for the development of energy plantations because of their large land to people ratios (e.g. Sweden has 0.052 km^2 per person, Ireland has 0.02 km^2 as compared to UK which has only 0.004 km^2 per person) and ideal soil and rainfall conditions. Norway also has the required land and climate with strong forestry traditions, the skills of which can be used for energy plantations.

Much work has been done on coppicable species including sycamore, sweetgum, alder, locust, maple eucalyptus and poplar hybrids. Of non-coppice species, pine and mesquite are members of the leguminosae and have the ability to fix nitrogen from the air. Thus they are self-fertilising and require no additional fertilisers. They show most potential because of the associated savings in energy costs .

4.7.1.2 Biofuels Energy Balances

Bio-ethanol is regarded as a competitor to bio-ultracarbofluid; therefore production of bio-ethanol is briefly reviewed. The energy balances for ethanol are based on " Study of the Environmental Impacts of Large Scale Bioethanol Production in Europe"[94], and shown in Table 4.9 .

Products	t/ha/yr
ex Field	
Grain	6.7
Harvested straw	5.0
Total Biomass	11.7
(b)	
ex Process Plant	
Ethanol Poduced (2,4901)	2.0
DDGS produced	2.3

Table 4.9 Wheat to Ethanol

Energy Input	Gj/ha
Agrochemicals	15.1
Fuel for Farming	4.6
Fuel for Transport	0.7
Process Energy	24.7
Drying Energy	14.9
Total	**60.0**
Energy allocated to DDGS	21.2
Energy allocated to Ethanol	38.8
Total	**60.0**
Energy Outputs	
Energy content of DDGS (12.6GJ/t)	29.0
Energy content of ethanol(26.5GJ/t)	53.0
Total	**82.0**

Table 4.10 Energy Input/Energy Output for Wheat

[The DDGS (Dried Distllers Grains with Solubles) is used as an animal feed and is therefore an energy product.]

Table 4.10 shows the energy input and energy output for wheat. The total energy has been allocated between the two products on the basis of energy content. The harvested straw has an energy content of 11.9 GJ/ha. Use of straw to fuel the wheat to ethanol conversion process, including drying, would reduce the fossil energy to 20.4 GJ/ha, or about 25% of the total energy in the DDGS and ethanol products.

4.7.1.3 Conversion of Sugar Beet to Ethanol

Table 4.11 shows the results of a study of energy balances in converting sugar beet to ethanol. The total energy has been allocated between the beet pulp/Vinasse and ethanol on the basis of product energy content and an energy content of only 2.1GJ/tonne. However this material can still be used as animal feed with an effective energy content.

Products	**t/ha**
(a) ex Field	
Beet	60
(b) ex Process Plant	
Beet tops	48
Beet pulp	3
Vinasse	1.1
Ethanol	4.7
Energy Inputs	GJ/ha
Agrochemicals	17.5
Fuel for Farming	7.7
Fuel for Transport	4.3
Process Energy	70.4
Drying Energy	34.3
Total	**134.2**
Energy allocated to pulp/vinasse	39.5
Energy allocated to Ethanol	94.7
Total	**134.2**
Energy Output	
Energy content of beet pulp/beet vinasse (12.6 GJ/t)	51.7
Energy content of Ethanol (26.5GJ/t)	124.0
Total	**175.7**

Table 4.11 Sugar beet to Ethanol

4.7.1.4 Rape Crop Energy Balance

Table 4.12 shows the energy balance for the production of rape crop. The analysis is based on the data prepared by Shell of France, with the same assumptions as to energy equivalents of agrochemicals as in the " Study of the Environmental Impacts of Large Scale Bioethanol Production in Europe".

Products	t/ha/yr
(a) ex Field	
Rape Seed	3.1
Straw	6.0
(b) ex Plant	
Rape Methyl Ester	1.2
Rape Seed cake	1.9
Glycerine	0.1
Energy Inputs	
Agrochemicals	14.1
Fuel for Farming	4.0
Fuel for Transport	1.1
Crushing	3.9
Esterification	2.5
Methanol	4.0
Total	**29.6**
Energy allocated to the Cake	12.1
Energy allocated to the Glycerine	1.0
Energy allocated to RME	16.5
Total	**29.6**

Table 4.12 Energy Input/Energy Output for Rape Crop

Table contiued from previous page.

Energy Output	t/ha/yr
Energy content of Cake (17.4GJ/t)	33.1
Energy content of RME(37.4Gj/t)	44.9
Total	**78.0**

Methanol is assumed to have an energy content of 19.9GJ/tonne at 60% conversion from natural gas i.e. energy input of 33.2GJ/tonne methanol.

The energy input was allocated to glycerine on the basis of mass yield and then divided between RME and Rape Cake on energy content. The straw has an energy content of 11.9 GJ/t, equivalent to over 70 GJ/ha and could be used as a solid fuel to further improve the energy balance.

From the previous energy input/output tables it is clear that the biomass yields far higher output energy than the input energy required. Therefore for future sustainable processes, obtaining energy from biomass can be a practical solution.

4.8 The Position and Role of Wood Fuels in Other Nations

While the role of wood as an energy source is significant but fairly limited in this country and other developed countries, it is larger in the developing economies of the world. In Brazil, for example, pulp production is expected to rise from 1.83×10^6 to 35.8×10^6 tonnes by the end of this century.

Increased utilisation of wood in the West appears to depend on political and environmental considerations rather than real economics.

CHAPTER 5

CHARCOAL CHEMISTRY

Chapter 5

5.0 CHARCOAL CHEMISTRY

5.1 Charcoal

Charcoal has a number of significant uses in the developed world. Charcoal lumps are very commonly used as the fuel in barbecues. Charcoal is used in the electronics industry in a process to produce pure silica for computer chips. It is also used in metallurgical processes to reduce metals such as copper, zinc and lead.

However, the largest market is for activated charcoal i.e. following treatment to increase its adsorptive power. Activated charcoal is produced by heating charcoal in an atmosphere of steam or carbon dioxide to a temperature in the range of 750-900^{0}C. This drives-off any residual volatiles and creates a finely-porous charcoal with a very large internal surface area. This is in the range 200-2000 square m^2/g, compared with 1-2 m^2/g for ordinary charcoal. About 3 tonnes of ordinary high quality charcoal is required to produce one tonne of activated charcoal.

The uses of activated charcoal include filtering-out organic substances from liquids or gases. It is used in industry for solvent vapour recovery and odour removal. Since activated charcoal can remove organic substances from water and other liquids, one common use is in the purification of water.

5.1.1 Charcoal as Fuel

In many developing countries charcoal is of major importance. The advantages of cooking with charcoal are that it is a clean burning fuel, and requires minimum preparation. Because of the reduction in volatiles the proportion of potential carcinogens in the combustion products is lower than with e.g. coal. Charcoal burns easily and consistently emits very low amounts of smoke and has nearly twice the energy content of wood. Therefore, for a given energy stock, charcoal occupies less storage space than wood. It is also ideal for storage since it does not rot or suffer attack by termites, a particularly important consideration in tropical countries. It is an ideal fuel for street vendors in these countries. In the developing countries, charcoal is mainly used in the cities since in rural areas wood is usually obtained free of charge from the locality.

5.1.2 Industrial Uses

For centuries charcoal has been used in industrial enterprises ranging from small cottage workshops to large steel smelting industries. Brazil uses large amounts of charcoal as industrial fuel and until the early 1950's Japan was a heavy domestic and industrial user of the fuel. In 1950, Japan produced over 2 million tonnes of charcoal but this had declined to 361,000 tonnes by 1968[95].

Florestal and Acesita[96] calculated the amount of charcoal used by the steel industry in Brazil at 4.1 million tonnes in 1982. In addition the cement industry of Brazil used another 270 000 tonnes[97]. The true amounts are probably much higher as these figures are Brazilian Government figures and so exclude the black-market which is substantial in South America.

5.1.3 Gas Producer Units

During the oil crisis of the 1970's, many alternative fuels were considered for the combustion engine. One such technology was the World War II gas producer units fuelled by wood/charcoal. This technology involves heating either wood or charcoal to produce a combustible gas inside a closed vessel, to power an internal combustion engine in automotive or stationary power units.

A number of gas producer units were made in Brazil of which the Siquieroli Company manufactured the most commercially successful model. However, even in their most successful year, 1983, only about 650 units were sold.

In the Philippines in the late-1970's it was anticipated that, by using the gasifier technology for powering automotives, boats and irrigation motors, the country could save a total of 34 million barrels of oil per year. This would have required about 7 million tonnes of charcoal. However, due to the low cost of fuel on the world markets, and many technical problems[98], the number of gasifier units in the Philippines was only around several thousand. Therefore, with the current relatively low price of oil, the future prospects for the gasifiers looks bleak.

5.2 Charcoal Production

Charcoal can be made from most organic materials, but wood, straw, coconut shells, or rice husks are the most common raw materials used. In the developing countries very little of the science of making charcoal is known to those who produce it; rather their skills are passed-on from generation to generation and the operators learn from experience.

The range of equipment in use for charcoal production, and its operating performance, are summarised in Table 5.1 .

Kiln type	Annual Production charcoal tonnes	Initial Investment $US 1986	Lifetime of Device (Yrs)	Wood consumption[1] per tonne charcoal	Energy[1,2] Efficiency
Earth Pile	Various	zero	ONE FIRING	8-12	17-25%
Pit kiln	Various	<200	2 Years	7-8	25-29%
Portable Metal Kiln	72	1000	3 Years	5-7	29-40%
Brick Kiln (Brazil)	150	800	5 Years	5.7	35%
Concrete Kiln (Missouri type)	310	2-10,000	7 Years	5	40%
Continuous Retort	20,000	2,000,000	30 Years	3.5	57%

Table 5.1 Kiln Type for Charcoal Production and Various Parameters

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[1] The figures are approximate and depend on many factors, such as wood type, moisture content and operating conditions.

[2] Energy content of charcoal as a percentage of energy content of wood. Charcoal is assumed to have double the energy content of wood.

There are many different methods of making charcoal, however two of the most common are the kiln and retort processes (Table 5.1). The kiln process is used mostly in poor developing countries, where little or no capital outlay is required beforehand and low cost is essential. Part of the wood for charcoal making is used as fuel for the initiation of the combustion reaction. Although air (oxygen) is required to initiate the process, once the combustion reaction has started the air is excluded by sealing all openings. Since no air is present for the reaction of turning wood into charcoal, the process is essentially different from combustion. The term carbonisation is more accurately used.

The retort process is mostly used in the West. Wood is placed inside a sealed container and the heat is regulated and supplied from the outside. The carbonisation process is the same as in the kiln method.

In both of the above methods the chemical processes appear to be very similar and three different distinct phases are identified; drying, pyrolysis and cooling. These are discussed below.

5.3 Chemistry of Charcoal Production

All the charcoal production processes have a similar underlying chemistry and this is described in more detail in the following sections.

5.3.1 The Drying Phase

The wood is placed inside the retort or kiln and ignited. Although the wood is oven dry, it still contains water which has to be released. The water is released in two stages. First the free water in the pores of the wood is expelled while the temperature remains at about 110°C. The higher the moisture content of the wood, the longer this stage takes and the more the energy consumed. Once all the water from the pores has been released the temperature rapidly rises to 150°C; in the kiln the water is released in the form of vapour. Here the remaining water which is tightly bound or adsorbed into the cellular structure of the wood is released while the temperature rises upto 200°C.

5.3.2 The Pyrolysis Phase

After all the water has been released, the temperature of the wood rises to 280°C; at this stage the pyrolysis reactions begin to occur. During pyrolysis the constituents of wood,viz cellulose, hemicellulose and lignin are further broken down in a complex series of chemical reactions to give pyrolysis products. Most of the pyrolysis products are in the form of gas or vapour, termed volatiles. An indication that the pyrolysis phase is proceeding is that, due to the presence of volatiles, the white smoke emitted turns to a dark colour.

Once the process of pyrolysis begins the heat required to maintain the reaction is very much less than to drive the water off in the drying stage. Hence, the process of pyrolysis is believed to be strongly exothermic[99].

5.3.3 The Cooling Phase

At the end of the pyrolysis reaction the temperature begins to fall steadily. The amount of dark smoke emitted decreases and eventually ceases. The kiln or retort remains tightly sealed, in case any air enters and re-ignites the charcoal resulting in useless combustion products. The temperature of the charcoal is allowed to decrease below the ignition temperature; only then is the kiln or retort vessel opened. The charcoal is left for a further 24 hours in the air, termed 'seasoning'. The remaining volatiles hence escape and small amounts of moisture and oxygen are also absorbed[100].

5.4 Products From the Carbonisation Process

The process of charcoal making yields solid, liquid and gaseous products. However, the quantities of these products depend on the raw materials and the manufacturing method used. Also, over the years, new methods have been developed to increase the yields.

5.5 Charcoal Properties

A key property of charcoal is the amount of pure carbon it contains. The calorific value of the charcoal, ash content, moisture content and density are also important in determining the suitability for a particular end use.

5.5.1 Fixed Carbon and Volatile Carbon Content

The pure carbon content of a sample of charcoal is obtained by deducting the moisture, volatile, and ash contents from the weight. It is usually expressed as a percentage, referred to as fixed carbon content. This is determined by heating a sample of dry charcoal in the absence of air at 900°C until it reaches a constant weight. The amount of carbon present in the end product depends especially upon the maximum temperature reached during the carbonisation and length of time at that temperature. Thus the data in Table 5.1 , shows that upto 500°C the fixed carbon content increases rapidly; however, from 500°C to 1000°C the increase in fixed carbon content is small.

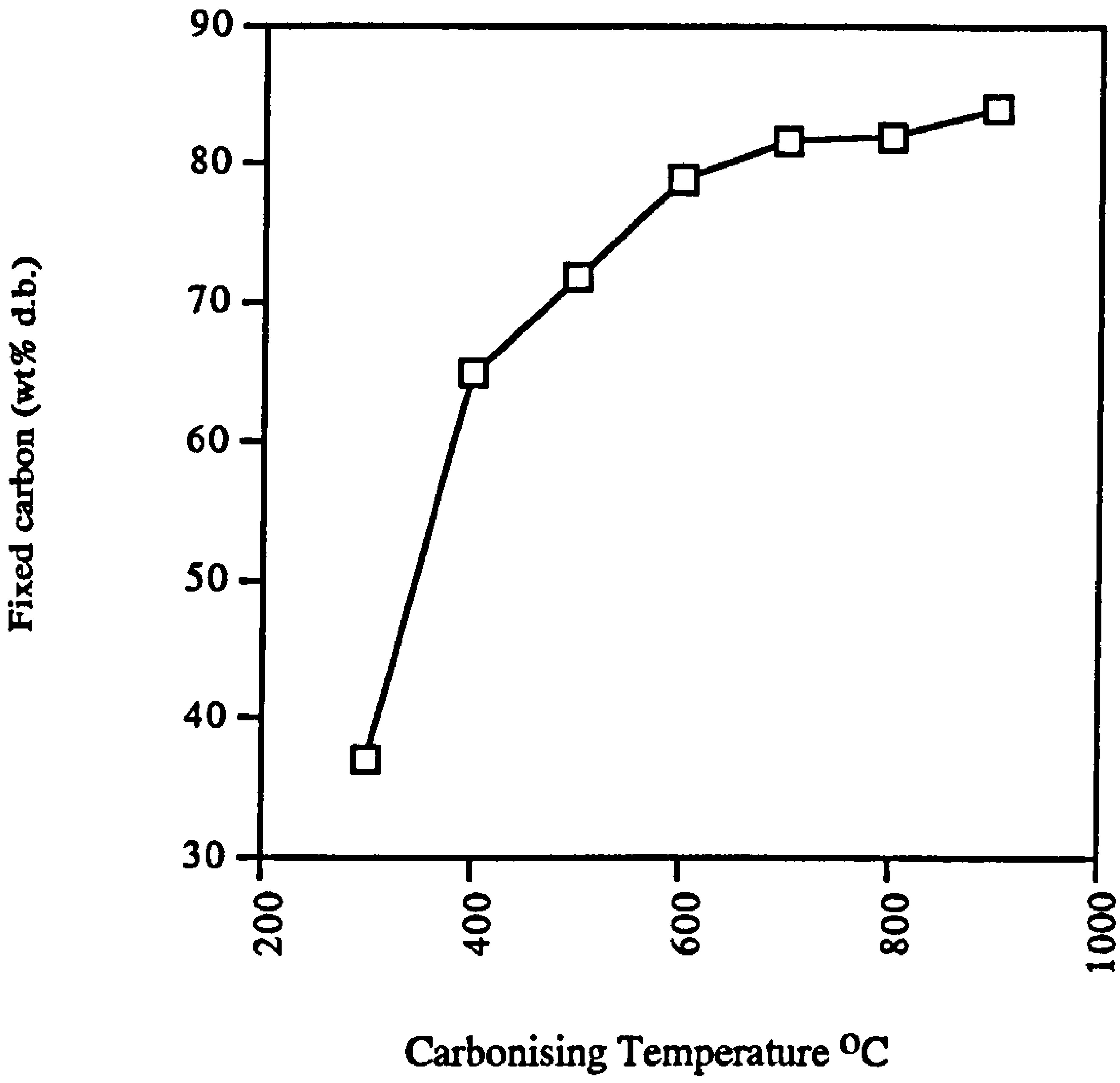

Figure 5.1 Relationship Between Carbonisation Temperature and Fixed Carbon Content of Charcoal[99]

For domestic cooking high contents of volatiles are required in the charcoal for easier lighting. However, for industrial use, such as in steel making, a fixed carbon content of 80-95% is required. This is 'high quality 'charcoal, and tends to be brittle and hard to ignite. Domestic charcoal tends to have a volatile content of 20-30%. Charcoal with a volatiles content of >40% is regarded as poor quality, since on combustion it emits strong-smelling smoke. Poor quality charcoal tends to stain clothing upon handling.

5.5.2 Density of Charcoal

The density of charcoal depends upon the wood source, the production method and its intended end use. In general the density of charcoal is 50% that of the wood from which it is produced.

5.5.3 The Gross Calorific Value of Charcoal

The gross calorific value of a particular charcoal depends on the proportion of fixed carbon, and thus volatiles, it contains. For most charcoals, the gross calorific values fall within the range 28-33 MJ/kg. The nett calorific value depends upon the water content of the charcoal but usually approximates to 28 MJ/kg. Charcoal may also contain ash within the range of 0.5% -5%. Ash usually consists of minerals such as clay, silica, and magnesium and calcium oxides.

Fresh charcoal contains no water but gains moisture from air. The higher the volatiles content the greater the moisture gain from the air. Moisture content can be as high as 15%.

5.5.4 Pyrolysis Products

When air dried wood is converted into charcoal, depending on the yield, the volatiles given-off can be 60% to 80% of the orignal mass of the wood. In the pyrolysis phase non-condensible gases, and the liquid products are also released.

The non-condensible (Table 5.2) gases are those which do not condense at room temperature. The yield of non-condensable gases is 10-15% of the air dry mass of the wood and they may be separated-out by passing the full pyrolysis products stream through a condensing pipe or chimney. The liquid products condense-out leaving the non-condensible gases, mainly carbon dioxide, carbon monoxide, methane, hydrogen, and some oxygen plus the nitrogen present when the reaction was initiated either in the kiln or retort vessel.

The carbonisation temperature again controls the differing amounts of non-condensible gases present in the pyrolysis stage.

Non-Condensible gases	% Yield
carbon dioxide	42.7
carbon monoxide	34.8
methane	14.8
hydrogen	5.4

Table 5.2 Non-condensibles produced from Carbonising Redwood

Increasing the carbonising temperature of the above reaction to 600°C gave 10% lower yield of carbon dioxide and an increase of 5% for both carbon monoxide and hydrogen contents[101].

5.5.5 Liquid Products

The liquid pyrolysis products are those which condense to a liquid at ambient temperature. The total yield of liquid products from air dry wood is usually around 59-60% by mass, half of which consists of water. The mixture of the liquid product, termed pyroligneous liquid, contains water, methanol (1.6% by mass from air dry wood), and acetic acid (5%). However separation into the different constituents can be expensive because of the capital equipment cost.

5.6 Charcoal Production from Specific Wood Species

Work by Shah and co-workers[102], has provided an insight into some of the specific parameters involved in charcoal making, by using batch metal partial combustion kilns (PCKs). Four species of wood were studied, viz Oak, Meranti, Spruce, and Chestnut. Similar species with varying moisture contents were also studied as shown in Table 5.3 . All tests were carried out under identical conditions .

	Species	Moisture content (wt%)	Energy Content (kJ/kg)	Ultimate Analysis (wt%)		
				C	H	O
1	Oak	14.7	15.3	52	5.3	42.4
2	Oak	14.7	15.3	51.5	5.5	42.9
3	Meranti	11.5	17.3	53.0	5.1	41.9
4	Meranti	11.5	12.2	53.3	5.2	42.1
5	Spruce	30.8	12.2	50.8	5.4	43.9
6	Spruce	42.9	9.6	50.2	5.4	44.4
7	Spruce	42.9	9.6	50.5	5.6	44.2
8	Chestnut	12	15.8	51.8	5.2	42.8

Table 5.3 The Ultimate Analysis of Named Tree Species

Species	Volatiles (wt%)	Fixed carbon (wt%)	Ultimate Analysis (wt%)		
			C	H	O
Oak	15.7	79.8	84	1.4	14.6
Oak	27.2	67	73.4	2.2	23.7
Meranti	20.6	77.4	85.1	2.1	12.7
Meranti	15.3	83.1	87.7	2.7	9.3
Spruce	9.7	89.3	94.2	2.2	3.5
Spruce	13.9	85.2	88.8	2.3	8.7
Spruce	18.3	80.7	85.4	2.7	11.5
Chestnut	22.9	75.2	79.2	3	17.3

Table 5.4 The Ultimate Analysis of Charcoal obtained from Named Species

The data show that despite the same initial raw materials and conditions the same kiln produced charcoals of different properties This is probably explained by the fact that non-uniform firing resulted in different final temperatures, which can range from 400-700°C.

The volatiles in the charcoal described in Table 5.4 ranged from 9.7 to 27.2% (by weight). A high volatiles release resulted in low carbon content in the final charcoal; conversely a low volatiles content resulted in a high carbon content.

The presence of hydrogen between 1.4% to 3% (by weight), apparently had no influence on the final energy content. Oxygen content varied from a low of 3.5% (by weight) upto a high of 23.7%. As demonstrated in Figure 5.2 the lower the oxygen content the higher the energy content of the final charcoal.

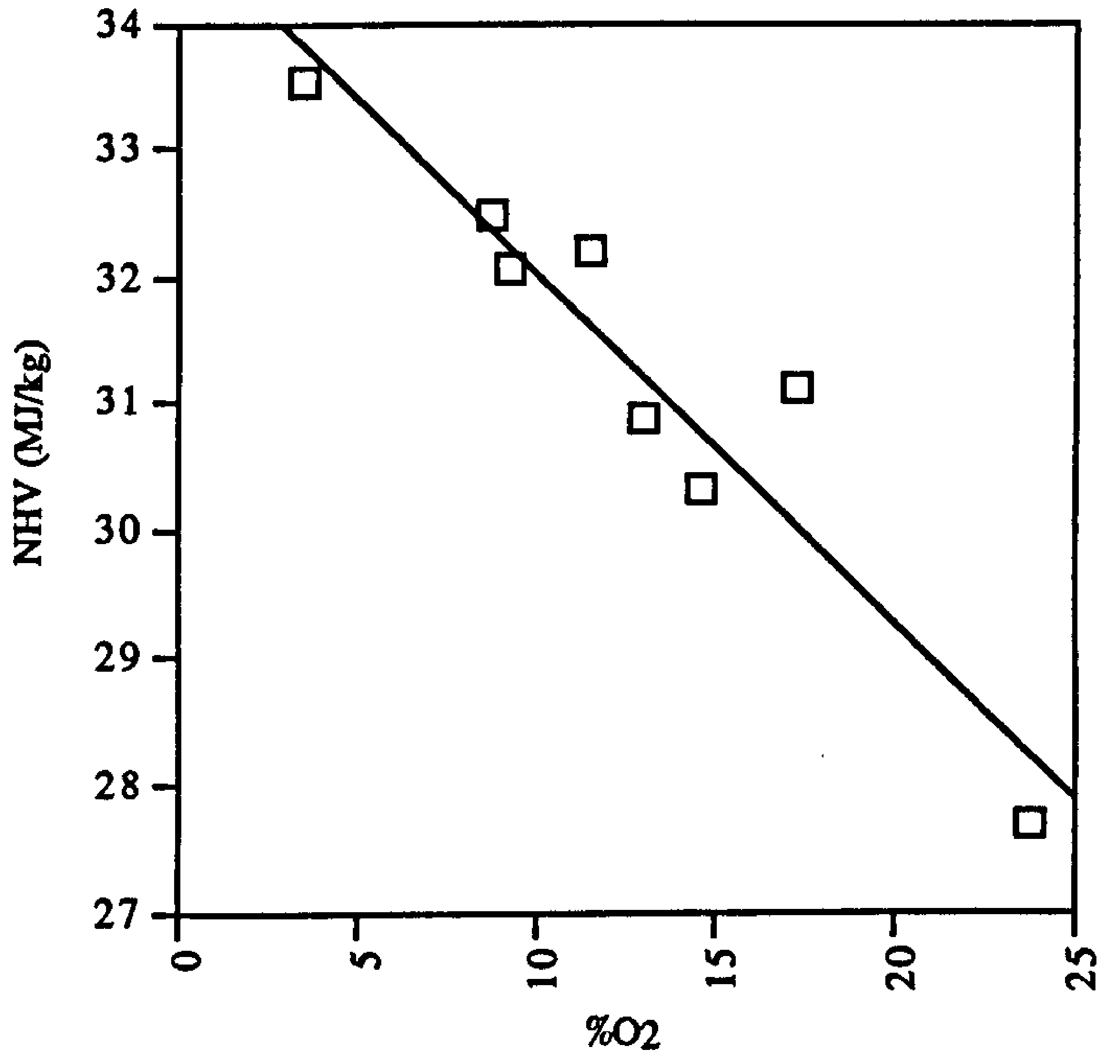

Figure 5.2 The Lower the Oxygen Content the Higher the Energy Content of the Final Charcoal

5.7 Use of Carbonaceous Solids in Diesel Engines

When Rudolph Diesel first designed the compression ignition (CI) engine, he envisaged using cheap abundant coal as the fuel. In the early experiments coal dust was inducted through the intake manifold using a 'fumigation' technique. Then, and in subsequent experiments problems arose, from unburned coal, and from severe wear by abrasive materials present in coal such as the high ash content. Diesel realised that liquid petroleum fuels offered greater potential and halted his research on solid coal fuels.

5.7.1 Work on a Coal-Dust Engine

Pavolikowski[103] and Morrison[104], described work with the German "RUPPA" engine, a slow speed engine designed to operate on coal dust. Soehngen[105] reviewed of the German work on development of a coal dust diesel engine. It was concluded that high speed coal dust engines are practicable.

Rich and Walker[106] developed a low compression-ratio coal dust diesel engine which used pilot injection of diesel fuel and "fumigation" of coal into the intake air. The results proved less than satisfactory due to coal delivery problems. The size of coal particles used in these experiments was approximately 200 microns. Further work was done by Marshall and Wallets[107] using a coal slurry-fuelled diesel engine.

Pavolikowski , developed the RUPPA engine which used compressed air for the injection of coal dust and operated at 160 rpm, producing 60 kW[108]. The engine ran for 12 years and 11,000 hours of research was carried out. The rings were replaced every 1000 hours. The disadvantages of the engine were that the delivery system comprised a feed screw to a low pressure chamber connected to the main combustion chamber passageway. Hence it had no ability to compensate for changes in the engine load, speed or fuel type[109].

Most interest in the coal-slurry powered engine was shown in Germany[110]. Nusselt and Wentzel performed early studies into the ignition and combustion processes of coal dust under simulated engine conditions[111]. Upto the Second World War, as many as 19 experimental coal/slurry engines were tested in Germany ranging in size from 1 to 150 lit/cylinder, and in speed from 160 to 1600 rpm. Problems of wear in the previous engines were solved by;

-Adjustable piston rings

-Increased lubrication

-Cylinder wall cleaning of coal particles

-Use of wear resistant materials

- An injection system using high pressure air.

The engines are reported to have run for 6,000 hours and had an efficiency of 35%. However, due to the outbreak of the Second World War, and termination of the experiments, none of the results could be validated. None of the engines were built on a commercial basis.

5.7.2 Coal-Slurry Fuels

The first, coal-slurry fuels experiments were conducted in 1934 in the United States[112]. At the same time England's Fuel Research Institute conducted several studies of cylinder and piston wear in spark-ignition engines.

In the early 1950's ample reserves of oil were discovered. The low cost newly discovered petroleum fuels quickly established themselves as the prime transportation fuels. The need for coal-slurry fuel diminished but a few projects, mostly in the United States, continued. Results[113] from these experiments generally showed, that with a 20-30% coal w/w in oil with a particle size 40-450 microns using an engine speed of greater than 800 rpm;

- Engine efficiency was low.

-Engine wear and lubrication oil contamination occurred.

-Problems were encountered in injection systems.

The four-fold increase in petroleum prices in the early 1970's prompted renewed interest in all types of alternative fuels.

Further research into coal-water slurries revealed the significance of chemical and physical properties i.e. problems of grinding coal (due to its hardness), viscosity, and high ash content.

New materials have been made e.g. ceramics, which are much more resistant to wear[114,115] Low heat-loss engines and improvements in lubricant technology mean that dilution of the lubricating oil has a minimal effect on performance. The better-designed injectors give longer lasting performance and do not become obstructed.

5.8 Slurry Fuel Properties

The results of Ryan, et al[116] indicated that there are mainly five areas of concern in the formulation of slurry fuels for diesel engines:

1) Dispersion characteristics of solid component.
2) Flow and stability characteristics of the slurry.
3) Injection and atomisation characteristics of the slurry .
4) Injection systems and engine durability characteristics with the slurry.
5) Engine combustion characteristics of the solid component and the slurry.

All the above areas depend on certain physical properties of the solid component. Hardness of the solid determines the type (grinding, homogenisation, dispersion, etc.), and the degree of processing required to produce the desired particle size distribution. This in turn affects the rheological stability and the injection and atomisation characteristics of the resulting slurry. These characteristics are also affected by the active surface area of the particles which in turn, is related to the porosity as well as their size distribution. The injection system and engine durability are also affected by particle hardness and size distribution as well as the presence of contaminants e.g. sulphur and ash. The engine combustion characteristics are affected to some degree by all the properties mentioned above. In addition, the combustion process is affected by the density, the heat of combustion and the chemical composition of the solid component.

5.8.1 Charcoal-Water Slurries

It was clear from the literature reviewed that a preferred solid would be one which had a low ash content and was relatively easy to grind- charcoal, which is readily available, fits these criteria. Moreover it is bio-renewable and, since the sulphur content is low, generates little SO_2 on combustion.

The volatile matter content of charcoal depends on the type of kiln, the procedure and the initial raw materials used. The amount of volatile matter ranges from 4% w/w to a high of approximately 45%. The higher the volatile content of charcoal in the ultracarbofluid, the better the fuel performance to be expected.

Not only is charcoal more easily ground than coal, it requires substantially less energy to grind and can be ground to very fine particles. It should ideally be ground to <30 µm in order to obtain optimum mixing of solid particles into an oil /water slurry. Therefore charcoal appeared to be an ideal solid fuel for incorporation to reduce the environmental impact of diesel engine operation. Hence it was selected for use in the present research. Incorporating charcoal into a liquid fuel by suspension in water, solves the major problems associated with solid biomass fuel. In the solid state, biomass presents problems in handling and transportation due mainly to its low bulk densities.

However, it is clear that the application of solid fuels in I.C engines requires a lot more research especially in the areas of:

1) Fuel preparation.

2) Design of fuel metering and injection systems.

3) Design and construction of pistons, combustion chambers and piston rings.

The possibilities for diesel fuel replacement which have been particularly investigated are as follows.

(i) Complete replacement by a suitable vegetable oil e.g. rape seed oil[117], soya bean oil[118], or esterified sugar beet extract[119]. Some research is also in progress into the use of elephant grass oil (Miscanthus)[120].

(ii) Partial replacement by blending diesel with vegetable oils in varying proportions up to 20% by weight[121].

(iii) Partial replacement by blending with an aqueous suspension of a non- renewable fossil fuel e.g. coal.

More recently at Universite de Technologie de Compiegne, some work has been reported on using fine coal dust[122]. Antonini et al[123] developed a technique for an oil agglomeration and "slurryation" process for clean slurry production. From previous work[124] it is known that coal with less ash can be formulated in a coal slurry for substitution as a fuel in diesel engine oils and gas-fired boilers.

Mixtures of coal, water and agglomerating agent were formulated as slurry fuels. Different types of coals were ground very finely (below 30 microns) in order to produce a 'super-clean' coal ternary mixture (coal, water, oil blend) with ash content below 0.5wt%. This mixture is termed an ultra-carbofluid.

(iv) Complete replacement by a slurry of coal in vegetable oil.

(v) Complete replacement by a 100% bio-renewable ultracarbofluid.

This describes the completely novel type of fuel, not previously reported in the literature, that was chosen for use in in the present research. This novel formulation comprised water, charcoal and a vegetable-derived oil. This was termed Bio-ultracarbofluid.

5.9 Bio-ultracarbofluid (Bio-ucf)

The vegetable-derived oil or oils needed to be commercially viable. It was also considered advantages that work with neat oils was reviewed for comparison. A search of the literature indicated rapeseed and soya oil fitted these criteria.

When using such oils, esterification was found to be necessary in order to reduce their viscosities. This also improves their long-term stability and in so doing reduces the tendency for spontaneous combustion under certain circumstances. For these reasons, and in particular to assist dispersion in water, methyl rapeseed and methyl soyate were chosen as the oils to be studied.

It was deduced initially, by analogy with the work of Antonini et al using coal dust , that a 'bio-ultracarbofluid' should comprise a mixture of particulate charcoal, fuel oil, and water generally in the ratio of 5: 3: 2 and a small amount of stabilising additive.

As discussed previously, charcoal can be produced by different pyrolysis techniques starting from various natural sources. It should presumably be present in the fluid at upto a maximum of around 50% by weight. The particle size was chosen to be usually in the range of <30 μm in order to remain in suspension, reduce fuel delivery problems and give efficient combustion. From the research with coal dust carried out by Antonini it was clear that volatile content of the charcoal would be variable, i.e. a higher volatile content coal had given higher energy outputs. Therefore this also had to be taken into account. The stability additives were chosen on the basis of Antonini's recommendation, since they had functioned satisfactorily with coal dust of similar particle size distribution.

The preparation and formulations of novel bio-ultracarbofluids to form the basis of this study are described in section 6.5.

CHAPTER 6

EXPERIMENTAL METHOD

Chapter 6

6.0 EXPERIMENTAL METHOD

Evaluation of the relative performance of the bio-ultracarbofluid formulations compared with diesel oil necessitated operation of a standard dirsel engine used with provision for exhaust gas analysis.

6.1 Apparatus

All of the equipment was designed and purchased, or constructed, as part of the present study. Commissioning tests were performed before the experimental tests described in chapter 7.

Diesel engines made by Lister-Petter vary from compact, light, versatile engines (e.g. LT1) with brake power output of 5.2 kW at 3600 rpm to large heavy duty engines (e.g. JWSC6) with brake power of 186.4 kW at 2000 rpm. The small engines are usually used for powering mobile traffic signals and small generators. The heavy duty engines are used for marine propulsion of large ships and also as generating sets on building sites. The ease of use, ease of starting on diesel fuel, and excellent reliability of Lister-Petter engines has resulted in the engines being sold to over 148 countries. They are especially popular in the developing countries. Some engines are locally manufactured in Argentina, Iran, Malaysia, South Africa and USA.

The engine used in the test programme was a new Lister-Petter LPWS2 model from the middle of the Lister-Petter range. It was a 2 cylinder, 4 stroke, 600cc diesel engine (Figure 6.1). A new engine test bed was designed and built. Special anti-vibration mountings were found to be necessary for smooth running of the engine and to avoid destabilising the data collection instrumentation, the specifications for which are given below (Figure 6.2).

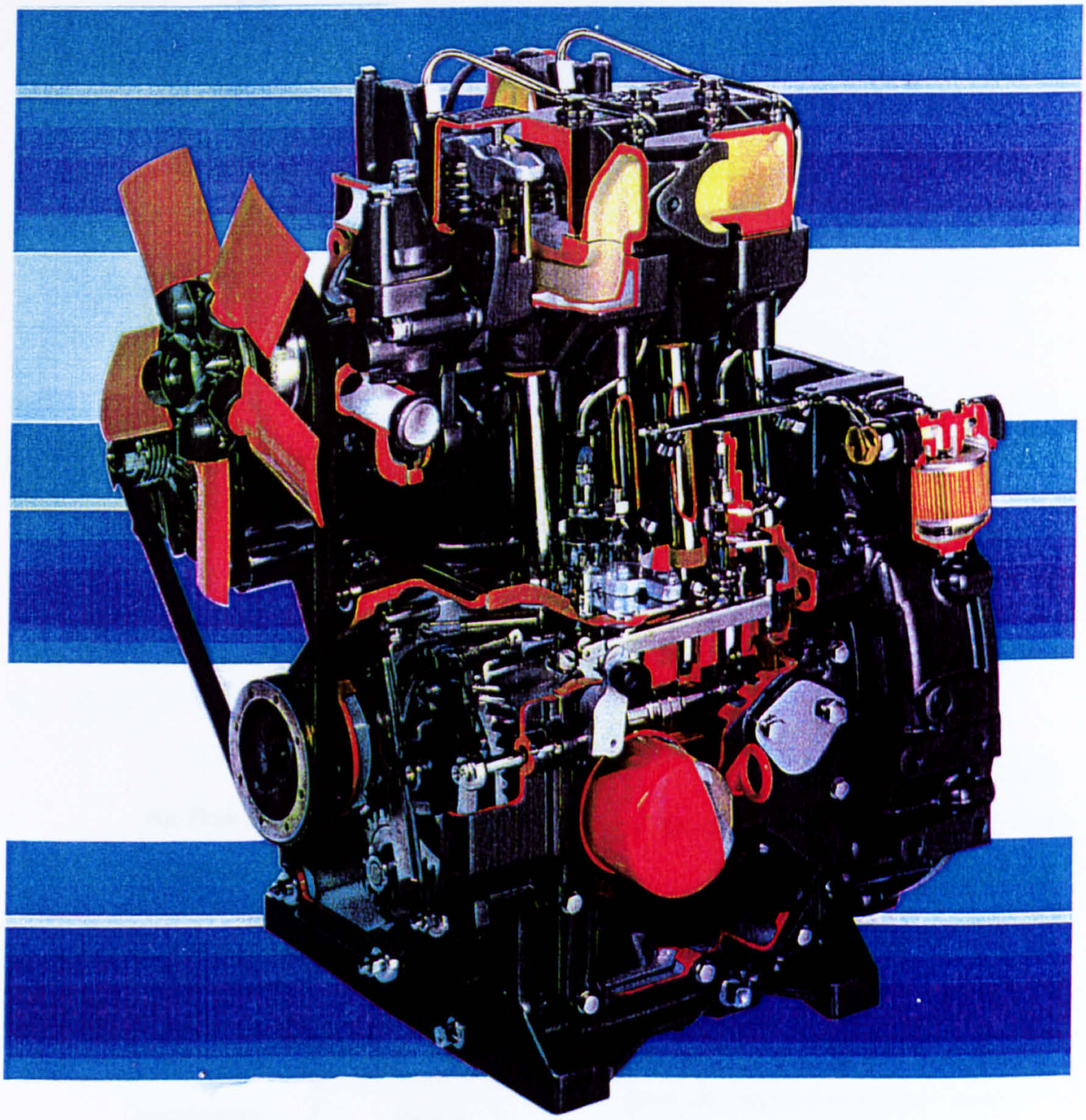

Figure 6.1 Lister-Petter LPWS2 Diesel Engine Used In The Experimental Programme

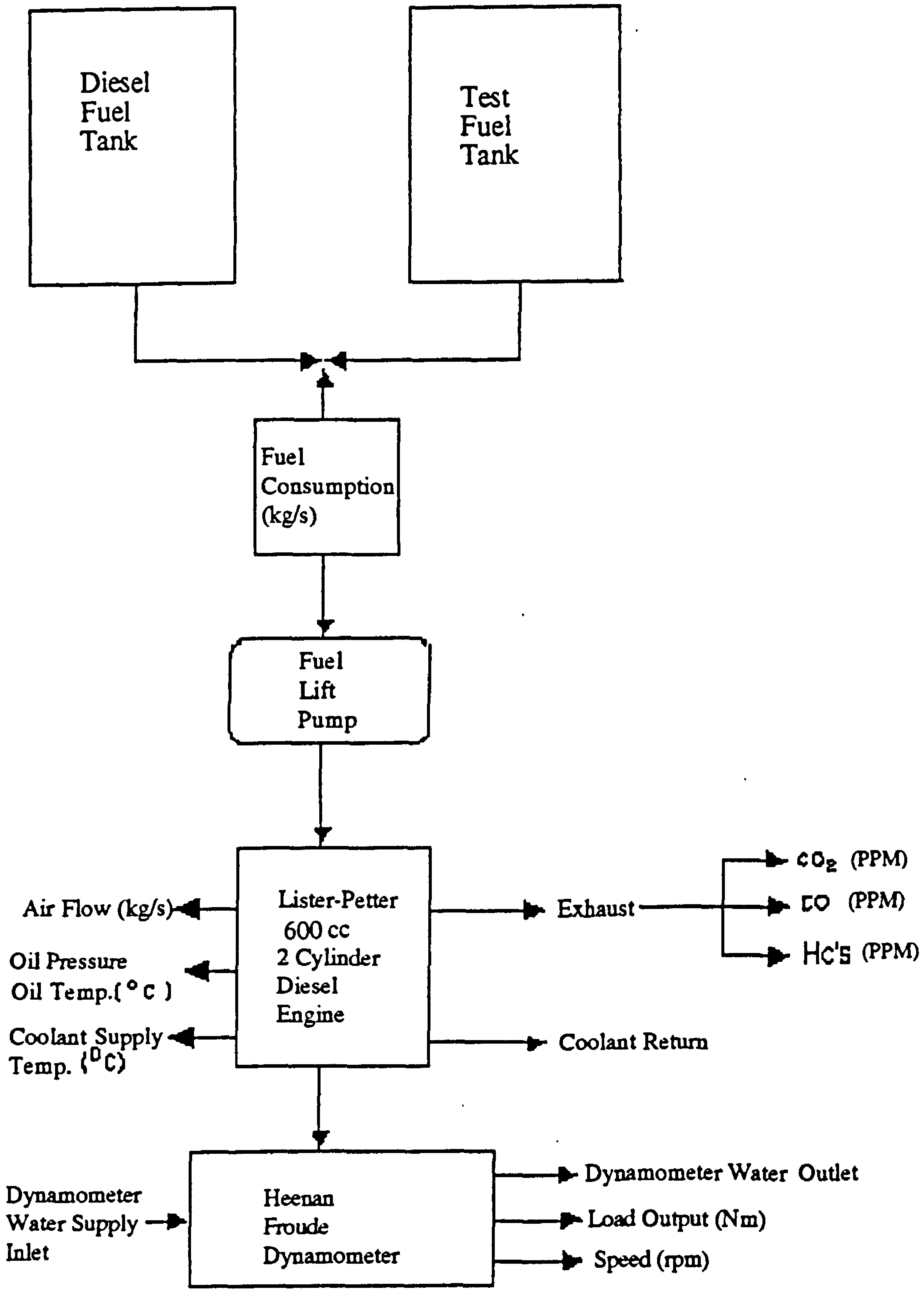

Figure 6.2 Engine Test Equipment Layout

Cooling of the engine is carried out by a belt driven water circulation pump and integral thermostat. An external cooling fan is also connected to the radiator. A gear driven rotary pump supplied lubricating oil at a constant pressure to all important working components with no external pipe-work being necessary.

For easy starting, the engine was connected to a 12 volt electric starter motor together with a 45 amp 12 volt battery charging alternator. The engine will start at temperatures as low as -10^{o}C on ordinary diesel fuel. The engine uses pintle injectors combined with an indirect injection system and individual fuel injection pumps. Full power from the engine was taken from the flywheel for direct drive by couplings. The engine rotated anti-clockwise, when viewed from the flywheel end.

6.2 Fuel System

All the prepared test fuels and the standard diesel obtained fuel were stored in Jerry cans. However a modified petrol can capable of holding 8 litres was used as the engine fuel tank. This contained Esso 2000 diesel fuel, on which the engine was warmed up and run on in-between test fuels. The fuel tank was also connected to a fuel measuring device as shown in Figure 6.3 .

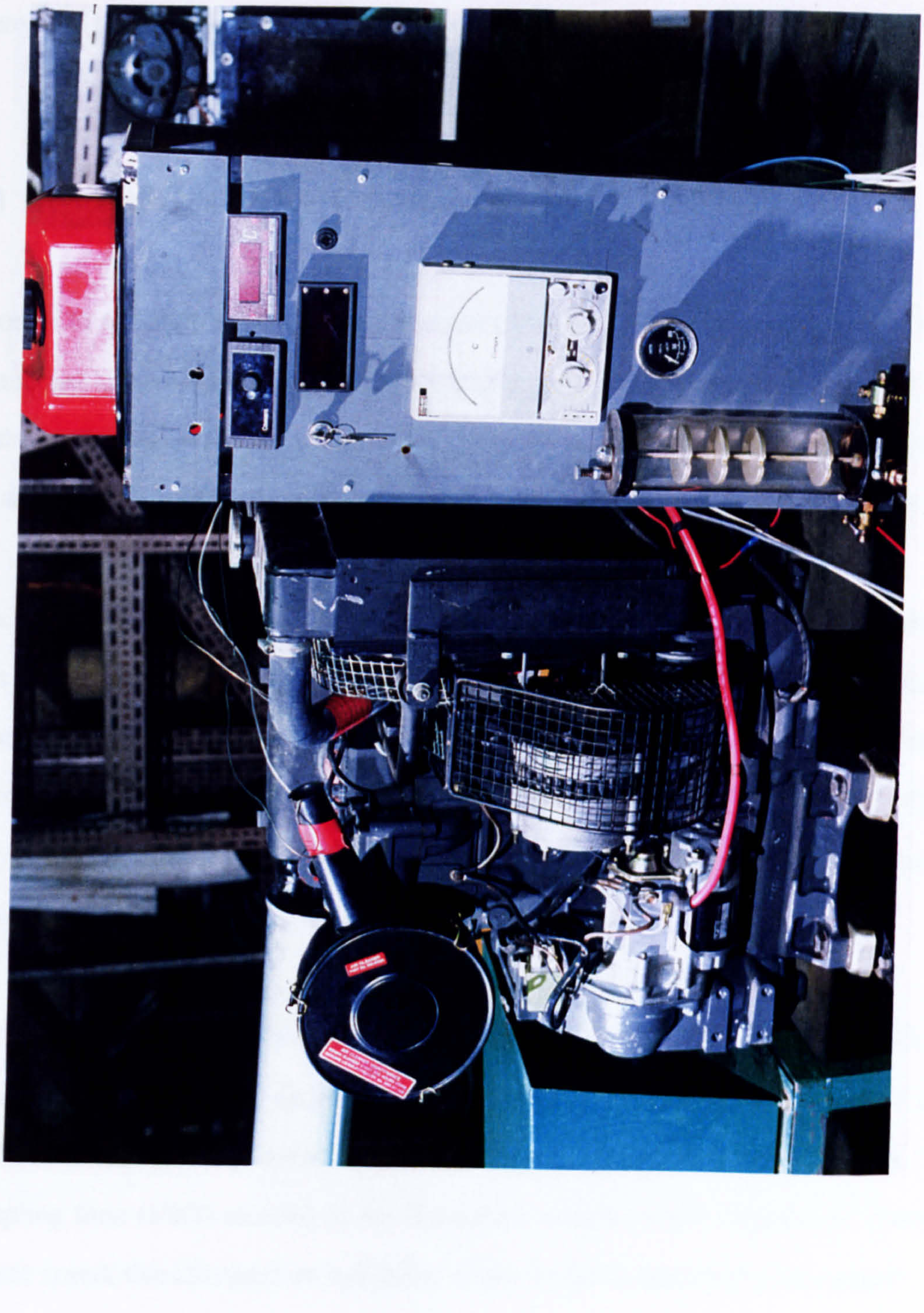

Figure 6.3 Fuel Measuring Device

6.2.1 Fuel Measuring Device

The fuel measuring device consisted of glass tube attached vertically to the rig with a threaded rod in the middle onto which were fixed a number of discs at known volumes (100, 200 and 400cc). Changes in level during time intervals recorded on a stop-watch were used to determine the fuel consumption rate.

6.3 Heenan-Froude DPX 1 Dynamometer

In order to facilitate engine operation under different loads, a hydraulic dynamometer was connected to the engine using a Hardy-Spicer propshaft . The universal joints at both ends of the shaft reduced the need for perfect alignment as small amounts of shaft flexing could be absorbed without damage to the bearings. The water brake is shown in Figure 6.4 .

The DPX 1 dynamometer, or 'water brake', used water to absorb the engine power. Load was exerted on the engine by directing the inlet water onto a rotor, using adjustable sluice gates. The power absorbed was converted to heat which was detected in the outlet water. The load applied by the dynamometer on the Lister-Petter engine at wide open throttle can vary the engine speed from a minimum idling speed of 850 to a maximum speed of 3300 rpm.

The engine rpm was measured using a M48 optical tachometer. A piece of reflective tape, affixed onto the end of the dynamometer, reflected the light emitted by the optical head back to the built-in receiver (Figure 6.5). The engine rpm was then displayed digitally. The short sampling time (1/100 second) of the instrument ensured a fast response to change in the engine speed; this also gave an indication of any irregular operation of the engine.

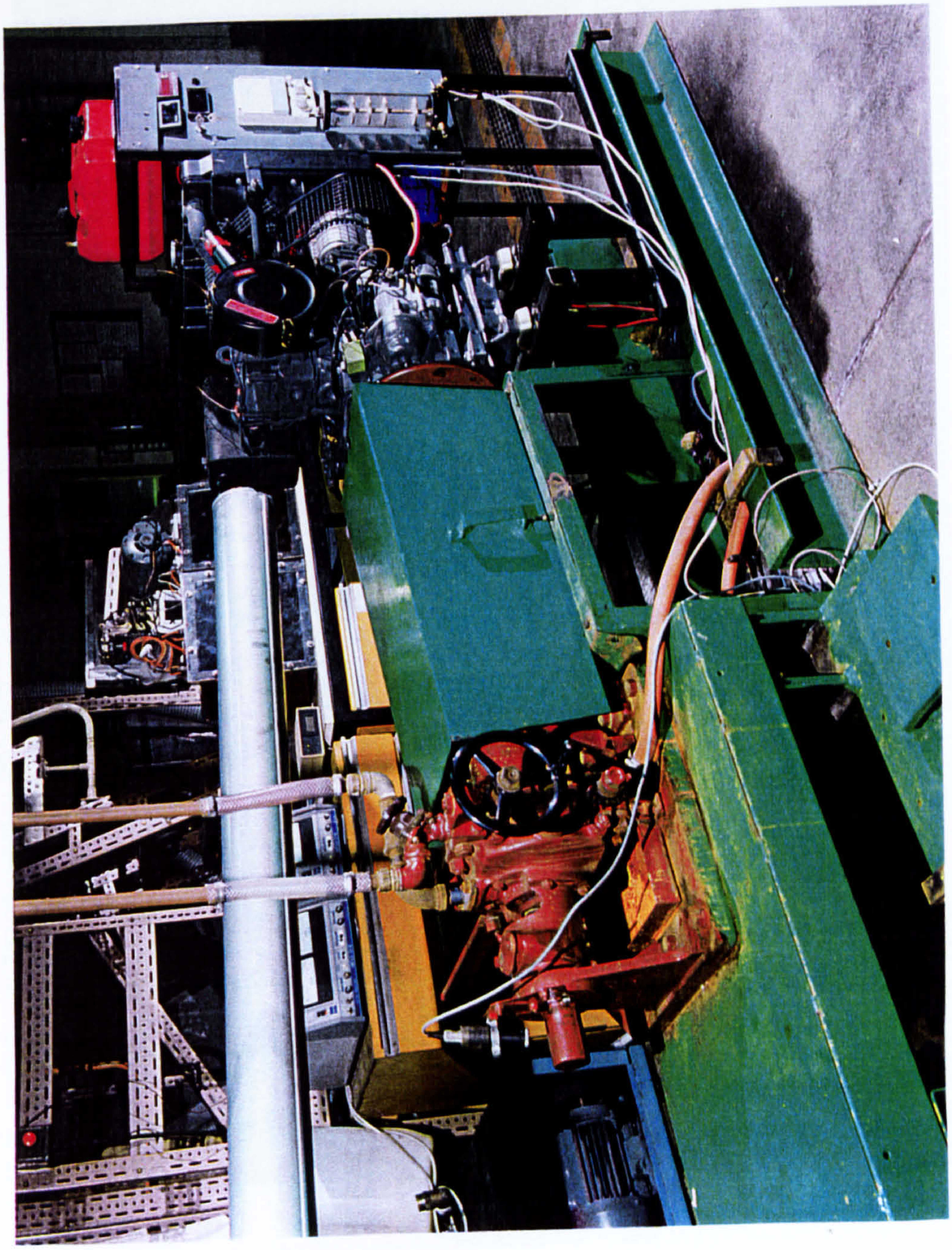

Figure 6.4 Heenan-Froude DPX 1 Dynamometer

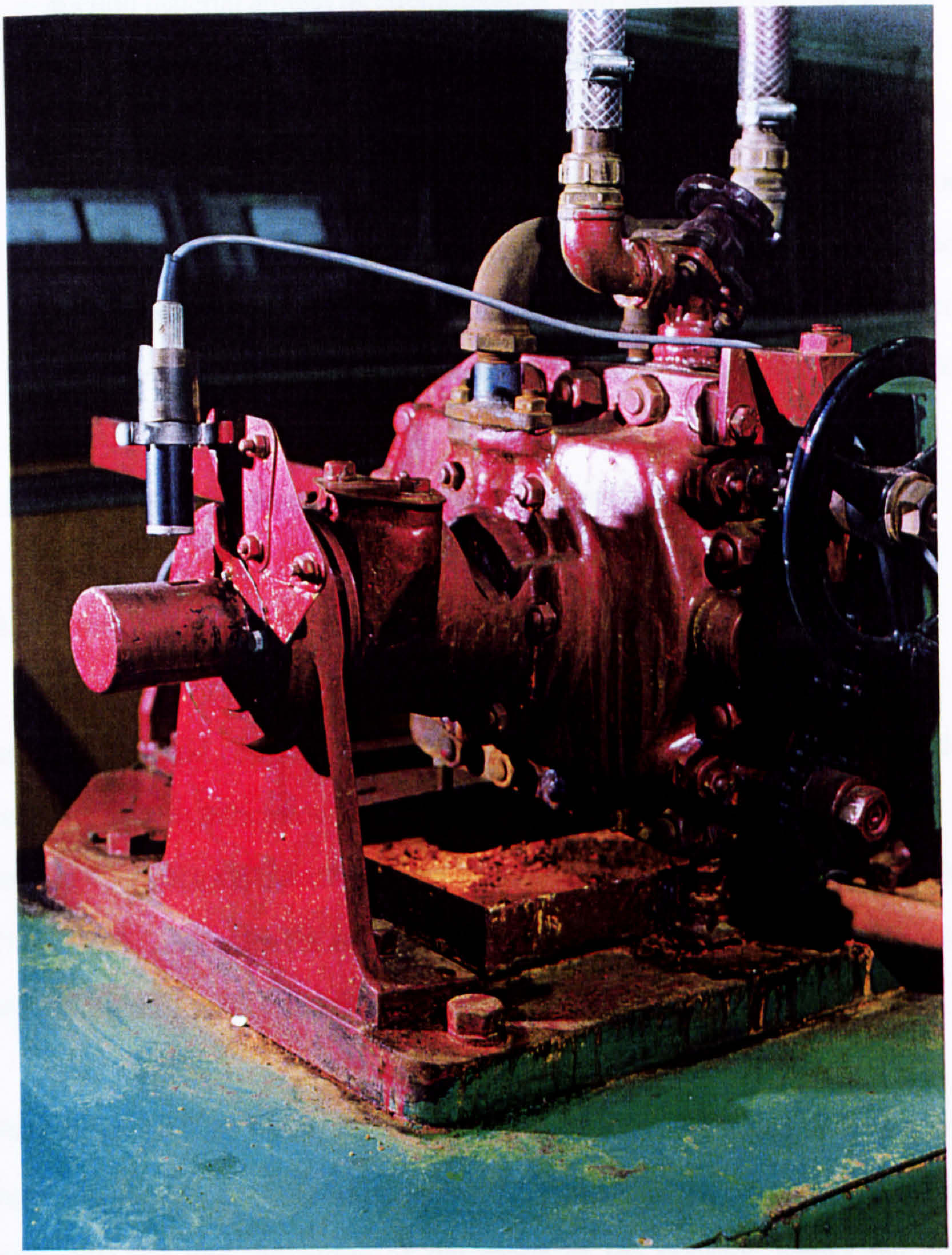

Figure 6.5 M48 Optical Tachometer

There are three main types of dynamometer;

(i) The friction brake dynamometer. Typically the engine flywheel has a band of friction material around its circumference , and the torque reaction on this corresponds to the torque output of the engine.

(ii) Electric dynamometer. In this case the dynamometer acts as a generator to absorb the power from the engine. The torque output, or the load, absorbed is calculated from the dynamometer field strength. The electric dynamometer however has a limitation on operating speed which may be as low as 3000 rpm.

(iii) Froude Hydraulic Dynamometer; as described below.

6.4.1 Froude Hydraulic Dynamometer

Both the rotor and casing of a Froude hydraulic dynamometer are designed to ensure maximum braking efficiency. The rotor is made with a series of cup-shaped pockets or vanes; similar pockets, but of opposite hand or pitch, are incorporated on the inside faces of the casing. Thus when the machine is assembled the pockets of the rotor and casing face each other with a small but definite clearance between them.

Water is fed into the casing so that as the rotor is driven round it carries with it water trapped in the rotor pockets. At the same time centrifugal force tends to throw this 'trapped' water outwards and, by virtue of the shape of the pockets, across the clearance gap between the rotor casing. The matching shape of the casing pockets returns the water in a like manner to the bottom of the rotor pockets, so that any single drop of water would trace out a vortex path, circulating between rotor and casing. This vortex produces a strong braking action which acts as a load for the engine and also to carry the casing around with the rotor.

In the actual dynamometer the rotor is double-sided, with two sets of casing pockets, serving the purpose of equalising side thrust and doubling the braking effect. A variable load effect is produced by interposing sluice gates in the clearance space between rotor and casing. Between the fully-open and fully-closed positions of the sluice gates a wide range, stepless control of speed and load is thus available with the engine running, merely by adjusting the hand wheel (Figure 6.6) controlling the sluice gates.

6.4.2 Load Measuring Device

A new load measuring device was constructed consisting of four strain gauges in a Wheatstone bridge arrangement mounted on a cantilever, acted on by an arm attached to the dynamometer case. Two strain gauges were mounted on the upper side and two on the lower side, resulting in two being under compression and two in tensile strain at any time (Figure 6.7) . A variable resistor was placed across the bridge circuit to enable zeroing, and power was supplied from a Brandenburg STI stabilised DC supply. The deflection of the beam, due to the load exerted on it, changed the resistance of the strain gauges proportionally; the change in voltage which resulted was measured using a digital voltmeter.

The beam attached to the dynamometer casing was designed to allow weights to be suspended freely for calibration and periodic checking of the bridge circuit (Figure 6.8) . This was an important aspect, as the readings were spread over a relatively long time and the arm attached to the dynamometer could have attained a permanent bend.

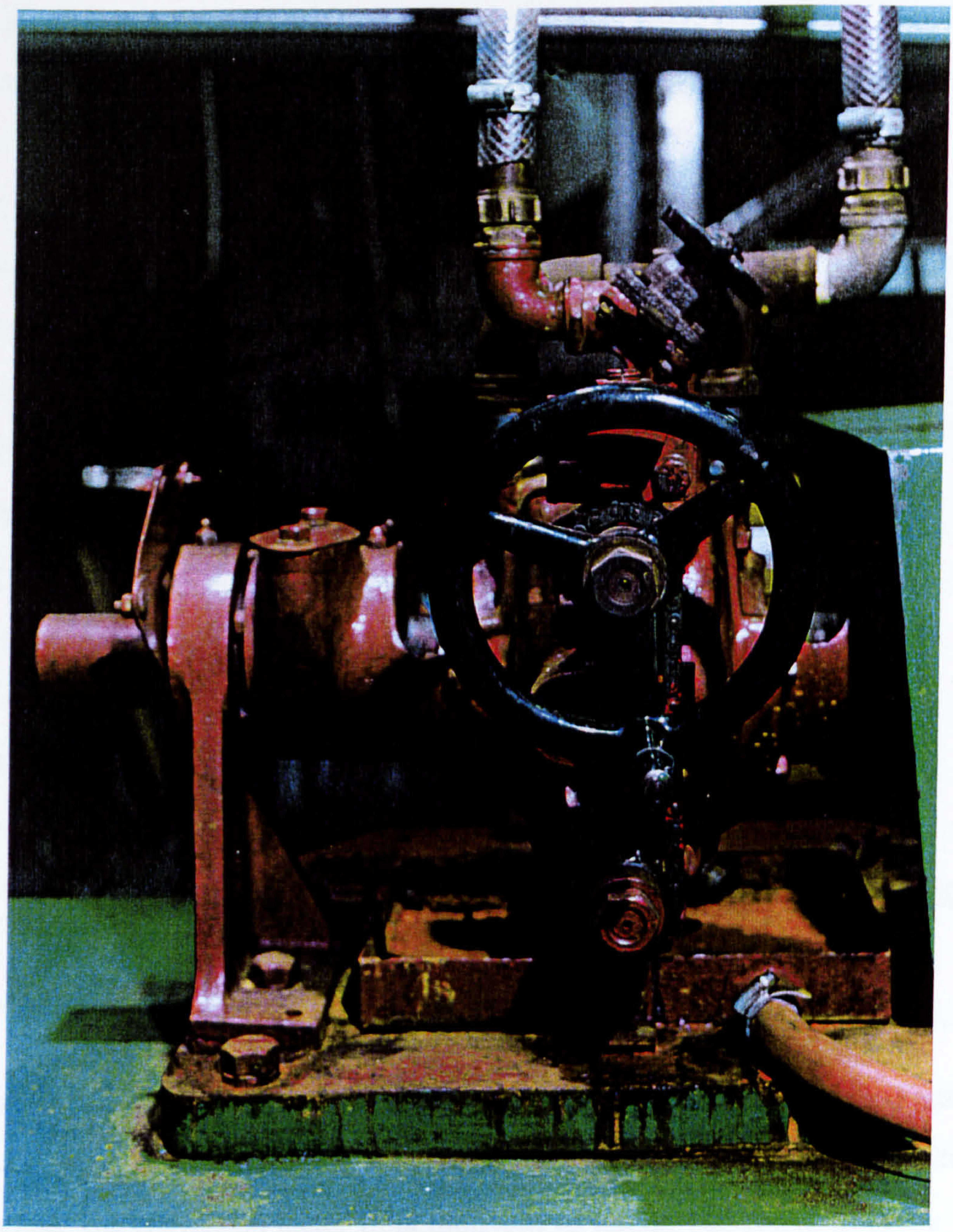

Figure 6.6 Dynamometer Hand Wheel Adjustment

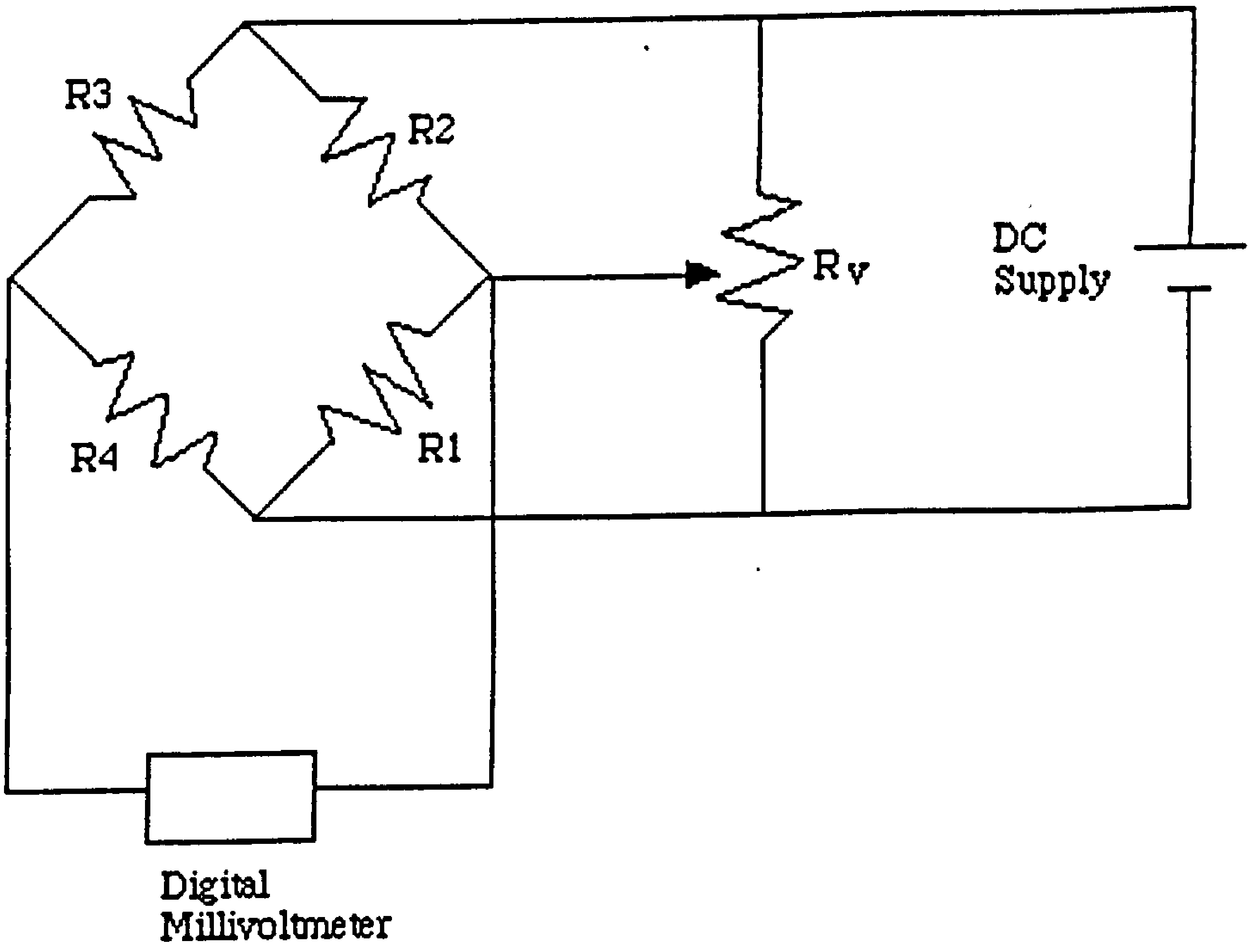

Figure 6.7 Bridge Circuit for Strain Gauges in the Load Measuring Device

Tables 6.10 shows the results of calibration, and from plots of these data (Figures 6.12 and 6.13), it can be seen that there was a straight line relationship between millivolts output and torque. The conversion factor from millivolts to torque was found from the graph to be 9.92.

6.4.3 Infra-red Gas Analysers

Two Horiba exhaust analysers (Fig 6.9) were used (A Mexa-321E, measured CO, and HC content whilst a Mexa-211E measured CO_2 content.). The infra-red process allows precise, selective measurement of individual exhaust-gas constituents. The process is based on the fact that infrared light is strongly absorbed by certain exhaust gas constituents at a characteristic wavelength which differs for each constituent .

An emitter which is heated to approximately 700°C emits infrared light which passes through a measuring cell and enters a receiver chamber. Gas with a defined CO component is held in the receiver chamber. A portion of the CO-specific radiation is absorbed in the chamber. This absorption increases the temperature of the gas, causing it to flow via a flow sensor into the second compensation space V_2, The rhythmic interruption of the radiation by a rotating chopper disc causes the direction of the basic gas flow to alternate between the two spaces V_1 and V_2. The flow sensor converts this signal into an alternating electrical signal. A test gas with variable CO contents absorbs a portion of the radiated energy as it flows through the measuring cell. The amount of energy absorbed depends upon the magnitude of the CO content and is lost to the receiver chamber. As a result, the basic flow in the receiver chamber is reduced. The deviation from the basic alternating signal indicates the CO content in the test gas.

As the composition of fuel is changed the composition of the exhaust gas is also naturally expected to change. It is also possible to measure carbon dioxide, carbon monoxide, and also hydrocarbon concentration. The total concentration expressed as parts per million of the hydrocarbons present can be obtained by summing the concentrations of each of the individual hydrocarbons. Expressing the concentration in such a manner provides a measure of the number of hydrocarbon molecules present in a given quantity of exhaust.

However, the complexity associated with the above technique can be recognised, since a significant number of individual hydrocarbons of differing molecular weight are present.

An alternative method for expressing the total hydrocarbon content in the exhaust consists of normalising the hydrocarbon concentration to an n-hexane basis. This is done, in effect, by determining the concentration of carbon atoms represented by the hydrocarbons in the exhaust gas and dividing by six, to give the n-hexane equivalent. The concentration is, as in this present research, conveniently expressed as parts per million by volume of C_6 .

6.4.4 Exhaust Extraction Fan

In order to remove all the exhaust waste products of the engine quickly and efficiently a powerful exhaust extraction fan was fitted to remove all the undesirable products. This discharged outside the building.

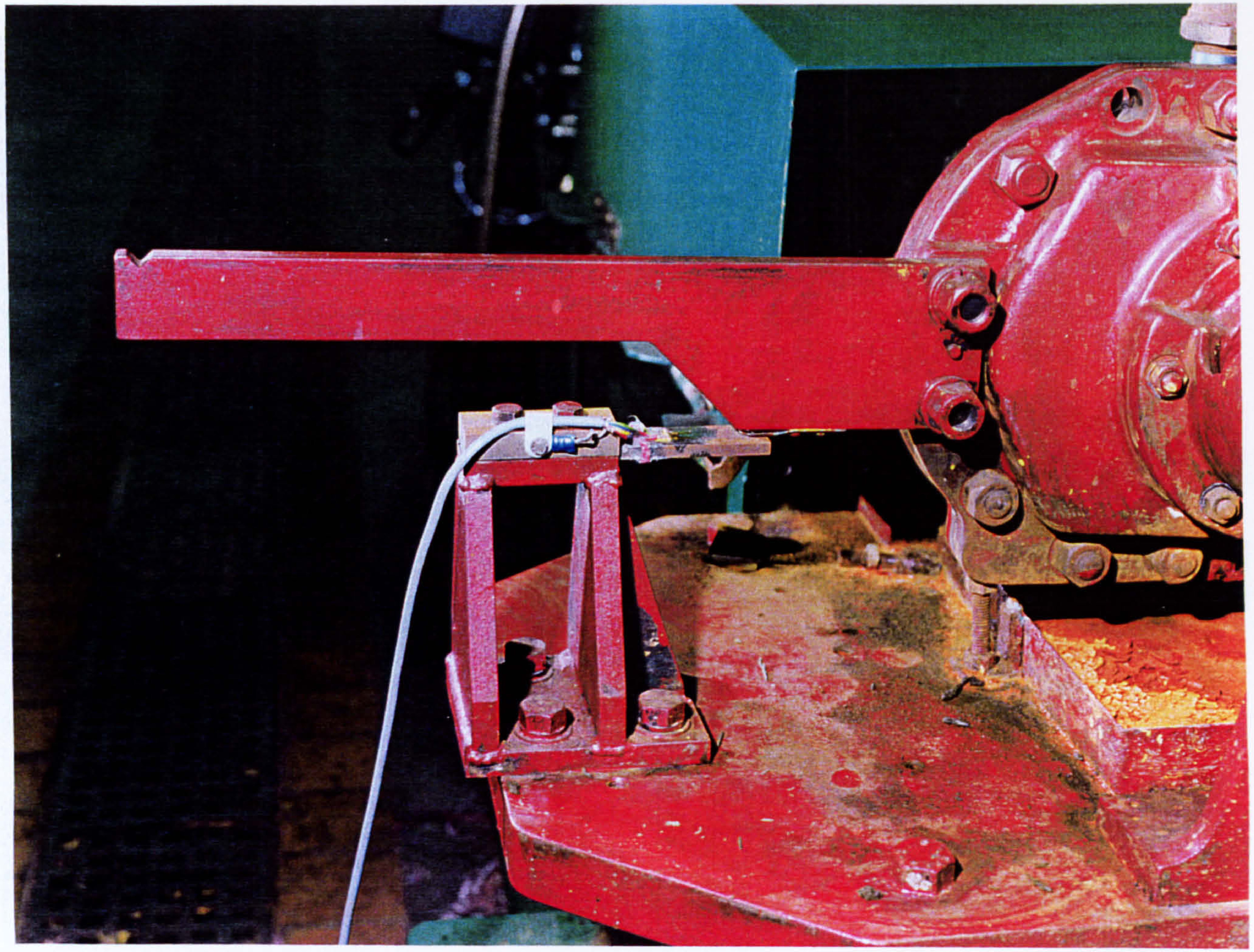

Figure 6.8 Load Measuring Device (Strain Gauge)

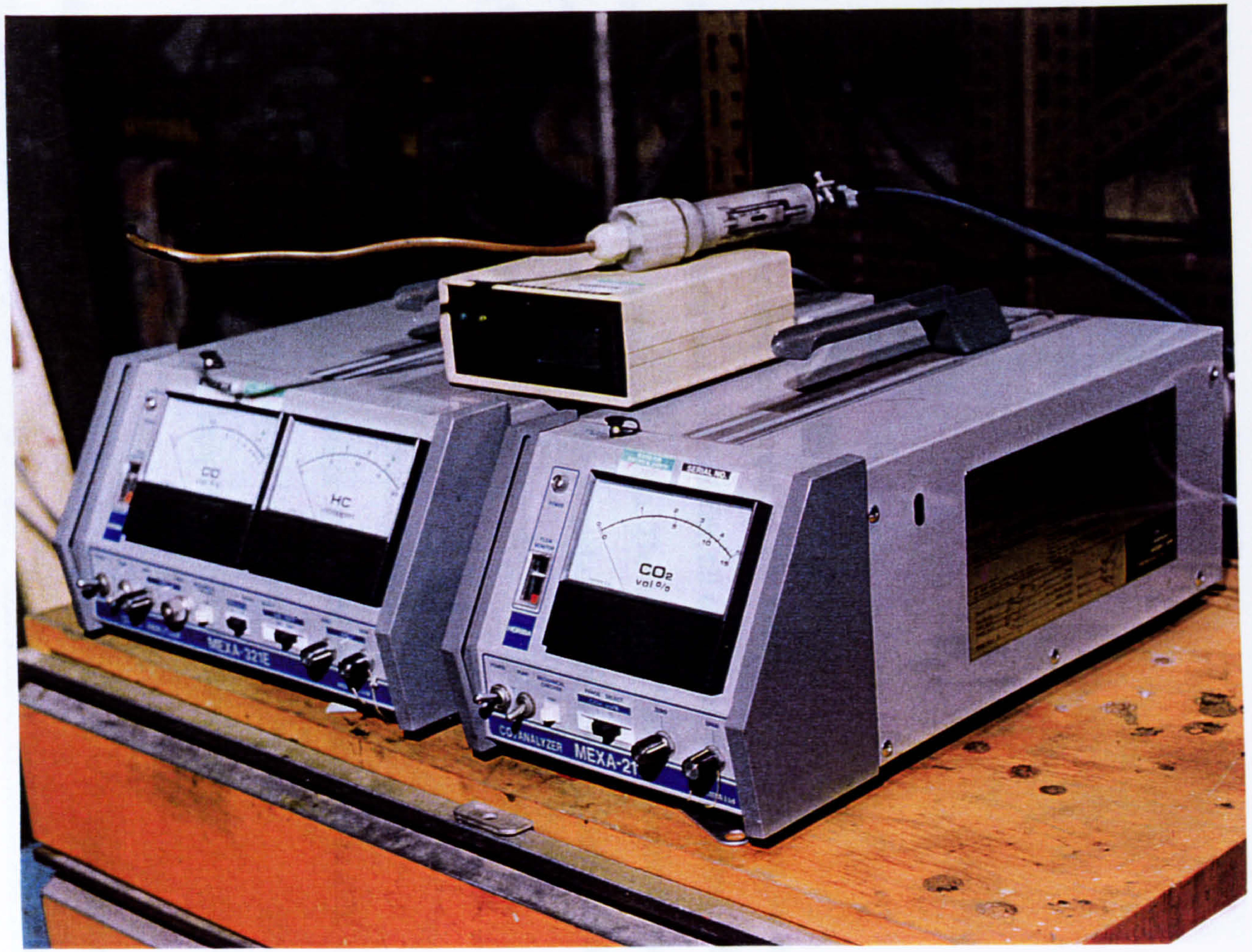

Figure 6.9 Horiba Exhaust Analysers Mexa-321E and Mexa-211E

6.4.5 Haake Viscometer

An Haake viscometer model RV12, was used to measure the viscosity of the fuels used in this project (Figure 6.10). The viscometer consisted of;

(i) The drive unit,
(ii) Temperature vessel,
(iii) The sensor system and
(iv) The recorder.

(i) The measuring drive unit comprised of the motor, tachogenerator, reduction gear, calibrated spring, transducer and pre-amplifier, all of which were connected to the recorder (basic unit) by means of a multi-core cable. The angle of twist measured by the calibrated spring when the liquid was sheared was picked-up by the sensor system and displayed on L.C.D. or if required a print-out was obtained.

(ii) The temperature vessel had three main functions:

(a) it connected the sensor system to the measuring drive unit,
(b) it centred the rotor and cup, and
(c) it controlled the temperature of the test substance.

(iii) The sensor system consisted of a coaxial cylindrical cup with three different rotors to provide different viscosity measuring ranges. The rotor was mechanically centred. The top and bottom surfaces of the rotor were recessed to minimise "end effects". The sample volume required was about 40 cm^3.

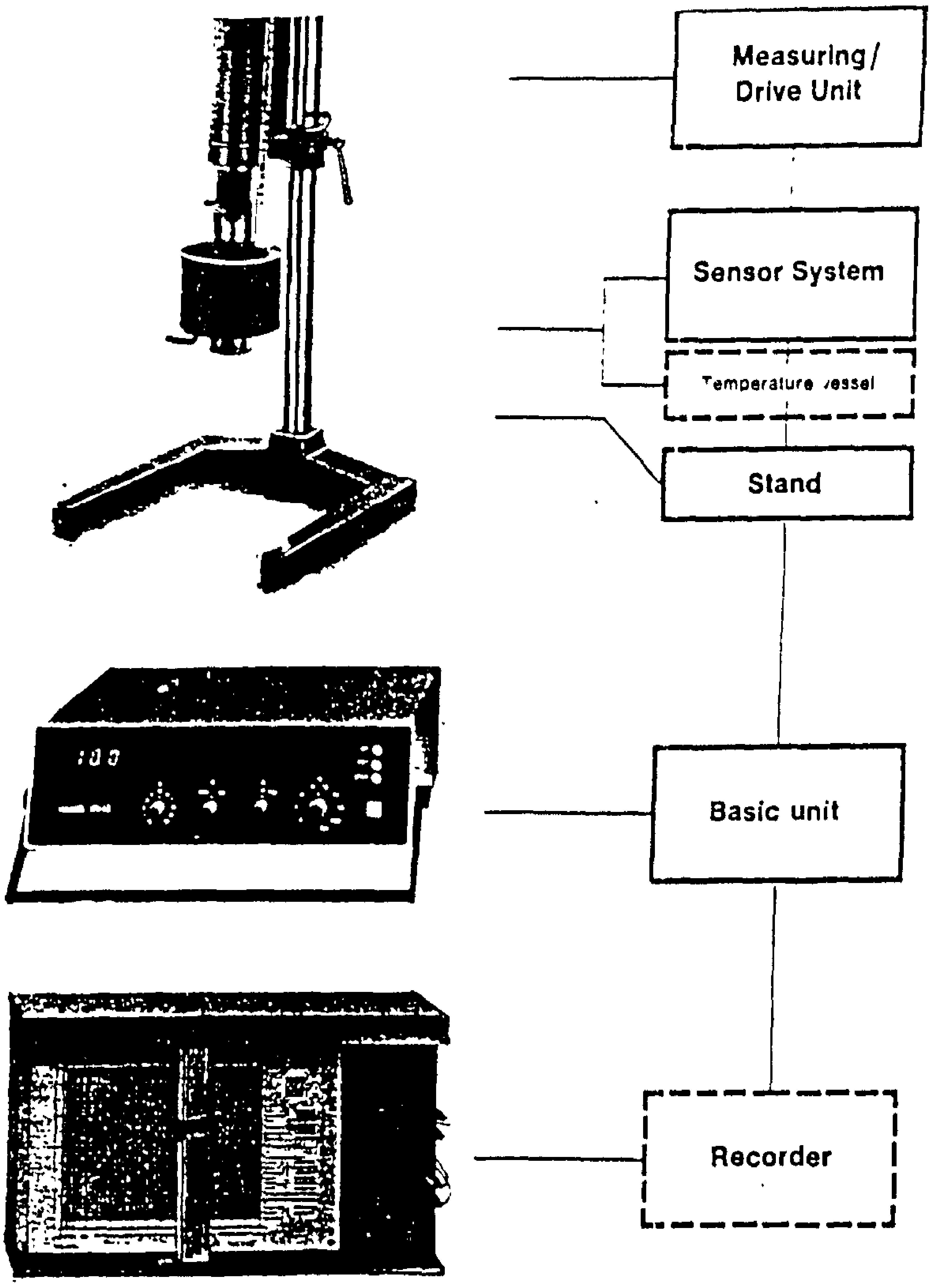

Figure 6.10 Haake Viscometer Model RV12

6.4.6 Bosch Smoke Density

The density of smoke emitted from the engine was measured using a Bosch smoke meter. The smoke was represented by the Bosch Smoke Unit (BSU). This device indicated the BSU density in the range of white 0 to Black 10 according to the reflection factor of the filter paper that collected soot over a fixed period.

6.5 Experimental Procedure

The preparation of bio-ultracarbofluids requires the homogeneous dispersion of the solid particulate fuel and the vegetable oil into water. The procedure followed in this work was as described below and shown in Figure 6.13;

(i) Charcoal was ground to <30 μm by using a wet ball mill.

(ii) Measured amounts (by mass) of oil blend (e.g.esterified rapeseed, or soya) and water were mixed at high speeds (2500 rpm) for 5 minutes.

(iii) A chemical dispersant (e.g. BASF Emulan-P or Albright and Wilson Colgan) was added as required to provide a stable suspension-emulsion. Surfactants are surface active agents which can assist the stabilisation of a suspension of finely divided solids in a liquid medium.

(iv) Introduction of charcoal into the oil/water emulsion was followed by high speed dispersion for 15 minutes. Dispersion into the charcoal suspension was achieved using high speed agitation as above.

Different formulations of ultra-carbofluids were made using the above method. Each formulation was tested within 48 hours of preparation. The proportion of oil was kept constant whilst the charcoal/water and additive ratios were varied as shown in Tables 6.02 to 6.09 . The viscosity of each fuel was measured using a Haake viscometer.

6.5.1 Types of Charcoal

Two charcoals with different properties were chosen for the experimental programme. Charcoal with a high volatile content (charcoal A) and with a low volatile content (charcoal B) were used; the full properties are described below. Charcoal may have varying amounts of volatile content. Once received, the two charcoals were stored under identical conditions. In order to obtain particles of less than 30 μm in the experimental test fuels both charcoals were passed through a 30 μm sieve before use.

The ultimate analyses of the two charcoals A and B used were;

Ultimate Analysis wt%

	C	H	O	volatiles wt %	Fixed Carbon Wt %
Charcoal A	73.4	1.4	14.6	27.2	67.0
Charcoal B	94.2	2.2	3.5	9.7	89.3

6.5.2 Modified Vegetable Oils Used in the Experimental Programme

Two different esterified vegetable oils were used in the experimental programme. Esterified rapeseed oil (Oil A) supplied by Chemoxy Chemicals and esterified soya oil supplied by Environ (Oil B).

The ratio of the vegetable oil was kept constant at 30%, since previous investigators reported that a minimum amount of fuel oil in coal-water slurries was required for efficient fuel combustion. No combustion problems were encountered using 30% vegetable oil. It was envisaged that using less than 30% could result in inefficient combustion, engine misfiring or engine arrest.

6.5.3 Additives Used in the Experimental Programme

Fine charcoal does not form a stable slurry in an oil-water medium. Therefore chemical additives such as surfactants are used to aid the rheological and stability properties of the slurry. Surfactants are chemical products whose molecules are able to modify the properties at an interface, e.g. liquid/air or liquid/liquid by lowering the surface or interfacial tension. Every surfactant possesses the fundamental characteristic of having two essential portions, one being water repellent, termed hydrophobic (or lipophilic), the other being water attractive, termed hydrophilic (or lipophobic). The number and arrangement of the hydrocarbon groups, together with the nature and position of the hydrophilic groups, combine to determine the surface active properties of the molecule. C_{12} to C_{20} is generally regarded as the range covering optimum detergency properties. For a charcoal-oil-water slurry the charcoal particles represent the finely-divided solids; oil and water are the liquid medium. Dispersion of a finely-divided solid into a liquid is usually described as a three step process: wetting the powder and displacing the trapped air; disaggregating or fragmenting particle clusters; and preventing reaggregation of the dispersed particles.

Two different additives were used in the experiments. The two types of additives were chosen on the basis of literature reports which revealed that the optimum results obtained with coal-water slurry were with BASF Emulan P and Albright & Wilson Colgan. Also the optimum quantity in a charcoal-water slurry was reported in the literature to be 1%.

Table 6.01 shows the different combinations of constituents used in the experimental programme.

Series	A	B	C	D	E	F	G	H
Charcoal A	Y	Y	N	N	Y	Y	N	N
Charcoal B	N	N	Y	Y	N	N	Y	Y
Oil A	Y	N	Y	N	Y	N	Y	N
Oil B	N	Y	N	Y	N	Y	N	Y
Water	Y	Y	Y	Y	Y	Y	Y	Y
Additive A	Y	Y	Y	Y	N	N	N	N
Additive B	N	N	N	N	Y	Y	Y	Y

Y= Yes N= No

Table 6.01 Constituents Used in the Experimental Programme

Series A

In Series A experiments; charcoal A, oil A esterified rapeseed oil, and Additive A were used in the different proportions shown in Table 6.02.

Component Mass %	Charcoal A	Oil A	Water	Additive A
Sample A1	15	30	54	1
A2	20	30	49	1
A3	25	30	44	1
A4	30	30	39	1
A5	35	30	34	1
A6	40	30	29	1

Table 6.02 Series A formulae

Series B

In Series B experiments; charcoal A, oil B esterified soya oil, and Additive A were used in the different proportions shown in Table 6.03.

Component Mass %	Charcoal A	Oil B	Water	Additive A
Sample B1	15	30	54	1
B2	20	30	49	1
B3	25	30	44	1
B4	30	30	39	1
B5	35	30	34	1
B6	40	30	29	1

Table 6.03 Series B formulae

Series C

In Series C experiments; charcoal B, oil A esterified rapeseed oil, and Additive A were used in the different proportions shown in Table 6.04

Component Mass %	Charcoal B	Oil A	Water	Additive A
Sample C1	15	30	54	1
C2	20	30	49	1
C3	25	30	44	1
C4	30	30	39	1
C5	35	30	34	1
C6	40	30	29	1

Table 6.04 Series C formulae

Series D

In the Series D formulae; charcoal B, oil B esterified soya oil, and Additive A were used in the different proportions shown in Table 6.05.

Component Mass %	Charcoal B	Oil B	Water	Additive A
Sample D1	15	30	54	1
D2	20	30	49	1
D3	25	30	44	1
D4	30	30	39	1
D5	35	30	34	1
D6	40	30	29	1

Table 6.05 Series D formulae

Series E

In the Series E experiments; charcoal A, oil A esterified rapeseed oil , and Additive B were used in the different proportions shown in Table 6.06 .

Component Mass %	Charcoal A	Oil A	Water	Additive B
Sample E1	15	30	54	1
E2	20	30	49	1
E3	25	30	44	1
E4	30	30	39	1
E5	35	30	34	1
E6	40	30	29	1

Table 6.06 Series E formulae

Series F

In the Series F experiments; charcoal A, oil B esterified soya oil, and Additive B were used in the different proportions shown in Table 6.07.

Component Mass %	Charcoal A	Oil B	Water	Additive B
Sample F1	15	30	54	1
F2	20	30	49	1
F3	25	30	44	1
F4	30	30	39	1
F5	35	30	34	1
F6	40	30	29	1

Table 6.07 Series F formulae

Series G

In the Series G experiments; charcoal B, oil A esterified rapeseed oil, and Additive B were used in the different proportions shown in Table 6.08 .

Component Mass %	Charcoal B	Oil A	Water	Additive B
Sample G1	15	30	54	1
G2	20	30	49	1
G3	25	30	44	1
G4	30	30	39	1
G5	35	30	34	1
G6	40	30	29	1

Table 6.08 Series G formulae

Series H

In the Series H formulae; charcoal B, oil B esterified soya oil, and Additive B were used in the different proportions shown in Table 6.09.

Component Mass %	Charcoal B	Oil B	Water	Additive B
Sample H1	15	30	54	1
H2	20	30	49	1
H3	25	30	44	1
H4	30	30	39	1
H5	35	30	34	1
H6	40	30	29	1

Table 6.09 Series H formulae

On testing it was discovered that all the test samples containing charcoal in excess of 30% by mass had viscosities far greater than was practible for a fuel (e.g. >40 cST at 38^{0}C) These fuels were therefore not tested further in the experimental programme. [These were experimental bio-ultracarbofluid fuels A5 and A6, B5 and B6, C5 and B6, C5 and C6, D5 and D6, E5 and E6, F5 and F6, G5 and G6, and also H5 and H6.] Also in order to avoid replication of tests, since it was expected that the different additives used would have a minimal effect on the parameters to be investigated, in series E, F, G and H; only fuels E1 and E4, F1 and F4, G1 and G4, and also H1 and H4 were tested.

Experiment	Mass kg	Load N	Output mV	Calc. Torque Nm
1	0	0	0	0
2	0.5	4.91	0.5	5
3	1	9.81	0.98	10
3	1.5	14.72	1.49	15
5	2	19.62	2.01	20
6	2.5	24.53	2.48	25
7	3	29.43	2.97	30
8	3.5	34.34	3.51	35
9	4	39.4	3.99	40
10	4.5	44.15	4.49	45
11	5	49.05	5.01	50
12	5.5	53.96	5.52	55
13	6.0	58.86	6.09	60

Table 6.10 Calibration Data from the Experimental Test Equipment

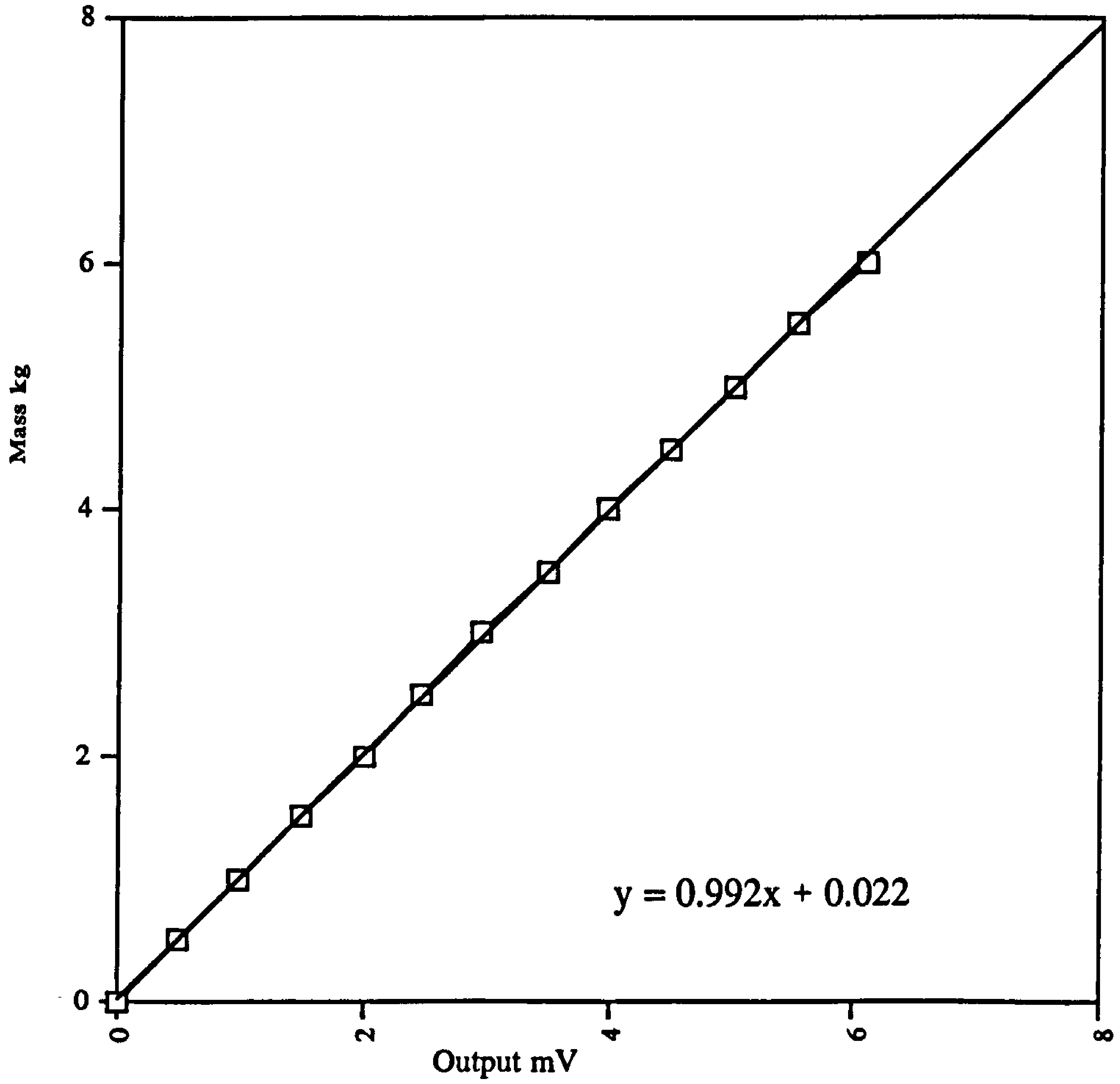

Figure 6.11 Calibration Curve for load Measuring Strain Gauge

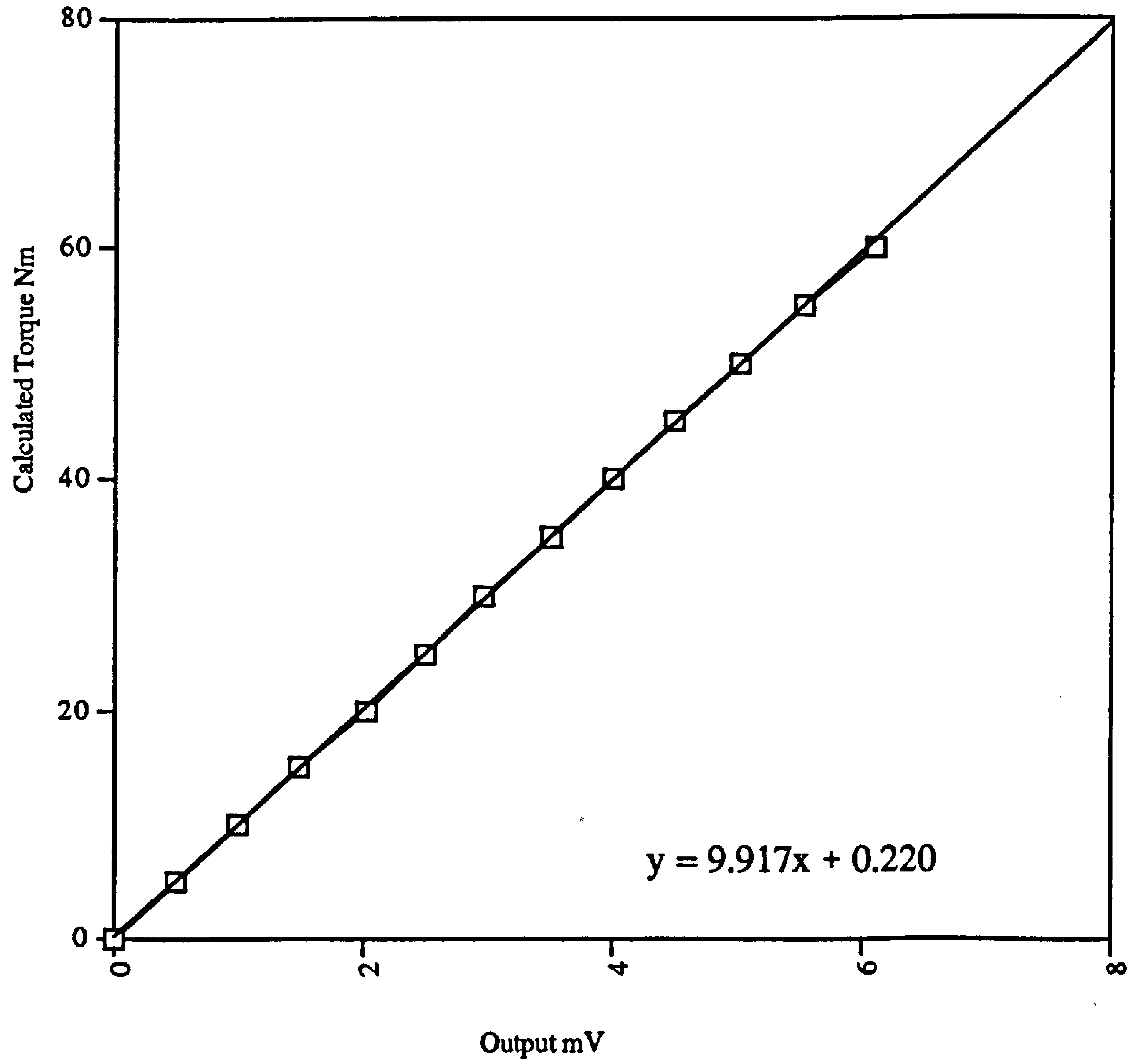

Figure 6.12 Torque Produced vs mV Output from Load Measuring System

6.6 The Test Procedure

The test procedure was as follows. The engine was first run using reference diesel fuel (Esso 2000 diesel) on a wide open throttle (WOT). The speed of the engine was controlled by slowly adjusting the load applied using the handwheel. After 15 minutes the engine was sufficiently warmed-up and the speed was set at 1000 rpm and test data recorded. The speed of the engine was increased by 200 rpm increments and further data recorded. The speed was increased upto a maximum of 3000 rpm. The engine speed was then reduced to 1000 rpm and the fuel supply switched over to ultra-carbofluid and the test data recorded. The procedure was repeated for all formulations.

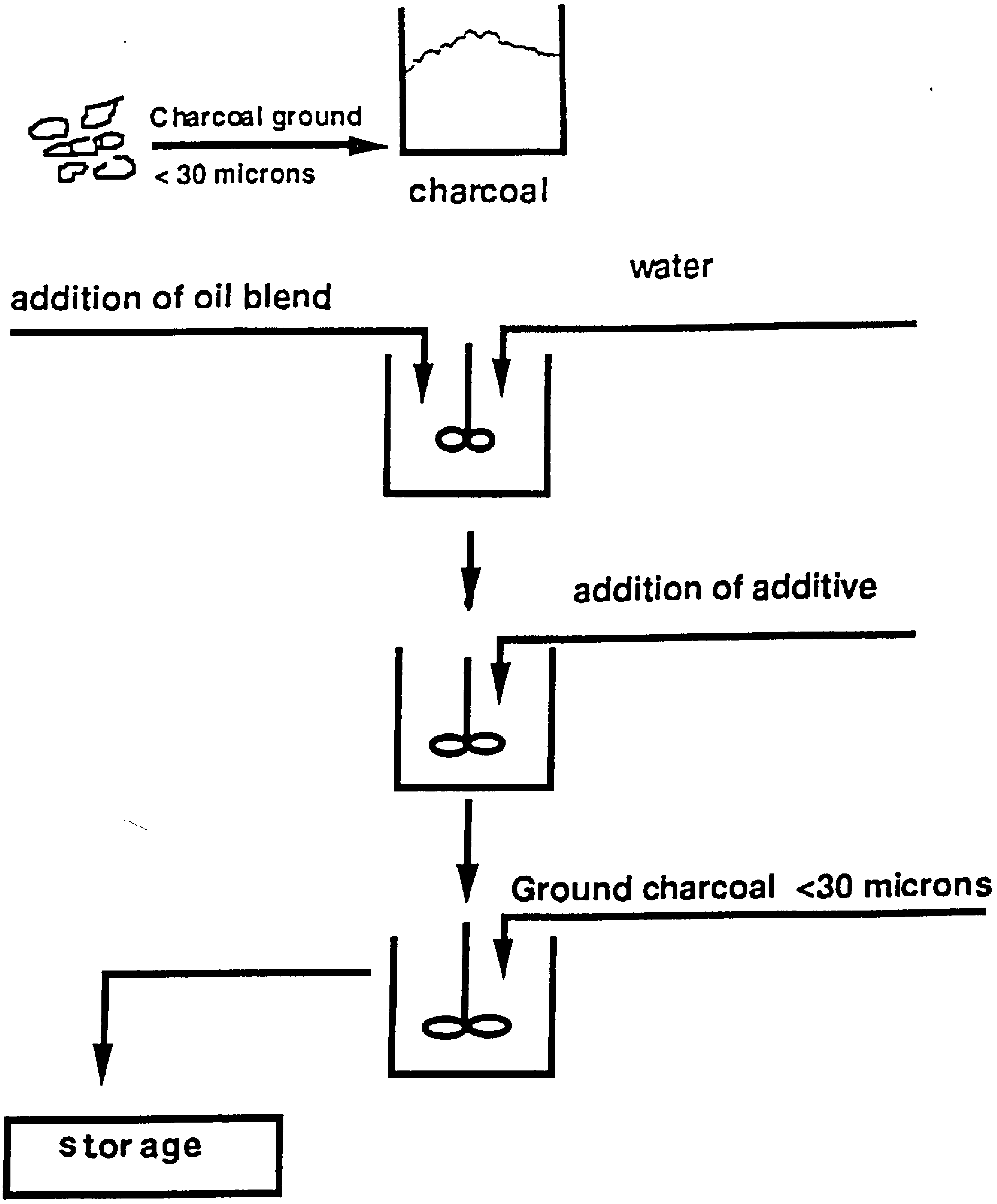

Figure 6.13 Bio-ultracarbofluid Production Scheme

CHAPTER 7

RESULTS AND DISCUSSION OF RESULTS

Chapter 7

7.0 RESULTS AND DISCUSSION OF RESULTS

All the comparisons of brake power, CO_2, CO and HC emissions were performed at 3000 rpm. [Although the speed of the engine could be increased to 3300 rpm, the handbook[125] recommended the safe operating limits of the engine as being between 1000 and 3000 rpm.]. The justification for this was that operators will naturally make use of the maximum safe operating limit, in this case 3000 rpm. The smoke emissions on the other hand were compared at an operating speed of 1000 rpm since the data demonstrated that the maximum smoke output was at low speeds i.e. at 1000 rpm.

The four reference fuels (A, B, C, and D Ref) were the same Esso diesel 2000 as sold from petrol station forecourts. The reference fuels were tested before and in-between the tests with the experimental bio-ultracarbofluids fuels. A comparison of reference fuels' brake power output, CO_2, CO, HC and smoke emissions results, confirmed good repeatability and these results together with results from bio-ultracarbofluids are discussed in the following sections.

The averages of brake power, % CO_2 emissions, % CO emissions, % HC emissions and Smoke Number of the four reference fuels were termed Average Ref. The Average Ref for CO_2, CO, HC and Smoke Number are compared with the bio-ultracarbofluids emissions in the following discussion.

7.1. Brake Power Output

7.1.1 Reference Fuels' Brake Power Output

The brake power output showed a maximum difference of 1.2% between the four reference fuels. The results obtained for the four reference fuels are all plotted in Figure 7.01¥ . It was therefore concluded that a plot of average values from the data for all four reference fuels (shown in Figure 7.02), provided a sound basis with which to compare the performance of the experimental bio-ultracarbofluids fuel mixtures.

The brake powers of reference fuel A Ref are shown in Table 7.01, and plotted in Figure 7.01 . For comparison the brake powers generated with reference fuels B, C and D Ref under similar operating conditions are also listed. The brake power outputs with fuel B Ref, shown in Table 7.02, were slightly higher but only on average by <0.5%. For reference fuel C Ref, the brake powers generated are shown in Table 7.03; the difference between brake power output A Ref, B Ref,C Ref was less than 0.3%. The brake power output with reference fuel D is shown in Table 7.04 . The maximum difference between power output A Ref, B Ref, C Ref and D Ref was 1.2%.

The average brake powers of the four reference fuels are shown in Table 7.05 and plotted in Figure 7.02 .

¥ The data points are joined by straight lines for convenience, since the trends in data-rather than interpolation-are of relevence.

Experiment	RPM	Output mV	Torque Nm	Brake Power kW
1	1000	3.54	35.1	3.68
2	1200	3.71	36.8	4.62
3	1400	4.08	40.4	5.92
3	1500	4.14	41	6.44
5	1600	4.2	41.6	6.97
6	1800	4.26	42.2	7.95
7	2000	4.46	44.2	9.26
8	2200	4.37	43.3	9.98
9	2400	4.26	42.2	10.61
10	2500	4.12	41.3	10.81
11	2600	4.05	40.1	10.92
12	2800	3.86	38.2	11.2
13	3000	3.82	37.9	11.91

Table 7.01 Millivolt Output, Torque and Brake Powers A Ref Fuel

Experiment	RPM	Output mV	Torque Nm	Brake Power kW
1	1000	3.56	35.3	3.7
2	1200	3.71	36.8	4.62
3	1400	4.09	40.5	5.94
3	1500	4.16	41.2	6.47
5	1600	4.21	41.7	6.99
6	1800	4.28	42.4	7.99
7	2000	4.49	44.5	9.32
8	2200	4.4	43.6	10.05
9	2400	4.26	42.2	10.61
10	2500	4.19	41.5	10.86
11	2600	4.08	40.4	11
12	2800	3.9	38.6	11.31
13	3000	3.87	38.3	12.03

Table 7.02 Millivolt Output, Torque and Brake Powers B Ref Fuel

Experiment	RPM	Output mV	Torque Nm	Brake Power kW
1	1000	3.56	35.3	3.37
2	1200	3.79	37.6	4.73
3	1400	4.06	40.2	5.89
3	1500	4.16	41.2	6.47
5	1600	4.23	41.9	7.02
6	1800	4.29	42.5	8.01
7	2000	4.48	44.4	9.3
8	2200	4.39	43.5	10.02
9	2400	4.29	42.5	10.68
10	2500	4.2	41.6	10.89
11	2600	4.08	40.4	11.01
12	2800	3.86	38.3	11.23
13	3000	3.85	38.1	11.97

Table 7.03 Millivolt Output, Torque and Brake Powers C Ref Fuel

Experiment	RPM	Output mV	Torque Nm	Brake Power kW
1	1000	3.59	35.6	3.73
2	1200	3.82	37.9	4.76
3	1400	4.1	40.6	5.95
3	1500	4.22	41.8	6.57
5	1600	4.27	42.3	7.09
6	1800	4.32	42.8	8.07
7	2000	4.49	44.5	9.32
8	2200	4.42	43.8	10.09
9	2400	4.32	42.8	10.76
10	2500	4.23	41.9	10.96
11	2600	4.07	40.3	10.98
12	2800	4	39.6	11.61
13	3000	3.89	38.6	12.13

Table 7.04 Millivolt Output, Torque and Brake Powers D Ref Fuel

Experiment	RPM	Brake Power kW A Ref	Brake Power kW B Ref	Brake Power kW C Ref	Brake Power kW D Ref	Brake Power kW, average of A,B,C and D Average Ref
1	1000	3.68	3.7	3.37	3.37	3.53
2	1200	4.62	4.62	4.73	4.76	4.68
3	1400	5.92	5.94	5.89	5.95	5.9
3	1500	6.44	6.47	6.47	6.57	6.49
5	1600	6.97	6.99	7.02	7.09	7.0
6	1800	7.95	7.99	8.01	8.07	8.0
7	2000	9.26	9.32	9.3	9.32	9.3
8	2200	9.98	10.05	10.02	10.09	10.0
9	2400	10.61	10.61	10.68	10.76	10.7
10	2500	10.81	10.86	10.89	10.96	10.9
11	2600	10.92	11	11.01	10.98	10.98
12	2800	11.2	11.31	11.23	11.61	11.34
13	3000	11.91	12.03	11.97	12.13	12.01

Table 7.05 A, B, C, D and Average Ref Fuels Brake Powers

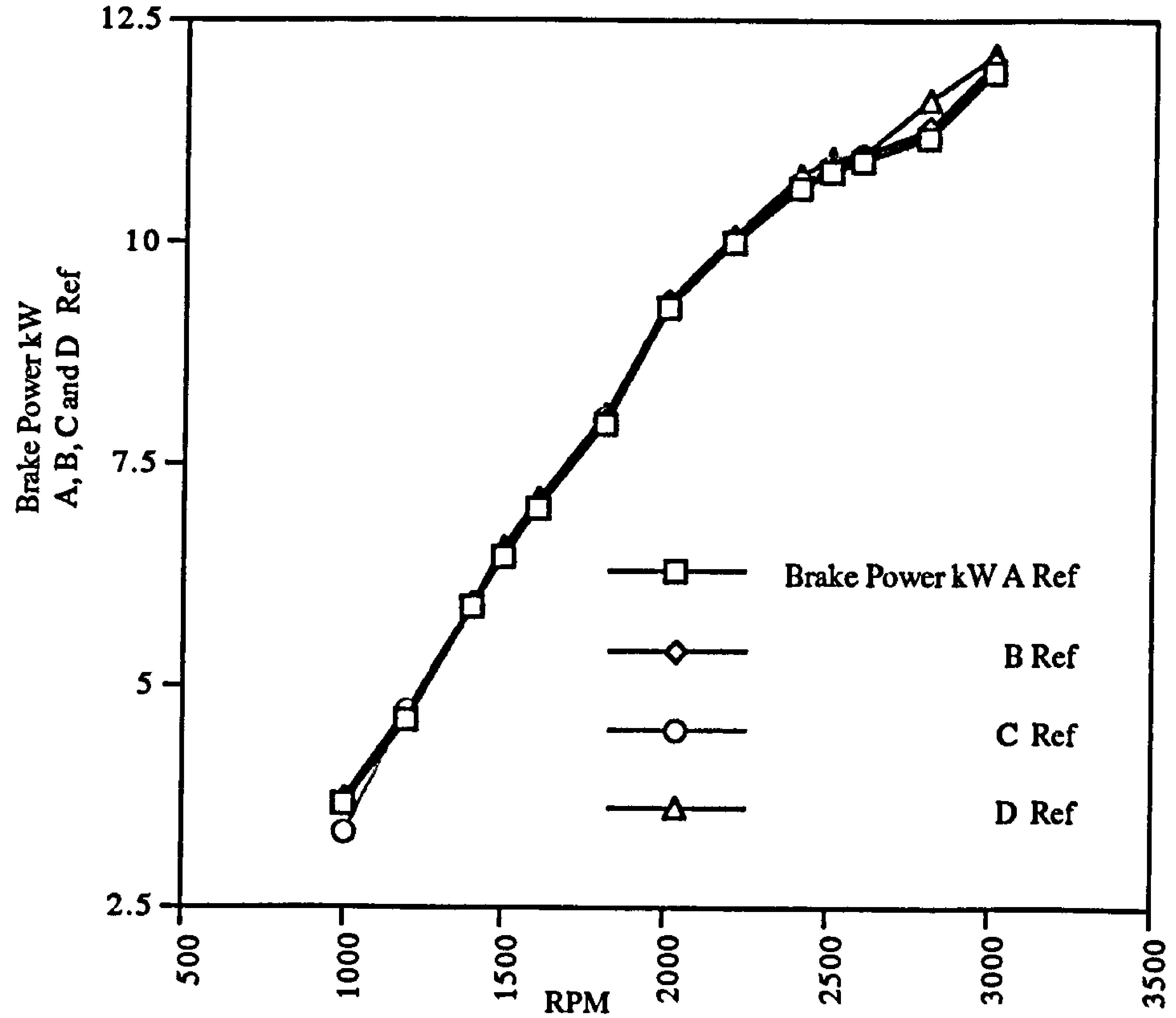

Figure 7.01 Brake Powers A, B, C and D Ref Fuels

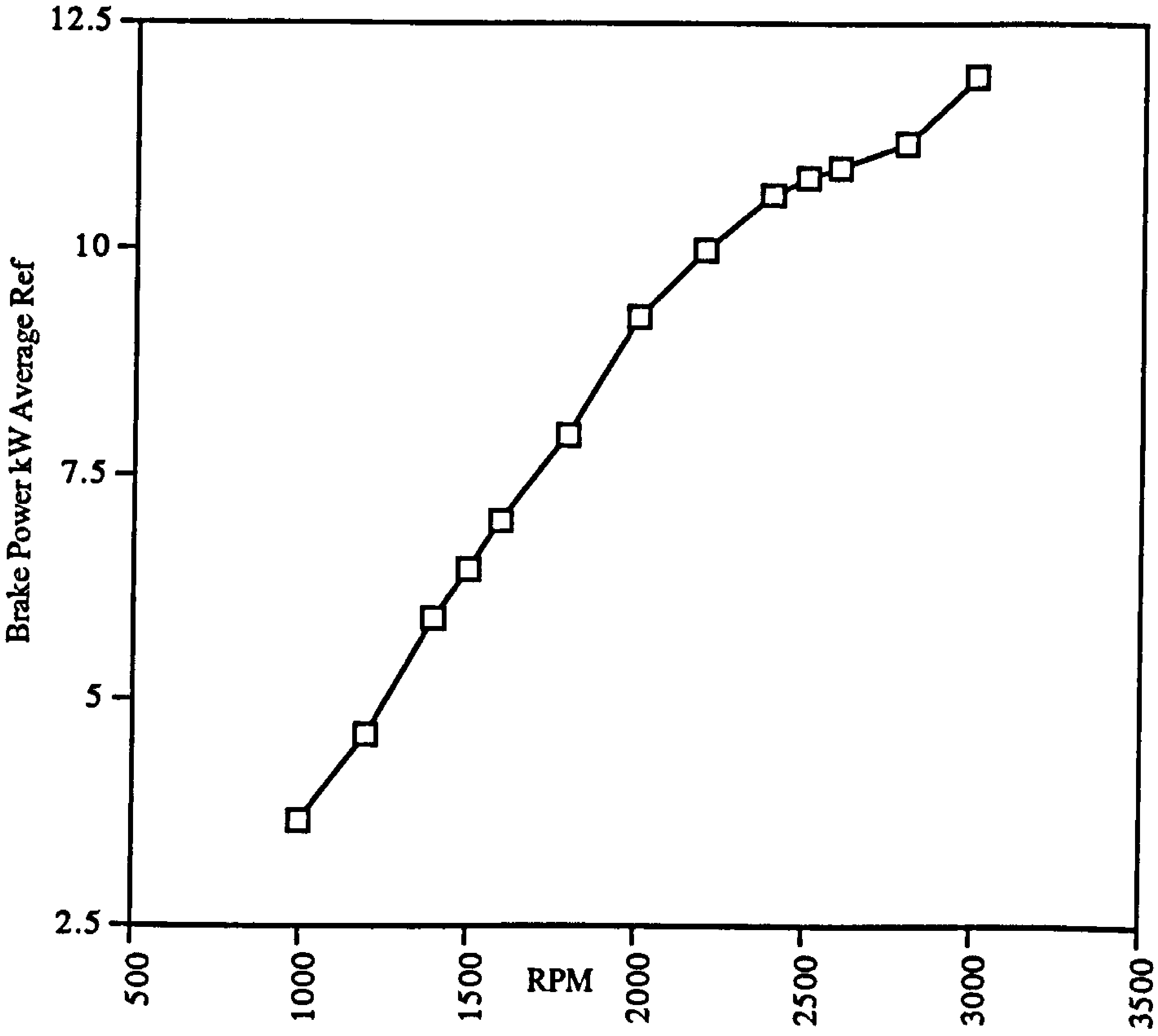

Figure 7.02 Average Brake Power For A, B, C and D Ref Fuels

7.1.2 Brake Power Output, Series A Fuels

Table 7.06 lists the millivolt output (mV), torque (Nm) and brake power (kW) data from the 13 experiments with A1 fuel. Tables 7.07, 7.08 and 7.09 give output (mV), torque (Nm) and brake power (kW) for A2, A3 and A4 respectively.

In Table 7.10 brake powers of A1, A2, A3 and A4 fuels are given; these are plotted in Figure 7.03 . A1 fuel produced the lowest brake power output in the A series at 3000 rpm. A1 fuel gave 9.7% lower brake power output than Average Ref at 3000 rpm. From A1 to A4 fuel the brake power output increased. A4 fuel shows the least difference from Average Ref with a brake power deficit of 6.9% at 3000 rpm.

Experiment	RPM	Output mV	Torque Nm	Brake Power kW
1	1000	3.2	31.8	3.33
2	1200	3.32	32.9	4.13
3	1400	3.48	34.5	5.06
3	1500	3.63	36	5.66
5	1600	3.71	36.8	6.17
6	1800	3.82	37.9	7.14
7	2000	3.88	38.5	8.06
8	2200	3.96	39.3	9.05
9	2400	3.88	38.5	9.68
10	2500	3.74	37.1	9.71
11	2600	3.66	36.3	9.88
12	2800	3.59	35.6	10.44
13	3000	3.38	34.5	10.84

Table 7.06 Millivolt Output, Torque and Brake Powers For A1 Fuel

Experiment	RPM	Output mV	Torque Nm	Brake Power kW
1	1000	3.26	32.3	3.38
2	1200	3.36	33.3	4.18
3	1400	3.56	35.3	5.18
3	1500	3.67	36.4	5.72
5	1600	3.78	37.5	6.28
6	1800	3.9	38.6	7.28
7	2000	3.99	39.2	8.21
8	2200	4.05	40.1	9.24
9	2400	3.93	38.9	9.78
10	2500	3.81	37.8	9.9
11	2600	3.69	36.8	10.02
12	2800	3.62	35.8	10.5
13	3000	3.52	34.9	10.96

Table 7.07 Millivolt Output, Torque and Brake Powers For A2 Fuel

Experiment	RPM	Output mV	Torque Nm	Brake Power kW
1	1000	3.31	32.8	3.44
2	1200	3.46	34.3	4.31
3	1400	3.67	36.4	5.34
3	1500	3.76	37.3	5.86
5	1600	3.85	38.2	6.4
6	1800	3.97	39.3	7.41
7	2000	4.03	39.9	8.36
8	2200	4.12	40.8	9.4
9	2400	3.98	39.4	9.78
10	2500	3.91	38.7	9.9
11	2600	3.75	37.2	10.13
12	2800	3.67	36.4	10.67
13	3000	3.59	35.7	11.18

Table 7.08 Millivolt Output, Torque and Brake Powers For A3 Fuel

Experiment	RPM	Output mV	Torque Nm	Brake Power kW
1	1000	3.39	33.6	3.52
2	1200	3.57	35.4	4.49
3	1400	3.78	37.5	5.5
3	1500	3.9	38.6	6.06
5	1600	3.94	39	6.54
6	1800	4.03	39.9	7.52
7	2000	4.12	40.8	8.55
8	2200	4.21	41.7	9.61
9	2400	4.09	40.5	10.18
10	2500	4.01	39.6	10.37
11	2600	3.79	37.6	10.24
12	2800	3.7	36.7	10.76
13	3000	3.6	35.6	11.22

Table 7.09 Millivolt Output, Torque and Brake Powers For A4 Fuel

Experiment	RPM	Brake Power kW A 1	Brake Power kW A2	Brake Power kW A3	Brake Power kW A4
1	1000	3.33	3.38	3.44	3.52
2	1200	4.13	4.18	4.31	4.49
3	1400	5.06	5.18	5.34	5.5
3	1500	5.66	5.72	5.86	6.06
5	1600	6.17	6.28	6.4	6.54
6	1800	7.14	7.28	7.41	7.52
7	2000	8.06	8.21	8.36	8.55
8	2200	9.05	9.24	9.4	9.61
9	2400	9.68	9.78	9.78	10.18
10	2500	9.71	9.9	9.9	10.37
11	2600	9.88	10.02	10.13	10.24
12	2800	10.44	10.5	10.67	10.76
13	3000	10.84	10.96	11.22	11.18

Table 7.10 A1, A2, A3 and A4 Fuels Brake Powers

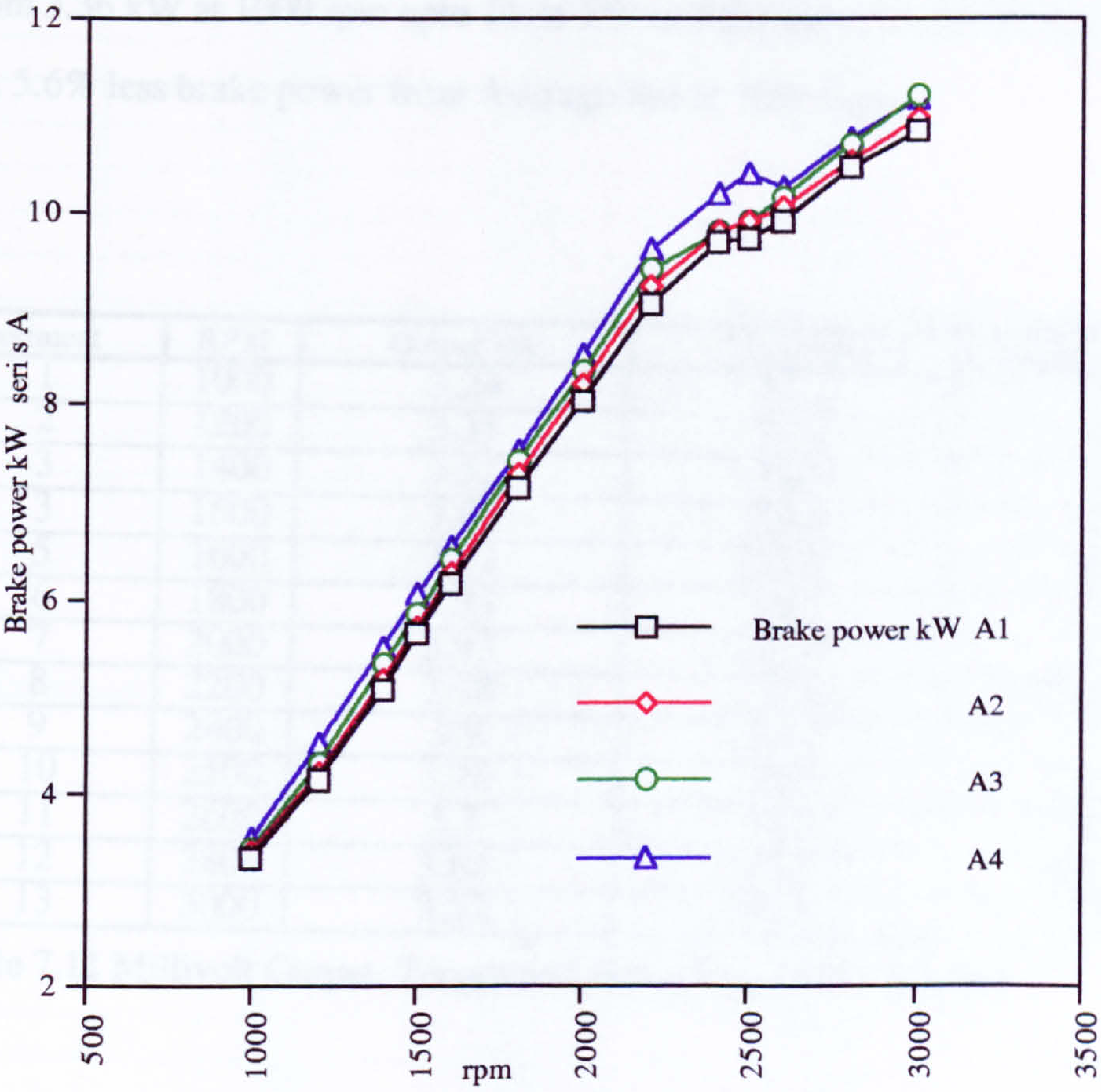

Figure 7.03 Brake Power kW Series A Fuels

7.1.3 Brake Power Output, Series B Fuels

Table 7.11 lists the millivolt output (mV), torque (Nm) and brake power (kW) data from the 13 experiments with B1 fuel. Tables 7.12, 7.13 and 7.14 show millivolt output (mV), torque (Nm) and brake power (kW) for B2, B3 and B4 fuels respectively.

Table 7.15 shows the brake power outputs of B1, B2, B3 and B4 fuels and these are plotted in Figure 7.04. This demonstrates that B1 fuel produced the lowest brake power output in the B series i.e. 8.9% less brake power than Average Ref at 3000 rpm. From B1 to B4 fuel (as before in the A series) the brake power increased linearly with speed from 3.36 kW at 1000 rpm upto 11.36 kW at 3000 rpm. B4 fuel shows the least difference i.e. 5.6% less brake power from Average Ref at 3000 rpm.

Experiment	RPM	Output mV	Torque Nm	Brake Power kW
1	1000	3.24	32.1	3.36
2	1200	3.31	32.8	4.12
3	1400	3.52	34.8	5.1
3	1500	3.66	36.3	5.7
5	1600	3.73	36.9	6.18
6	1800	3.85	38.1	7.18
7	2000	3.93	38.9	8.15
8	2200	3.98	39.4	9.08
9	2400	3.9	38.6	9.7
10	2500	3.76	37.3	9.76
11	2600	3.7	36.7	9.98
12	2800	3.62	35.9	10.52
13	3000	3.52	34.9	10.96

Table 7.11 Millivolt Output, Torque and Brake Powers For B1 Fuel

Experiment	RPM	Output mV	Torque Nm	Brake Power kW
1	1000	3.28	32.5	3.4
2	1200	3.39	33.6	4.22
3	1400	3.52	34.9	5.12
3	1500	3.7	36.7	5.77
5	1600	3.83	38	6.37
6	1800	3.91	38.7	7.3
7	2000	3.98	39.4	8.26
8	2200	4.15	41.1	9.47
9	2400	3.99	39.5	9.93
10	2500	3.88	38.4	10.05
11	2600	3.78	37.5	10.21
12	2800	3.66	36.3	10.64
13	3000	3.57	35.4	11.12

Table 7.12 Millivolt Output, Torque and Brake Powers For B2 Fuel

Experiment	RPM	Output mV	Torque Nm	Brake Power kW
1	1000	3.34	33.1	3.47
2	1200	3.49	34.6	4.35
3	1400	3.72	36.9	5.41
3	1500	3.81	37.8	5.94
5	1600	3.91	38.7	6.48
6	1800	4.01	39.7	7.48
7	2000	4.09	40.5	8.48
8	2200	4.17	41.3	9.52
9	2400	4.1	40.6	10.2
10	2500	4.01	39.7	10.39
11	2600	3.82	37.9	10.32
12	2800	3.71	36.8	10.79
13	3000	35.9	35.9	11.28

Table 7.13 Millivolt Output, Torque and Brake Powers For B3 Fuel

Experiment	RPM	Output mV	Torque Nm	Brake Power kW
1	1000	3.42	33.9	3.55
2	1200	3.61	35.8	4.5
3	1400	3.85	38.1	5.56
3	1500	3.92	38.8	6.1
5	1600	3.93	39	6.53
6	1800	4.03	39.9	7.52
7	2000	4.17	41.3	8.65
8	2200	4.22	41.8	9.63
9	2400	4.16	41.2	10.36
10	2500	4.05	40.1	10.5
11	2600	3.86	38.2	10.4
12	2800	3.74	37.1	10.88
13	3000	3.64	36.1	11.34

Table 7.14 Millivolt Output, Torque and Brake Powers For B4 Fuel

Experiment	RPM	Brake Power kW B1	Brake Power kW B2	Brake Power kW B3	Brake Power kW B4
1	1000	3.36	3.4	3.47	3.55
2	1200	4.12	4.22	4.35	4.5
3	1400	5.1	5.12	5.41	5.56
3	1500	5.7	5.77	5.94	6.1
5	1600	6.18	6.37	6.48	6.53
6	1800	7.18	7.3	7.48	7.52
7	2000	8.15	8.26	8.48	8.65
8	2200	9.08	9.47	9.52	9.63
9	2400	9.7	9.93	10.2	10.36
10	2500	9.76	10.05	10.39	10.5
11	2600	9.98	10.21	10.32	10.4
12	2800	10.52	10.64	10.79	10.88
13	3000	10.96	11.12	11.28	11.34

Table 7.15 B1, B2, B3 and B4 Fuels Brake Powers

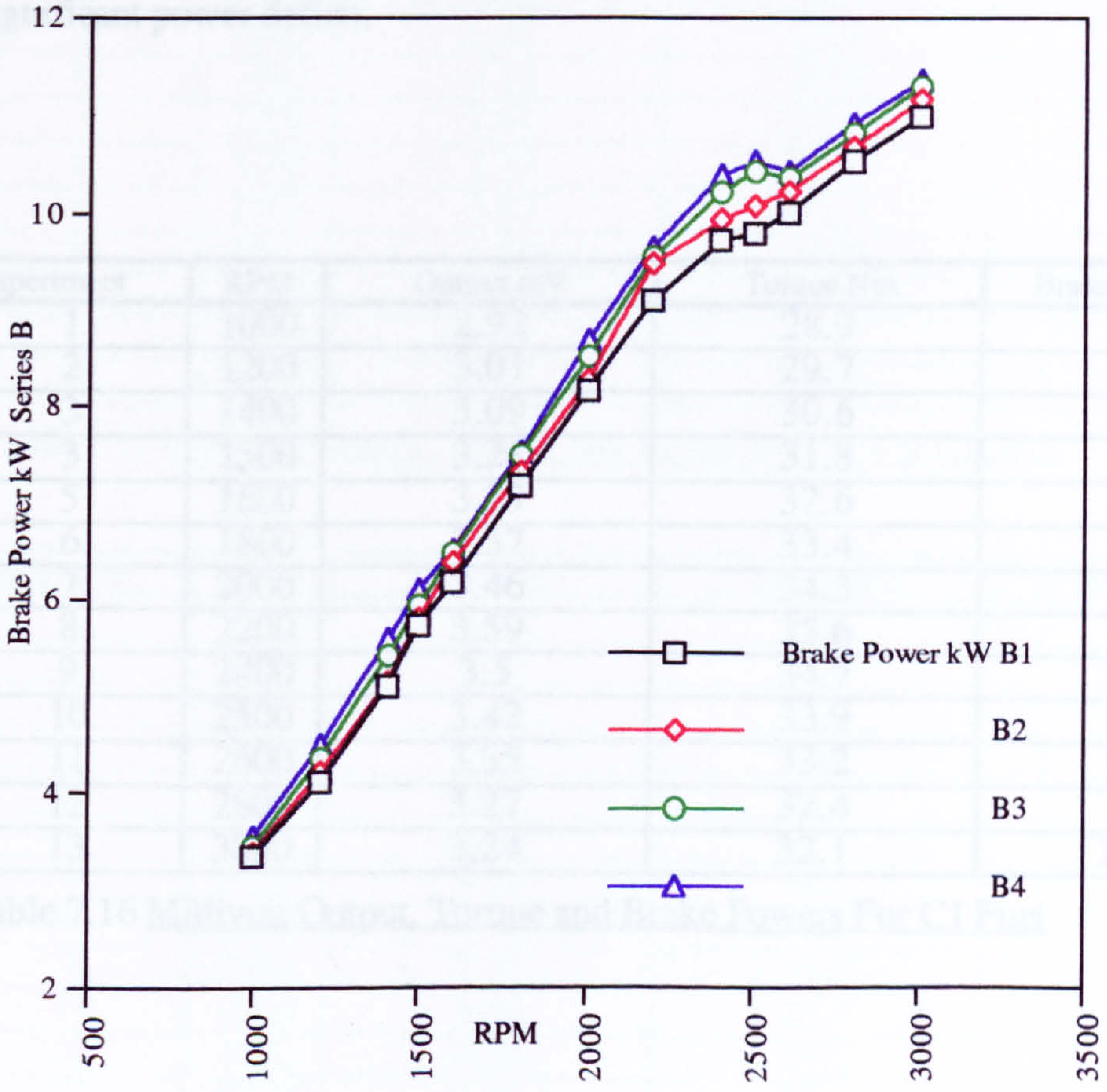

Figure 7.04 Brake Power Series B Fuels

7.1.4 Brake Power Output, Series C Fuels

Table 7.16 lists the millivolt output (mV), torque (Nm) and brake power (kW) data from the 13 experiments with C1 fuel. Tables 7.17, 7.18 and 7.19 give millivolt output (mV), torque (Nm) and brake power (kW) for C2, C3 and C4 fuels respectively.

Figure 7.05 demonstrates that C1 fuel produced the lowest brake power output in the C series; approximately 16.1% lower brake power output than Average Ref at 3000 rpm. C4 fuel gave the least power deficit of 12.7% as compared with Average Ref at 3000 rpm. In comparison with A and B series, in which charcoal A was used, the C series exhibited a significant power deficit.

Experiment	RPM	Output mV	Torque Nm	Brake Power kW
1	1000	2.92	28.9	3.03
2	1200	3.01	29.7	3.73
3	1400	3.09	30.6	4.49
3	1500	3.21	31.8	5
5	1600	3.29	32.6	5.46
6	1800	3.37	33.4	6.3
7	2000	3.46	34.3	7.18
8	2200	3.59	35.6	8.2
9	2400	3.5	34.7	8.72
10	2500	3.42	33.9	8.88
11	2600	3.35	33.2	9.04
12	2800	3.27	32.4	9.5
13	3000	3.24	32.1	10.08

Table 7.16 Millivolt Output, Torque and Brake Powers For C1 Fuel

Experiment	RPM	Output mV	Torque Nm	Brake Power kW
1	1000	2.97	29.4	3.08
2	1200	3.09	30.6	3.85
3	1400	3.16	31.3	4.59
3	1500	3.27	32.4	5.09
5	1600	3.36	33.3	5.81
6	1800	3.45	34.2	6.45
7	2000	3.56	35.3	7.39
8	2200	3.64	36.1	8.32
9	2400	3.57	35.4	8.9
10	2500	3.5	34.7	9.08
11	2600	3.47	34.4	9.37
12	2800	3.37	33.4	9.79
13	3000	3.27	32.4	10.18

Table 7.17 Millivolt Output, Torque and Brake Powers For C2 Fuel

Experiment	RPM	Output mV	Torque Nm	Brake Power kW
1	1000	3.02	29.9	3.13
2	1200	3.14	31.1	3.91
3	1400	3.22	31.9	4.68
3	1500	3.32	32.9	5.17
5	1600	3.41	33.8	5.66
6	1800	3.51	34.8	6.56
7	2000	3.61	35.8	7.5
8	2200	3.75	37.2	8.57
9	2400	3.65	36.2	9.1
10	2500	3.56	35.3	9.24
11	2600	3.52	34.9	9.5
12	2800	3.41	33.8	9.91
13	3000	3.27	32.8	10.3

Table 7.18 Millivolt Output, Torque and Brake Powers For C3 Fuel

Experiment	RPM	Output mV	Torque Nm	Brake Power kW
1	1000	3.06	30.3	3.17
2	1200	3.17	31.4	3.95
3	1400	3.29	32.6	4.78
3	1500	3.37	33.4	5.25
5	1600	3.47	34.4	5.76
6	1800	3.54	35.1	6.62
7	2000	3.65	36.1	7.56
8	2200	3.82	37.9	8.73
9	2400	3.71	36.8	9.25
10	2500	3.62	35.9	9.4
11	2600	3.55	35.2	9.58
12	2800	3.44	34.1	10.01
13	3000	3.37	33.4	10.49

Table 7.19 Millivolt Output, Torque and Brake Powers For C4 Fuel

Experiment	RPM	Brake Power kW C1	Brake Power kW C2	Brake Power kW C3	Brake Power kW C4
1	1000	3.03	3.13	3.08	3.17
2	1200	3.73	3.91	3.85	3.95
3	1400	4.49	4.68	4.59	4.78
3	1500	5.0	5.17	5.09	5.25
5	1600	5.46	5.66	5.81	5.76
6	1800	6.3	6.56	6.45	6.62
7	2000	7.18	7.5	7.39	7.56
8	2200	8.2	8.57	8.32	8.73
9	2400	8.72	9.1	8.9	9.25
10	2500	8.88	9.24	9.08	9.4
11	2600	9.04	9.5	9.37	9.58
12	2800	9.5	9.91	9.79	10.01
13	3000	10.08	10.3	10.18	10.49

Table 7.20 C1, C2, C3 and C4 Fuels Brake Powers

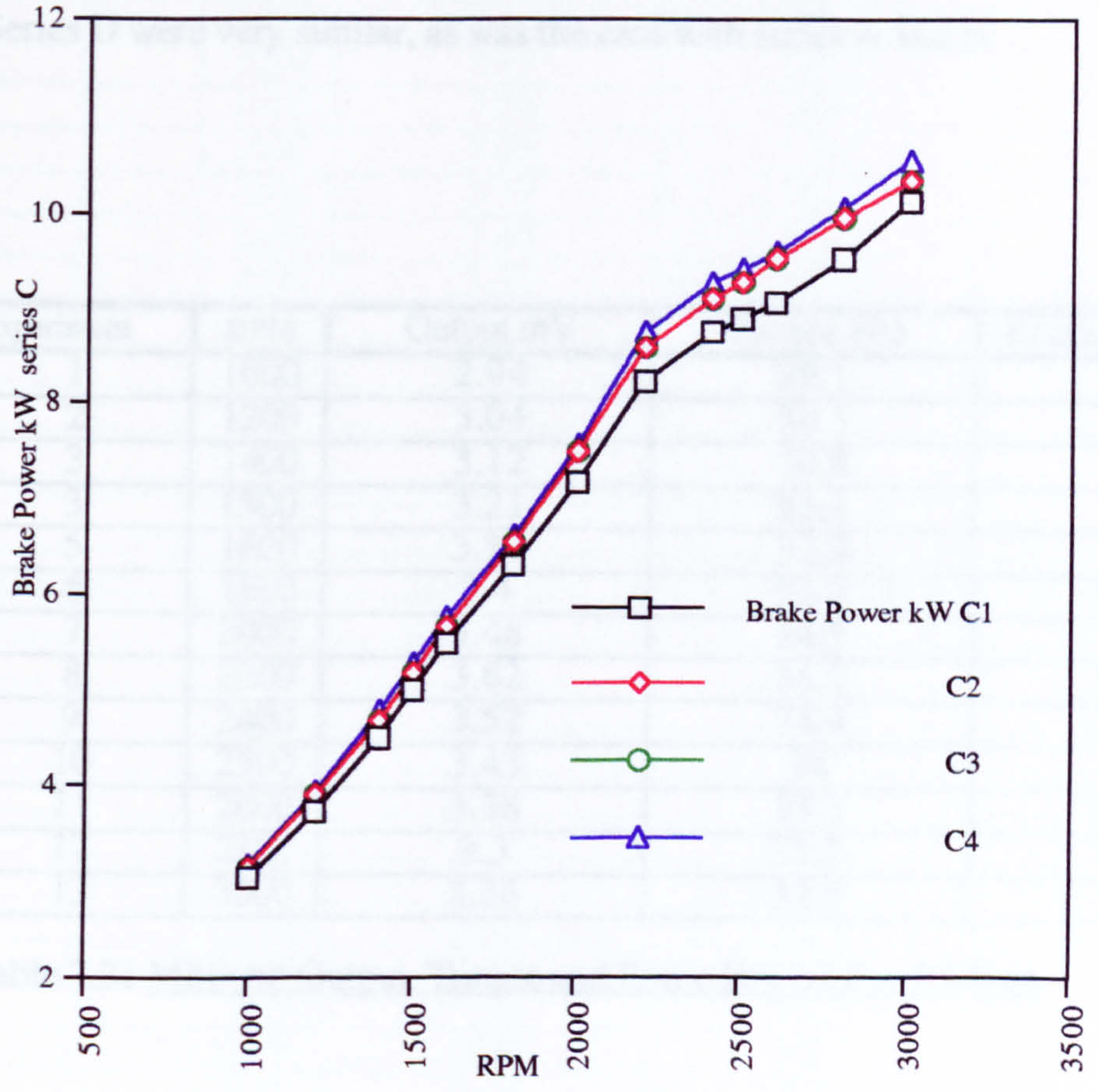

Figure 7.05 Brake Powers Series C Fuels

7.1.5 Brake Power Output, Series D Fuels

Table 7.21 lists the millivolt output (mV), torque (Nm) and brake power (kW) data from the 13 experiments with D1 fuel. Tables 7.22, 7.23 and 7.24 give millivolt output (mV), torque (Nm) and brake power (kW) data for D2, D3 and D4 fuels respectively.

Table 7.25 and Figure 7.06 show that D1 fuel gave the lowest brake power output in the D series. The reduction in power was the greatest with D1 fuel, approximately 20.7% brake power less than Average Ref at 3000 rpm. The power loss decreased from D1 to D4 fuels; the latter D4 fuel had the lowest power loss in the D series with brake power output of 12.9% less than that of Average Ref. The trends obtained from Series C and Series D were very similar, as was the case with series A and B.

Experiment	RPM	Output mV	Torque Nm	Brake Power kW
1	1000	2.94	29.1	3.05
2	1200	3.04	30.1	3.78
3	1400	3.12	30.8	4.52
3	1500	3.21	31.9	5.01
5	1600	3.32	32.9	5.51
6	1800	3.4	33.7	6.35
7	2000	3.48	34.5	7.23
8	2200	3.62	35.9	8.27
9	2400	3.52	34.9	8.77
10	2500	3.43	34	8.9
11	2600	3.38	33.5	9.12
12	2800	3.3	32.7	9.59
13	3000	3.28	32.5	10.2

Table 7.21 Millivolt Output, Torque and Brake Powers For D1 Fuel

Experiment	RPM	Output mV	Torque Nm	Brake Power kW
1	1000	3	29.7	3.11
2	1200	3.12	30.9	3.88
3	1400	3.16	31.3	4.59
3	1500	3.28	32.5	5.11
5	1600	3.39	33.6	5.63
6	1800	3.48	34.5	6.5
7	2000	3.58	35.5	7.44
8	2200	3.67	36.4	8.39
9	2400	3.61	35.8	9.01
10	2500	3.52	34.9	9.14
11	2600	3.44	34.1	9.28
12	2800	3.4	33.7	9.88
13	3000	3.32	32.9	10.34

Table 7.22 Millivolt Output, Torque and Brake Powers For D2 Fuel

Experiment	RPM	Output mV	Torque Nm	Brake Power kW
1	1000	3.06	30.3	3.17
2	1200	3.17	31.4	3.95
3	1400	3.25	32.2	4.72
3	1500	3.34	33.1	5.2
5	1600	3.45	34.2	5.73
6	1800	3.56	35.3	6.65
7	2000	3.63	36	7.54
8	2200	3.79	37.6	8.66
9	2400	3.69	36.6	9.2
10	2500	3.61	35.8	9.37
11	2600	3.54	35.1	9.56
12	2800	3.48	34.5	10.12
13	3000	3.36	33.3	10.46

Table 7.23 Millivolt Output, Torque and Brake Powers For D3 Fuel

Experiment	RPM	Output mV	Torque Nm	Brake Power kW
1	1000	3.1	30.7	3.21
2	1200	3.21	31.8	4
3	1400	3.32	32.9	4.82
3	1500	3.4	33.7	5.29
5	1600	3.49	34.6	5.8
6	1800	3.59	35.6	6.71
7	2000	3.69	36.5	7.65
8	2200	3.84	38.1	8.78
9	2400	3.72	36.9	9.27
10	2500	3.66	36.3	9.5
11	2600	3.57	35.4	9.64
12	2800	3.51	34.8	10.2
13	3000	3.36	33.3	10.46

Table 7.24 Millivolt Output, Torque and Brake Powers For D4 Fuel

Experiment	RPM	Brake Power kW D1	Brake Power kW D2	Brake Power kW D3	Brake Power kW D4
1	1000	3.05	3.11	3.17	3.21
2	1200	3.78	3.88	3.95	4
3	1400	4.52	4.59	4.72	4.82
3	1500	5.01	5.11	5.2	5.29
5	1600	5.51	5.63	5.73	5.8
6	1800	6.35	6.5	6.65	6.71
7	2000	7.23	7.44	7.54	7.65
8	2200	8.27	8.39	8.66	8.78
9	2400	8.77	9.01	9.2	9.27
10	2500	8.9	9.14	9.37	9.5
11	2600	9.12	9.28	9.56	9.64
12	2800	9.59	9.88	10.12	10.2
13	3000	9.53	10.34	10.46	10.46

Table 7.25 D1, D2, D3 And D4 Fuels Brake Powers

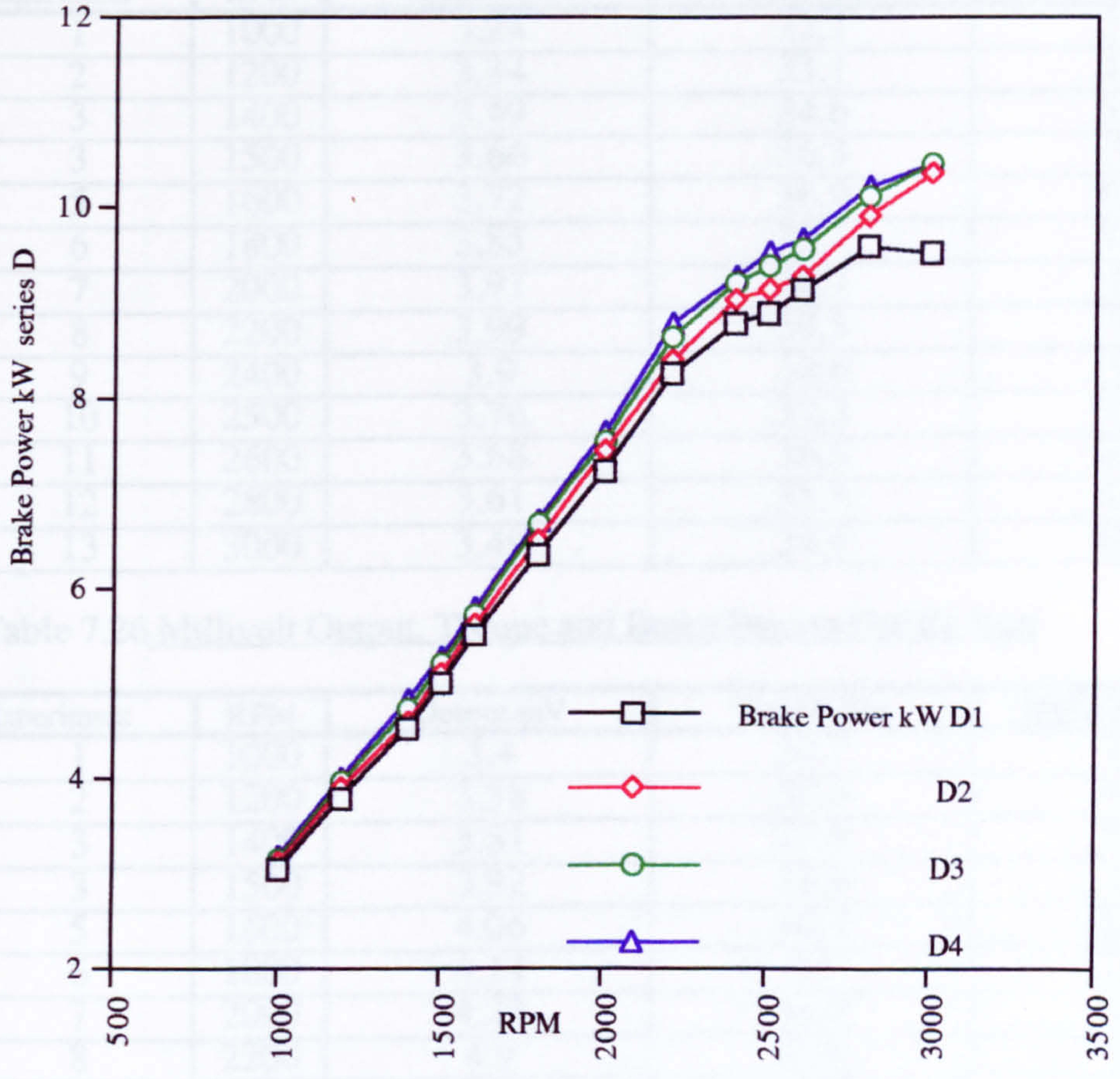

Figure 7.06 Brake Powers Series D Fuels

7.1.6 Brake Power Output, Series E Fuels

Table 7.26 lists the millivolt output (mV), torque (Nm) and brake power (kW) data for the 13 experiments with E1 fuel. Table 7.27 summarises similar data for the 13 experiments with E4 fuel.

Table 7.28 and Figure 7.07 show that E1 fuel gave a lower brake power output than E4 fuel. The brake power output of E series was very similar to that of the A series. E1 fuel gave 9.5% less, and E4 fuel 6.6% less brake power output than Average Ref at 3000 rpm, In fact the E series brake power output performance was indistinguishable from that of the A series.

Experiment	RPM	Output mV	Torque Nm	Brake Power kW
1	1000	3.24	32.1	3.36
2	1200	3.34	33.1	4.16
3	1400	3.49	34.6	5.07
3	1500	3.66	36.3	5.7
5	1600	3.72	36.9	6.18
6	1800	3.85	38.1	7.18
7	2000	3.91	38.7	8.1
8	2200	3.99	39.5	9.1
9	2400	3.9	38.6	9.7
10	2500	3.76	37.3	9.77
11	2600	3.68	36.5	9.94
12	2800	3.61	35.8	10.5
13	3000	3.49	34.6	10.87

Table 7.26 Millivolt Output, Torque and Brake Powers For E1 Fuel

Experiment	RPM	Output mV	Torque Nm	Brake Power kW
1	1000	3.4	33.7	3.53
2	1200	3.58	35.5	4.46
3	1400	3.81	37.8	5.54
3	1500	3.92	38.8	6.1
5	1600	4.06	40.2	6.74
6	1800	4.14	41	7.73
7	2000	4.23	41.9	8.78
8	2200	4.9	40.6	9.35
9	2400	4.02	39.8	10
10	2500	3.93	38.9	10.18
11	2600	3.8	37.7	10.26
12	2800	3.7	36.7	10.76
13	3000	3.6	35.7	11.22

Table 7.27 Millivolt Output, Torque and Brake Powers For E4 Fuel

Experiment	RPM	Brake Power kW E1	Brake Power kW E4
1	1000	3.36	3.53
2	1200	4.16	4.46
3	1400	5.07	5.54
3	1500	5.7	6.1
5	1600	6.18	6.74
6	1800	7.18	7.73
7	2000	8.1	8.78
8	2200	9.1	9.35
9	2400	9.7	10
10	2500	9.77	10.18
11	2600	9.94	10.26
12	2800	10.5	10.76
13	3000	10.87	11.22

Table 7.28 E1 And E4 Fuels Brake Powers

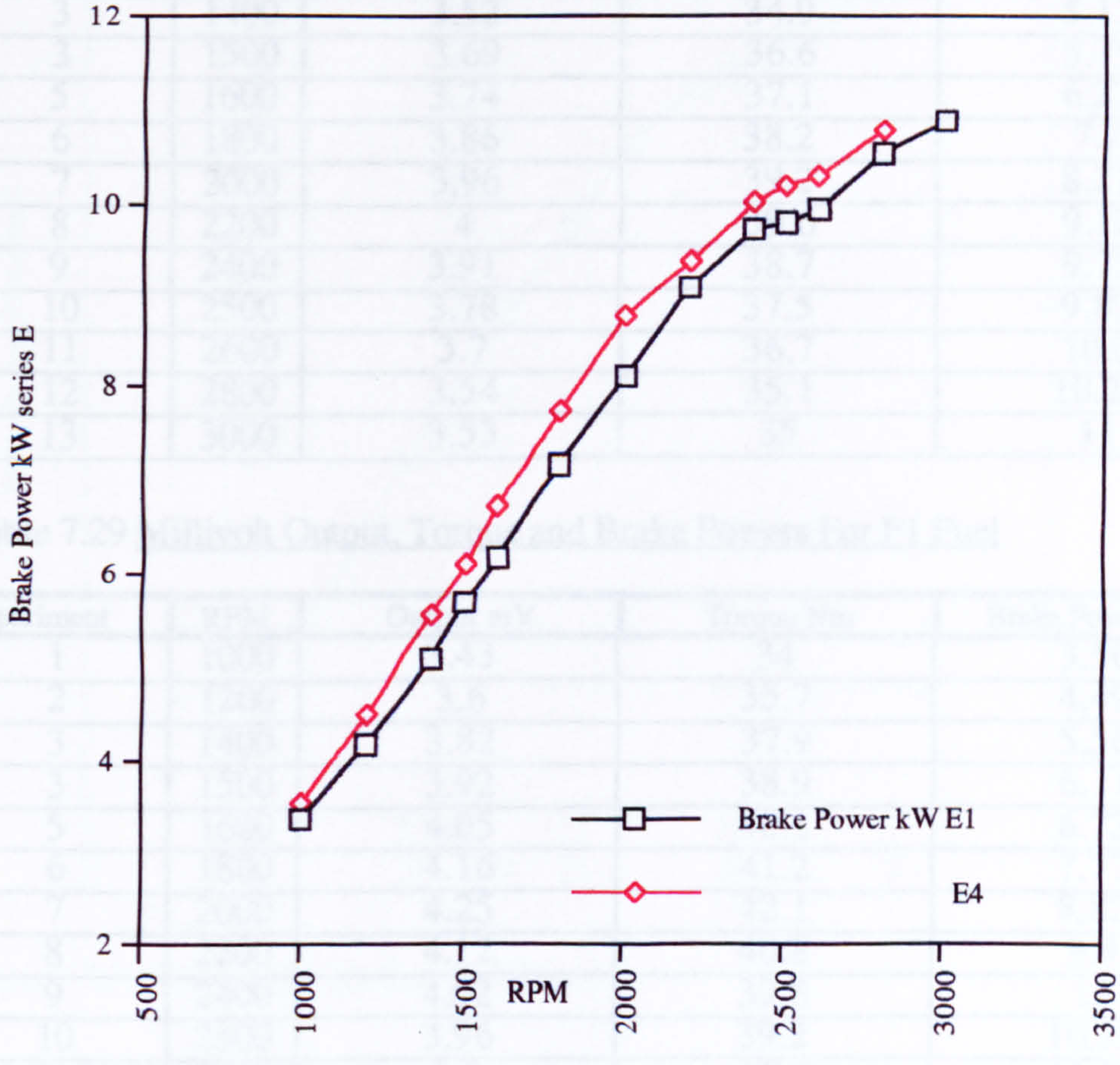

Figure 7.07 Brake Powers Series E Fuels

7.1.7 Brake Power Output, Series F Fuels

Table 7.29 lists the millivolt output (mV), torque (Nm) and brake power (kW) data from the 13 experiments with F1 fuel. Table 7.30 summarises similar data for the 13 experiments with F4 fuel.

Table 7.31 and Figure 7.08 show that F1 fuel gave a lower brake power output than F4 fuel and 8.4% lower brake power output than Average Ref. F4 fuel 5.8% lower brake power output than Average Ref fuel at 3000 rpm. The power outputs from the F series fuels were very similar to those from the B series.

Experiment	RPM	Output mV	Torque Nm	Brake Power kW
1	1000	3.26	32.3	3.38
2	1200	3.34	33.1	4.16
3	1400	3.52	34.9	5.12
3	1500	3.69	36.6	5.75
5	1600	3.74	37.1	6.22
6	1800	3.86	38.2	7.2
7	2000	3.96	39.2	8.21
8	2200	4	39.6	9.12
9	2400	3.91	38.7	9.73
10	2500	3.78	37.5	9.82
11	2600	3.7	36.7	10.0
12	2800	3.54	35.1	10.29
13	3000	3.53	35	11

Table 7.29 Millivolt Output, Torque and Brake Powers For F1 Fuel

Experiment	RPM	Output mV	Torque Nm	Brake Power kW
1	1000	3.43	34	3.56
2	1200	3.6	35.7	4.49
3	1400	3.82	37.9	5.56
3	1500	3.92	38.9	6.11
5	1600	4.05	40.1	6.72
6	1800	4.16	41.2	7.77
7	2000	4.25	42.1	8.82
8	2200	4.12	40.8	9.4
9	2400	4.02	39.8	10
10	2500	3.96	39.2	10.26
11	2600	3.8	37.7	10.27
12	2800	3.72	36.9	10.82
13	3000	3.63	36	11.31

Table 7.30 Millivolt Output, Torque and Brake Powers For F4 Fuel

Experiment	RPM	Brake Power kW F1	Brake Power kW F4
1	1000	3.38	3.56
2	1200	4.16	4.49
3	1400	5.12	5.56
4	1500	5.75	6.11
5	1600	6.22	6.72
6	1800	7.2	7.77
7	2000	8.21	8.82
8	2200	9.12	9.4
9	2400	9.73	10
10	2500	9.82	10.26
11	2600	10	10.27
12	2800	10.29	10.87
13	3000	11	11.31

Table 7.31 F1 And F4 Fuels Brake Powers

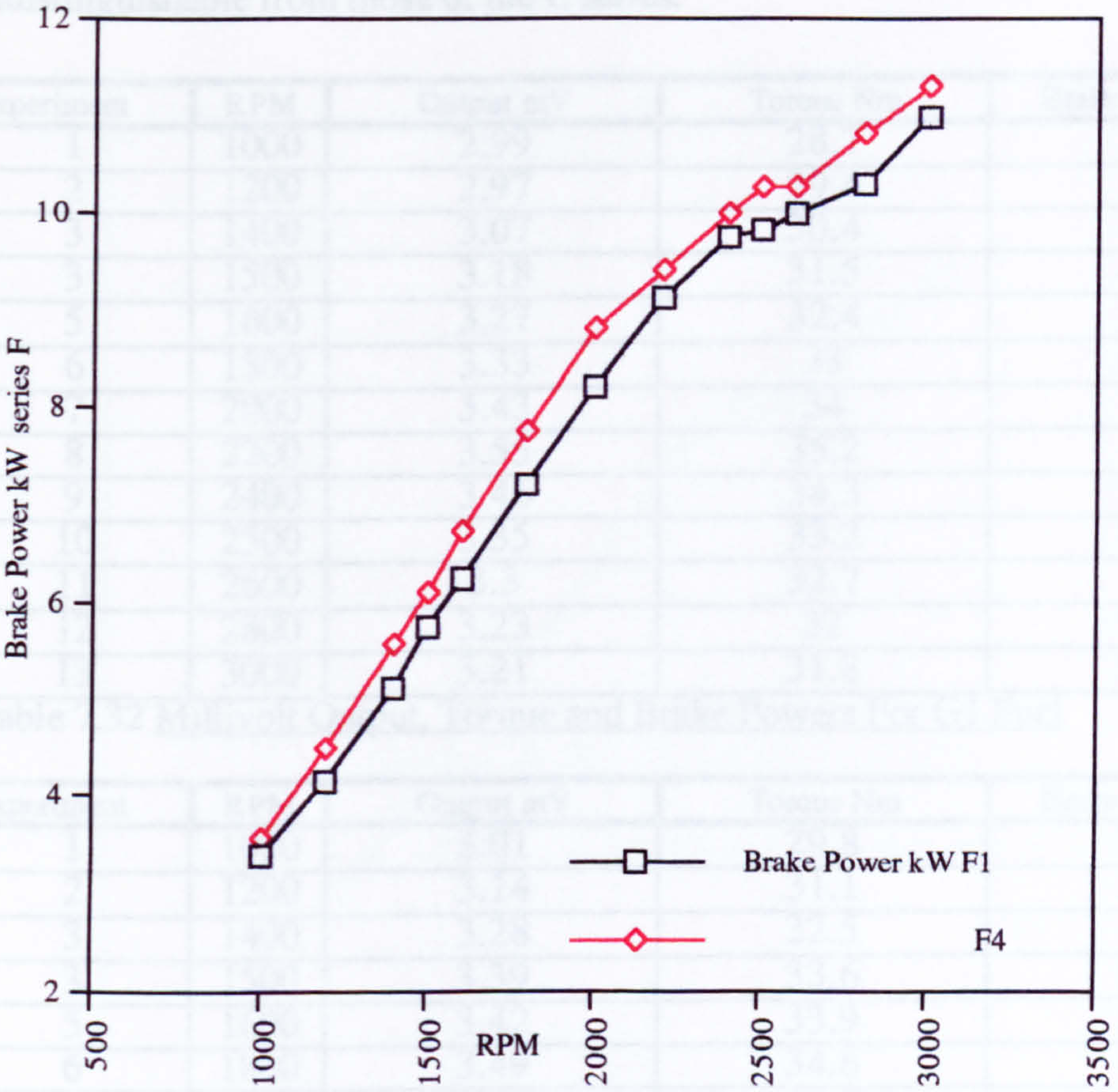

Figure 7.08 Brake Powers Series F Fuels

7.1.8 Brake Power Output, Series G Fuels

Table 7.32 lists the millivolt output (mV), torque (Nm) and brake power (kW) data from the 13 experiments with G1 fuel. Table 7.33 summarises similar data for the 13 experiments with G4 fuel.

Table 7.34 and Figure 7.09 demonstrate that G1 fuel gave a lower brake power output than G4 fuel. G1 fuel gave 16.9% less and G4 gave 13.7% less brake power than Average Ref at 3000 rpm. The power outputs of both G1 fuel and G4 fuel were very similar to those of C1 fuel and C4 fuel. In fact the brake power outputs for the G series appear to be indistinguishable from those of the C series.

Experiment	RPM	Output mV	Torque Nm	Brake Power kW
1	1000	2.99	28.7	3.01
2	1200	2.97	29.4	3.69
3	1400	3.07	30.4	4.46
3	1500	3.18	31.5	4.95
5	1600	3.27	32.4	5.43
6	1800	3.33	33	6.22
7	2000	3.43	34	7.12
8	2200	3.55	35.2	8.1
9	2400	3.46	34.3	8.6
10	2500	3.35	33.2	8.68
11	2600	3.3	32.7	8.9
12	2800	3.23	32	9.38
13	3000	3.21	31.8	9.98

Table 7.32 Millivolt Output, Torque and Brake Powers For G1 Fuel

Experiment	RPM	Output mV	Torque Nm	Brake Power kW
1	1000	3.01	29.8	3.12
2	1200	3.14	31.1	3.91
3	1400	3.28	32.5	4.76
3	1500	3.39	33.6	5.28
5	1600	3.42	33.9	5.68
6	1800	3.49	34.6	6.52
7	2000	3.62	35.9	7.52
8	2200	3.79	37.6	8.66
9	2400	3.67	36.4	9.15
10	2500	3.55	35.2	9.22
11	2600	3.51	34.8	9.48
12	2800	3.4	33.7	9.88
13	3000	3.33	33	10.37

Table 7.33 Millivolt Output, Torque and Brake Powers For G4 Fuel

Experiment	RPM	Brake Power kW G1	Brake Power kW G4
1	1000	3.01	3.12
2	1200	3.69	3.91
3	1400	4.46	4.76
3	1500	4.95	5.28
5	1600	5.43	5.68
6	1800	6.22	6.52
7	2000	7.12	7.52
8	2200	8.1	8.66
9	2400	8.6	9.15
10	2500	8.68	9.22
11	2600	8.9	9.48
12	2800	9.38	9.88
13	3000	9.98	10.37

Table 7.34 G1 And G4 Fuels Brake Powers

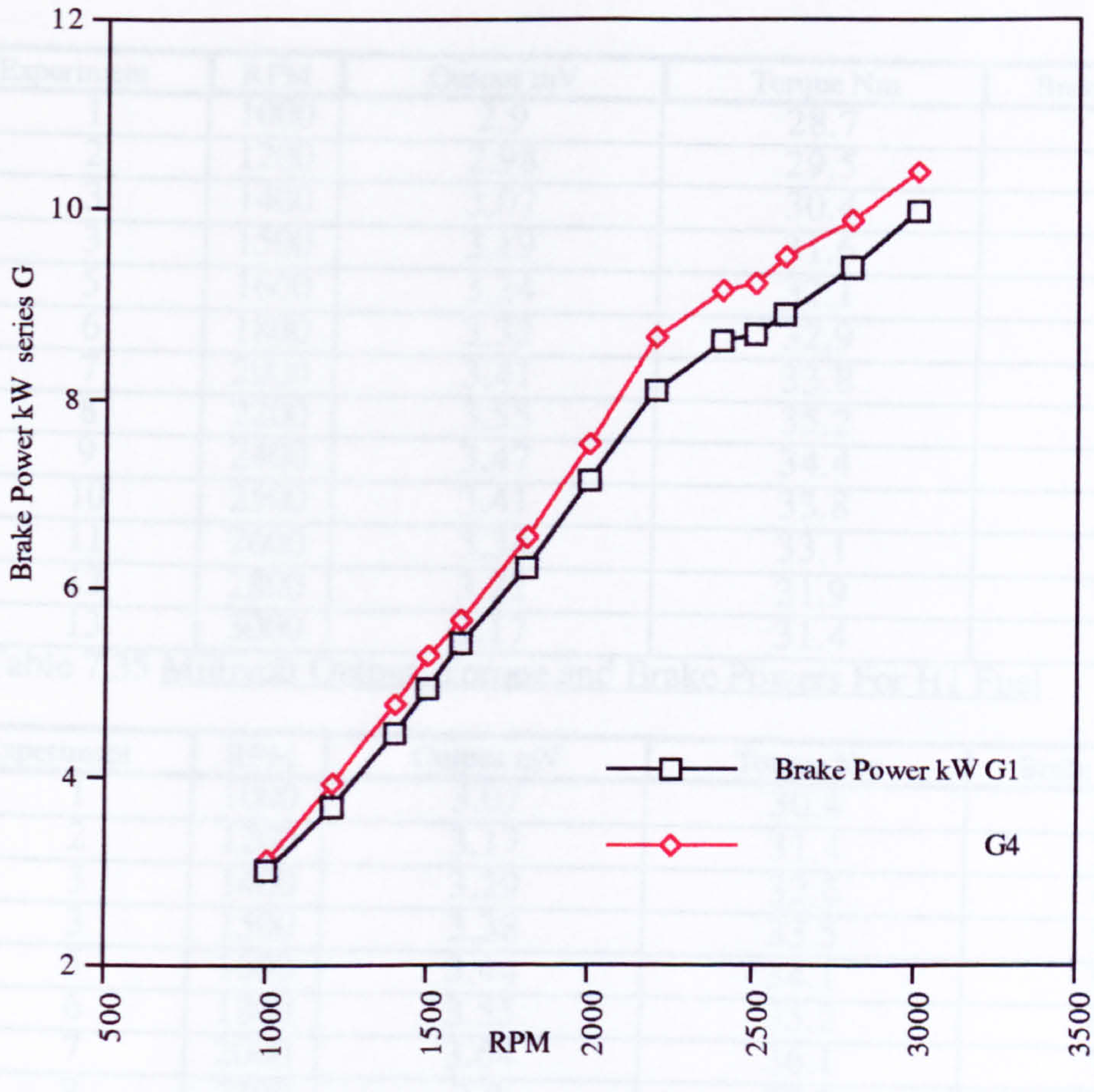

Figure 7.09 Brake Powers Series G Fuels

7.1.9 Brake Power Output Series H Fuels

Table 7.35 lists the millivolt output (mV), torque (Nm) and brake power (kW) data from the 13 experiments with H1 fuel. Table 7.36 summarises similar data for the 13 experiments with H4 fuel.

Table 7.37 and Figure 7.10 demonstrate that the brake power outputs of the H series fuels were very similar to those of the D series fuels. H1 fuel showed a brake power output deficit of 17.9% and H4 fuel of 13.9% compared to Average Ref at 3000 rpm. In fact the brake power output performances of H1 and H4 fuels were indistinguishable from those of D1 and D4 fuels.

Experiment	RPM	Output mV	Torque Nm	Brake Power kW
1	1000	2.9	28.7	3.01
2	1200	2.98	29.5	3.71
3	1400	3.07	30.4	4.46
3	1500	3.19	31.6	4.96
5	1600	3.24	32.1	5.38
6	1800	3.32	32.9	6.2
7	2000	3.41	33.8	7.08
8	2200	3.55	35.2	8.11
9	2400	3.47	34.4	8.65
10	2500	3.41	33.8	8.85
11	2600	3.34	33.1	9.01
12	2800	3.22	31.9	9.35
13	3000	3.17	31.4	9.86

Table 7.35 Millivolt Output, Torque and Brake Powers For H1 Fuel

Experiment	RPM	Output mV	Torque Nm	Brake Power kW
1	1000	3.07	30.4	3.18
2	1200	3.17	31.4	3.95
3	1400	3.29	32.6	4.78
3	1500	3.38	33.5	5.26
5	1600	3.44	34.1	5.71
6	1800	3.55	35.2	6.64
7	2000	3.64	36.1	7.56
8	2200	3.8	37.7	8.69
9	2400	3.67	36.4	9.15
10	2500	3.63	36	9.42
11	2600	3.54	35.1	9.56
12	2800	3.48	34.5	10.12
13	3000	3.32	32.9	10.34

Table 7.36 Millivolt Output, Torque and Brake Powers For H4 Fuel

Experiment	RPM	Brake Power kW H1	Brake Power kW H4
1	1000	3.01	3.18
2	1200	3.71	3.95
3	1400	4.46	4.78
3	1500	4.96	5.26
5	1600	5.38	5.71
6	1800	6.2	6.64
7	2000	7.08	7.56
8	2200	8.11	8.69
9	2400	8.65	9.15
10	2500	8.85	9.42
11	2600	9.01	9.56
12	2800	9.35	10.12
13	3000	9.86	10.34

Table 7.37 H1 and H4 Fuels Brake Powers

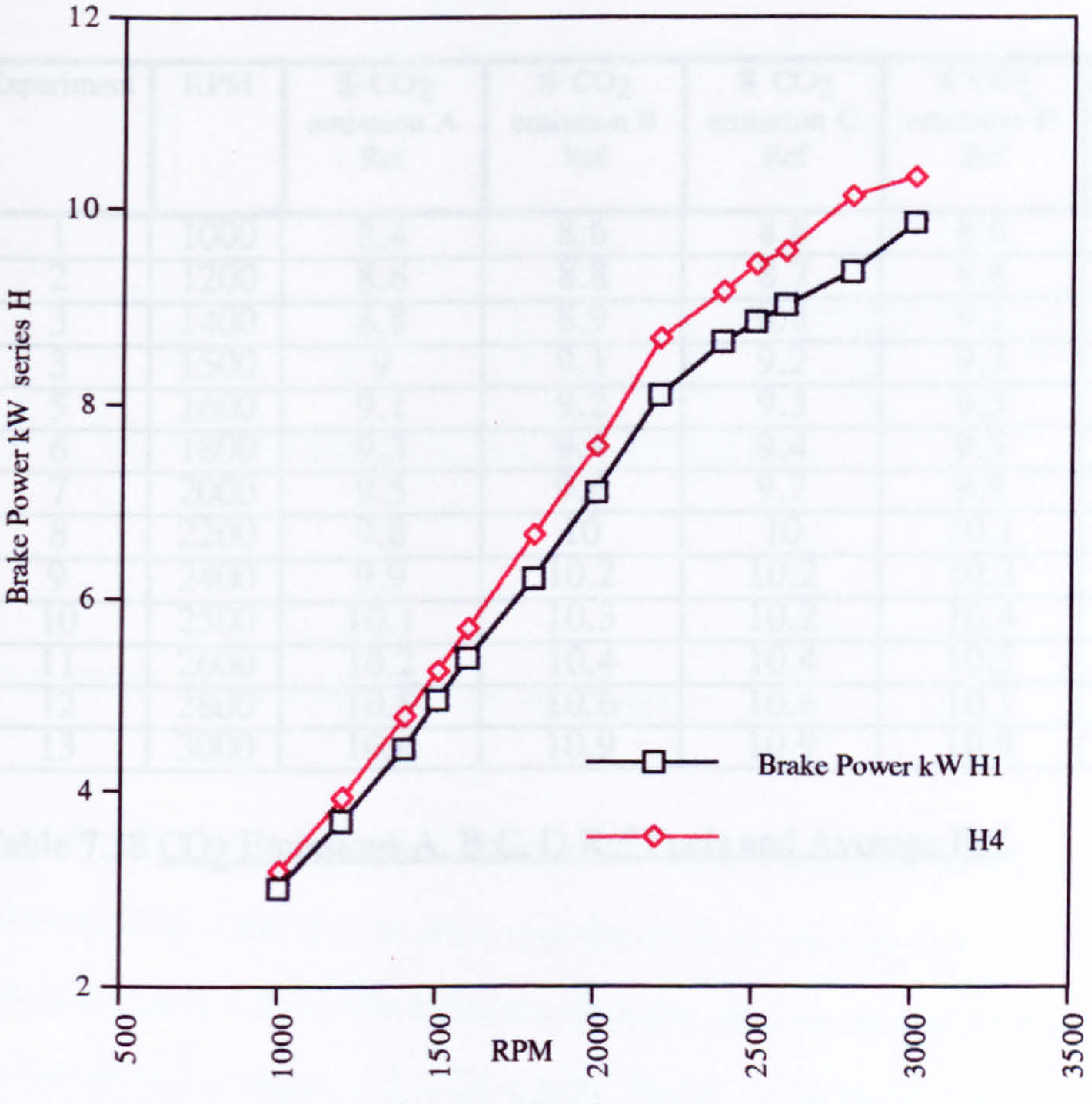

Figure 7.10 Brake Powers Series H Fuels

7.2 Carbon Dioxide Emissions

7.2.1 Carbon Dioxide Emissions from Reference and Experimental Fuels

The data for CO_2 emissions of A Ref, B Ref, C Ref and D Ref fuels are shown in Table 7.38 together with the average CO_2 emissions of the four references (Average Ref fuel). Figure 7.11 shows that when the readings for the four reference fuels were compared there was good agreement. The maximum difference between the 4 reference fuels was only 2.1%.

Experiment	RPM	% CO_2 emission A Ref	% CO_2 emission B Ref	% CO_2 emission C Ref	% CO_2 emission D Ref	% CO_2 emission (average of A,B, C and D Ref) Average Ref
1	1000	8.4	8.6	8.6	8.6	8.6
2	1200	8.6	8.8	8.7	8.8	8.7
3	1400	8.8	8.9	8.8	9.1	8.9
3	1500	9	9.1	9.2	9.3	9.2
5	1600	9.1	9.2	9.3	9.3	9.2
6	1800	9.3	9.4	9.4	9.5	9.4
7	2000	9.5	9.6	9.7	9.9	9.7
8	2200	9.8	10	10	10.1	10.0
9	2400	9.9	10.2	10.2	10.3	10.2
10	2500	10.1	10.3	10.2	10.4	10.3
11	2600	10.2	10.4	10.4	10.5	10.4
12	2800	10.5	10.6	10.6	10.7	10.6
13	3000	10.6	10.9	10.9	10.9	10.9

Table 7.38 CO_2 Emissions A, B,C, D Ref Fuels and Average Ref.

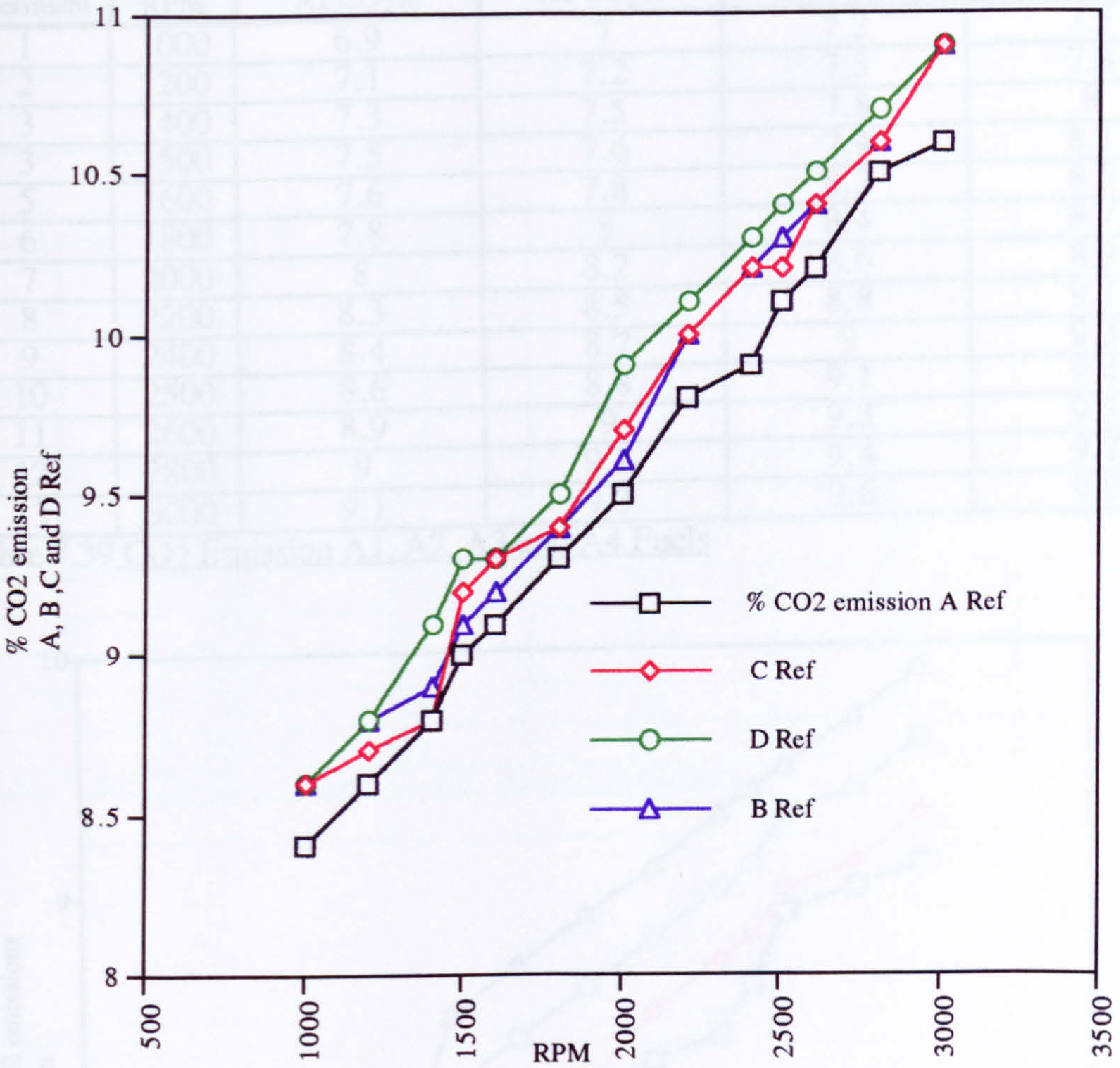

Figure 7.11 CO$_2$ Emissions A, B, C and D Ref Fuels

7.2.2 CO2 Emissions, Series A Fuels

As shown in Table 7.39 the % CO$_2$ in the exhaust emission increased as the speed was increased from 1000 rpm to 3000 rpm for each of the test fuels A1 to A4. The results plotted in Figure 7.12 confirm that the increase was, for all practical purposes, linear and that the ranking in terms of % CO$_2$ was A1 to A4. A1 gave the lowest emission of CO$_2$ in the A series, 16.6% less than Average Ref at 3000 rpm. A4 gave the highest CO$_2$ emission in the A series, with 9.3% less CO$_2$ than Average Ref at 3000 rpm.

Experiment	RPM	A1 CO_2%	A2 CO_2%	A3 CO_2%	A4 CO_2%
1	1000	6.9	7	7.2	7.5
2	1200	7.1	7.2	7.5	7.8
3	1400	7.3	7.5	7.8	8
3	1500	7.5	7.6	7.9	8.1
5	1600	7.6	7.8	8.2	8.5
6	1800	7.8	8	8.4	8.7
7	2000	8	8.2	8.6	8.9
8	2200	8.3	8.5	8.8	9.1
9	2400	8.4	8.7	9	9.3
10	2500	8.6	8.8	9.1	9.4
11	2600	8.9	9	9.3	9.5
12	2800	9	9.1	9.4	9.7
13	3000	9.1	9.3	9.6	9.9

Table 7.39 CO_2 Emission A1, A2, A3 and A4 Fuels

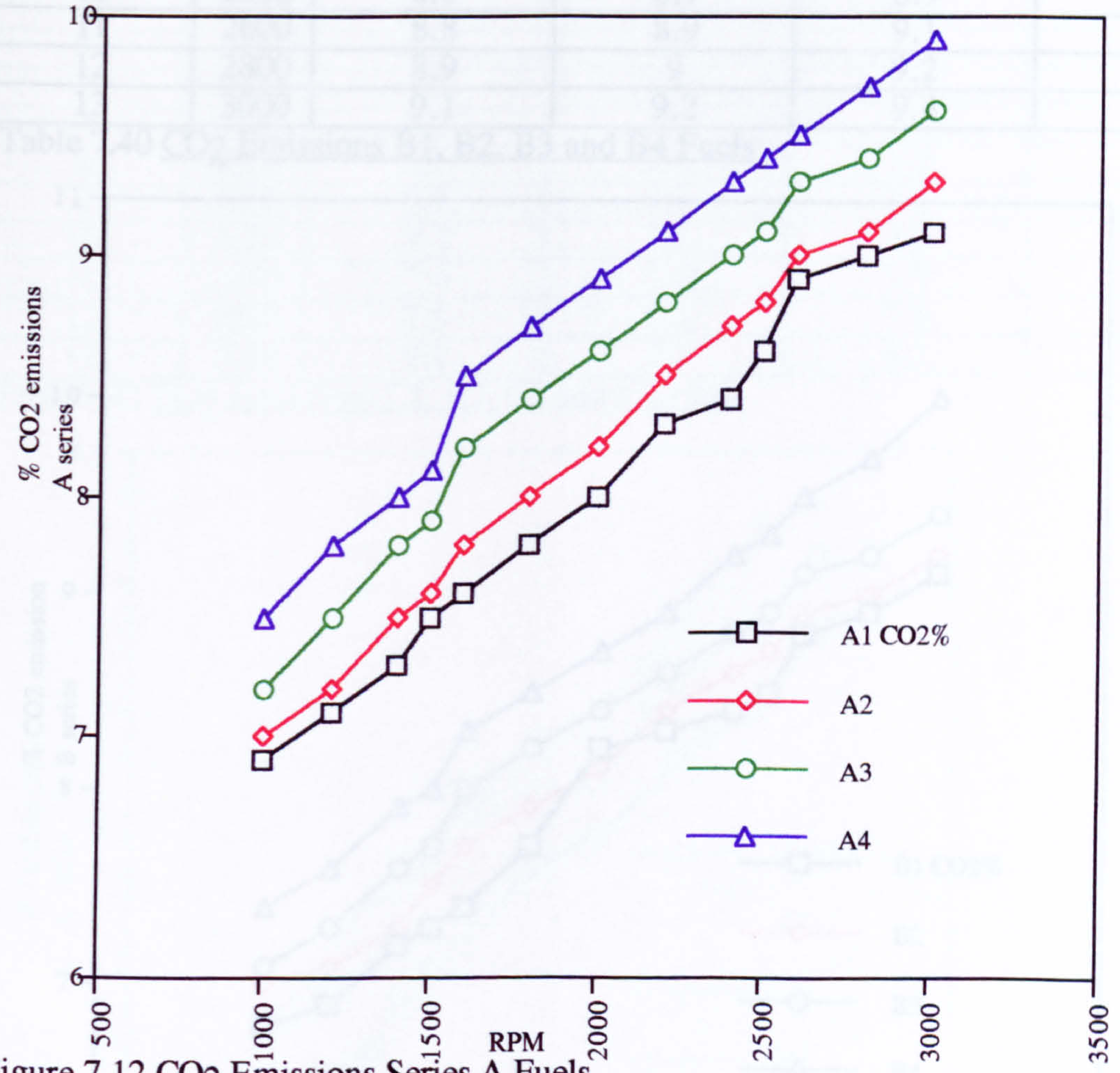

Figure 7.12 CO_2 Emissions Series A Fuels

7.2.3 CO2 Emissions, Series B Fuels

Table 7.40 summarises CO2 emission data from the 13 experiments for B1, B2, B3 and B4 fuels. Figure 7.13, shows that B1 fuel gave the lowest CO_2 emission in the B series fuels at 3000 rpm. From B1 to B4 fuel there was a steady increase in the CO_2 emissions as compared with Average Ref. B1 fuel gave a 16.5% and B4 a fuel 8.3% lower CO_2 emission level than Average Ref at 3000 rpm.

Experiment	RPM	B1 CO_2%	B2 CO_2%	B3 CO_2%	B4 CO_2%
1	1000	6.8	7	7.1	7.4
2	1200	6.9	7.1	7.3	7.6
3	1400	7.2	7.3	7.6	7.9
3	1500	7.3	7.5	7.7	8
5	1600	7.4	7.7	8	8.3
6	1800	7.7	7.9	8.2	8.5
7	2000	8.2	8.1	8.4	8.7
8	2200	8.3	8.4	8.6	8.9
9	2400	8.4	8.6	8.8	9.2
10	2500	8.5	8.7	8.9	9.3
11	2600	8.8	8.9	9.1	9.5
12	2800	8.9	9	9.2	9.7
13	3000	9.1	9.2	9.4	10

Table 7.40 CO_2 Emissions B1, B2, B3 and B4 Fuels

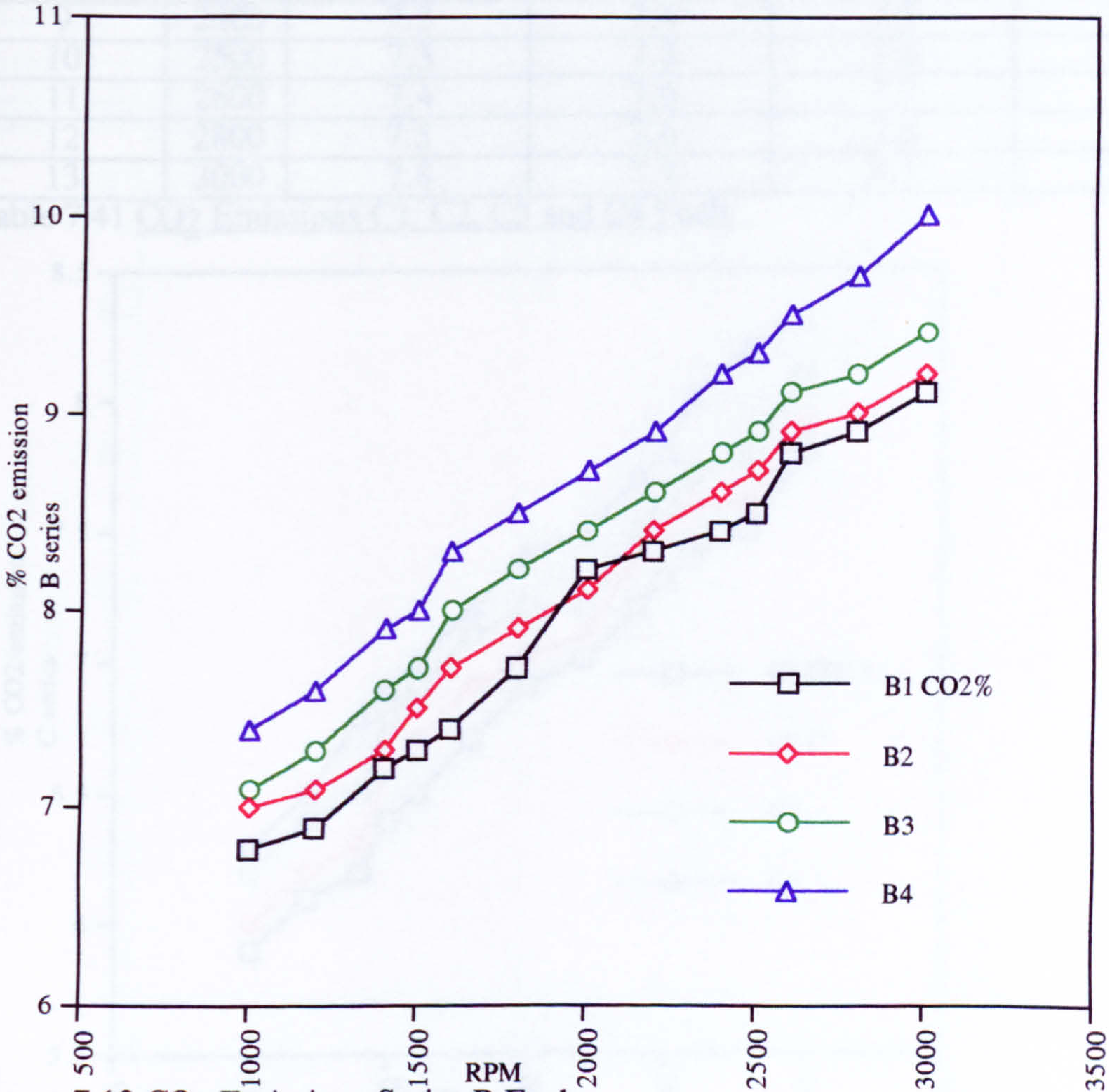

Figure 7.13 CO_2 Emissions Series B Fuels

7.2.4 CO_2 Emissions, Series C Fuels

Table 7.41 summarises CO_2 emissions for the 13 experiments with C1, C2, C3 and C4 fuels. Figure 7.14 shows that C1 fuel gave the lowest value of CO_2 emission in the C series fuels at 3000 rpm. Compared to Average Ref, 28.5% less CO_2 was emitted by C1 fuel at 3000 rpm. The level of CO_2 emissions increased from C1 to C4; the latter emitted 23.9% less CO_2 than the Average Ref at 3000 rpm.

Experiment	RPM	C1 CO_2%	C2 CO_2%	C3 CO_2%	C4 CO_2%
1	1000	5.9	6	6.2	6.3
2	1200	6.1	6.2	6.4	6.5
3	1400	6.2	6.3	6.5	6.8
3	1500	6.4	6.6	6.8	6.9
5	1600	6.5	6.7	6.9	7
6	1800	6.7	6.9	7.1	7.2
7	2000	6.9	7	7.2	7.4
8	2200	7	7.1	7.2	7.5
9	2400	7.2	7.4	7.5	7.7
10	2500	7.3	7.5	7.6	7.8
11	2600	7.4	7.6	7.7	8
12	2800	7.5	7.6	7.8	8.2
13	3000	7.8	7.9	8.1	8.3

Table 7.41 CO_2 Emissions C1, C2, C3 and C4 Fuels

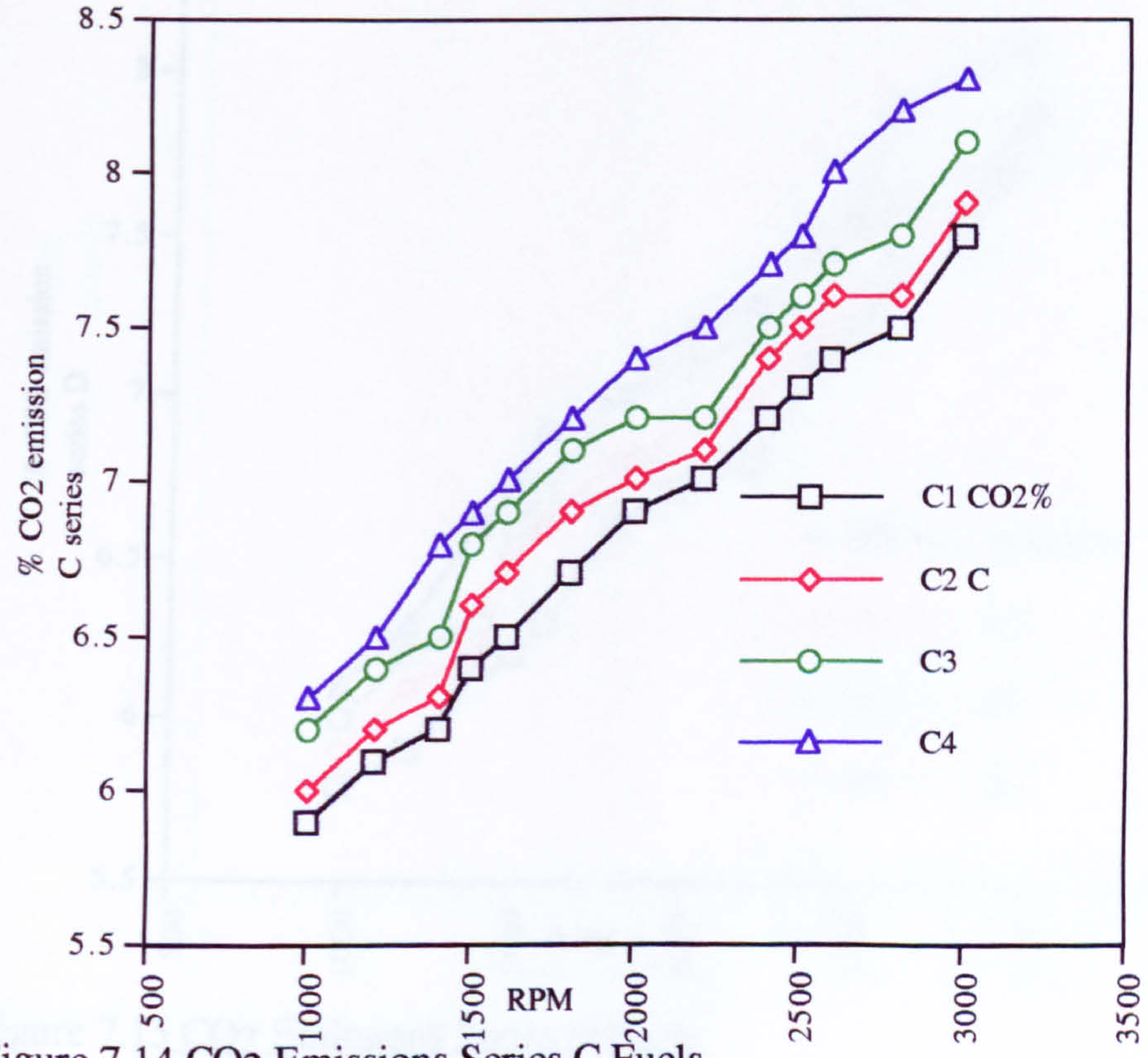

Figure 7.14 CO_2 Emissions Series C Fuels

7.2.5 CO_2 Emissions, Series D Fuels

Table 7.42 summarises CO_2 emissions data from the 13 experiments with D1, D2, D3 and D4 fuels. Figure 7.15 shows that D1 fuel had the lowest CO_2 emissions in the D series. There was an increase in the amount of CO_2 produced from D1 to D4 fuels. D1 fuel generated 29.5% lower and D4 a 25.8% lower level of emission of CO_2 than Average Ref at 3000 rpm.

Experiment	RPM	D1 CO_2%	D2 CO_2%	D3 CO_2%	D4 CO_2%
1	1000	5.8	5.9	6	6.1
2	1200	5.9	6.1	6.2	6.3
3	1400	6.1	6.2	6.3	6.6
3	1500	6.2	6.5	6.6	6.7
5	1600	6.3	6.6	6.7	6.9
6	1800	6.6	6.8	7	7
7	2000	6.7	6.9	7.1	7.2
8	2200	6.8	7	7.2	7.3
9	2400	7.1	7.2	7.4	7.5
10	2500	7.2	7.3	7.5	7.6
11	2600	7.4	7.5	7.6	7.9
12	2800	7.5	7.6	7.8	8
13	3000	7.7	7.8	7.9	8.1

Table 7.42 CO_2 Emissions D1, D2, D3 and D4 Ref

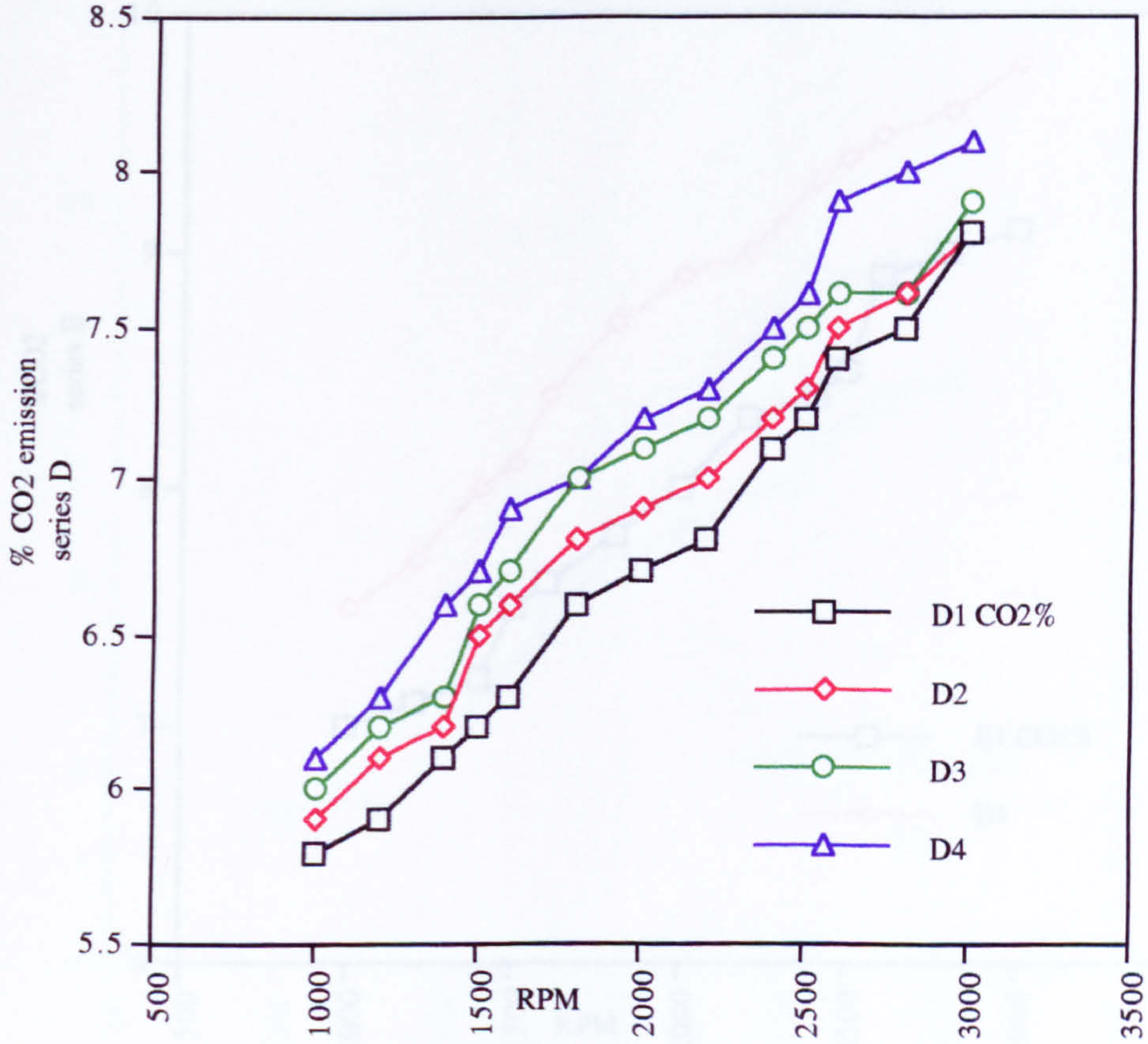

Figure 7.15 CO_2 Emissions Series D Fuels

7.2.6 CO_2 Emissions, Series E Fuels

Table 7.43 summarises CO_2 emissions data from the 13 experiments for test fuels E1 and E4. Figure 7.16 shows that E1 fuel emitted 17.7% less and E4 fuel 10.0% less CO_2 than Average Ref at 3000 rpm.

Experiment	RPM	E1 CO_2%	E4 CO_2%
1	1000	7	7.5
2	1200	7.1	7.7
3	1400	7.2	8
3	1500	7.5	8.1
5	1600	7.6	8.4
6	1800	7.8	8.7
7	2000	8	8.9
8	2200	8.3	9
9	2400	8.4	9.3
10	2500	8.5	9.4
11	2600	8.9	9.5
12	2800	9	9.6
13	3000	9.1	9.8

Table 7.43 CO_2 Emissions E1 and E4 Fuels

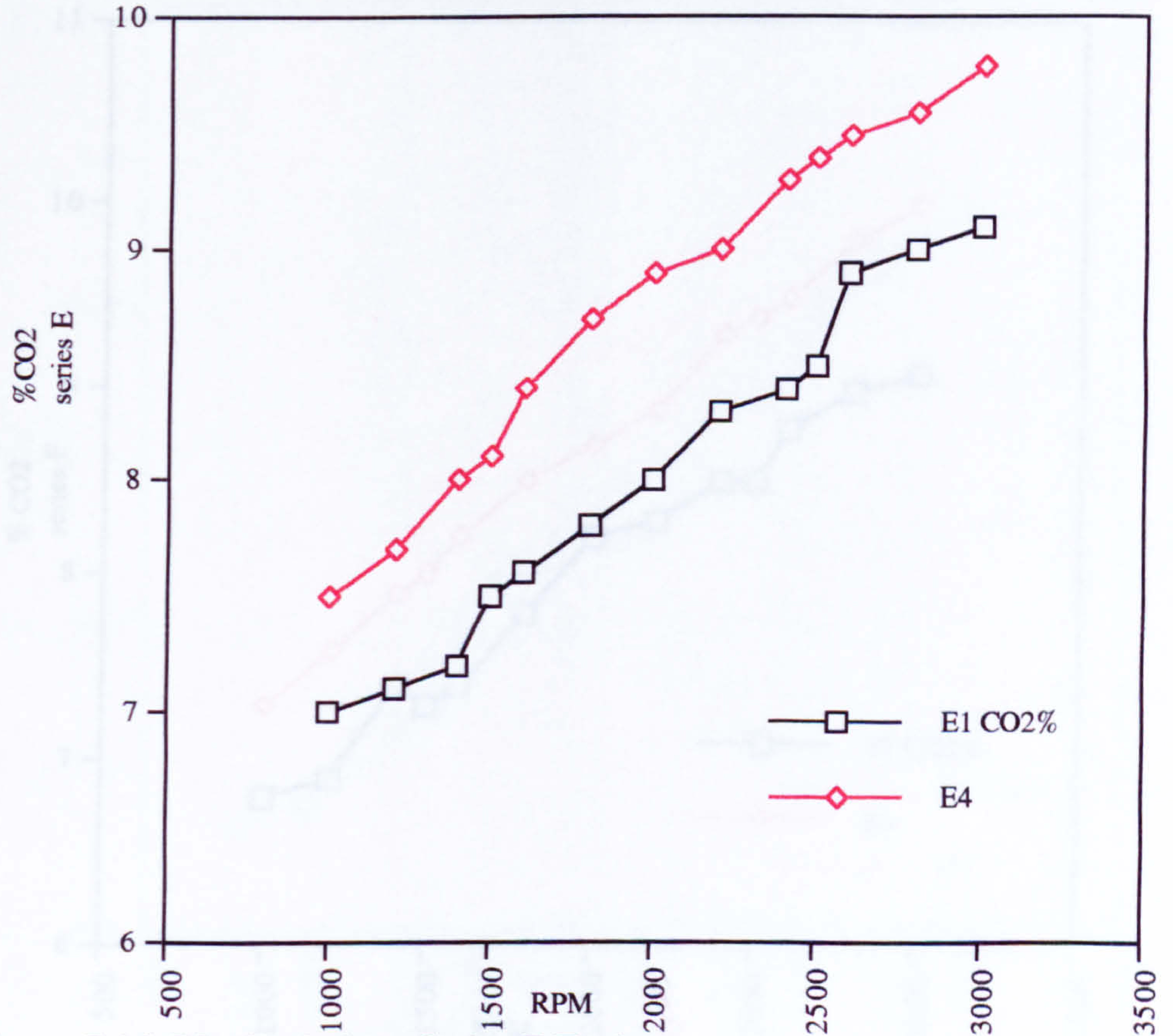

Figure 7.16 CO_2 Emissions Series E Fuels

7.2.7 CO_2 Emissions, Series F Fuels

Table 7.44 summarises CO_2 emissions data from the 13 readings for test fuels F1 and F4. Figure 7.17 shows F1 fuel emitted less CO_2 than F4 fuel, i.e. F1 emitted 16.5% less and F4 fuel 8.4% less CO_2 than Average Ref at 3000 rpm.

Experiment	RPM	F1 CO_2%	F4 CO_2%
1	1000	6.8	7.3
2	1200	6.9	7.6
3	1400	7.4	7.9
3	1500	7.3	8
5	1600	7.4	8.2
6	1800	7.8	8.5
7	2000	8.2	8.7
8	2200	8.3	8.9
9	2400	8.5	9.3
10	2500	8.5	9.4
11	2600	8.8	9.5
12	2800	9	9.8
13	3000	9.1	10

Table 7.44 CO_2 Emissions F1 and F4 Fuels

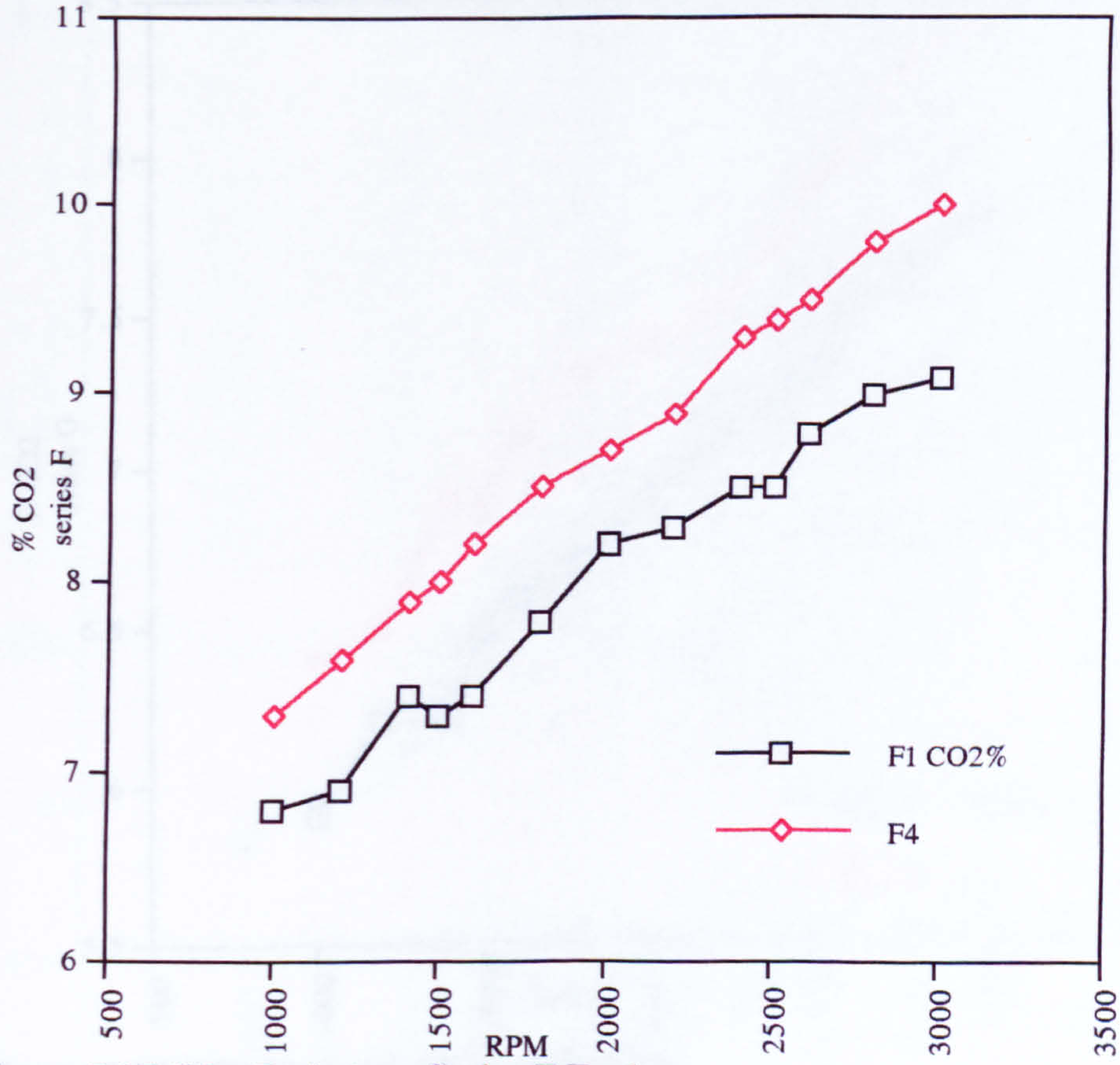

Figure 7.17 CO_2 Emissions Series F Fuels

7.2.8 CO_2 Emissions, Series G Fuels

Table 7.45 summarises CO_2 emissions data from the 13 experiments for test fuels G1 and G4. Figure 7.18 shows G1 emitted less CO_2 than G4 fuel. G1 emitted 28.5 % less and G4 fuel 22.9% less CO_2 than Average Ref at 3000 rpm.

Experiment	RPM	G1 CO_2%	G4 CO_2%
1	1000	5.9	6.4
2	1200	6.2	6.5
3	1400	6.2	6.9
3	1500	6.5	6.9
5	1600	6.6	7.1
6	1800	6.7	7.3
7	2000	6.9	7.4
8	2200	7.1	7.5
9	2400	7.2	7.7
10	2500	7.3	7.9
11	2600	7.5	8
12	2800	7.6	8.3
13	3000	7.8	8.4

Table 7.45 CO_2 Emissions Series G Fuels

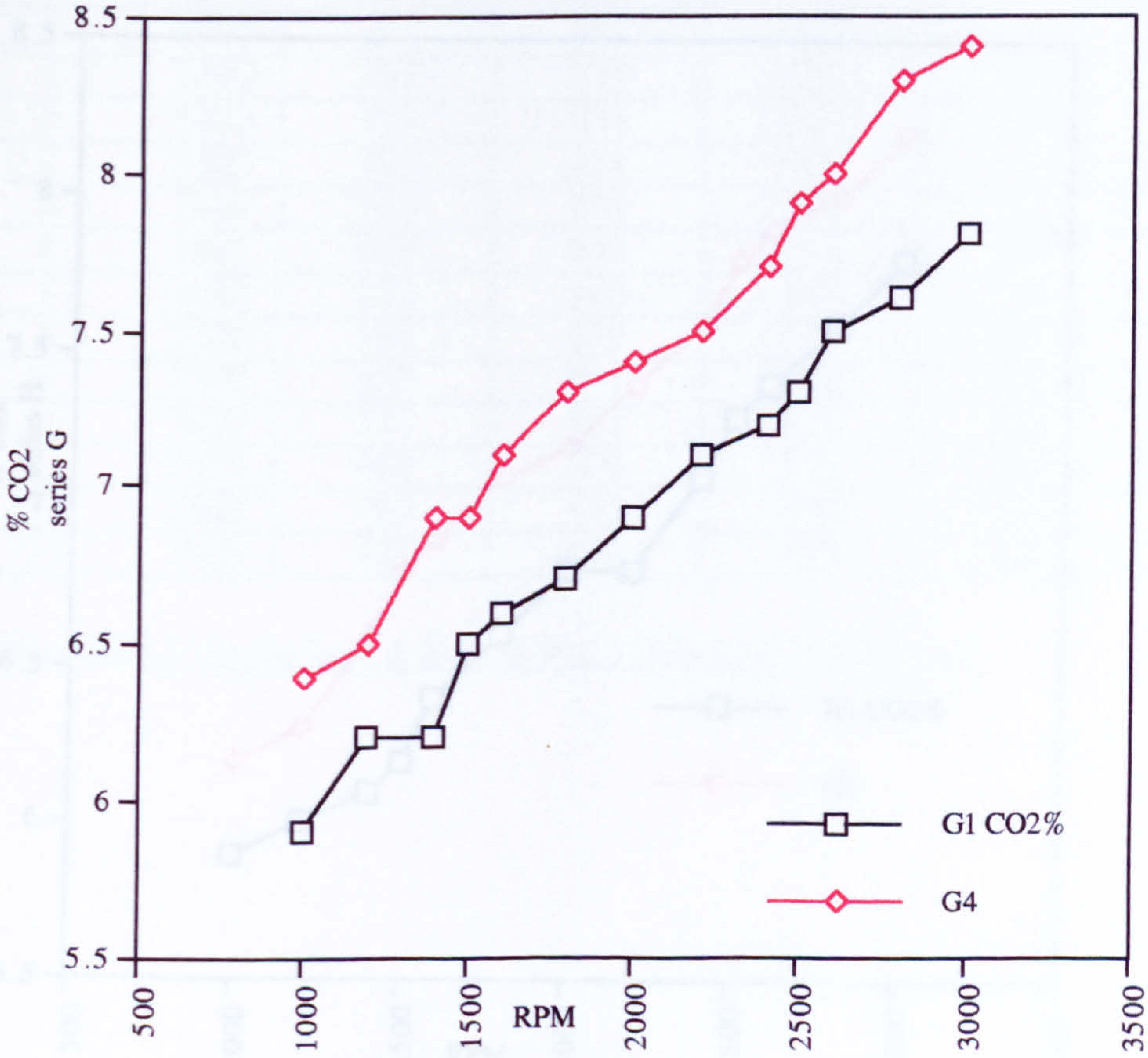

Figure 7.18 CO_2 Emissions Series G Fuels

7.2.9 CO_2 Emissions, In Series H Fuels

Table 7.46 summarises CO_2 emissions data from the 13 experiments for test fuels H1 and H4. Figure 7.19 and Table 7.45 show that H1 fuel emitted less CO_2 than H4 fuel, i.e. H1 fuel emitted 28.5 % less and H4 24.9% less CO_2 than Average Ref at 3000 rpm.

Experiment	RPM	H1 CO_2%	H4 CO_2%
1	1000	5.9	6.2
2	1200	6	6.3
3	1400	6.1	6.6
3	1500	6.2	6.8
5	1600	6.4	6.9
6	1800	6.6	7.1
7	2000	6.8	7.2
8	2200	6.8	7.4
9	2400	7.1	7.6
10	2500	7.3	7.8
11	2600	7.4	7.9
12	2800	7.6	8
13	3000	7.8	8.2

Table 7.46 CO_2 Emissions Series H Fuels

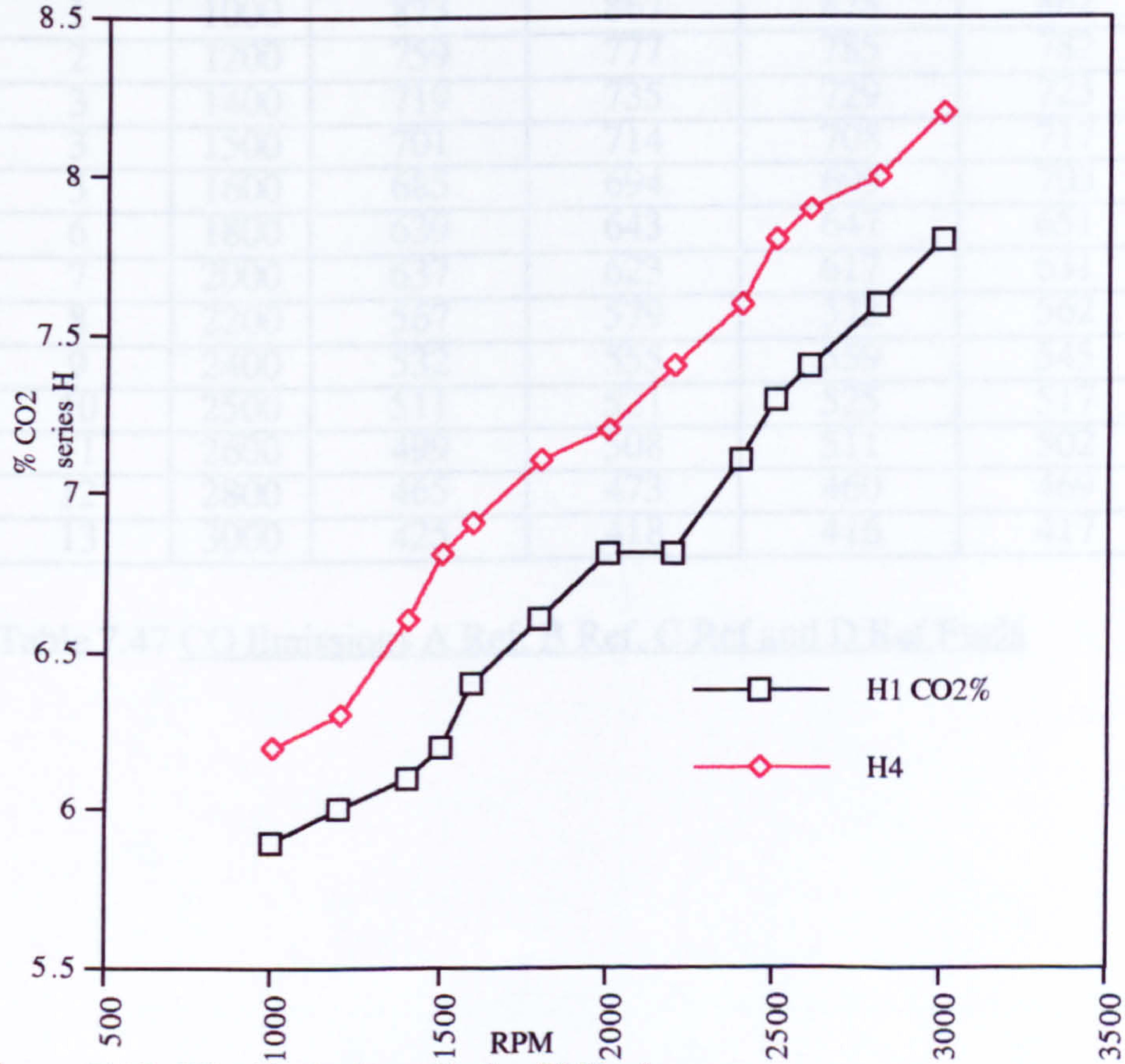

Figure 7.19 CO_2 Emissions Series H Fuels

7.3 Carbon Monoxide Emissions from Reference and Experimental Fuels

7.3.1 Carbon Monoxide Emissions from Reference Fuels

The total CO emission contents data from the 13 experiments with the four reference fuels Ref A, Ref B Ref C and Ref D are shown in Table 7.47 . The average ppm CO at various speeds (rpm) of the four reference fuels are also given in Table 7.47 as Average Ref. From Figure 7.20 the maximum difference was between Ref B and Ref D fuels. This difference was 2.1%.

Experiment	RPM	PPM CO Ref A	PPM CO Ref B	PPM CO Ref C	PPM CO Ref D	Average Ref PPM CO
1	1000	873	867	878	862	870
2	1200	759	777	785	782	776
3	1400	719	735	729	723	727
3	1500	701	714	708	717	710
5	1600	685	694	699	703	695
6	1800	639	643	647	651	645
7	2000	637	623	617	631	627
8	2200	567	579	572	562	570
9	2400	532	555	559	545	548
10	2500	511	521	525	517	519
11	2600	499	508	511	502	505
12	2800	465	473	460	469	467
13	3000	425	418	416	417	419

Table 7.47 CO Emissions A Ref. B Ref. C Ref and D Ref Fuels

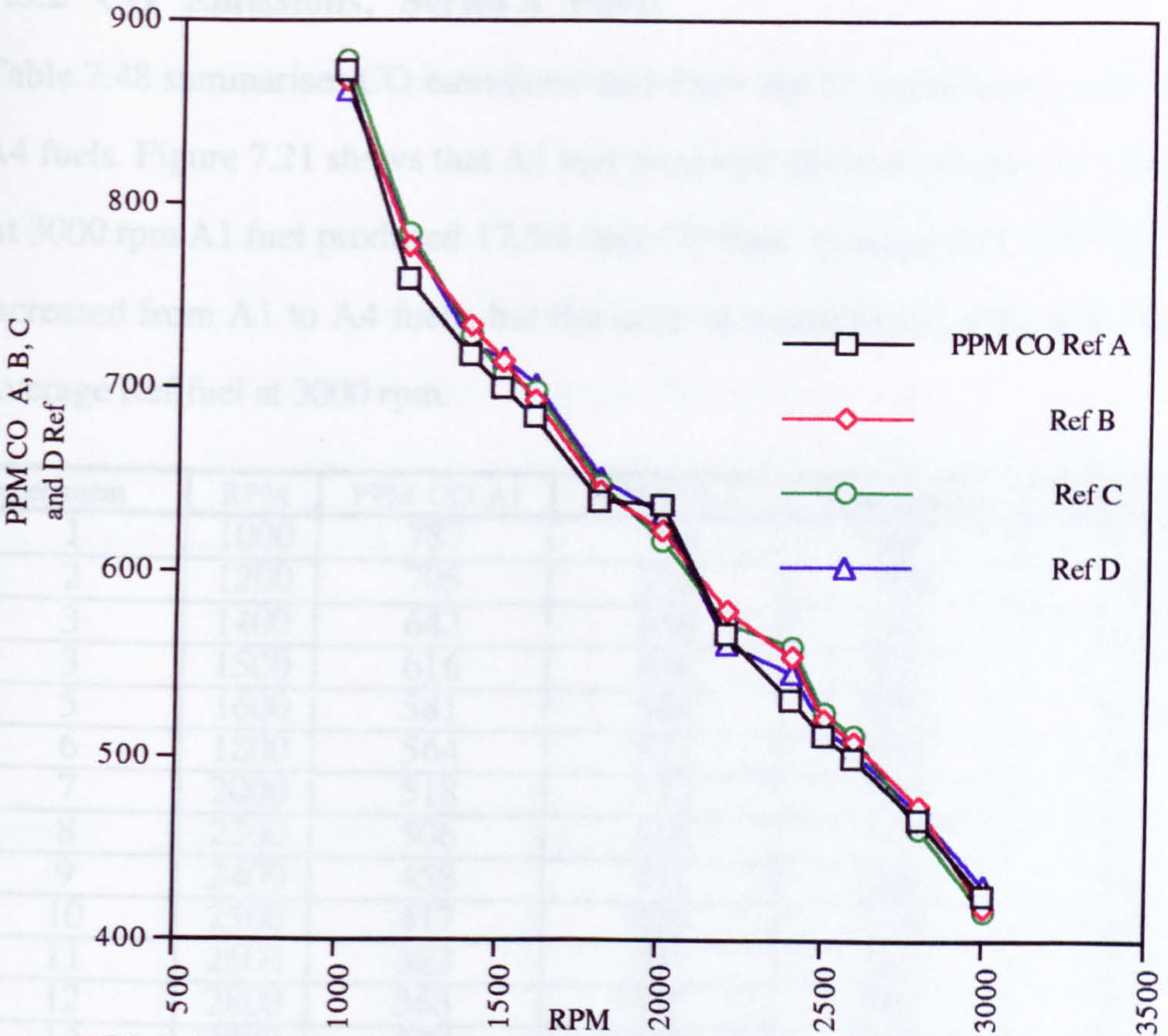

Figure 7.20 CO Emissions A,B,C and D Ref Fuels

7.3.2 CO Emissions, Series A Fuels

Table 7.48 summarises CO emissions data from the 13 experiments with A1, A2, A3 and A4 fuels. Figure 7.21 shows that A1 fuel produced the least amount of CO in the A series. At 3000 rpm A1 fuel produced 17.5% less CO than Average Ref. The CO content emitted increased from A1 to A4 fuels, but the latter still produced 12.9% less CO emission than Average Ref fuel at 3000 rpm.

Experiment	RPM	PPM CO A1	PPM CO A2	PPM CO A3	PPM CO A4
1	1000	787	796	809	819
2	1200	705	718	730	741
3	1400	642	656	678	690
3	1500	616	626	633	641
5	1600	581	594	605	618
6	1800	564	573	589	597
7	2000	518	533	549	564
8	2200	506	516	528	531
9	2400	458	471	485	496
10	2500	417	429	446	459
11	2600	383	397	406	418
12	2800	363	372	381	390
13	3000	346	353	357	365

Table 7.48 CO Emissions A1, A2, A3 and A4 Fuels

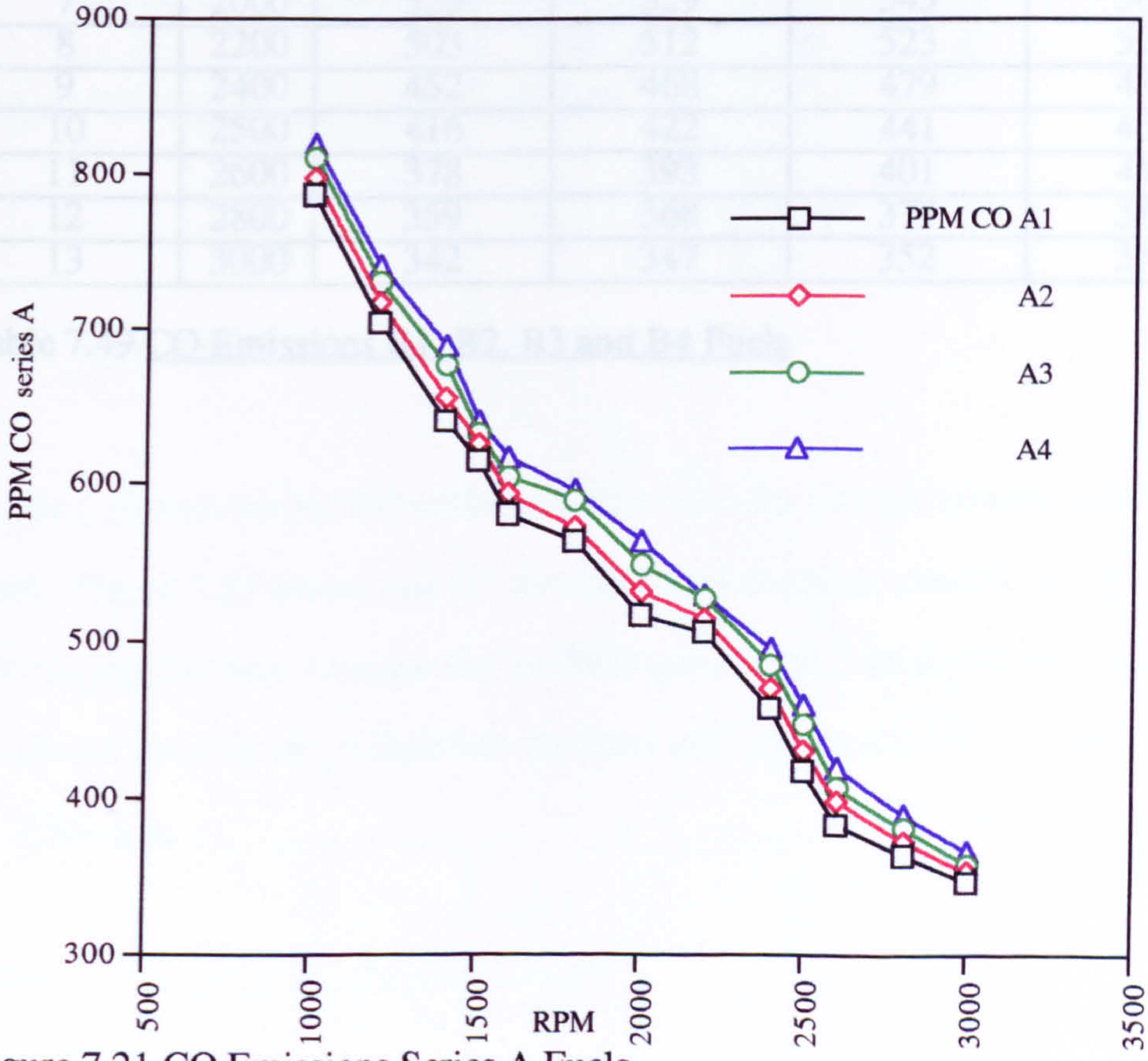

Figure 7.21 CO Emissions Series A Fuels

7.3.3 CO Emissions, Series B Fuels

Table 7.49 summarises CO emissions data from the 13 experiments with B1, B2, B3 and B4 fuels. Figure 7.22 shows that B1 fuel produced the least amount of CO in the B series, i.e. 19.5 % less CO than Average Ref at 3000 rpm. The CO content emitted increased from B1 to B4 fuels, but the latter still produced 14.4% less CO emission than Average Ref fuel at 3000 rpm.

Experiment	RPM	PPM CO B1	PPM CO B2	PPM CO B3	PPM CO B4
1	1000	783	793	803	813
2	1200	699	717	726	737
3	1400	637	651	674	685
3	1500	613	623	628	635
5	1600	577	589	599	612
6	1800	560	568	583	595
7	2000	520	529	545	560
8	2200	503	512	523	527
9	2400	452	468	479	489
10	2500	416	422	441	452
11	2600	378	393	401	417
12	2800	359	368	377	384
13	3000	342	347	352	359

Table 7.49 CO Emissions B1, B2, B3 and B4 Fuels

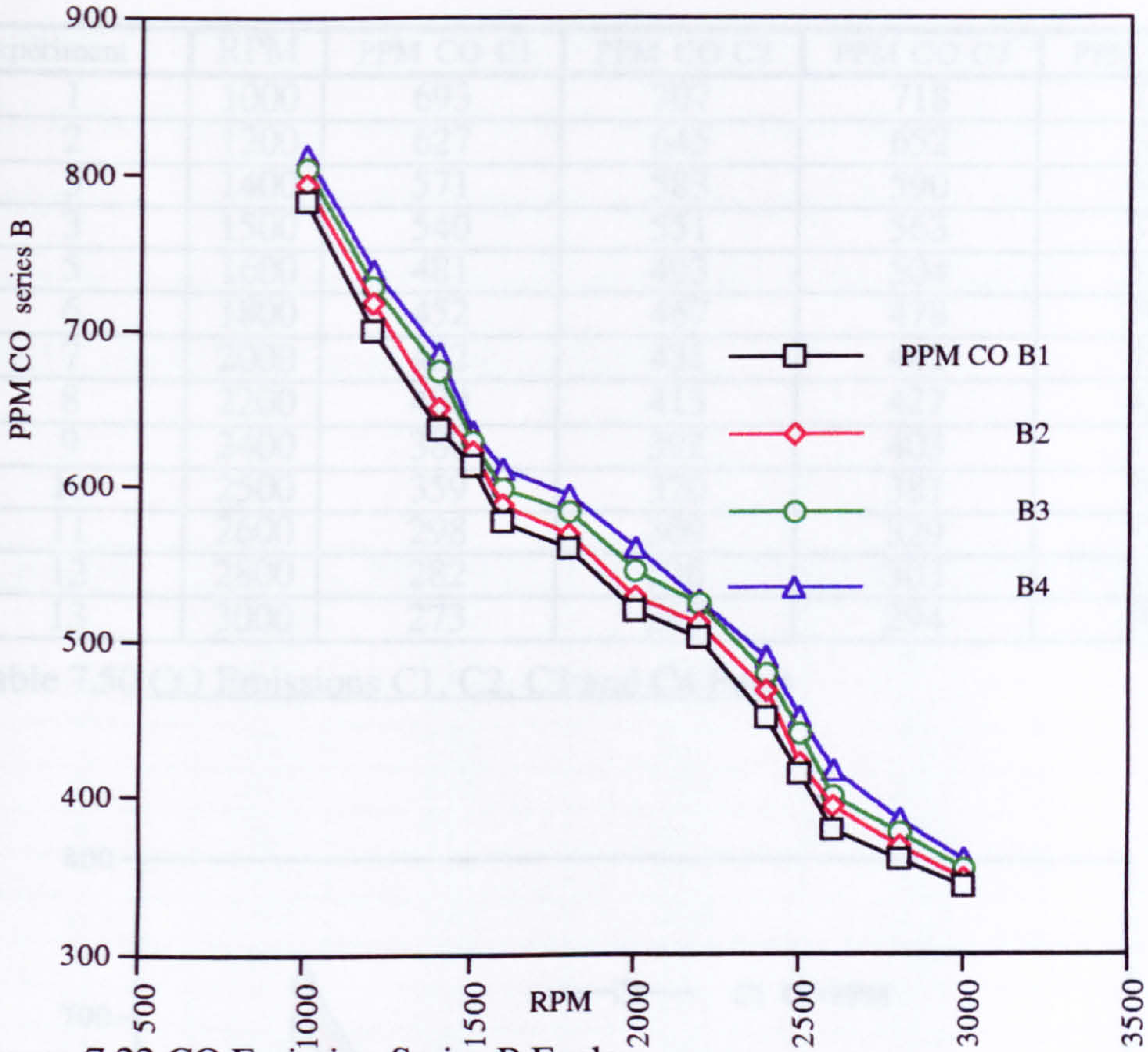

Figure 7.22 CO Emission Series B Fuels

7.3.4 CO Emissions, Series C Fuels

Table 7.50 summarises CO emissions data from the 13 experiments with C1, C2, C3 and C4 fuels. Figure 7.23 shows that C1 fuel produced the least amount of CO in the C series, i.e. 34.9% less CO than Average Ref at 3000 rpm. There was an increase in the amount of CO produced from C1 to C4 fuels but the latter still produced 27.5% less CO than Average Ref at 3000 rpm.

Experiment	RPM	PPM CO C1	PPM CO C2	PPM CO C3	PPM CO C4
1	1000	693	707	718	730
2	1200	627	645	652	662
3	1400	571	583	590	606
3	1500	540	551	563	574
5	1600	481	493	504	519
6	1800	452	467	478	793
7	2000	422	431	442	458
8	2200	400	413	427	439
9	2400	380	392	403	417
10	2500	359	370	381	390
11	2600	298	309	329	338
12	2800	282	296	303	315
13	3000	273	282	294	304

Table 7.50 CO Emissions C1, C2, C3 and C4 Fuels

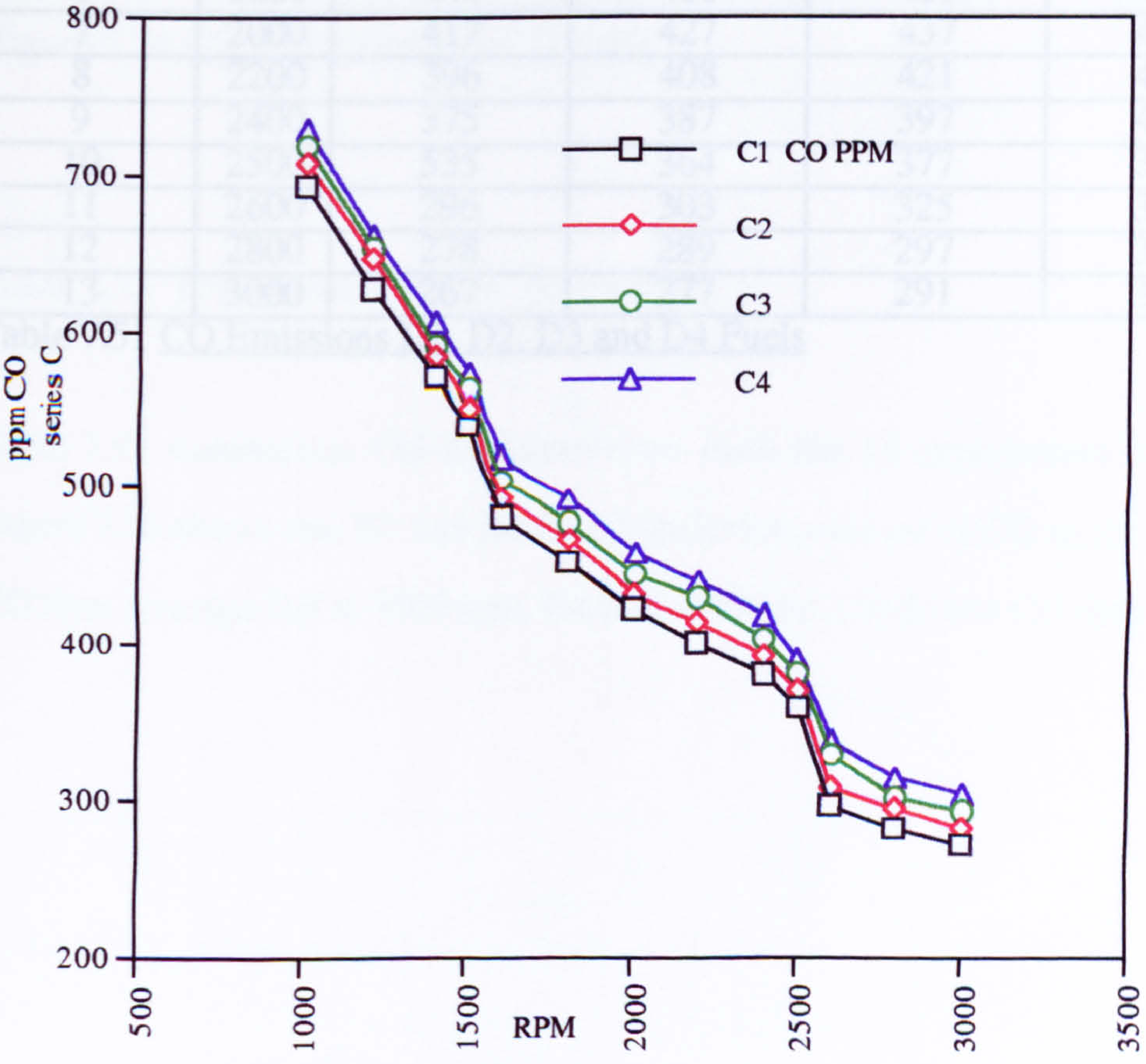

Figure 7.23 CO Emission Series C Fuels

7.3.5 CO Emissions, Series D Fuels

Table 7.51 summarises CO emissions data from the 13 experiments with D1, D2, D3 and D4 fuels. Figure 7.24 shows that D1 fuel produced the least amount of CO in the D series, i.e. 36.4% less CO emission than Average Ref at 3000 rpm. There was an increase in the amount of CO produced from D1 to D4 fuel but even the latter produced 28.5% less CO than Average Ref at 3000 rpm.

Experiment	RPM	PPM CO D1	PPM CO D2	PPM CO D3	PPM CO D4
1	1000	692	702	711	724
2	1200	623	639	647	657
3	1400	568	578	647	599
3	1500	536	546	558	569
5	1600	476	489	499	512
6	1800	447	461	467	487
7	2000	417	427	437	451
8	2200	396	408	421	433
9	2400	375	387	397	411
10	2500	535	364	377	383
11	2600	296	303	325	331
12	2800	278	289	297	309
13	3000	267	277	291	300

Table 7.51 CO Emissions D1, D2, D3 and D4 Fuels

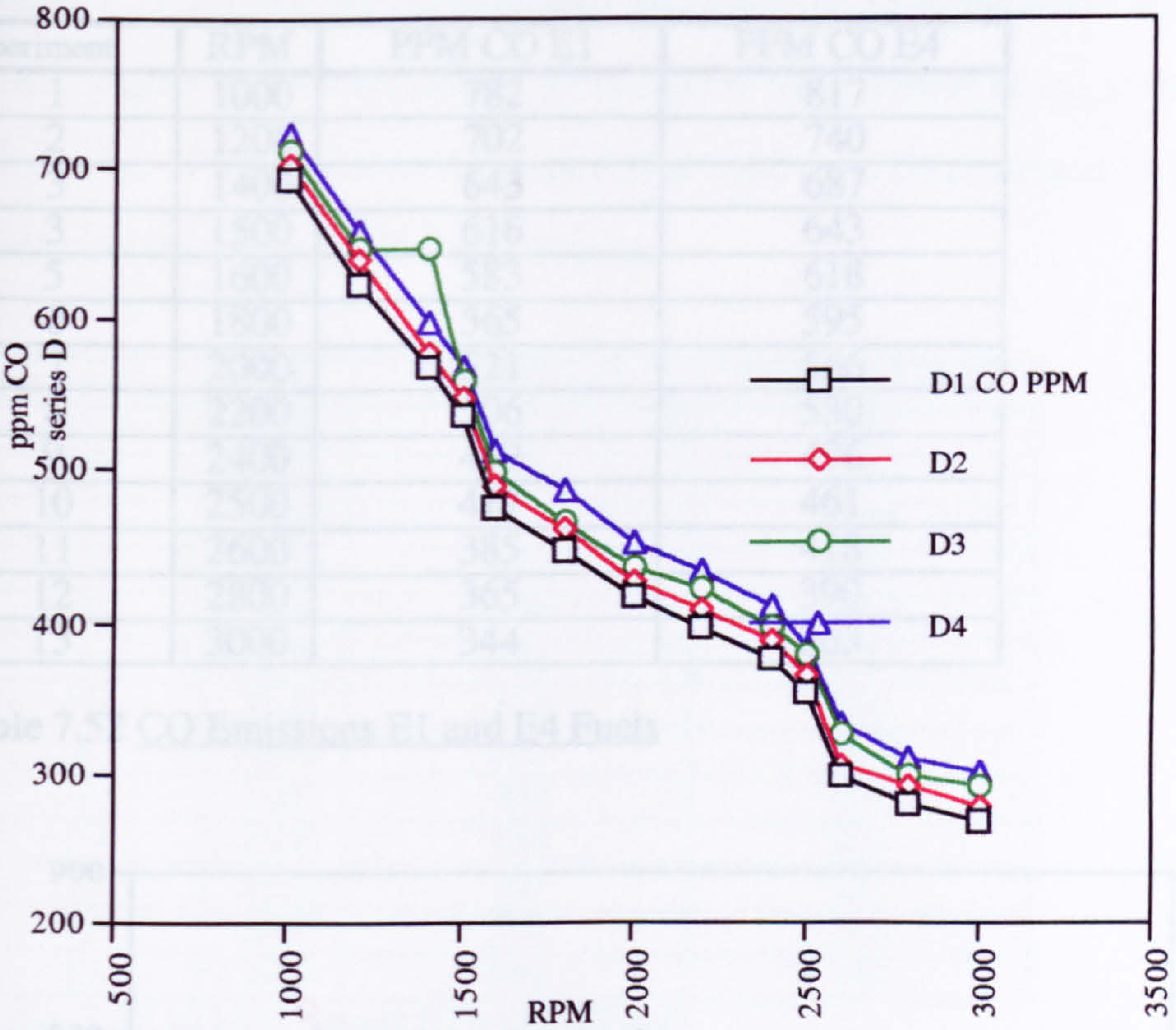

Figure 7.24 CO Emissions Series D Fuels

7.3.6 CO Emissions, Series E Fuels

Table 7.52 summarises CO emissions data from the 13 experiments with E1 and E4 fuels. Figure 7.25 shows that E1 fuel produced the lowest amount of CO in the E Series, 17.9% less CO than Average Ref at 3000 rpm. E4 fuel produced 13.4% less CO than A Ref at 3000 rpm.

Experiment	RPM	PPM CO E1	PPM CO E4
1	1000	782	817
2	1200	702	740
3	1400	643	687
3	1500	616	643
5	1600	583	618
6	1800	565	595
7	2000	521	566
8	2200	506	530
9	2400	459	496
10	2500	417	461
11	2600	385	418
12	2800	365	390
13	3000	344	363

Table 7.52 CO Emissions E1 and E4 Fuels

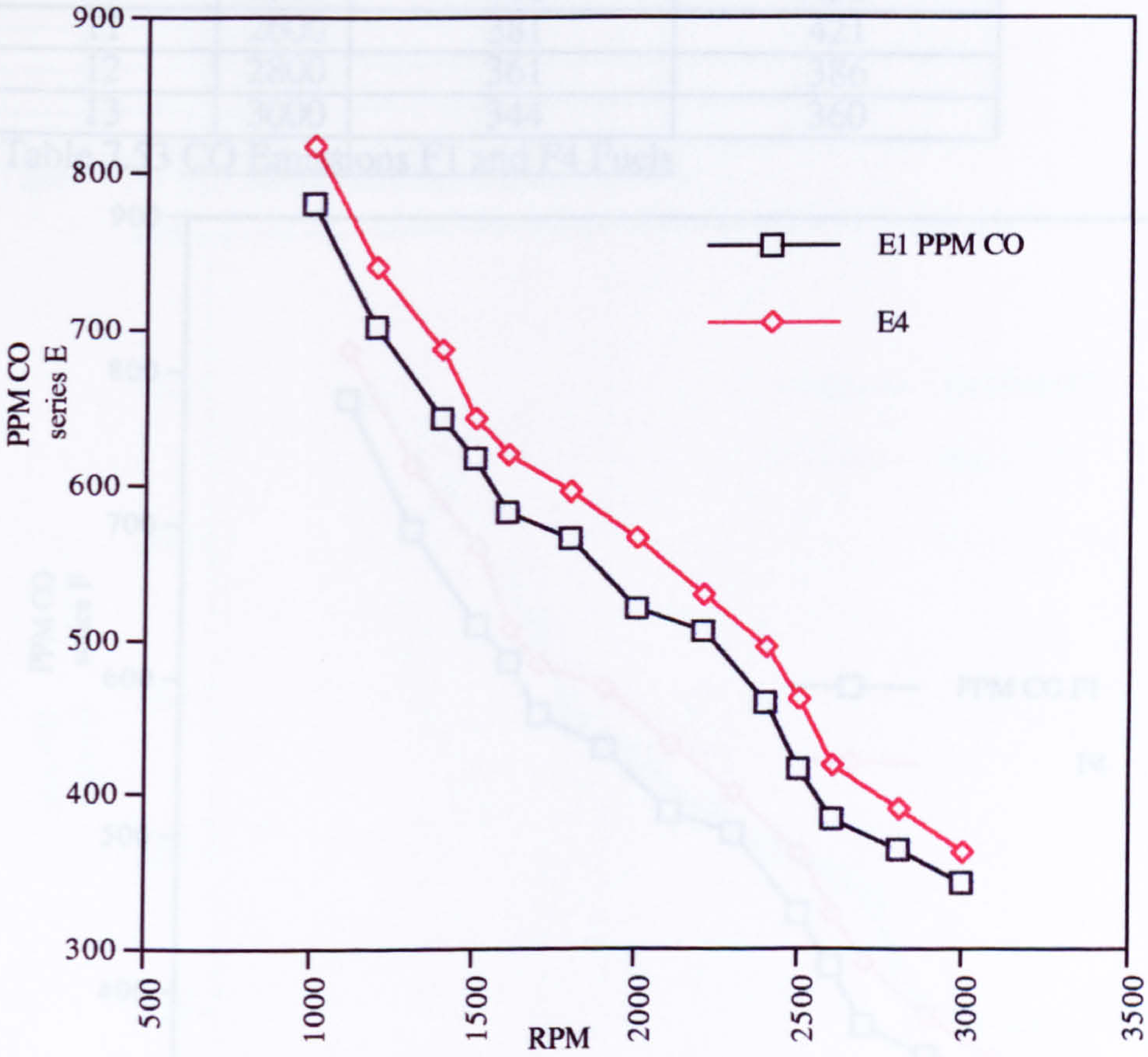

Figure 7.25 CO Emissions Series E Fuels

7.3.7 CO Emissions, Series F Fuels

Table 7.53 summarises CO emissions data from the 13 experiments with F1 and F4 fuels. Figure 7.26 shows that F1 produced the least amount of CO in the F fuels Series i.e. 17.9% less than Average Ref at 3000 rpm. F4 produced 14.1% less CO emission than Average Ref at 3000 rpm.

Experiment	RPM	PPM CO F1	PPM CO F4
1	1000	782	815
2	1200	698	739
3	1400	636	687
3	1500	614	634
5	1600	579	611
6	1800	558	597
7	2000	518	559
8	2200	505	529
9	2400	454	491
10	2500	418	454
11	2600	381	421
12	2800	361	386
13	3000	344	360

Table 7.53 CO Emissions F1 and F4 Fuels

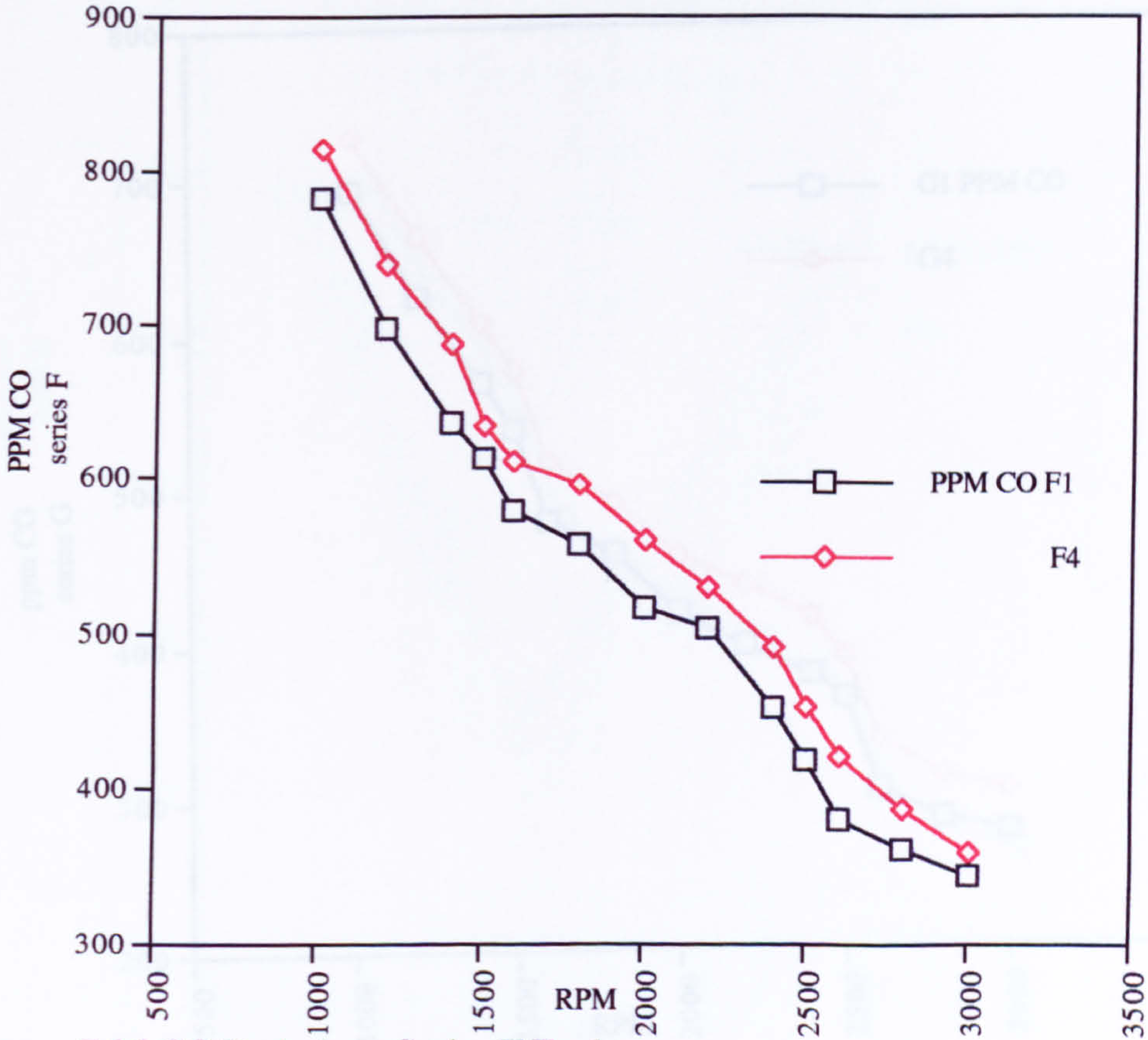

Figure 7.26 CO Emissions Series F Fuels

7.3.8 CO Emissions, Series G Fuels

Table 7.54 summarises CO emissions data from the 13 experiments with G1 and G4 fuels. Figure 7.27 shows that G1 fuel produced the least amount of CO in the G Series i.e. 34.2% less CO than Average Ref at 3000 rpm. G4 fuel produced 29.3% less CO emission than Average Ref at 3000 rpm.

Experiment	RPM	PPM CO G1	PPM CO G4
1	1000	695	728
2	1200	626	664
3	1400	570	609
3	1500	538	576
5	1600	479	517
6	1800	457	489
7	2000	418	455
8	2200	397	437
9	2400	378	415
10	2500	363	388
11	2600	303	335
12	2800	285	312
13	3000	276	301

Table 7.54 CO Emissions G1 and G4 Fuels

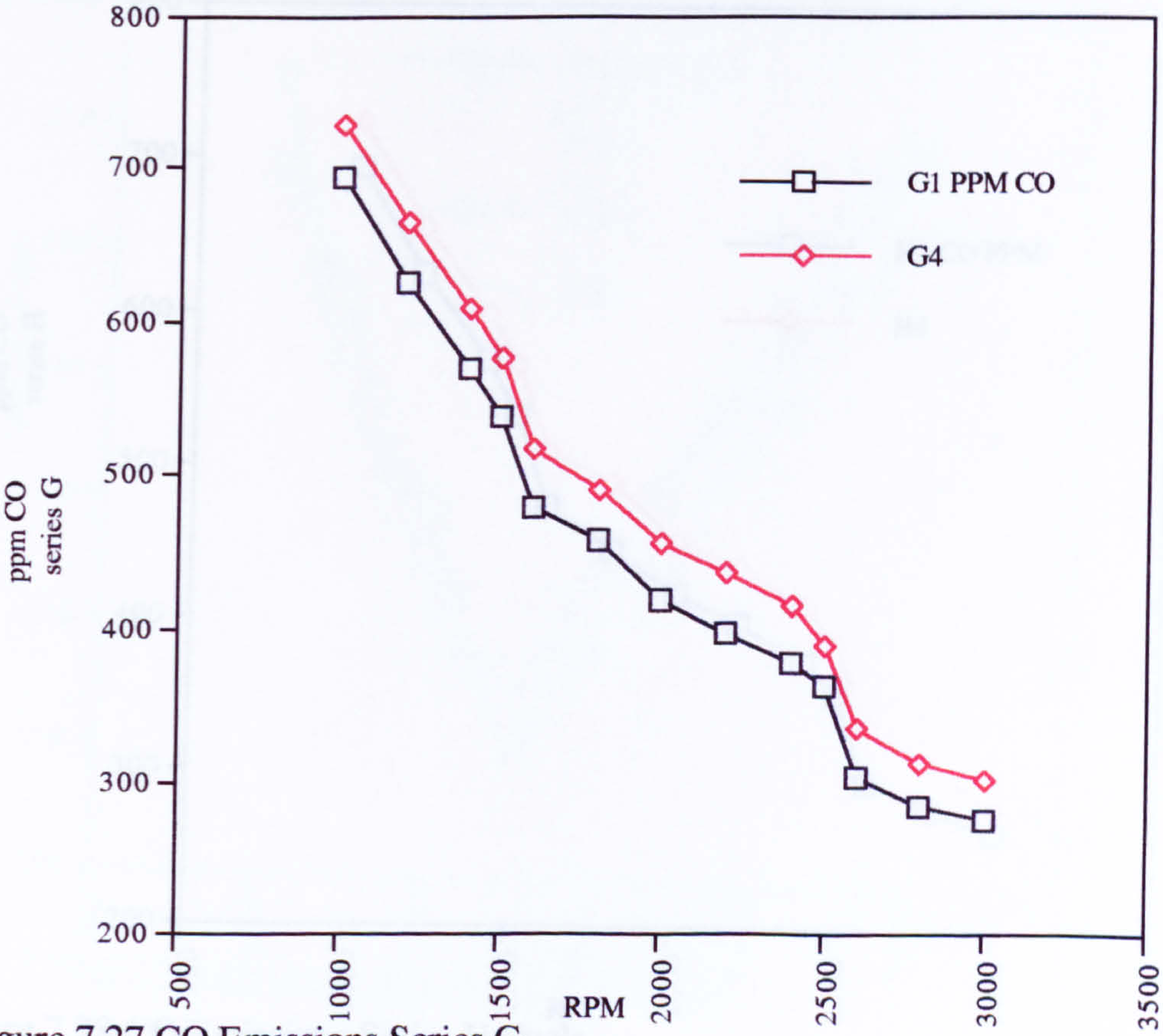

Figure 7.27 CO Emissions Series G

7.3.9 CO Emissions, Series H Fuels

Table 7.55 summarises CO emissions data from the 13 experiments with H1 and H4 fuels. Figure 7.28 shows that H1 fuel produced the least amount of CO in the H series i.e. 36.9% less CO than Average Ref at 3000 rpm. H4 produced 33.7% less CO emission than Average Ref at 3000 rpm.

Experiment	RPM	PPM CO H1	PPM CO H4
1	1000	693	723
2	1200	625	656
3	1400	569	600
3	1500	534	568
5	1600	474	510
6	1800	445	489
7	2000	419	449
8	2200	398	435
9	2400	376	412
10	2500	354	385
11	2600	297	333
12	2800	280	310
13	3000	265	278

Table 7.55 CO Emissions H1 and H4 Fuels

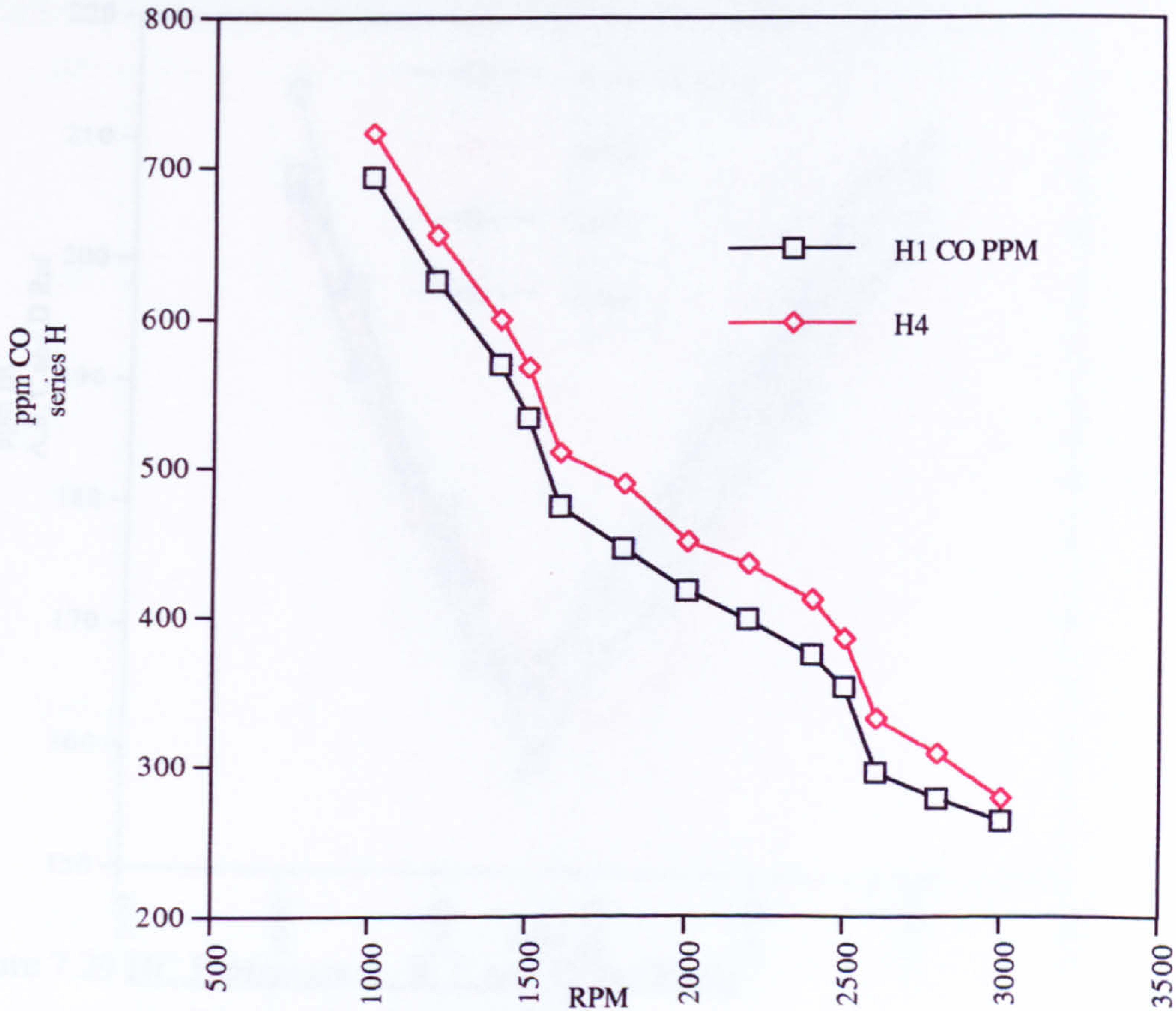

Figure 7.28 CO Emissions Series H Fuels

7.4 Hydrocarbon Emissions

7.4.1 Hydrocarbon (HC) Emissions from Reference Fuels

Data for HC emissions of reference fuels A, B, C and D Ref are summarised in Table 7.56 . The values are plotted in Figure 7.29 . Also in Table 7.56 the average HC PPM at various speeds (RPM) of the four reference fuels are given as Average Ref.

Experiment	RPM	A Ref HC PPM	B Ref HC PPM	C Ref HC PPM	D Ref HC PPM	Average Ref PPM
1	1000	207	203	214	206	208
2	1200	198	195	193	191	194
3	1400	182	179	182	179	181
3	1500	178	178	180	175	178
5	1600	173	175	171	172	173
6	1800	162	167	167	165	165
7	2000	168	166	172	171	169
8	2200	175	177	180	181	178
9	2400	182	181	187	184	184
10	2500	186	187	189	190	188
11	2600	191	193	195	197	194
12	2800	198	199	203	203	201
13	3000	203	201	205	204	203

Table 7.56 HC Emissions A Ref, B Ref, C Ref and D Ref

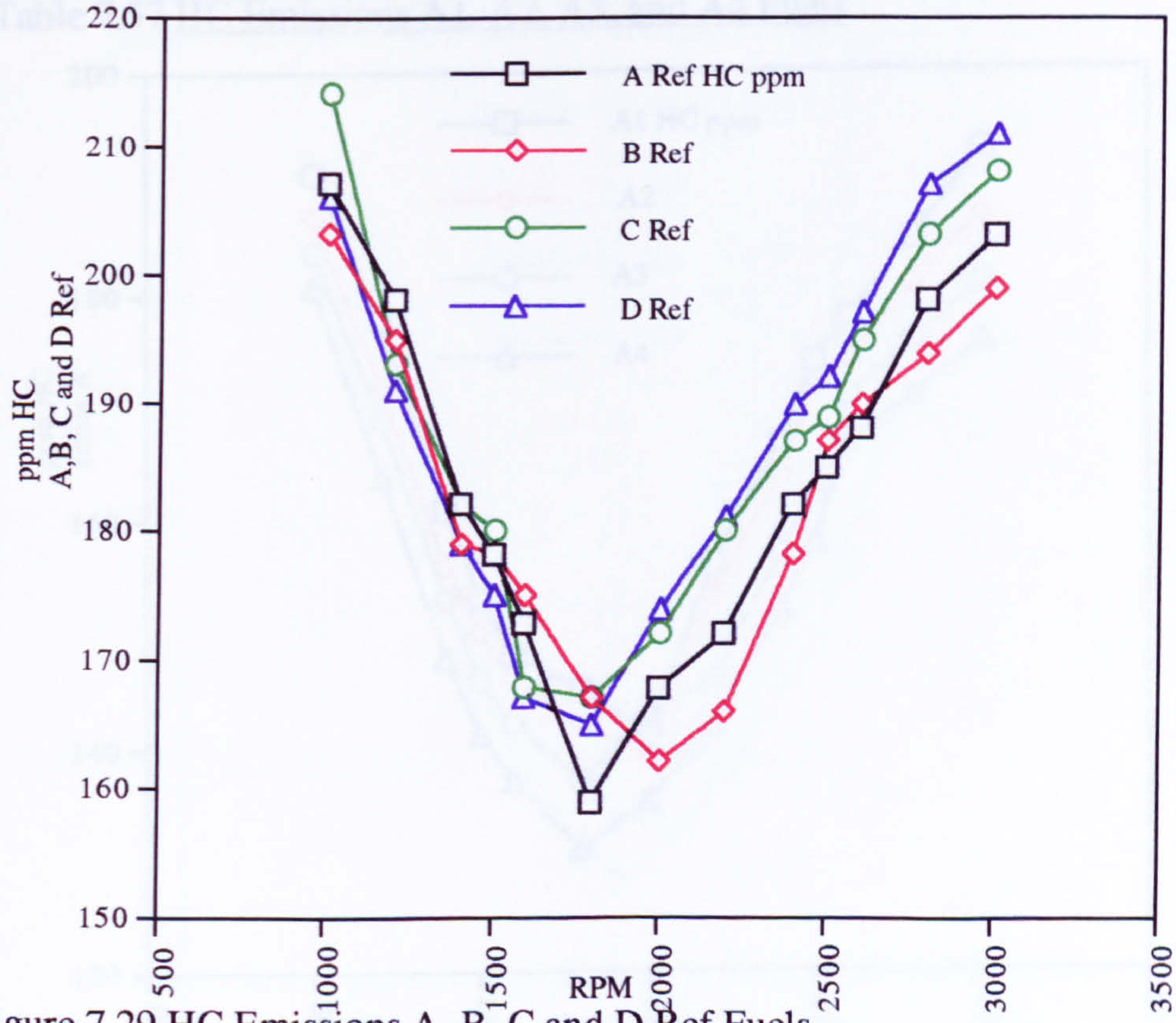

Figure 7.29 HC Emissions A, B, C and D Ref Fuels

7.4.2 HC Emissions, Series A Fuels

Table 7.57 shows that the total hydrocarbon emissions for fuels A1 to A4 each tended to a minimum at an intermediate speed between 1000 rpm and 3000 rpm. The data plotted in Figure 7.30, confirm that the magnitude of the emissions were ranked in the order A1 to A4. The minimum HC output lay between 1800 and 2000 rpm. Figure 7.30 shows that A4 had the lowest HC emission of 24.2% less than Average Ref at 3000 rpm. From A4 the order of increase in HC emission was A3, A2 and A1 respectively, but the latter still emitted 18.8% less HC than Average Ref at 3000 rpm.

Experiment	RPM	A1 HC PPM	A2 HC PPM	A3 HC PPM	A4 HC PPM
1	1000	166	164	162	158
2	1200	153	151	143	145
3	1400	144	141	139	136
3	1500	135	132	128	124
5	1600	129	127	125	123
6	1800	126	123	124	120
7	2000	124	118	121	118
8	2200	131	126	114	115
9	2400	145	141	138	135
10	2500	151	148	145	141
11	2600	154	151	149	146
12	2800	157	153	151	148
13	3000	165	161	158	154

Table 7.57 HC Emissions A1, A2, A3, and A4 Fuels

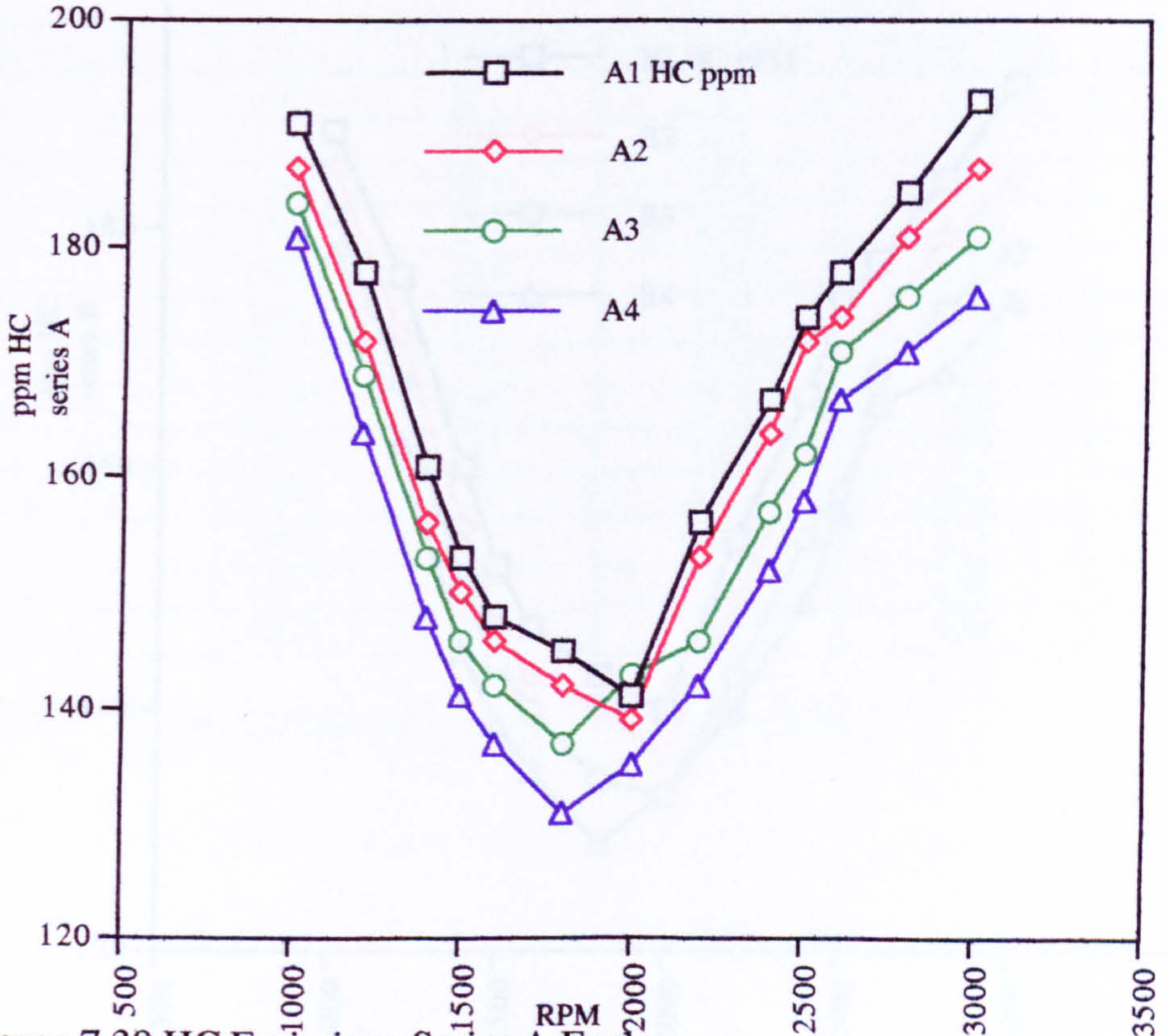

Figure 7.30 HC Emissions Series A Fuels

7.4.3 HC Emissions, Series B Fuels

As shown in Table 7.58 the total hydrocarbon emissions for fuels B1 to B4 each tended towards a minimum at an intermediate speed between 1000 rpm and 3000 rpm. The data plotted in Figure 7.31, confirm that the emissions were ranked in decreasing order from B1 to B4.

The minimum HC output lay between 1800 and 2000 rpm. B4 generated the lowest HC emission in the B series, i.e. 26.6 % less HC than Average Ref at 3000 rpm. The order of increase was B3, B2 and B1 respectively; the latter emitted 20.8% less HC than Average Ref at 3000 rpm.

Experiment	RPM	B1 HC PPM	B2 HC PPM	B3 HC PPM	B4 HC PPM
1	1000	162	160	159	155
2	1200	149	149	140	143
3	1400	141	139	136	134
3	1500	132	129	126	122
5	1600	126	124	124	121
6	1800	123	120	123	118
7	2000	119	116	119	113
8	2200	129	123	121	116
9	2400	143	139	135	133
10	2500	148	147	142	139
11	2600	152	149	146	143
12	2800	153	151	148	145
13	3000	161	158	155	151

Table 7.58 HC Emissions B1, B2, B3, and B4 Fuels

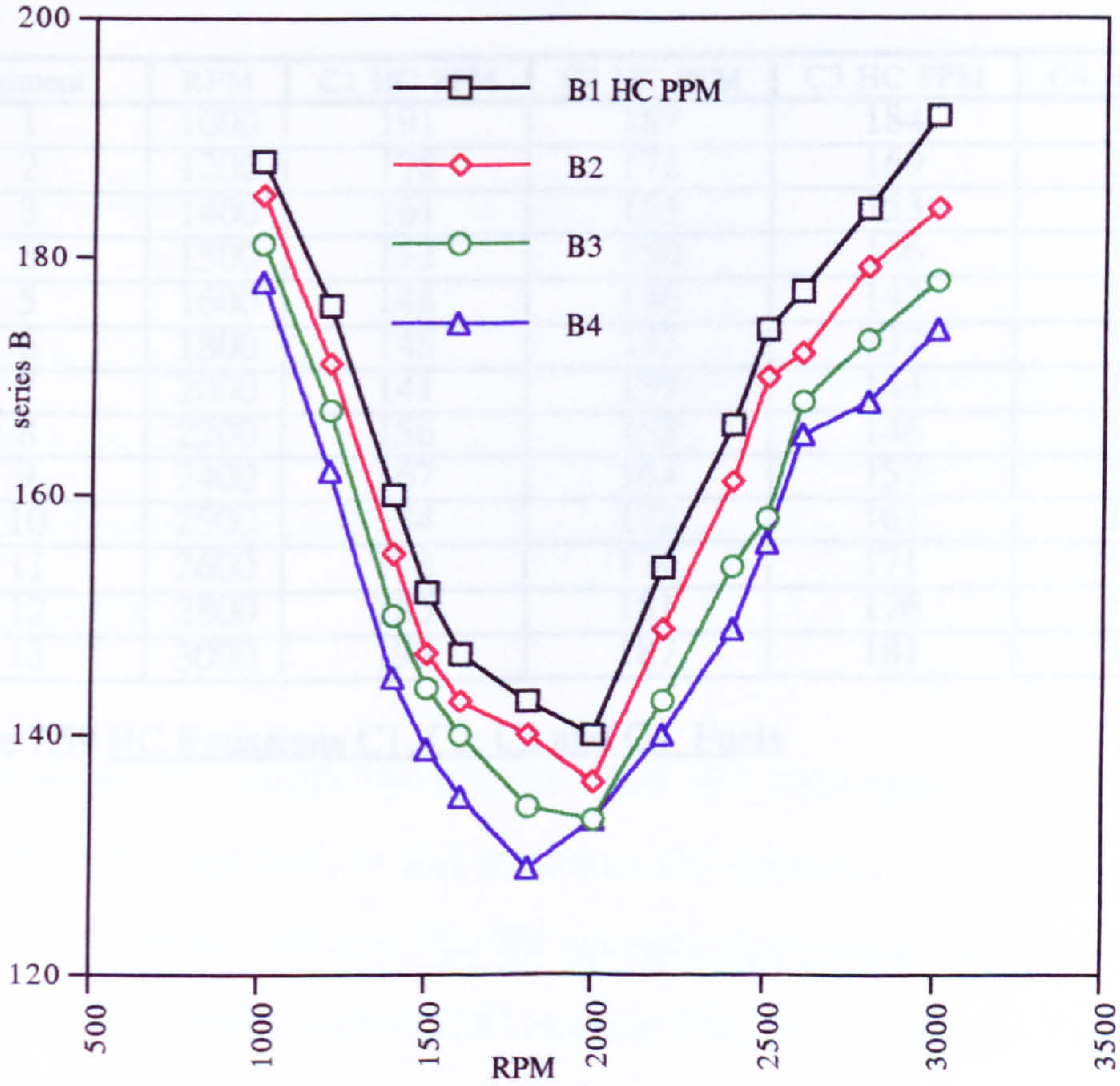

Figure 7.31 HC Emissions Series B Fuels

7.4.4 HC Emissions, Series C Fuels

As shown in Table 7.59 the hydrocarbon emissions for fuels C1 to C4 each tended to a minimum at an intermediate speed between 1000 rpm and 3000 rpm. The data plotted in Figure 7.32, confirm that there was a decrease of emissions in the order C1 to C4.

The minimum HC emission output lay between 1800 and 2000 rpm. Figure 7.32 shows that as compared to Average Ref, C4 had the lowest HC emission, i.e. 13.4% less HC than Average Ref at 3000 rpm. C1 emitted 4.0% less HC emission than Average Ref at 3000 rpm.

Experiment	RPM	C1 HC PPM	C2 HC PPM	C3 HC PPM	C4 HC PPM
1	1000	191	187	184	181
2	1200	178	172	169	164
3	1400	161	156	153	148
3	1500	153	150	146	141
5	1600	148	146	142	137
6	1800	145	142	137	131
7	2000	141	139	143	135
8	2200	156	153	146	142
9	2400	167	164	157	152
10	2500	174	172	162	158
11	2600	178	174	171	167
12	2800	185	181	176	171
13	3000	193	187	181	176

Table 7.59 HC Emissions C1, C2, C3 and C4 Fuels

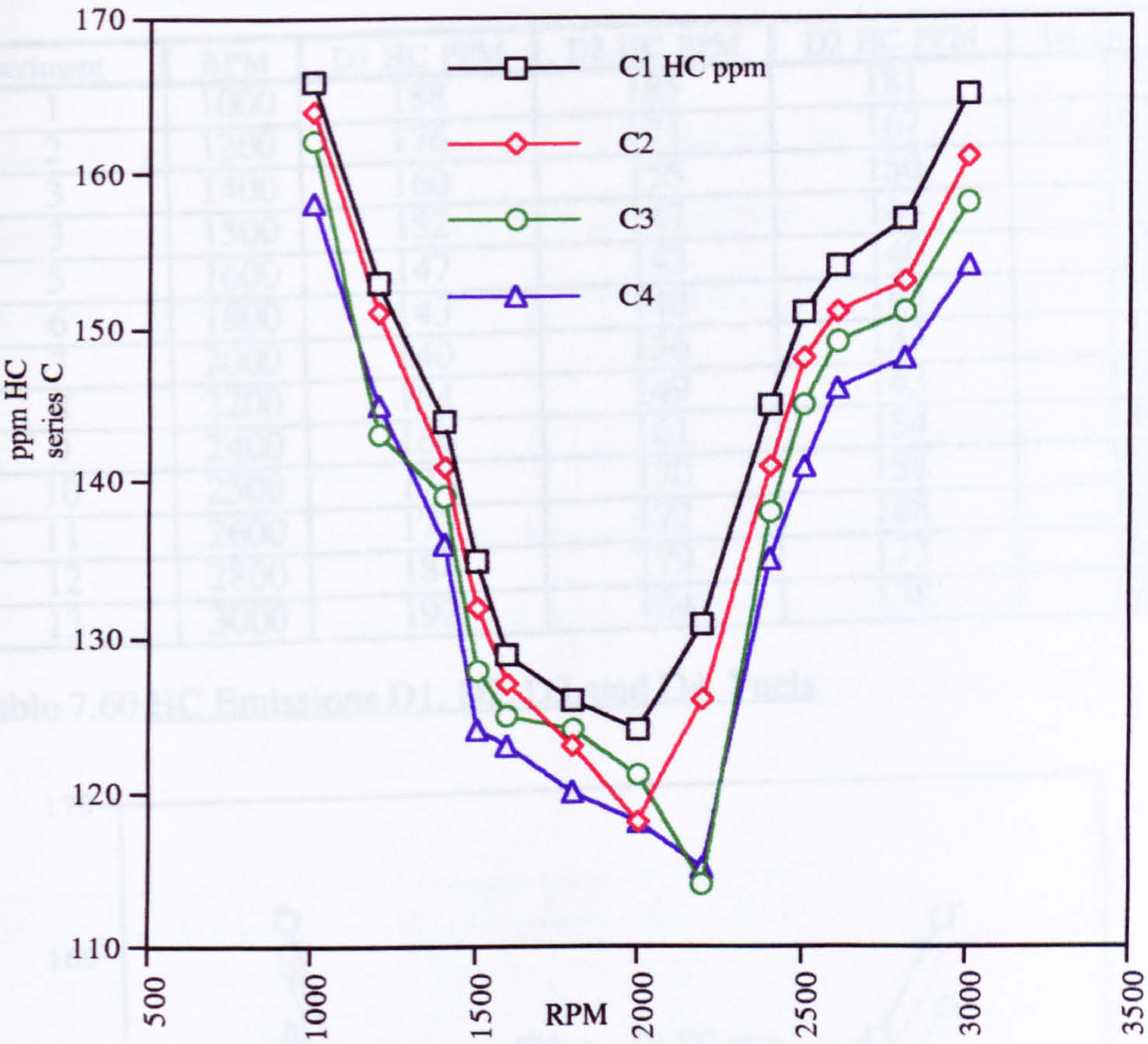

Figure 7.32 HC Emissions Series C Fuels

7.4.5 HC Emissions, Series D Fuels

As shown in Table 7.60 the total hydrocarbon emissions for fuels D1 to D4 each tended towards a minimum at an intermediate speed between 1000 rpm and 3000 rpm. The data plotted in Figure 7.33, confirm that the magnitude of the emissions were ranked in the order D1 to D4.

The minimum HC output lay between 1800 and 2000 rpm. Figure 7.33 shows that compared to Average Ref, D4 had the lowest HC emission i.e. 14.4% less HC emission than Average Ref at 3000 rpm. The HC emission decreased in the order D3, D2 and D1 respectively; D1 emitted 5.4% less HC emission than Average Ref at 3000 rpm.

Experiment	RPM	D1 HC PPM	D2 HC PPM	D3 HC PPM	D4 HC PPM
1	1000	188	185	181	178
2	1200	176	171	167	162
3	1400	160	155	150	145
4	1500	152	147	144	139
5	1600	147	143	140	135
6	1800	143	140	143	129
7	2000	140	136	133	133
8	2200	154	149	143	140
9	2400	166	161	154	149
10	2500	174	170	158	156
11	2600	177	172	168	165
12	2800	184	179	173	168
13	3000	192	184	178	174

Table 7.60 HC Emissions D1, D2, D3, and D4 Fuels

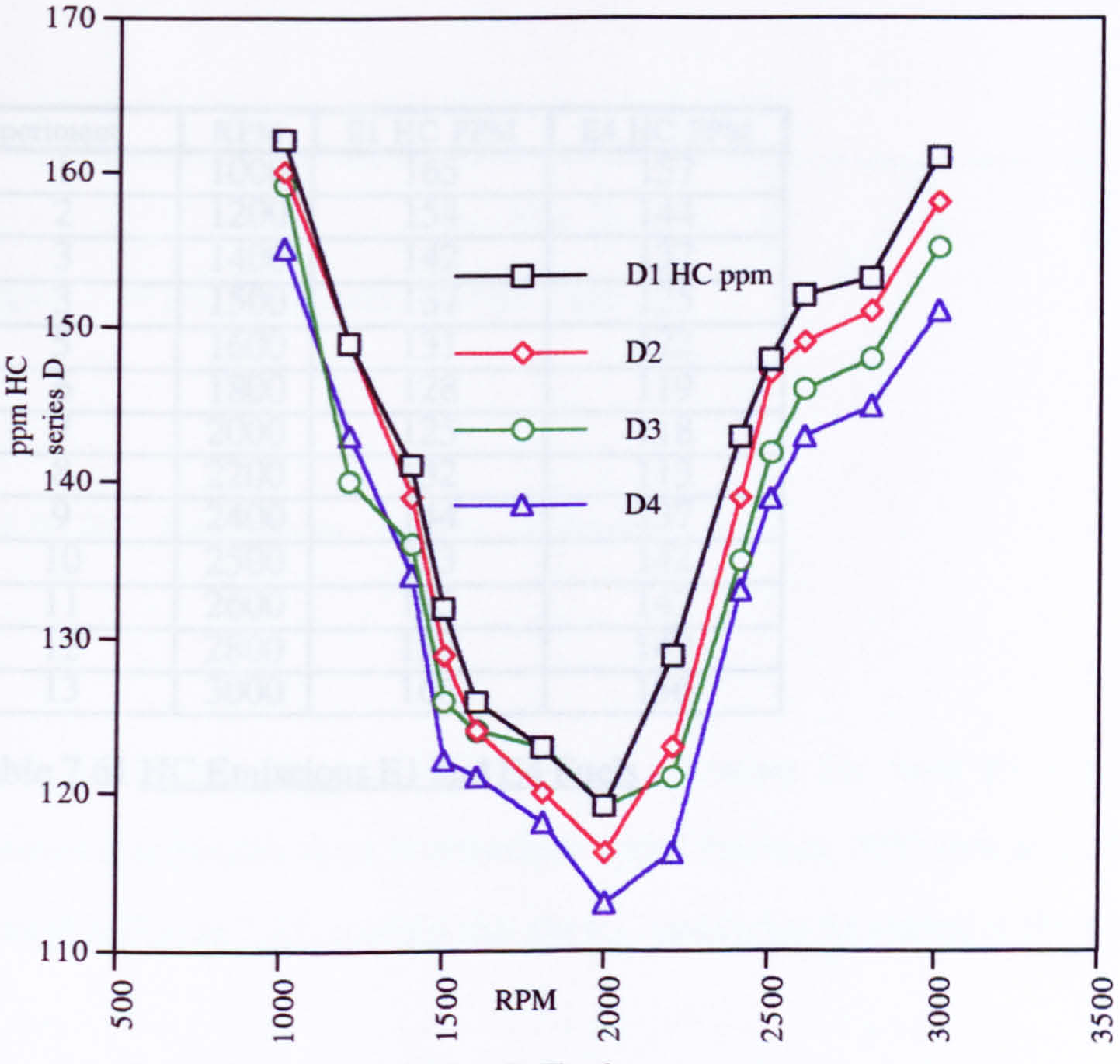

Figure 7.33 HC Emissions Series D Fuels

7.4.6 HC Emissions, Series E Fuels

Table 7.61 shows the total hydrocarbon emissions for fuels E1 and E4. Each tended towards a minimum at an intermediate speed between 1000 rpm and 3000 rpm. The data plotted in Figure 7.34, confirm that the emissions decreased in the order E1 to E4.

For each fuel the minimum HC output lay between 1800 and 2000 rpm. (The reason for this is discussed in Section 7.6.4). From Figure 7.34, E4 fuel generated a lower level of HC emissions than E1 and a 23.3% lower level than Average Ref at 3000 rpm. Even E1 fuel generated an 18.2% lower level of HC emissions than Average Ref at 3000 rpm.

Experiment	RPM	E1 HC PPM	E4 HC PPM
1	1000	165	157
2	1200	154	144
3	1400	142	137
3	1500	137	125
5	1600	131	122
6	1800	128	119
7	2000	125	118
8	2200	132	113
9	2400	144	137
10	2500	153	142
11	2600	155	147
12	2800	159	149
13	3000	166	156

Table 7.61 HC Emissions E1 and E4 Fuels

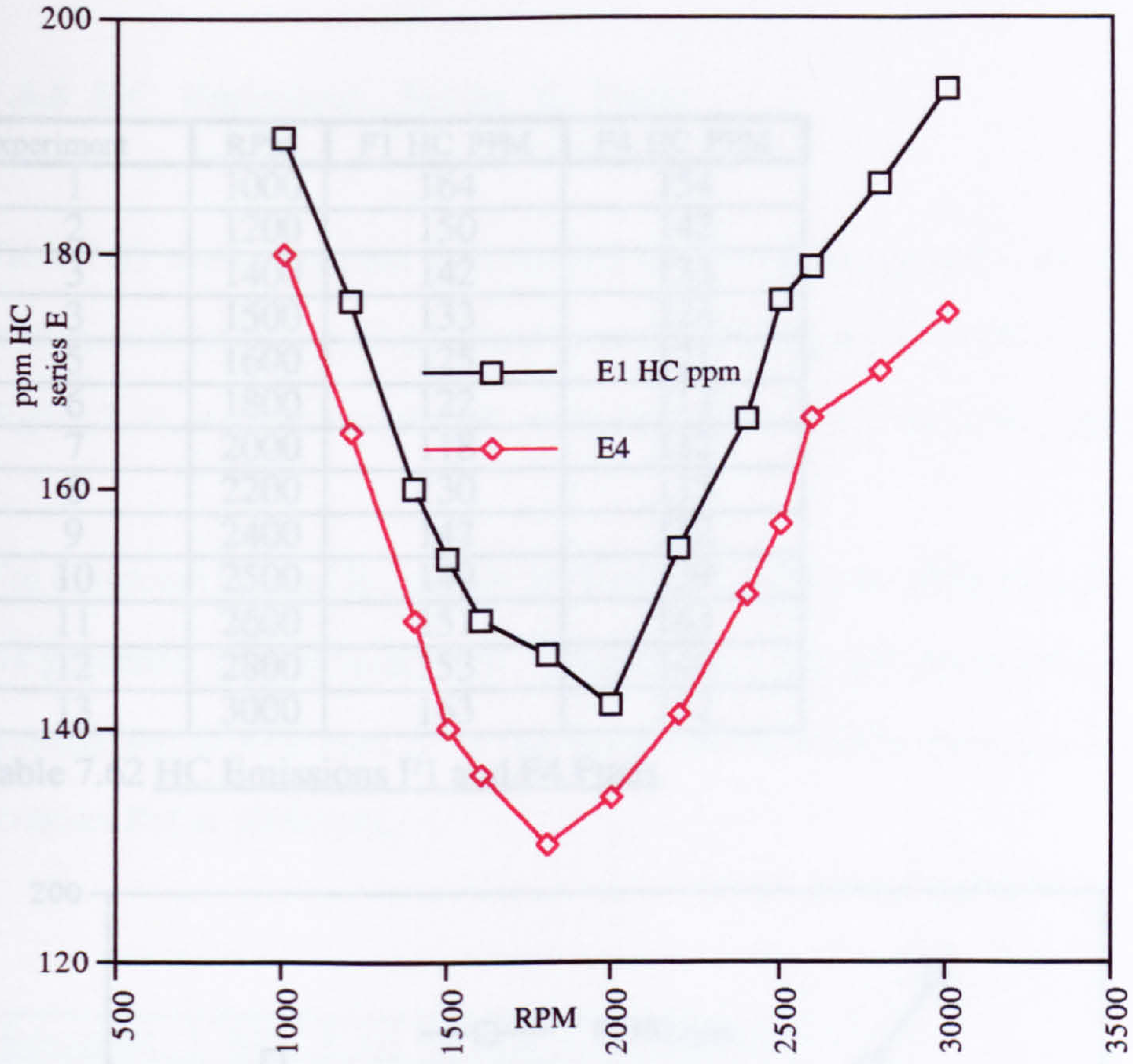

Figure 7.34 HC Emissions E Series Fuels

7.4.7 HC Emissions, Series F Fuels

Table 7.62 shows the total hydrocarbon emissions for fuels F1 and F4. Each tended towards a minimum at an intermediate speed between 1000 rpm and 3000 rpm. The data plotted in Figure 7.35, confirm that the HC emissions decreased in the order fuel F1 to F4.

The minimum level of HC output lay between 1800 and 2000 rpm. From Figure 7.35 fuel F4 generated a lower level of HC emissions than F1. F4 and a 25.2% lower level than Average Ref at 3000 rpm. Even fuel F1 generated an 19.8% lower level of HC emissions than Average Ref at 3000 rpm.

Experiment	RPM	F1 HC PPM	F4 HC PPM
1	1000	164	154
2	1200	150	142
3	1400	142	133
3	1500	133	124
5	1600	125	121
6	1800	122	117
7	2000	118	112
8	2200	130	115
9	2400	142	132
10	2500	149	139
11	2600	151	143
12	2800	153	146
13	3000	163	152

Table 7.62 HC Emissions F1 and F4 Fuels

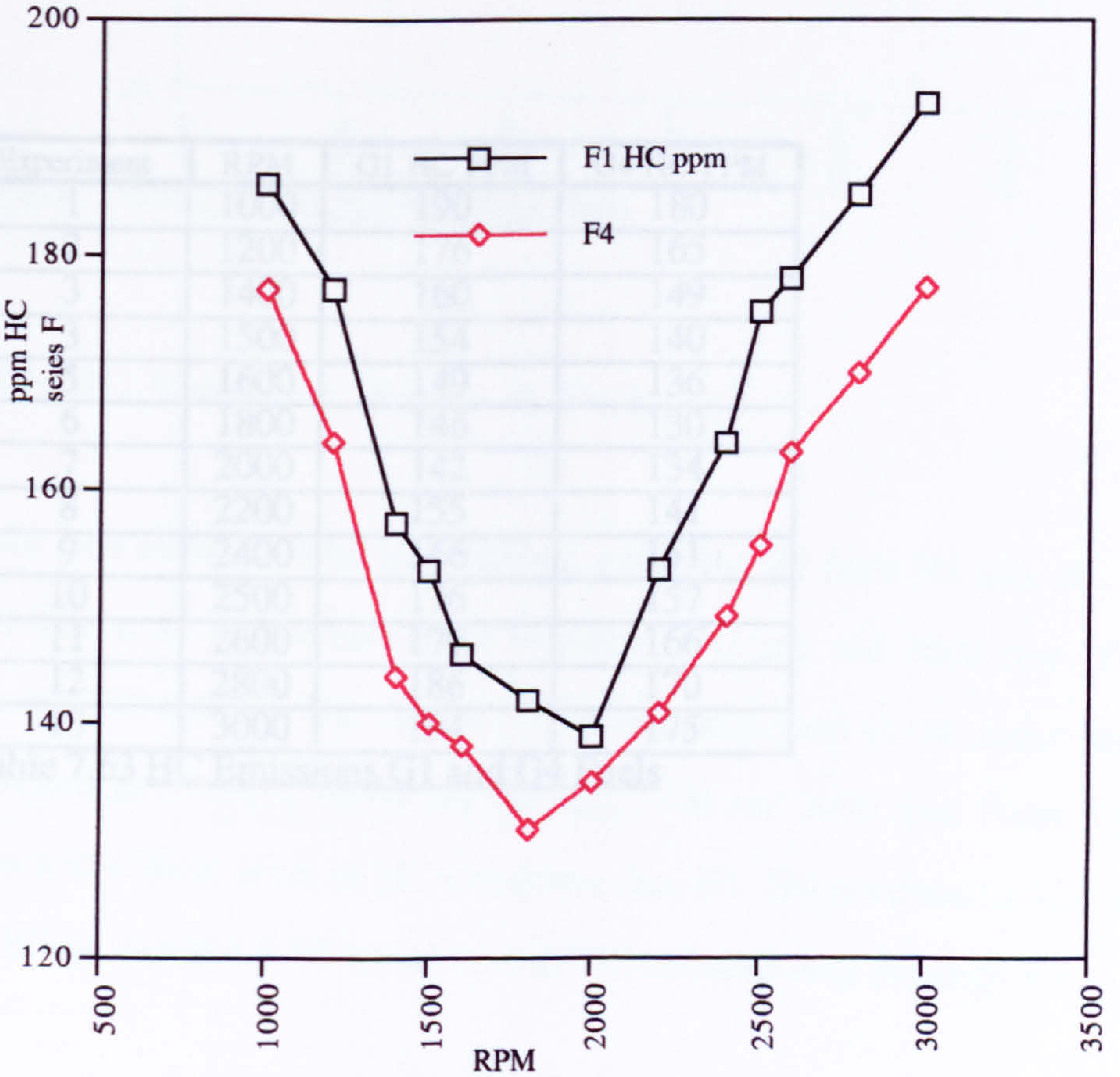

Figure 7.35 HC Emissions Series F Fuels

7.4.8 HC Emissions, Series G Fuels

Table 7.63 shows the total hydrocarbon emissions for fuels G1 and G4. Each tended to a minimum at an intermediate speed between 1000 rpm and 3000 rpm. The data plotted in Figure 7.36, confirm that the HC emissions decreased in the order fuel G1 to G4 fuels.

The minimum level of HC output lay between 1800 and 2000 rpm. From Figure 7.36 fuel G4 generated a lower level of HC emissions than G1. G4 generated 13.8% lower level than Average Ref at 3000 rpm. Even fuel G1 generated a 4.4% lower level of HC emissions than Average Ref at 3000 rpm.

Experiment	RPM	G1 HC PPM	G4 HC PPM
1	1000	190	180
2	1200	176	165
3	1400	160	149
3	1500	154	140
5	1600	149	136
6	1800	146	130
7	2000	142	134
8	2200	155	141
9	2400	166	151
10	2500	176	157
11	2600	179	166
12	2800	186	170
13	3000	194	175

Table 7.63 HC Emissions G1 and G4 Fuels

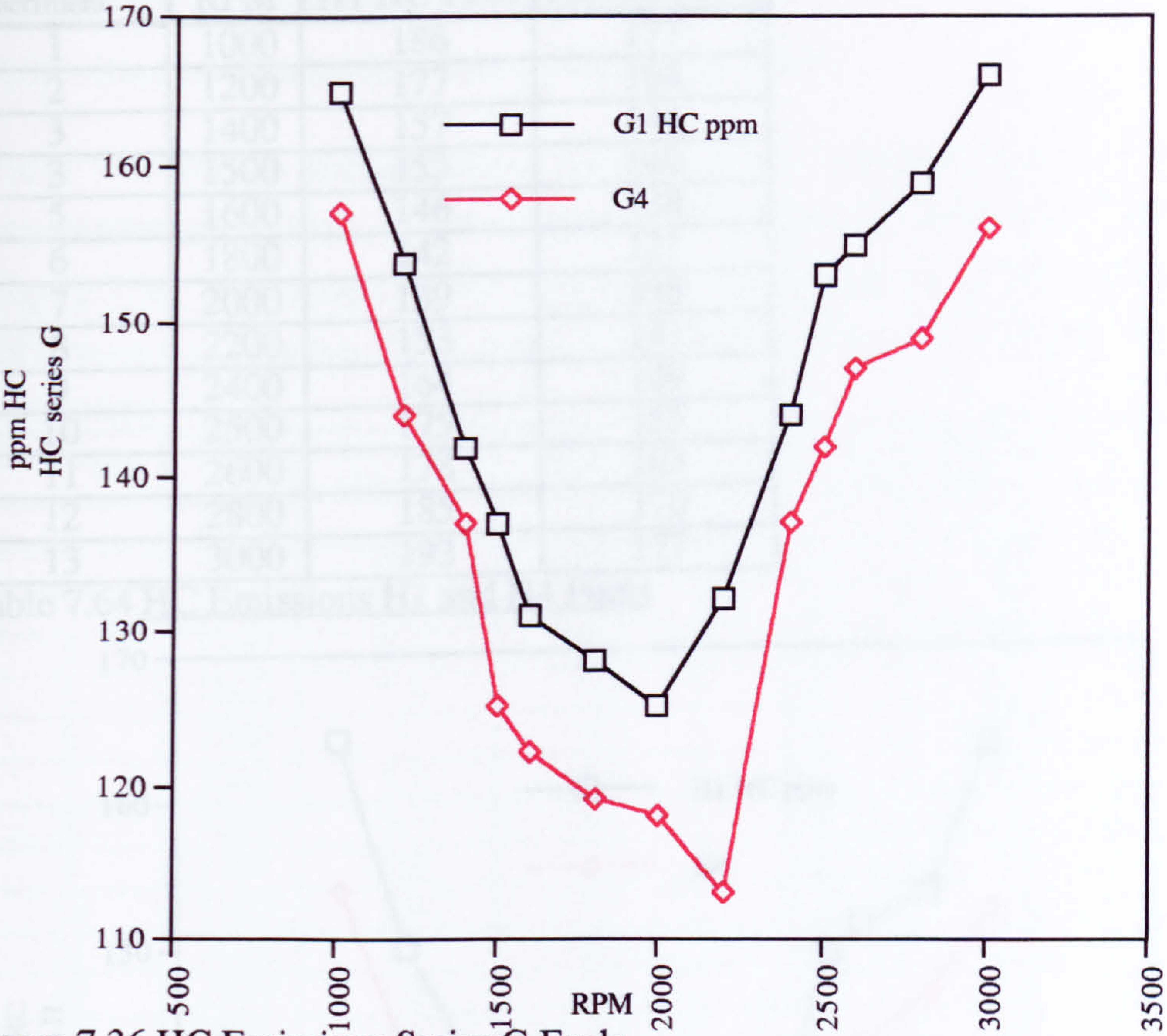

Figure 7.36 HC Emissions Series G Fuels

7.4.9 HC Emissions, Series H Fuels

Table 7.64 show the total hydrocarbon emissions for fuels H1 and H4. Each tended to a minimum at an intermediate speed between 1000 rpm and 3000 rpm. The data plotted in Figure 7.37, confirm that the HC emissions decreased in the order fuel H1 to H4. The minimum level of HC output lay between 1800 and 2000 rpm. From Figure 7.37 fuel H4 generated a lower level of HC emissions than H1. H4 generated a 12.9% lower and even fuel H1 generated a 4.9% lower level of HC emission than Average Ref at 3000 rpm.

Experiment	RPM	H1 HC PPM	H4 HC PPM
1	1000	186	177
2	1200	177	164
3	1400	157	144
3	1500	153	140
5	1600	146	138
6	1800	142	131
7	2000	139	135
8	2200	153	141
9	2400	164	149
10	2500	175	155
11	2600	178	163
12	2800	185	170
13	3000	193	177

Table 7.64 <u>HC Emissions H1 and H4 Fuels</u>

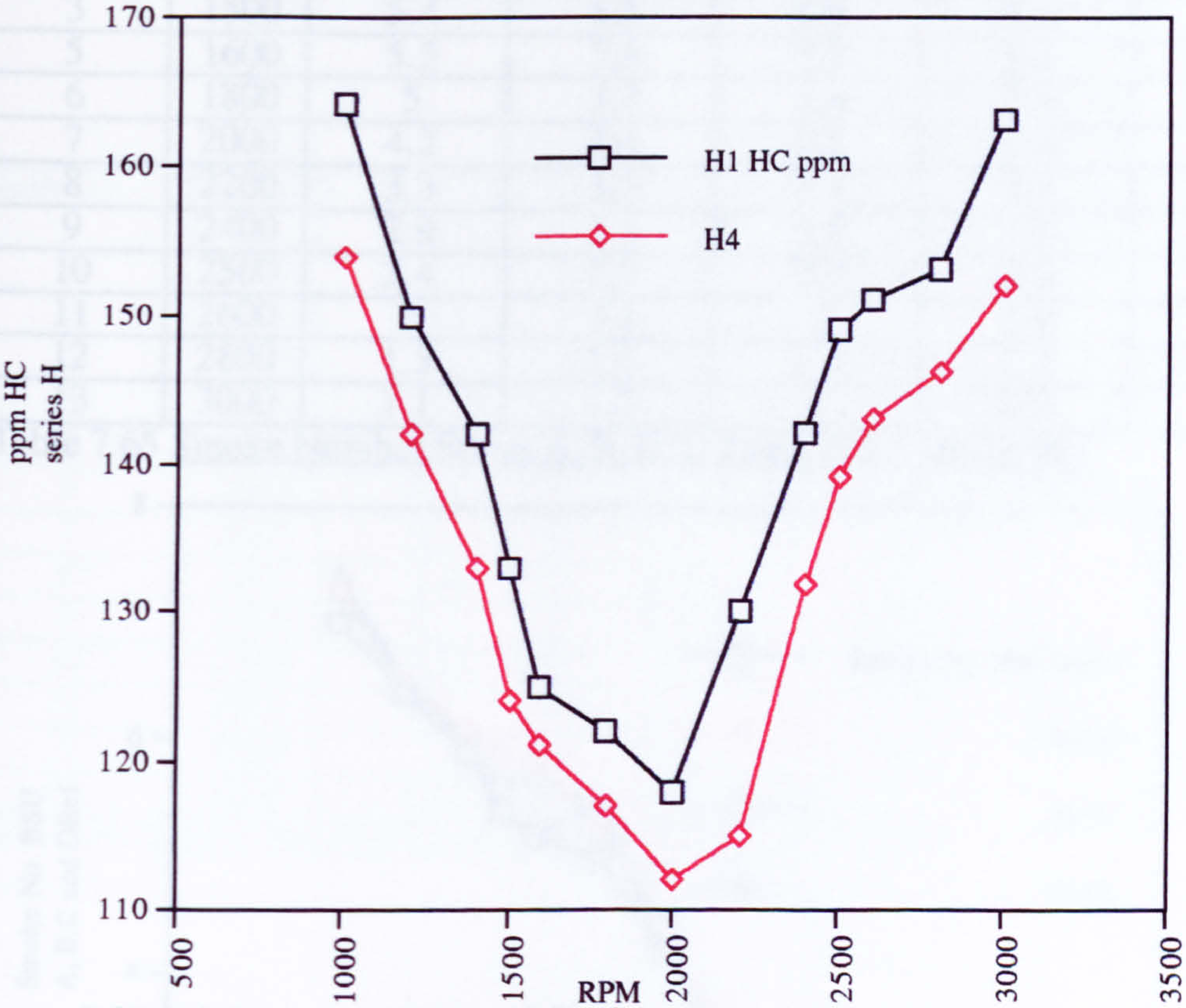

Figure 7.37 <u>HC Emissions Series H Fuels</u>

7.5 Smoke Emissions

7.5.1 Smoke Emissions from Reference Fuels

Table 7.65 lists the smoke emission output data of reference A, B, C and D fuels from the 13 experiments performed, in speed range of 1000 rpm to 3000 rpm. From Table 7.65, and Figure 7.38, the average of the four references gave Average Ref Smoke. The maximum difference was between Ref B and C, this being less than 3.2%. All the results were in mutual agreement.

Experiment	RPM	Smoke No. BSU Ref A	Smoke No. BSU Ref B	Smoke No. BSU Ref C	Smoke No. BSU Ref D	Average Ref Smoke No.BSU
1	1000	7	7.3	7.3	7.4	7.2
2	1200	6.4	6.5	6.4	6.5	6.5
3	1400	5.9	6.1	6	6	6
3	1500	5.4	5.5	5.6	5.5	5.6
5	1600	5.3	5.8	5.7	5.4	5.5
6	1800	5	5.3	5.4	5.5	5.3
7	2000	4.2	4.4	4.2	4.4	4.3
8	2200	3.3	3.5	3.4	3.3	3.8
9	2400	2.9	3.1	3.2	3.1	3.1
10	2500	2.4	2.7	2.7	2.8	2.4
11	2600	2	2.1	2	1.9	2
12	2800	1.5	1.6	1.4	1.5	1.5
13	3000	1.1	1.2	1	0.9	1.1

Table 7.65 Smoke Number Series A, B, C, D Fuels and Average Ref

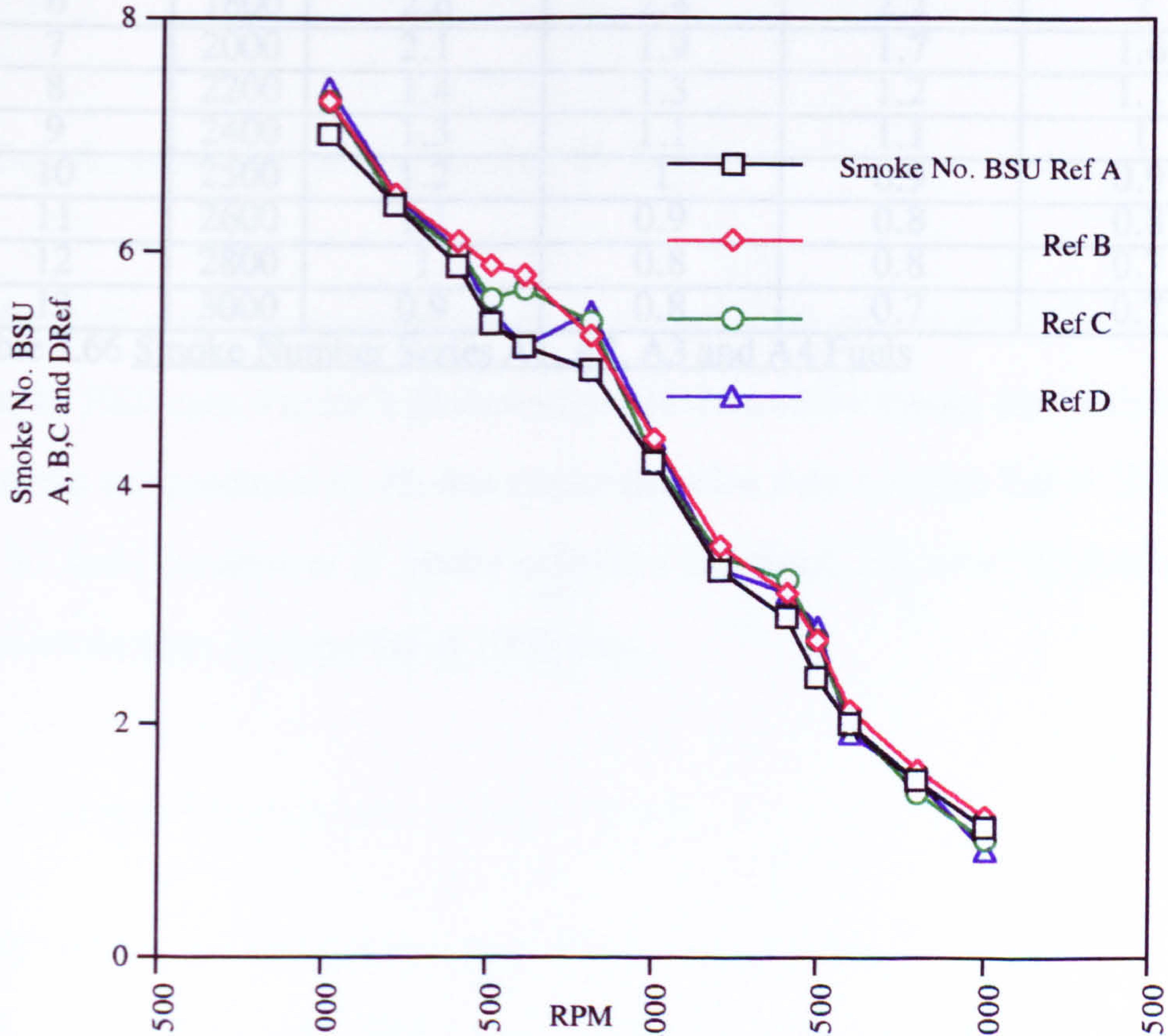

Figure 7.38 Smoke Emissions A, B, C and D Fuels

7.5.2 Smoke Emissions, Series A Fuels

Table 7.66 summarises series A fuels smoke emission data covering the speed range of 1000 rpm to 3000 rpm. Figure 7.39 shows that A4 fuel produced the lowest smoke emission level of the A series with 41.8% less smoke emission than Average Ref at 1000 rpm. From A4 to A1 fuels the amount of smoke emissions increased, but even A1 fuel generated 34.8% less smoke than Average Ref at 1000 rpm. [The reasons are discussed in section 7.6.5].

Experiment	RPM	Smoke No. BSU A1	Smoke No. BSU A2	Smoke No. BSU A3	Smoke No. BSU A4
1	1000	4.7	4.5	4.3	4.2
2	1200	4.4	4.2	4	3.9
3	1400	4.1	3.9	3.7	3.6
3	1500	3.7	3.6	3.5	3.3
5	1600	3.5	3.3	3.1	3.2
6	1800	2.6	2.4	2.2	2
7	2000	2.1	1.9	1.7	1.6
8	2200	1.4	1.3	1.2	1.1
9	2400	1.3	1.1	1.1	1
10	2500	1.2	1	0.9	0.9
11	2600	1.1	0.9	0.8	0.8
12	2800	1	0.8	0.8	0.7
13	3000	0.9	0.8	0.7	0.7

Table 7.66 Smoke Number Series A1, A2, A3 and A4 Fuels

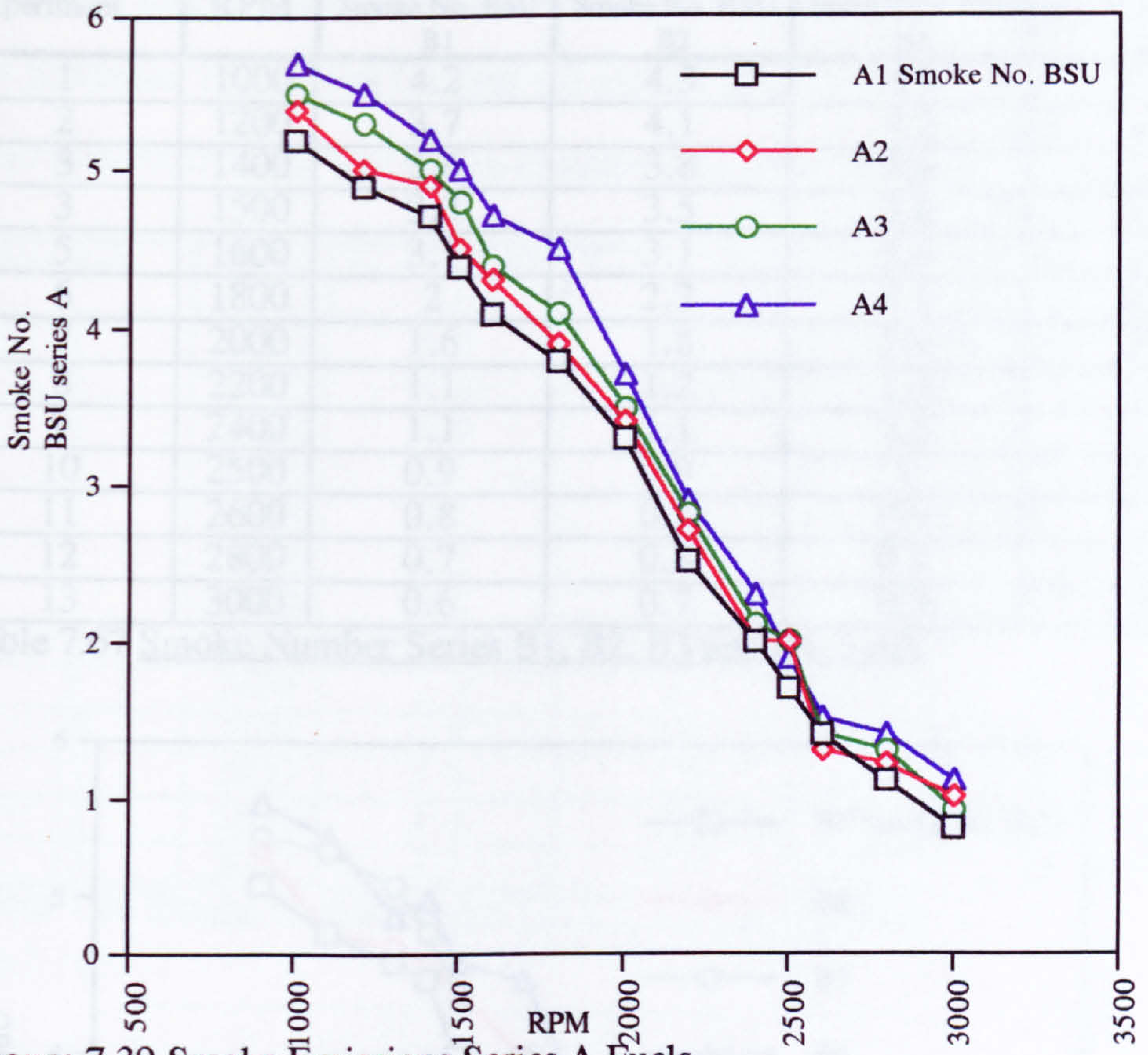

Figure 7.39 Smoke Emissions Series A Fuels

7.5.3 Smoke Emissions, Series B Fuels

Table 7.67 summarises series B fuels smoke emission data covering the speed range of 1000 rpm to 3000 rpm. Figure 7.40 shows that B4 showed the lowest smoke emission level of the B series and produced 41.4% less smoke emission than Average Ref at 1000 rpm. From B4 to B1 fuels the amount of smoke emissions increased, but even B1 fuel generated 34.8% less smoke than Average Ref at 1000 rpm.

Experiment	RPM	Smoke No. BSU B1	Smoke No. BSU B2	Smoke No. BSU B3	Smoke No. BSU B4
1	1000	4.2	4.3	4.5	4.7
2	1200	3.7	4.1	4.2	4.5
3	1400	3.6	3.8	3.9	4.3
3	1500	3.3	3.5	3.6	3.8
5	1600	3.1	3.1	3.4	3.6
6	1800	2	2.2	2.4	2.6
7	2000	1.6	1.8	1.9	2.2
8	2200	1.1	1.2	1.3	1.4
9	2400	1.1	1.1	1.2	1.3
10	2500	0.9	0.9	1	1.2
11	2600	0.8	0.9	0.9	1.1
12	2800	0.7	0.8	0.9	1
13	3000	0.6	0.7	0.8	1

Table 7.67 Smoke Number Series B1, B2, B3 and B4 Fuels

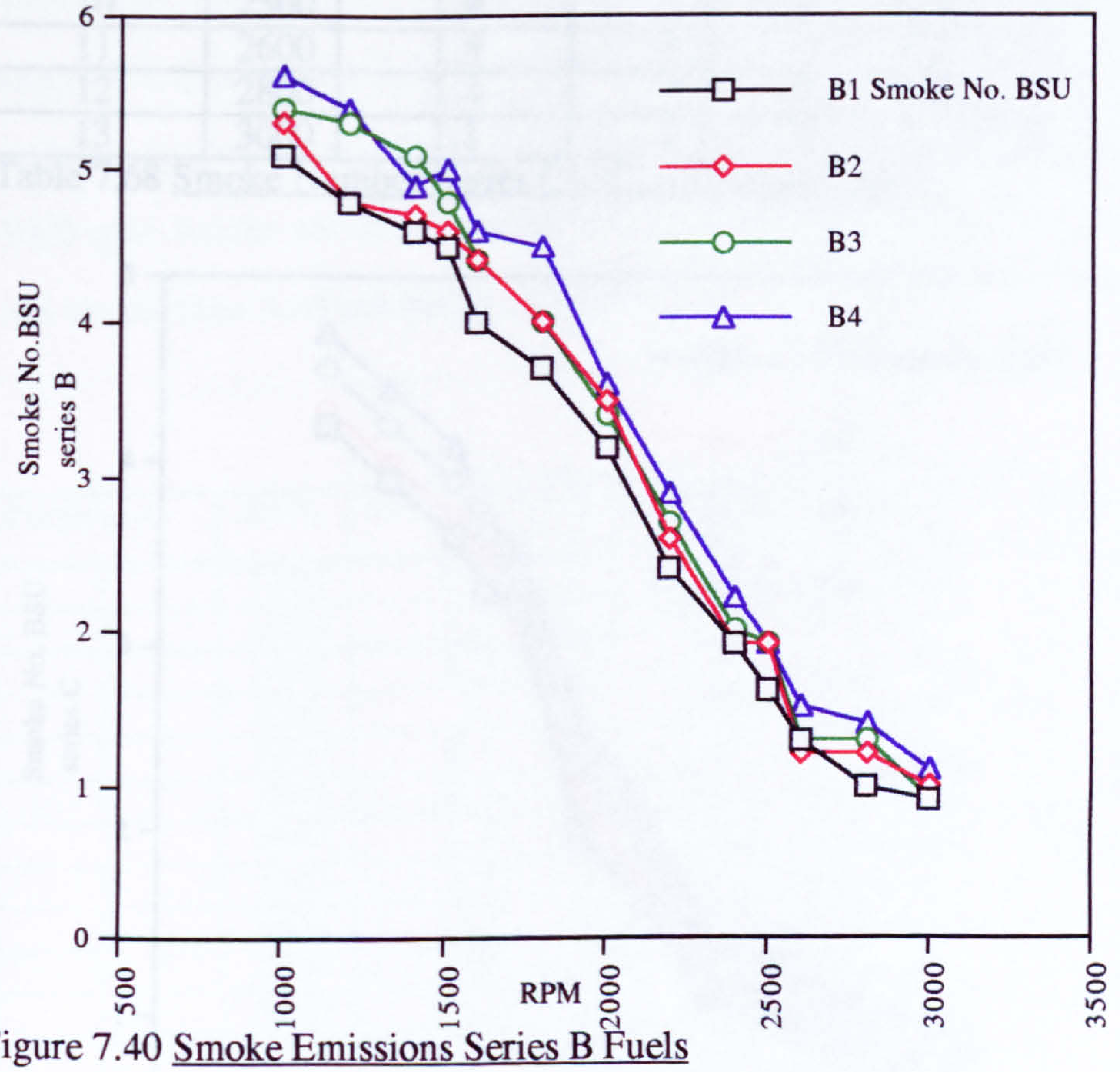

Figure 7.40 Smoke Emissions Series B Fuels

7.5.4 Smoke Emissions, Series C Fuels

Table 7.68 summarises C series fuels smoke emission data covering the speed range of 1000 rpm to 3000 rpm. Figure 7.41 shows that C4 fuel showed the lowest smoke emission level of the C series and produced 41.4% less smoke emission than Average Ref at 1000 rpm. From C1 to C4 fuels the amount of smoke emissions decreased, but even C1 fuel generated 34.8% less smoke emission than Average Ref at 1000 rpm.

Experiment	RPM	Smoke No. BSU C1	Smoke No. BSU C2	Smoke No. BSU C3	Smoke No. BSU C4
1	1000	5.6	5.4	5.3	5.1
2	1200	5.4	5.3	4.8	4.8
3	1400	4.9	5.1	4.7	4.6
3	1500	5	4.8	4.6	4.5
5	1600	4.6	4.4	4.4	4
6	1800	4.5	4	4	3.7
7	2000	3.6	3.4	3.5	3.2
8	2200	2.9	2.7	2.6	2.4
9	2400	2.2	2	1.9	1.9
10	2500	1.9	1.9	1.9	1.6
11	2600	1.5	1.3	1.2	1.3
12	2800	1.4	1.3	1.2	1
13	3000	1.1	0.9	1	0.9

Table 7.68 Smoke Number Series C1, C2, C3 and C4 Fuels

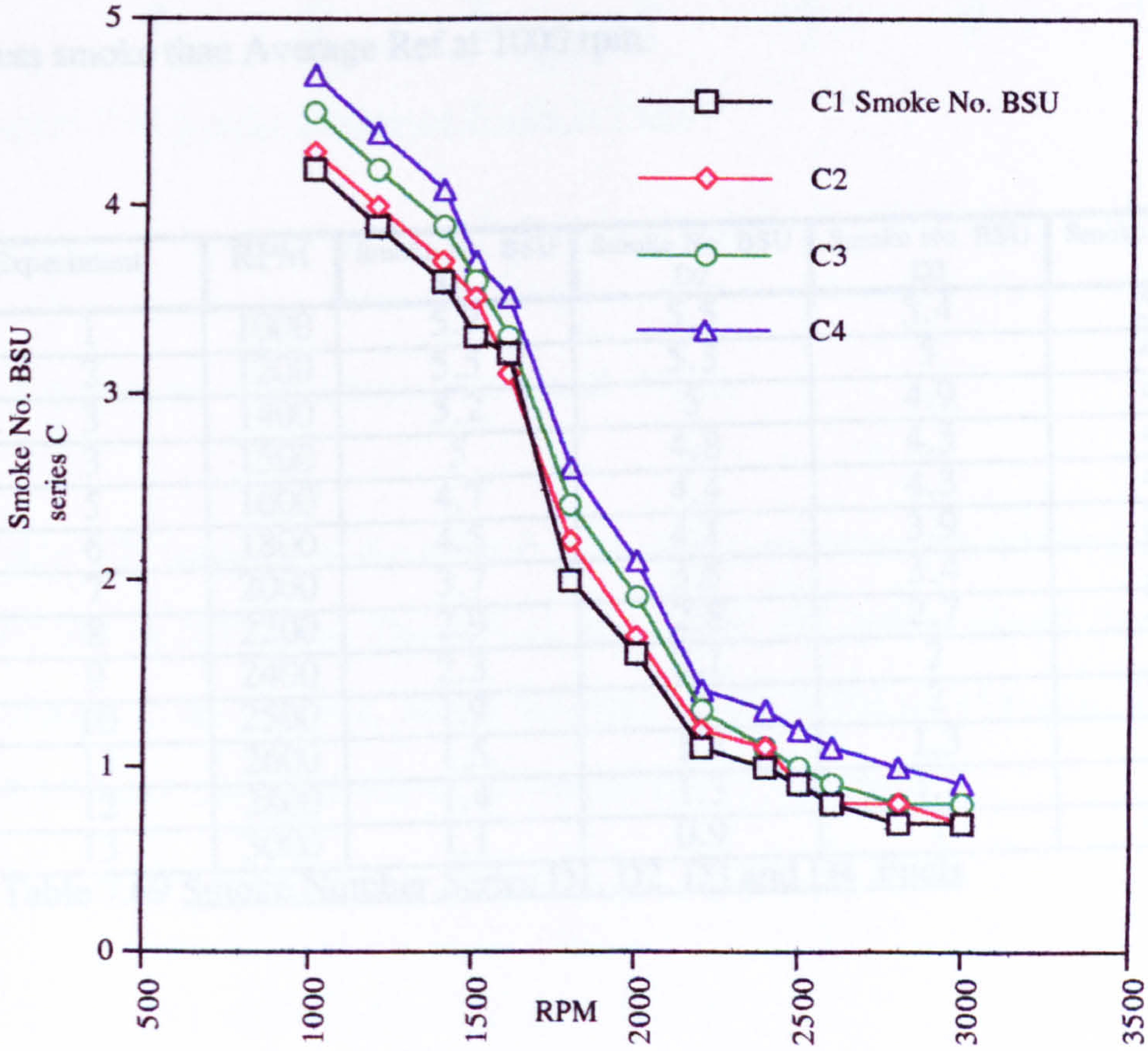

Figure 7.41 Smoke Emissions Series C Fuels

7.5.5 Smoke Emissions Series D Fuels

The smoke emission data for series D fuels are summarised in Table 7.69 and plotted in Figure 7.42. In each case the level fell from peak values of 5.2 BSU (D4) to 7 BSU (D1) at 1000 rpm to 0.8 (D1) to 1.1 BSU (D4) at 3000 rpm. In order of increasing emissions the ranking order was D4 to D1 fuels.

There was a clear trend whereby the decrease in BSU with increasing speed was almost linear from 1000 rpm to 1400 rpm; it then decreased more rapidly, and almost linearly, upto 3000 rpm. Figure 7.42 demonstrates that D4 generated the lowest level of smoke emission in the D series fuels. D1 fuel emitted 27.9% less smoke than Average Ref at 1000 rpm. Smoke emissions increased from D4 to D1 fuels but even D1 emitted 20.9% less smoke than Average Ref at 1000 rpm.

Experiment	RPM	Smoke No. BSU D1	Smoke No. BSU D2	Smoke No. BSU D3	Smoke No. BSU D4
1	1000	5.7	5.5	5.4	5.2
2	1200	5.5	5.3	5	4.9
3	1400	5.2	5	4.9	4.7
3	1500	5	4.8	4.5	4.4
5	1600	4.7	4.4	4.3	4.1
6	1800	4.5	4.1	3.9	3.8
7	2000	3.7	3.5	3.4	3.3
8	2200	2.9	2.8	2.7	2.5
9	2400	2.3	2.1	2	2
10	2500	1.9	2	2	1.7
11	2600	1.5	1.4	1.3	1.4
12	2800	1.4	1.3	1.2	1.1
13	3000	1.1	0.9	1	0.8

Table 7.69 Smoke Number Series D1, D2, D3 and D4 Fuels

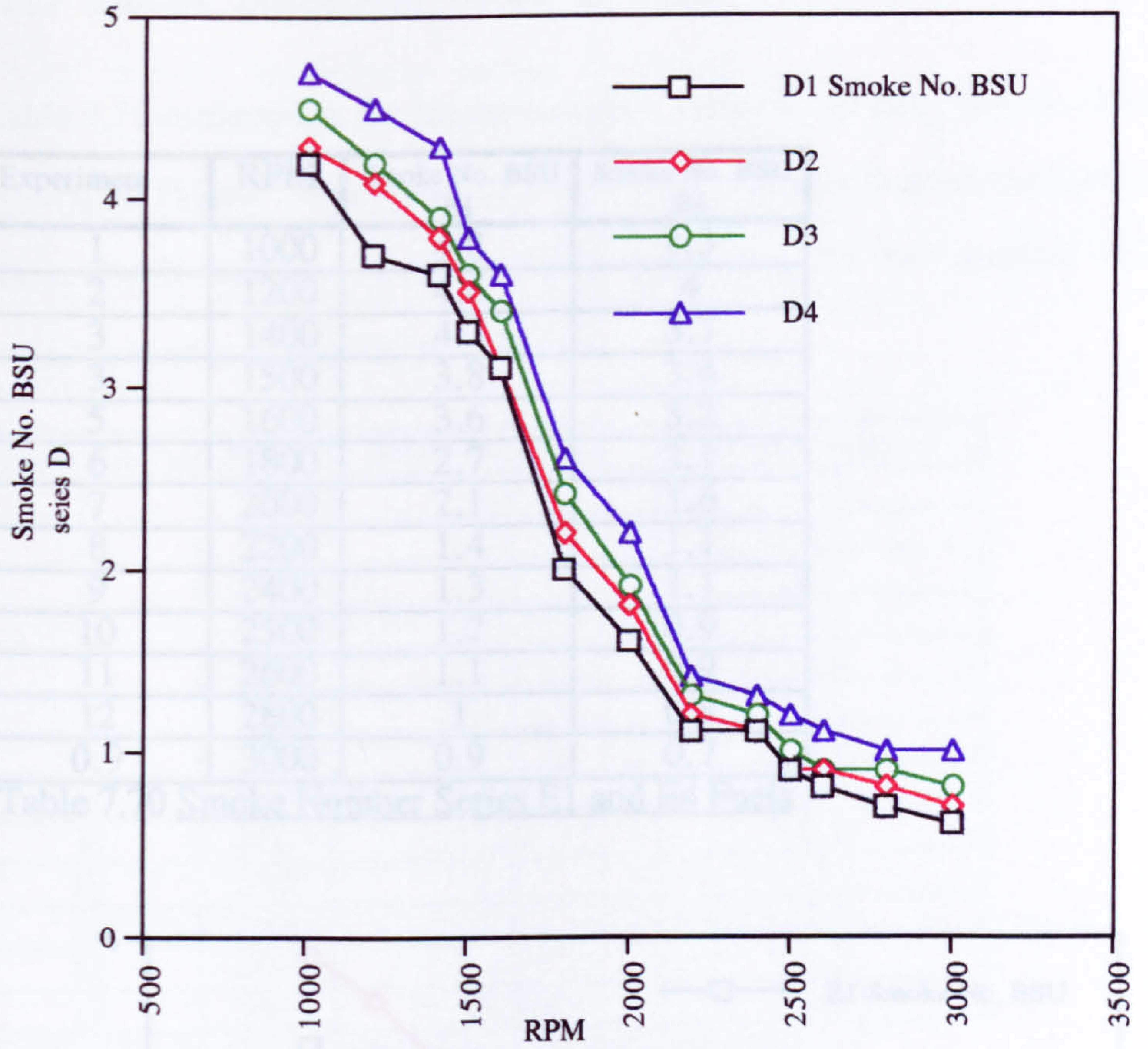

Figure 7.42 Smoke Emissions Series D Fuels

7.5.6 Smoke Emissions, Series E Fuels

Table 7.70 summarises the series E fuels smoke emission data covering the speed range of 1000 to 3000 rpm. Figure 7.43 shows that E4 fuel produced the lowest smoke emission in the E series, 40.4% less than Average Ref at 1000 rpm. E1 fuel emitted 33.3% less smoke emission than Average Ref at 1000 rpm.

Experiment	RPM	Smoke No. BSU E1	Smoke No. BSU E4
1	1000	4.8	4.3
2	1200	4.6	4
3	1400	4.3	3.7
3	1500	3.8	3.4
5	1600	3.6	3.2
6	1800	2.7	2.1
7	2000	2.1	1.6
8	2200	1.4	1.1
9	2400	1.3	1.1
10	2500	1.2	0.9
11	2600	1.1	0.9
12	2800	1	0.8
0.9	3000	0.9	0.7

Table 7.70 Smoke Number Series E1 and E4 Fuels

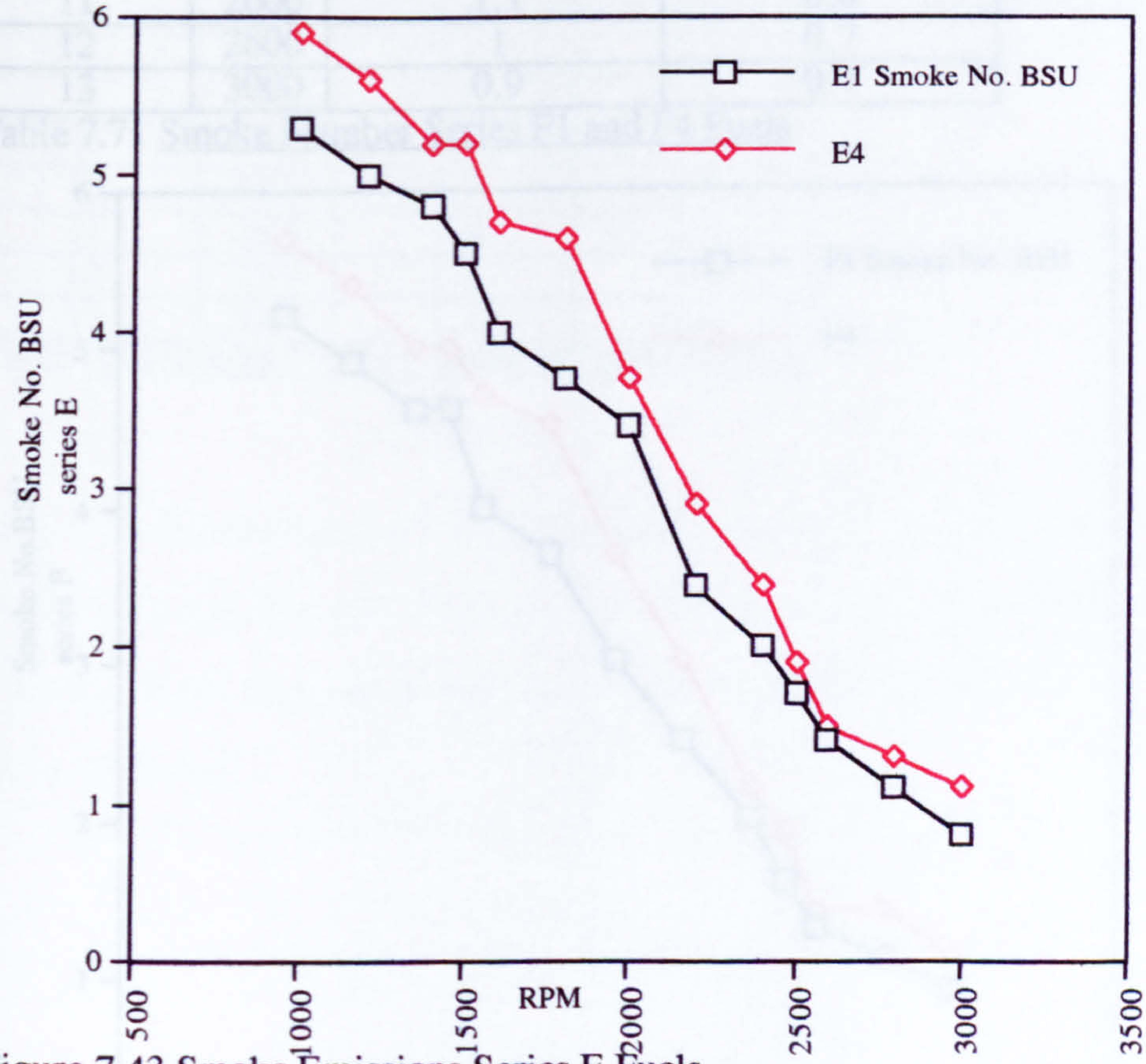

Figure 7.43 Smoke Emissions Series E Fuels

7.5.7 Smoke Emissions, Series F Fuels

Table 7.71 summarises the smoke emission series F covering the speed range of 1000 to 3000 rpm. Figure 7.44 shows that F4 produced the lowest smoke emission in the F series fuels, 40.4% less than Average Ref at 1000 rpm. F1 fuel emitted 32.1% less smoke emission than Average Ref at 1000 rpm.

Experiment	RPM	Smoke No. BSU F1	Smoke No. BSU F4
1	1000	4.9	4.3
2	1200	4.7	3.7
3	1400	4.5	3.7
3	1500	4	3.3
5	1600	3.8	3.2
6	1800	2.7	2.1
7	2000	2.3	1.7
8	2200	1.5	1.2
9	2400	1.3	1.1
10	2500	1.2	1
11	2600	1.1	0.8
12	2800	1	0.7
13	3000	0.9	0.7

Table 7.71 Smoke Number Series F1 and F4 Fuels

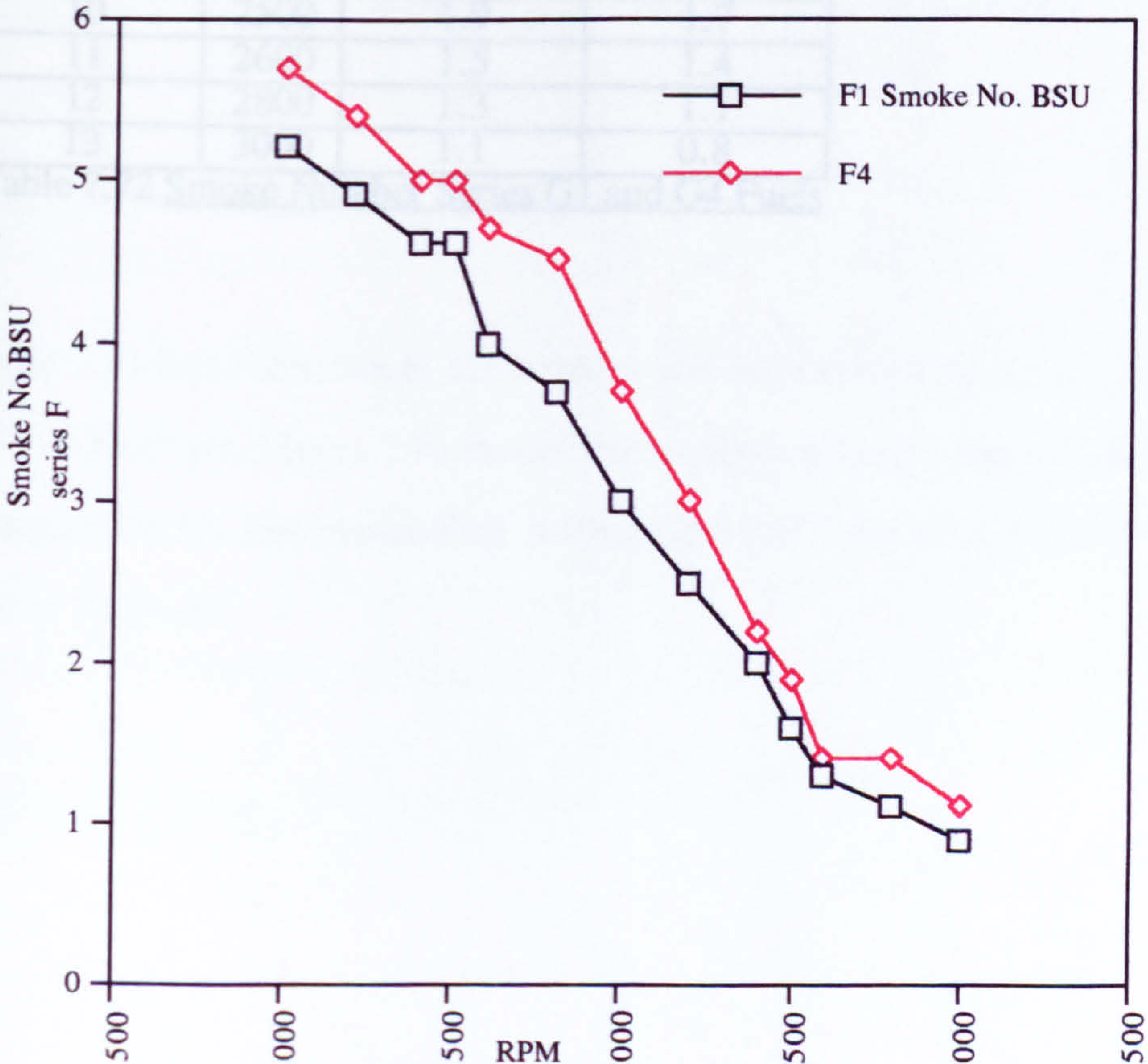

Figure 7.44 Smoke Emissions Series F Fuels

7.5.8 Smoke Emissions Series G Fuels

Table 7.72 lists the series G fuels smoke emission data covering the speed range of 1000 rpm to 3000 rpm. Figure 7.45 shows that G4 emitted the lowest level of smoke emission in the G series, 26.5% less Average Ref at 1000 rpm. G1 fuel generated 18.1% less smoke than Average Ref at 1000 rpm.

Experiment	RPM	Smoke No. BSU G1	Smoke No. BSU G4
1	1000	5.9	5.3
2	1200	5.6	5
3	1400	5.2	4.8
3	1500	5.2	4.5
5	1600	4.7	4
6	1800	4.6	3.7
7	2000	3.7	3.4
8	2200	2.9	2.4
9	2400	2.4	2
10	2500	1.9	1.7
11	2600	1.5	1.4
12	2800	1.3	1.1
13	3000	1.1	0.8

Table 7.72 Smoke Number Series G1 and G4 Fuels

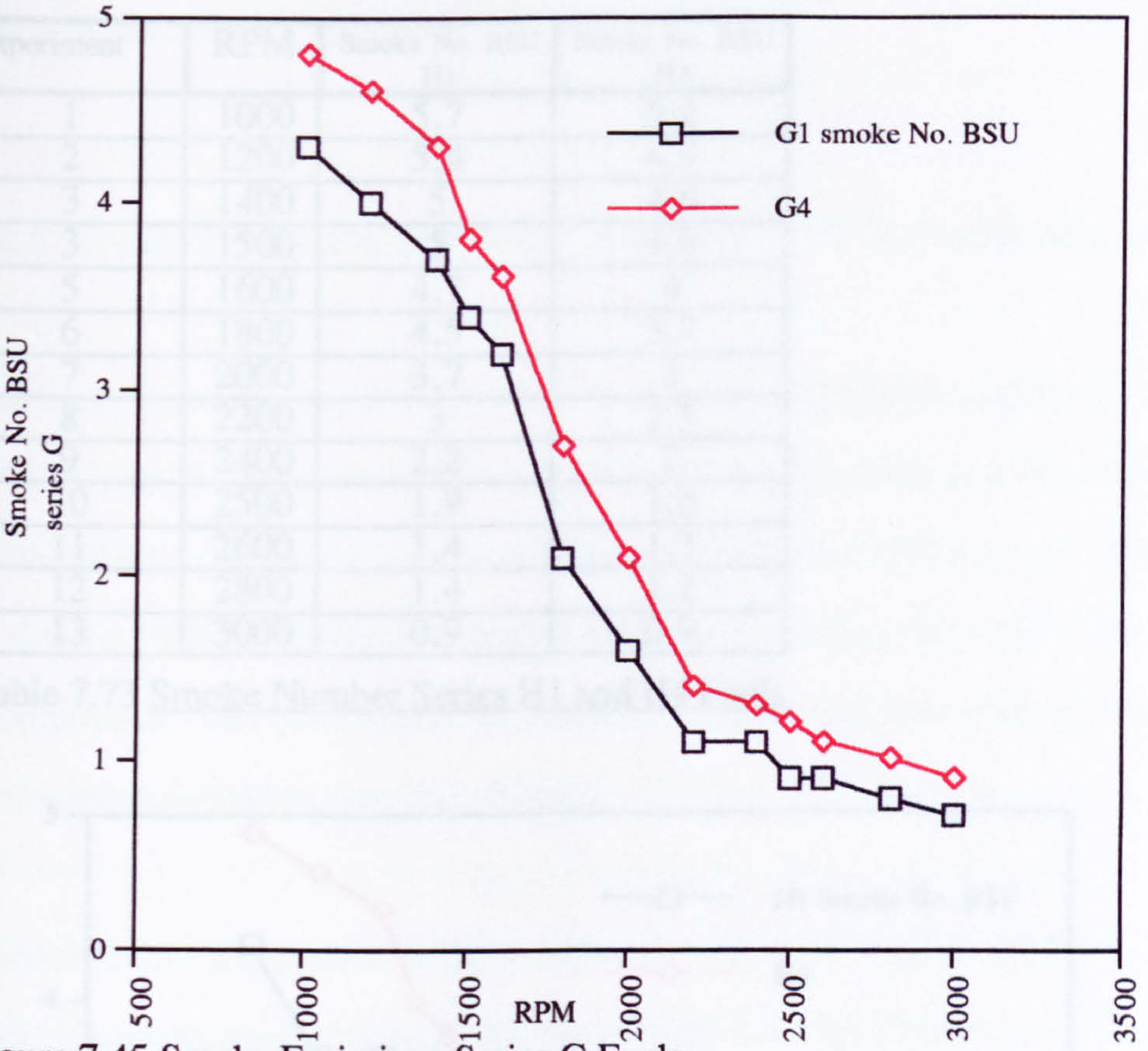

Figure 7.45 Smoke Emissions Series G Fuels

7.5.9 Smoke Emissions Series H Fuels

Table 7.73 lists the series H fuels smoke emission data covering the speed range of 1000 rpm to 3000 rpm. Figure 7.73 shows that H4 fuel emitted the lowest smoke emission in the H series, 28.8% less smoke than Average Ref. H1 fuel emitted 20.9% less than Average Ref at 1000 rpm.

Experiment	RPM	Smoke No. BSU H1	Smoke No. BSU H4
1	1000	5.7	5.2
2	1200	5.4	4.9
3	1400	5	4.6
3	1500	5	4.6
5	1600	4.7	4
6	1800	4.5	3.7
7	2000	3.7	3
8	2200	3	2.5
9	2400	2.2	2
10	2500	1.9	1.6
11	2600	1.4	1.3
12	2800	1.4	1.1
13	3000	0.9	0.9

Table 7.73 Smoke Number Series H1 and H4 Fuels

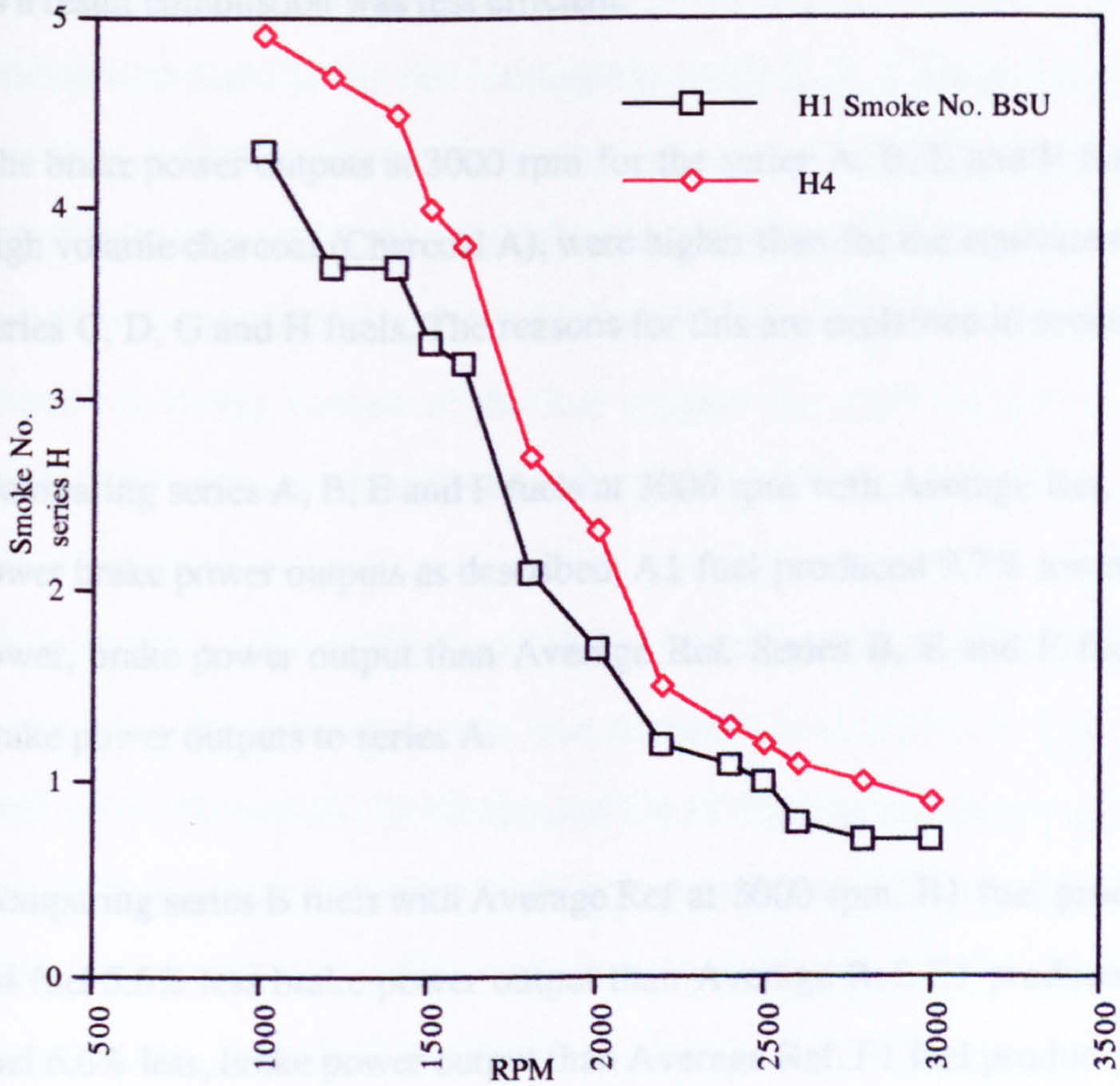

Figure 7.46 Smoke Emissions Series H Fuels

7.6 Discussion of Results

7.6.1 Brake Power Output from Reference and Experimental Fuels

The brake power output of all the fuels in series A to H demonstrated a similar trend. From 1000 rpm to 2500 rpm the trend was for all practicable purposes a linear increase. Between 2500 to 3000 rpm there was a linear increase in slope but with a lower gradient. The change in slope at 2500 to 3000 rpm is attributable to the fact that at this speed the fuel mixture had proportionally less combustion air, because of increased flow resistance in the intake, and as a result combustion was less efficient.

The brake power outputs at 3000 rpm for the series A, B, E and F fuels, which contained high volatile charcoal (Charcoal A), were higher than for the equivalent formulations in the series C, D, G and H fuels. The reasons for this are explained in sections 7.6.6.1 .

Comparing series A, B, E and F fuels at 3000 rpm with Average Ref, the results indicated lower brake power outputs as described; A1 fuel produced 9.7% lower, and A4 fuel 6.9% lower, brake power output than Average Ref. Series B, E and F fuels produced similar brake power outputs to series A.

Comparing series B fuels with Average Ref at 3000 rpm. B1 fuel produced 8.9% less and B4 fuel 5.6% less brake power output than Average Ref. E1 produced 9.5% less, and E4 fuel 6.6% less, brake power output than Average Ref. F1 fuel produced 8.4% less, and F4 fuel 5.8% less, brake power output than Average Ref.

Comparison of brake power output at 3000 rpm between series C, D, G, and H fuels (which contained charcoal B with a low volatile content) showed that C1 fuel produced 16.1% less brake power than the Average Ref, and that C4 produced the lowest difference in brake power output in the C series, 12.7% less brake power than Average Ref. D1 fuel produced 20.7% less brake power than Average Ref at 3000 rpm. D4 fuel produced 12.9% less brake power output than Average Ref at 3000 rpm. G1 produced 16.9% and G4 fuel 13.7% less brake power output than Average Ref at 3000 rpm. H1 fuel produced 17.9% and H4 fuel 13.9% less brake power output than Average Ref.

Clearly then the use of charcoal A or B resulted in significantly different power outputs from the test fuels. In the test formulation series A, B, E and F fuels in which charcoal A was used, the brake power outputs were lower than that of the Average reference fuel, and varied from A1 to A4 fuels. The brake power output increased as the proportion of charcoal content was increased i.e. from A1 to A4 fuels. This is attributable to the associated increase in energy content of the fuel samples (i.e. 15% to 30% by mass) and also the decrease in water content of the samples (54% to 39% by mass).

By comparison series C, D, G and H fuels contained charcoal B. The power output again increased as the charcoal content was increased from C1 to C4 fuels. However whilst A1 produced 9.7% less, C1 16.1% less and C4 12.7% lower brake power output than Average Ref, A4 fuel gave 6.9% lower brake power output at 3000 rpm. The same trend of lower brake power output was followed when series D, G and H fuels were compared with corresponding series B, E and F fuels.

Therefore charcoal with a high volatile content yielded a significantly higher brake power output than charcoal with a low volatile content as shown in Tables 7.01 to 7.33. The reasons for this are explained below.

From Table 7.75 the formulations that gave the highest brake power outputs were B4 and F4 fuels. (B4 fuel produced 5.6% less and F4 fuel 5.8% less brake power output than Average Ref.) The least power was obtained from D1 and H1 fuels, 20.7% less and 17.9% less brake power respectively than Average Ref. In Table 7.75 a clear trend was observed for brake power output. For all series A to H fuels, in moving from e.g. A1 to A4 fuel, B1 to B4 fuel etc. the power output increased. This was related to the fact that in all formulations the charcoal content was increased from e.g. A1 to A4 fuel, whilst the oil and additive content remained constant; as a consequence the water content of the samples was decreased. It is clear that significantly better brake power output results were obtained when charcoal A was used in, series A, B, E and F fuels compared with series C, D, G and H fuels which contained charcoal B.

Formulations that contained oil B show a slightly improved performance over the corresponding formulation containing oil A. This arose because oil B had a higher (i.e. 2.2% greater) energy content than oil A.

The type of charcoal used is clearly an important factor determining the brake power output. The use of type A charcoal in series A, B, E and F fuels gave substantially better brake power output performance than series C, D, G and H fuels, which contained type B charcoal.

The ultimate analyses of the two charcoals A and B were determined experimentally and are given in Table 7.74.

	C (%)	H (%)	O (%)	Volatiles wt (%)	Fixed Carbon Wt (%)
Charcoal A	73.4	1.4	14.6	27.2	67.0
Charcoal B	94.2	2.2	3.5	9.7	89.3

Table 7.74 Ultimate Analysis Of Charcoal A and Charcoal B

Evidently charcoal A contains 3 times the volatile content of charcoal B. These volatiles burn easily at the temperatures (700 to 900°C) generated in the diesel engine. Non-volatiles which usually consist of ash, silica and small quantities of metals such as aluminium and magnesium, do not. This both explains the improved brake power output with charcoal A and suggests that introduction of a different charcoal of a high volatile content from tree species such as American Redwood and Sycamore would yield further improvements.

The only difference between series A and series B was the oil used in the formulation (i.e. oil A or B). The difference in brake power outputs was small, but series B gave slightly better brake power outputs than series A. This is as expected because series B contains oil B(esterified soya oil) with a 2.2% higher energy content than oil A (esterified rapeseed oil)

The use of either additive A or B made no difference to the brake power output with any combination of the test fuels. Since the additives are present only at 1% by mass and, apart from exhibiting detergency properties they show no other chemical interaction in the bio-ultracarbofluids, this result is not unexpected.

7.6.2 Carbon Dioxide Emissions

The CO_2 emissions for Average Ref fuels increased with an increase in speed in the range 1000 rpm to 3000 rpm. This increase was, for all practicable purposes, linear from A1 to A4 fuel. It correlated with an increase in charcoal content from A1 to A4 fuel and also with a decrease in water content, which factors would tend to promote complete combustion.

From Tables 7.35, 7.36, 7.38 and 7.39 the level of carbon dioxide emissions from the series A, B, E and F fuels were very similar. When compared to Average Ref, A1 fuel resulted in 16.5% less CO_2 emission at 3000 rpm. From A1 to A4 fuel, as the charcoal proportion increased the CO_2 emission also increased and A4 fuel emitted 9.3% lower CO_2 than Average Ref at 3000 rpm. Therefore, in comparison with Average Ref, CO_2 emissions of series A, B, E and F fuels were significantly lower at 3000 rpm.

A1 gave the lowest level of CO_2 emissions in the A series fuels, 16.5% less than the Average Ref at 3000 rpm. A4 gave the maximum CO_2 emission in the A series fuels, 9.2% less CO_2 than Average Ref at 3000 rpm. In the B series B1 fuel gave the lowest CO_2 emission, 16.5% lower than Average Ref. B4 fuel produced 8.4% less. E1 fuel 17.6% less and E4 fuel 10% less CO_2 emission than Average Ref. F1 fuel emitted 16.5% less and F4 fuel 8.4% less CO_2 than Average Ref at 3000 rpm.

From Tables 7.41, 7.42, 7.45 and 7.46 series C, D, G and H fuels demonstrated similar CO_2 emission trends but different output levels to series A, B, E and F fuels. When compared to Average Ref, C1 produced 28.5% less CO_2 emission at 3000 rpm. As before when the proportion of charcoal was increased from, e.g. C1 through to C4, the level of

CO_2 emission also increased and C4 fuel emitted 24% less CO_2 than Average Ref at 3000 rpm. Overall, charcoal B in series C, D, G and H fuels resulted in a greater reduction in CO_2 emissions than charcoal A in the series A, B, E and F fuels.

Table 7.75 shows that the CO_2 output content varied quite considerably. It was 8.4% and 8.3% greater for F4 and B4 fuels respectively, and 29.5% and and 28.5% greater for D1 and H1 fuels respectively, compared with Average Ref CO_2 emission at 3000 rpm. The results show a relationship between CO_2 output and brake power output i.e. the greater the CO_2 output the greater the power output. This would be expected since the higher output of CO_2 indicates improved combustion performance; this results in a higher engine efficiency and hence a greater brake power output.

C1 fuel generated the lowest level of CO_2 emission, 28.5% less than Average Ref in the C series fuels at 3000 rpm C4 fuel generated the highest CO_2 output, but still 23.9% less than Average Ref fuels. D1 generated 29.5% less and D4 had 25.8% less CO_2 emissions than Average Ref at 3000 rpm. G1 emitted 28.5% less and G4 22.9% less CO_2 than Average Ref at 3000 rpm. H1 fuel emitted 28.5% less and H4 24.9% less CO_2 than Average Ref at 3000 rpm.

7.6.3 Carbon Monoxide Emissions

The CO emissions in internal combustion engines (I.C.) are essentially controlled by the fuel/air equivalence ratio. Spark-ignition engines usually operate very near to stoichiometric ratio (Λ=0.9 to 1.1). The CO emissions are therefore significant and must be controlled. Diesel engines usually operate on the fuel lean (Λ=0.6 to 0.9) side of stoichiometric; as a result CO emissions from diesel engines are very low and present no problem as pollutants except when they are operated in a confined space,e.g. a closed garage.

The average level of CO emissions with the four reference fuels (Average Ref) was 419 ppm at 3000 rpm. The Maximum CO emissions were produced by A4, B4, E4, and F4 fuels samples, in the range 12.9% to 14.4% less than Average Ref at 3000 rpm. The CO output is clearly related to CO_2 emission, i.e. that the higher the CO_2 emission the lower the CO emission. The CO emission is, like CO_2 emission, related to the initial carbon content of the fuel. Therefore as the carbon content of fuel was increased e.g. from A1 to A4 naturally the combustion efficiency increased; hence there were increased CO_2 emissions. From e.g. A1 to A4 fuels the CO output increased in proportion to increased carbon present in the test fuels. In the test series A to H fuels; C1, D1, G1 and H1 fuels produced the lowest level of CO emission but this was associated with the lowest power output.

In the series A, B, E and F fuels the level of CO emissions decreased as the speed increased from 1000 rpm to 3000 rpm. The levels of CO emissions from the series A, B, E and F fuels were very similar. In the A series A1 fuel produced the least CO, 17.4% less than Average Ref at 3000 rpm. From A1 to A4, CO emissions increased with A4 producing 12.9% less CO than A Ref at 3000 rpm. Series B, E, and F fuels gave similar CO output results and trends to series A fuels, because all contained charcoal A.

In the series C, D, G and H fuels, C1 produced a 34.6% lower level of CO emission than Average Ref at 3000 rpm. The CO emissions in the C series fuels increased from C1 to C4 fuels. C4 gave 27.5% lower CO emission than C Ref at 3000 rpm. Series D, G and H fuels gave similar CO output results and trends to the C series, because all contained charcoal B.

7.6.4 Hydrocarbon (HC) Emissions

Organic emissions, termed 'hydrocarbons', in the exhaust emissions result from incomplete combustion of the hydrocarbon fuel. The level of hydrocarbons is given by the total hydrocarbon concentration expressed in parts per million carbon atoms e.g. C_6. because the standard detection instrument, a flame ionisation detector (FID), is effectively a carbon atom counter: e.g., one hexane molecule generates six times the response generated by a methane molecule.

The composition of the fuel is a predominant factor in determining the types and amounts of hydrocarbons produced in the final exhaust. Fuels containing high proportions of aromatics and olefins produce significantly higher levels of reactive hydrocarbons. Many of the organic compounds found in the exhaust are not present in the initial fuel e.g. oxygenates, low molecular weight carbonyls such as formaldehyde, phenols and other non-carbonyls[126]. This indicates that pyrolysis and synthesis reactions occur during the combustion process, and the resulting pollutants may be paticularly significant in terms of environmental impact both upon human exposures (e.g. carbonyls act as respiratory irritants) and the environment.

Diesel fuel differs from petrol in that it contains larger molecular weight, and therefore higher boiling point, hydrocarbons. During the diesel combustion process substantial combustion takes place within the fuel sprays; as a result more complex hydrocarbons are formed than in the spark-ignition engine. There are two major causes of HC emissions in the diesel engine under normal operating conditions: (i) fuel is mixed to a concentration below the lean combustion limit during the delay period and (ii) undermixing of fuel which leaves the injector nozzle at low velocity, late in the combustion process.

7.6.4.1 Hydrocarbon Emissions for Reference and Experimental Fuels

The levels of HC emissions from all series A to H fuels followed similar trends. It decreased in a linear manner from 1000 rpm to reach a minimum between 1800 and 2000 rpm; it then increased as the speed was increased from 2000 to 3000 rpm. The reason was that engine idling and light-load operation produce significantly higher HC emissions than full load operations. At low speeds, e.g. 1000 rpm, the combustion of fuel is not efficient and consequently a greater proportion of it remains uncombusted resulting in high HC output at low speeds. Very efficient combustion occurs at 1800 to 2000 rpm; hence the lowest HC levels are emitted at these speeds. From 2000 to 3000 rpm the level of HC emissions increased due to an increased proportion of fuel to air, which results in overmixing i.e. fuel/air equivalence ratio of 1.1 to 1.5 .

The average performance of the four reference fuels (Average Ref) was compared with those of the experimental series fuels. All the comparisons were made at 3000 rpm. Tables 7.57, 7.58,7.61 and 7.62 demonstrate that the hydrocarbon emissions in the series A, B, E and F fuels which contained charcoal A (high volatile content) were very similar, but much lower than Average Ref in Table 7.56. In the A series, A1 generated the highest HC emission (18.8% less) and A4 the lowest (24.2% less) compared with A Ref at 3000 rpm. The output and trends of series B, E and F fuels were very similar to those for A series fuels.

In the B series B4 fuel generated the lowest HC emission (26.6% less) as compared to Average Ref; B1 generated 20.8% less. In the E series E1 fuel 18.2% less and E4 fuel produced 23.3% less. F4 fuel produced 25.2% less and F1 fuel 19.8% less HC emissions than Average Ref at 3000 rpm.

Series C, D, G and H fuels demonstrated similar HC emissions output and trends, but lower HC emissions than Average Ref. In comparison with series A, B, E and F fuels the HC emissions were much higher. In the C series C1 fuel generated the highest HC emission 4.0% less than Average Ref at 3000 rpm, and C4 fuel the lowest (13.4% less). The output and trends of series D, G and H fuels were very similar to those of C series fuels. D4 fuel produced 14.4% less and D1 5.4% less HC emissions than Average Ref at 3000 rpm. G4 produced 13.8% less and G1 4.4% less HC emissions than Average Ref. H4 fuel generated 12.9% less and H1 4.9% less HC emissions than Average Ref.

The levels of HC emissions generated by the samples in Table 7.76 were primarily determined by the amount and type of charcoal present in the formulation. Samples containing charcoal B gave significantly lower HC emissions than samples containing charcoal A. As the content of charcoal was increased in each sample so the HC emissions decreased. The HC emissions follow the opposite trend to CO_2 emissions in that the more efficient the combustion process, the greater the CO_2 emission. The greater the CO_2 emission the lower the HC emission in the exhaust. The results which are consistent for all samples, are as would be expected since efficient combustion should result in CO_2 and water only. Hence improvements in, or changes in the type of, charcoal and its amount could be useful in reducing HC emissions which, as discussed 7.6.1.1 in , are considered particularly harmful to health.

7.6.5 Smoke Number

The smoke emission comparisons were made at 1000 rpm since the maximum levels of smoke emissions were observed, at this speed. At 3000 rpm the levels of smoke emissions decreased by a factor of seven compared with those at 1000 rpm.

Many types of particulates are emitted in the diesel exhaust depending upon the load and operating conditions. When the engine is started, particulates appear as a dense cloud of white fumes. These consist mainly of fuel and small amounts of lubricating oil emitted without combustion. Once the engine is running, black smoke is emitted due to incomplete combustion of the fuel particularly at maximum loads. Other particulates in the smoke include lubricating oil and fuel additives. According to Heywood[127] the black smoke consists of irregularly shaped, agglomerated fine carbon particles. These carbon particulates can be formed from the hydrocarbon fuels in the presence or absence of oxygen.

The average smoke number of the four reference fuels (Average Ref) was compared with those for the experimental series fuels. All the comparisons were made at 1000 rpm at which level the smoke emissions were at a maximum. For the four reference fuels the decrease from 1000 rpm was for all practicable purposes linear upto a speed of 3000 rpm.

In the series A fuels the smoke emissions decreased linearly from a maximum at 1000 rpm to 1400 rpm and then more rapidly from 1400 rpm to 2500 rpm; from 2500 rpm there was then a less rapid decrease upto 3000 rpm. The levels of smoke emissions also decreased from A1 to A4 fuels i.e. A1 produced 34.8% less and A4 41.8% less smoke than Average Ref at 1000 rpm.

In series B fuels the same trend for smoke emissions was followed as for series A fuels. B1 fuel produced the lowest level of smoke emission in the B series fuels. B1 produced 34.8% less and B4 41.4% less smoke than Average Ref at 1000 rpm.

For the E and F series fuels the plot of smoke emission against speed follows those for series A and B fuels. The level of smoke emission decreased in moving from E1 to E4 and from F1 to F4 fuels. E1 produced 33.3% less and E4 40.4% less smoke emission than Average Ref at 1000 rpm. F1 produced 32.1% less and F4 40.4% less smoke than Average Ref at 1000 rpm.

Series C and D fuels resulted in very similar plots of smoke emissions, but they were distinctly different from those for series A and B fuels. The maximum smoke emission was at 1000 rpm, and decreased from 1000 to 3000 rpm. The level increased in moving from C1 to C4, and from D1 to D4 fuel respectively. However, the rate of change was clearly different from that with series A and B fuels.

C1 produced 20.9% less and C4 27.9% less smoke than Average Ref at 1000 rpm. Similarly, D1 fuel produced 22.3% less and D4 29.3% less smoke emissions than Average Ref at 1000 rpm.

In the series G and H the smoke output results were similar to those for series C and D fuels. G1 produced 18.1% less and G4 26.5% less smoke emission than Average Ref at 1000 rpm. H1 fuel produced 18.1% less and H4 28.8% less smoke emission than Average Ref at 1000 rpm.

The smoke output data in Table 7.75 show a clear relationship with type and proportion of charcoal. The results show that when charcoal A was used smoke emissions were significantly reduced. The level of smoke emission also decreased as the proportion of charcoal was increased. Samples containing charcoal B showed very similar trends in smoke emission with the corresponding charcoal A formulation but at significantly lower levels, i.e. comparison of A1 fuel smoke emission with C1 show A1 produced 31.8% less, whereas C1 fuel produced 20.9% less smoke emission than Average Ref under same conditions at 1000 rpm.

The use of oil A or B in the test formulations resulted in only a slight difference in the level of smoke emission as expected, since the chemical structure of both oil A and B are very similar, although oil B had a 2.2% greater energy content than A.

There was no noticeable difference in smoke emission when either of the additives was used in the test formulations. This would be expected, because they were only present at 1% by mass and have no other chemical interaction apart from exhibiting their detergency property.

Series A, B, E and F yielded similar results and hence, are placed together in Table 7.75.

Sample	% difference brake power	% difference CO_2	% difference CO	% difference HC	% difference Smoke Number
A1	-9.7	+16.6	+34.9	+18.8	+34.8
A2	-8.7	+14.7	+32.7	+20.7	+37.5
A3	-6.9	+11.9	+29.8	+21.2	+40.3
A4	-6.6	+9.3	+27.5	+24.2	+41.8
B1	-8.9	+16.5	+36.4	+20.8	+34.8
B2	-7.4	+15.6	+33.9	+21.2	+37.5
B3	-6.1	+13.8	+30.5	+23.6	+40.3
B4	-5.6	+8.3	+28.5	+26.6	+41.4
E1	-9.5	+17.7	+34.2	+18.2	+33.3
E4	-6.6	+10.0	+29.3	+23.3	+40.4
F1	-8.4	+16.5	+36.9	+19.8	+32.1
F4	-5.8	+8.4	+33.7	+25.2	+40.4
C1	-16.1	+28.5	+17.5	+4.0	+20.9
C2	-13.2	+27.5	+15.7	+7.9	+23.7
C3	-14.2	+25.7	+14.8	+10.8	+25.0
C4	-12.7	+23.9	+12.9	+13.4	+27.9
D1	-20.7	+29.5	+19.5	+5.4	+22.3
D2	-13.9	+28.4	+17.2	+9.4	+25.0
D3	-12.9	+27.5	+16.0	+12.3	+26.4
D4	-12.9	+25.8	+14.4	+14.4	+29.3
G1	-16.9	+28.5	+17.9	+4.4	18.1
G4	-13.7	+22.9	+13.4	+13.8	+26.5
H1	-17.9	+28.5	+17.9	+4.9	+18.1
H4	-13.9	+24.9	+14.1	+12.9	+28.8

Table 7.75 Comparison of Test Fuel Results with Average Ref

+ = Better performance than Average Ref at specified rpm.
- = Worse performance than Average Ref at specified rpm.

The comparisons were of course performed in this inital study with one engine. The correct comparison in future work of brake power, %CO_2, %CO, %HC and smoke number (%) should be compared per unit of energy generated.

7.6.6 Technical Assessment

Previous work by Antonini[128] at Compiegne University of Technology, using coal-oil-water slurries, involving experiments conducted on a 1.5 litre Lister-Petter monocylinder diesel engine, produced brake power output data in line with the results obtained in this study. Earlier work carried out using coal-oil-water slurries[129] also confirmed lower levels of exhaust pollutant emissions compared with mineral oil fuels. The results obtained from the use of bio-ultracarbofluid test fuels confirmed expectations of slightly lower brake power outputs but greatly reduced exhaust pollutant emissions as compared with diesel fuel.

7.6.6.1 Charcoal Properties

There is, in theory, no reason why bio-ultracarbofluid cannot be formulated to produce an equivalent brake power output to mineral diesel fuel. From the experimental results it is clear that the higher the volatile content and proportion of charcoal in the bio-ultracarbofluid, the greater the brake power output. Charcoal A had the highest volatile content of 27.2%. However, charcoals from certain species of trees can contain upto 40% volatile content e.g. American Redwood. If charcoals from these were used in the experimental programme then higher brake power outputs would be obtained.

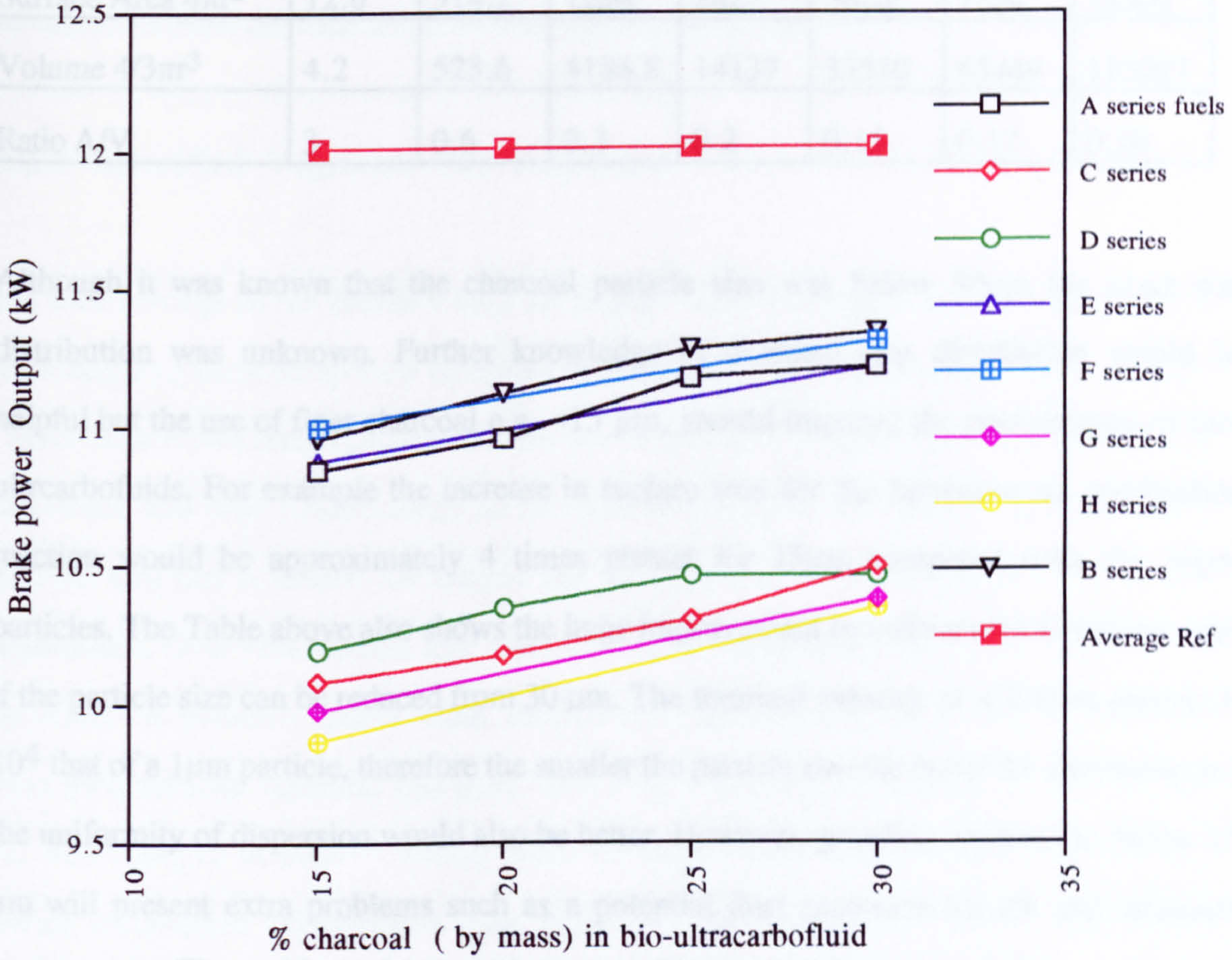

Figure 7.47 Brake Power versus % Charcoal in Bio-ultracarbofluid

Figure 7.47 suggests that if the extrapolation to higher charcoal contents (e.g. 45%) were practicable, by finer grinding and the use of appropriate viscosity improvers, the power output of a bio-ultracarbofluid formulation could match that of diesel oil.

The use charcoal A or B produced different power outputs and exhaust emissions results. Although this was expected, the magnitude of the difference in results as between charcoal A and B was surprising. Clearly therefore, in this test programme charcoal A present at 30% by mass in the bio-ultracarbofluid demonstrated optimum performance.

Particle radius r (μm)	1	5	10	15	20	25	30
Surface Area $4\pi r^2$	12.6	314.2	1256	2827	5026	7854	11309
Volume $4/3\pi r^3$	4.2	523.6	4188.8	14137	33510	65449	113097
Ratio A/V	3	0.6	0.3	0.2	0.15	0.12	0.10

Although it was known that the charcoal particle size was below 30μm the exact size distribution was unknown. Further knowledge of charcoal size distribution would be helpful but the use of finer charcoal e.g. <15 μm, should improve the performance of bio-ultrcarbofuids. For example the increase in surface area for the hetrogeneous combustion reaction would be approximately 4 times greater for 15μm compared with the 30μm particles. The Table above also shows the huge improvement in surface area to volume ratio if the particle size can be reduced from 30 μm. The terminal velocity of a 100μm particle is 10^4 that of a 1μm particle, therefore the smaller the particle size the better the dispersion and the uniformity of dispersion would also be better. However, grinding charcoal to below 15 μm will present extra problems such as a potential dust explosion hazard and increased energy costs. The problem of dust explosion could be reduced by the addition of 1% oil to charcoal, prior to grinding. This agglomerates the very small size particles produced, reducing the risk of dust explosion.

Some consideration can be given to charcoal particle shape. Although the charcoal particles used in this experimental programme were sphere shaped, it is envisaged that the use of charcoal flakes, will result in charcoal particles giving a larger surface area per unit mass, thereby producing better combustion and hence, brake power. Also the smaller settling velocity of flaked charcoal particles would result in a more homogenous suspension in the oil-water mixture.

A method of improving charcoal property i.e. volatile content, could be to pre-condition charcoal by soaking it in a 'volatile' liquid before mixing. In this way the performance of a low volatile content charcoal could be considerably enhanced.

7.6.6.2 Esterified Vegetable Oil Properties

Rape seed belongs to the Brassica seed oil family. These are made up of triacylglycerols, comprising a glycerol component esterified to three fatty acyl residues, the chemical nature of which determines the properties and end-use of the oil. The fatty acids can vary in their chain length and their functionality, i.e. the type of rape seed oil which is ideal for use as lubricants and fuel is termed the 'double low' variety, because it contains low erucic/ low glucosinolate. Over 98% 'double low' rape seed oil is made up of only five C16 and C18 fatty acids, i.e. palmitic, stearic, oleic, linoleic and alpha-linolenic fatty acids. Other high erucic/ glucosinolate rapeseed oils have very long fatty acid chain lengths e.g. C20 and C22. According to Mithen[130] methyl esters of double low variety offer a significantly superior combustion performance over other rape seed varieties. In the experimental programme the double low variety of methyl ester was used.

Whereas rapeseed oil is liable to self-heating, leading to spontaneous combustion when adsorbed onto a porous media this should present no problems with the bio-ultracarbofluid formulations because of the presence of substantial quantities of water. The same consideration applies to the charcoal which remains suspended in liquid, i.e. it is not freely-exposed to oxidation.

Esterified soya oil exhibits very similar properties to esterified rape seed oil. The nett energy output of esterified soya (methyl soyate) oil was 37.8 MJ/kg and esterified rape seed (methyl rape) was 37.0 MJ/kg. Methyl rape has a viscosity of 3.89 cST and methyl soyate has a viscosity of 5.85 cST at 40^{O}C[131].

The use of other esterified vegetable oils would present severe practical problems. Palm oil methyl ester has a superior stability and ignition properties but solidifies at very low temperatures. Sunflower oil demonstrates poor stability problems. Castor bean oil presents severe viscosity problems at ambient temperatures .

7.6.6.3 Use of Additives in Bio-ultracarbofluids

Despite the routine application of surfactants in slurry fuels production, little is known about their influence on the atomisation process and on the behaviour of slurry droplets upon entering the high temperature environment of the combustion chamber. Work carried out by Rankin[132], suggests that using coal particles below 15μm together with a surfactant, such as ammonium naphthalene sulphonate (Diamond Shamrock), results in an improved combustion performance of slurry fuels. The three main conclusions of this work were; (i) once the coal/water slurry enters the combustion chamber, the coal/water slurry agglomerate remains intact after the slurry water has evaporated, (ii) the dispersant additive contributes to the agglomerate stability by forming a smooth shell around it and (iii) the properties of combustion are determined by the formation of this shell around the agglomerate. Hence, future research into the formation, and effect, of the shells formed around the slurry-charcoal agglomerate by different surfactants, could lead to the production of specific surfactants for use in the bio-ultracabofluids to improve combustion and therefore brake power output.

The additives used in this experimental programme were low-cost, readily-available, BASF Emulan P and Albright & Wilson Colgan. Future research using ammonium naphthalene sulphonate (Diamond Shamrock) additive could improve bio-ultracarbofluid's performance.

It would of interest to investigate the effect of such surfactants upon phase inversion, i.e. producing a fuel in which water is suspended in oil.

7.6.6.4 Viscosity Index (VI) Improvers

Viscosity index (VI) improvers can be used to lower the viscosity of high charcoal content (i.e. greater than 40% by mass) bio-ultracarbofluids. There are many different types of VI improvers and all are used in very small quantities (i.e. 0.5%). The effects of VI improvers on the test parameters of the bio-ultracarbofluids are unknown and would therefore, need to be determined.

7.6.6.5 Engine Modifications

Takeuchi et al (1985)[133] have shown that increasing the compression ratio of a diesel engine from 18:1 to 19:1 led to a substantial decrease in the level of hydrocarbon (HC) emissions. However, the other consequences of increasing compression ratio are usually an increase in noise and smoke level. Stone[134] states that an increase of compression ratio in a diesel engine results in reduced fuel economy and loss of efficiency. The timing of fuel into the combustion chamber is maximised for mineral diesel fuel. Because of the slightly higher viscosity of bio-ultracarbofluids it is envisaged that introducing the fuel earlier into the chamber (i.e. changing the timing e.g. by 3 degrees) will result in improved combustion.

7.6.6.6 Pre-heating Bio-ultracarbofluids

Pre-heating of a bio-ultracarbofluid in the fuel tank, could allow the use of a higher charcoal content in the test fuels. Pre-heating could therefore be an alternative method to solving the viscosity problem associated with the use of high charcoal content (i.e. greater than 40% by mass) in the bio-ultracarbofluids. This may be done by recirculating exhaust heat or by placing a heater in the fuel tank e.g. similar in principle to the glow plugs presently used in the combustion chamber of diesel engines.

7.6.7 Assessment of the Potential of Bio-ultracarbofluids

The technical factors, discussed in 7.6.6, show that all the major problems associated with the use of bio-ultracarbofluids in standard diesel engines have been overcome.

Other factors which determine the potential use of bio-ultracarbofluids in the EU and U.S are ;

(a) Crude oil price
(b) Pollution legislation
(c) Financial support for crop-growing
(d) Taxation policy on fuel

7.6.7.1 Crude Oil Price

For any alternative energy source to succeed commercially the price has to be competitive in comparison to an equivalent fuel derived from crude oil. The price of commercially-traded crude oil (Rotterdam Spot Price) has varied considerably over the last 30 years from a low of $4 per barrel in January 1973 to $37 per barrel in June 1980; the price stabilised at $17 per barrel for the year 1995. At this price of crude oil, the incentives to use bio-ultracarbofluids are, on a purely commercial basis, unattractive. However, the unpredictability of the oil market was again shown by the sudden rise in the price of a barrel of crude oil to $23 in March 1996. At $22 and above, the proposition of using bio-ultracarbofluids becomes a much more viable alternative.

7.6.7.2 Pollution Legislation in the EU and U.S

New stricter EC laws have been drafted and enforced to reduce harmful exhaust emissions from vehicles and industrial plants. Of particular concern have been CO_2 emissions resulting in the 'greenhouse' effect, and SO_x and NO_x emissions which, in combination with rain, produce 'acid rain'. Other reductions are required in harmful exhaust emissions from vehicles e.g. carbon monoxide, hydrocarbons (HC's) and smoke particulates.

Recent concern relates to one particular pollutant from diesel engines, viz. particulate matter less than 10μm in diameter. Characteristically the variation of the ability to inhale particulate matter, so that it is available for deposition in the respiratory tract is[135],

Particle diameter μm	0	10	30	60	100
% Inhalable	100	77.4	58.3	51.4	50.1

The variation of 'respirable' dust (i.e. that fraction able to penetrate into the lower respiratory tract) with size is,

diameter μm	0	2	3	4	5	7	8
% Inhalable	100	96.8	80.5	55.9	33.4	10.9	3.2

Hence the importance of the fraction <10 μm in size.

The PM_{10} particles are known to be carcinogenic but the mechanism of action in the human body is unknown. American evidence, from the Harvard School of Public Health[136], suggests, that whilst its precise extent is uncertain, the broad-linking of particulate levels to death rate is accurate. An extrapolation of American results suggests 10,000 extra deaths per annum due to PM_{10} emissions in the UK. These results should be treated with caution as many factors in Britain are different from the US. e.g. the diet, exercise level, the exposure to pollutants and other factors which differ between the two counties; (e.g. driving habits, weather conditions and different diesel fuel specifications).

A reduction in these pollutants by the use of bio-ultracarbofluids could however be of significant benefit to the environment. The evidence suggests that the use of bio-ultracarbofluids will be able to meet the strictest EC laws for exhaust emissions.

7.6.7.3 Financial Support for Crop-Growing

In the 20 years from 1971 to 1991 the production of edible fats and oils has increased from 50.2 to 84.9 million tonnes per year world-wide. Soyabean oil remains the primary source with 20% of the total edible oil market; palm oil and rapeseed oil are the next most-produced edible oils[137]. At an increase of just over 3% per annum, production of vegetable oils in the EU has been strongly influenced by the Common Agricultural Policy of set-aside. In the set-aside scheme farmers are paid not to grow food crops on part of their land but to use this for non-food production. The US. and Canadian governments operate similar schemes to set-aside for their farmers.

For any successful introduction of bio-ultracarbofluids, the set-aside scheme will be central to its development.

7.6.7.4 Taxation Policy on Fuel

Research into renewable energy systems is being undertaken by EU states in order to find alternatives to fossil fuels. Biomass is only one of several options under consideration. The Non-Fossil Fuel Obligation (NFFO) encourages research and use of other renewable energies such as from; wind, hydro, solar, landfill and sewage gas.

The excise duty payable on transport fuel has been harmonised across EU, and this includes bio-diesel. Table 7.74 shows a comparison of diesel, bio-ultracarbofluid and biodiesel production[138], taxation and retail prices.

	Diesel pence/litre (p/l)	**Biodiesel p/l**	**Bio-ultracarbofluid p/l**
Production Price	7.70	20.0	17.9
Distribution	6.57	3.94	3.94
Excise	30.70	30.70	30.70
	44.97	**54.64**	**52.54**
VAT @ 17.5%	7.87	9.56	9.20
	52.84	**64.20**	**61.74**
Retail margin +VAT	4.14	4.14	4.14
Total Retail Price	**56.98**	**68.43**	**65.88**

Table 7.76 Comparison of Diesel, Bio-ultracarbofluid and Biodiesel Retail Prices 1995.

From Table 7.76 the price of bio-ultracarbofluid is 3.7% lower than biodiesel per litre. However, biodiesel is already sold in Europe at 12.5p higher than mineral diesel fuel per/litre. This difference is overcome by countries such as Germany, France and Italy by exempting the excise duty on biodiesel under the Scrivenor Directive. This Directive may be used under European Law so long as the policy objectives are sound and that it does not cause market distortions. The justifications are as follows.

1) The development of sustainable (renewable) energy systems to extend the life of the world's fossil reserves.

2) The reduction of atmospheric emissions due to combustion of fossil fuels.

3) A reduction in economic dependency associated with the import of crude oil from politically-unstable regions.

4) The re-deployment of land that is no longer required to satisfy the EU's food and fibre markets.

5) The creation of new jobs in the production of bio-renewable fuels.

Another mechanism under consideration to overcome the difference is the so-called 'carbon tax'. The carbon tax under consideration involves a 5% excise duty on all fossil fuels. However Carruthers[139] believes the introduction of a carbon tax will have no immediate relevance to the use of bio-renewables fuels due to political resistance and the long-time scale of implementation.

Chapter 8

CONCLUSIONS AND RECOMMENDATIONS

CHAPTER 8

8.0 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The diesel engine and associated equipment performed satisfactorily for the comparison of the performance of bio-ultracarbofluids with the reference fuels (Average Ref) in the experimental programme. The analytical methods used e.g. viscosity determination, ultimate analysis of charcoals, and determination of the energy content of various vegetable oils gave reproducible results. Some limitations arose because the exact origin and chemical compositions of the esterified vegetable oil used were not known. As discussed in section 7.6.6.2 the different fatty-acid compositions from which vegetable oils are made can affect combustion and emissions. It would have been useful to be able measure corrosion and coking of engine components as proposed for future work in section 8.1 .

The results obtained with bio-ultracarbofluids show that they can be used in a diesel engine without it requiring modification, and produce less pollutants than Average Ref with a slight loss of power depending on the formulation used. (Extensive running trials would of course be required before adoption in order to prove to engine manufacturers that bio-ultracarbofluids could be used over the life of an engine without fall-off in performance or excessive wear).

The results provide an initial basis for the specification of a bio-ultracarbofluid to give optimum performance. The type, and amount, of charcoal used in the bio-ultracarbofluids was identified as the major factor affecting torque output and the levels of emission of exhaust gases namely CO_2, CO, HC and smoke emissions. Charcoal A with a high volatile content produced significantly better brake power output and less exhaust pollutants than charcoal B. In comparison with reference diesel fuel Average Ref the brake power output was 6.2% lower with all the formulations containing 30% charcoal A by mass at 3000 rpm. All formulations containing 30% charcoal B by mass produced 13.3% lower brake power output than Average Ref at 3000 rpm.

Formulations containing either charcoal A or B resulted in reduced CO_2, CO, HC and smoke emissions compared with reference mineral diesel fuel, Average Ref. Formulations of bio-ultracarbofluids containing charcoal A produced significantly lower CO, HC and smoke emission levels than test fuels containing charcoal B. The levels of CO_2 emissions with test fuels containing charcoal A were higher than those containing charcoal B but again significantly lower than Average Ref as summarised in Table 7.75.

The type of modified vegetable oil used i.e. oil A (methyl rapeseed) or oil B (methyl soyate) were minor factors affecting the brake power output and exhaust emissions. The bio-ultracarbofluid formulations which contained methyl soyate oil produced higher brake power output than those which contained oil A (methyl rapeseed). The exhaust emissions output varied only slightly with the use of oil A or B. The choice of oil also had only a marginal effect upon the exhaust emissions, with oil B showing slightly lower levels of CO_2, CO, HC and smoke emissions. The data are summarised in Table 7.75 .

The use of the two different additives had no effect whatsoever upon brake power output or the level of exhaust emissions from any of the bio-ultracarbofluids. This was expected since the additives were present at only 1% by mass and, apart from their normal detergency properties, they will not be involved in other interactions.

The results show that in order to obtain the highest brake power output and lowest exhaust emissions from the range studied the bio-ultracarbofluid must contain charcoal A at 30% by mass, oil B (methyl soyate oil) and either additive A or B.

The economics of using bio-ultracarbofluids as compared to mineral diesel fuel are currently unfavourable[140]. The calculations show that the price of bio-ultracarbofluids at the retail level will be 12.5p per litre more than that of mineral diesel oil. However, the use of bio-ultracarbofluids offers many other benefits i.e. the fuel is completely bio-renewable, and the major exhaust pollutants are all significantly reduced. Furthermore on spillage 98% of bio-ultracarbofluids degrade within 21 days, whereas only 73% of the mineral diesel degrades within this period.

Clearly the study was exploratory in nature and useful areas of future work, covering technical investigations and economic evaluation, are suggested in section 7.8 . In such work the trade-off between various pollutants per unit of energy produced will require careful comparison.

8.2 Economic Evaluation

The economic costs of producing the bio-ultracarbofluids are greater; hence there will be no incentive for their use unless stricter environmental and agricultural policies are imposed in the future. However, the possible immediate environmental benefits from their use are immense, and their strategic and bio-renewability advantages can more than offset the short term economic priorities.

A comprehensive study of the costing of producing bio-ultracarbofluids needs to be carried out, although as noted in 7.6.7 various studies of bio-diesels confirm that bio-diesel is on average 12.5p per litre more costly than mineral diesel fuel. The cost of charcoal by mass is 8% cheaper than bio-diesel and as a consequence bio-ultracarbofluids are 3.7% cheaper than bio-diesel fuels as no extra problems are envisaged in the mixing stage. The study should concentrate on supplying a niche market e.g. 100,000 gallons in the first year, within suitable selected areas at an easy transportation distance from the production plant. Moreover the proper comparison should be between kJ/litre, or kilometres/litre using a specific vehicle. The costing should include production, transportation, taxes and retail profits. This trial should give a clear understanding of any further work required.

8.3 Future Work

8.3.1 Future Work With The Present Equipment

The results obtained with the selected bio-ultracarbofluid formulations used clearly show that their use in a standard unmodified diesel engine is perfectly feasible. The potential for their future use in existing diesel engines without major technical modifications is therefore reasonably promising. More work needs to be done to determine their effects on engine components, particularly fuel lines and injectors, in the long-term. Of special interest should be the corrosion and coking of the injectors in the engine.

components, particularly fuel lines and injectors, in the long-term. Of special interest should be the corrosion and coking of the injectors in the engine.

A logical test programme would be to study corrosion over 20 weeks using the accelerated corrosion method developed by Sidhu[141]. In this method a known amount of the test fuel (in this case bio-ultracarbofluid) is placed inside a flask, with the material to be tested for corrosion (e.g. injector nozzle) at ambient temperature. Aeration is carried out for 15 minutes, 6 times a day using a small pump. Visual observations are carried out every 4 days and the material weighed every week to determine weight loss or gain. Quantitative and qualitative assessments can be made of corrosion .

In preparation for future work a continuous fuel injection system has been designed[142] to investigate the injection of test fuels into an empty chamber. The equipment consists of a set of four ordinary Bosch diesel injectors connected in line with a high power fuel pump modified to run on 13 volts A.C. The equipment can be assembled and disassembled easily, and it can be run over 20 weeks, 24 hours a day. Coking of the injectors can be measured over time by dismantling injectors and using an electron microscope to photograph surfaces at regular intervals e.g. every week. The build-up of carbon can therefore be measured both quantitatively and qualitatively.

8.3.2 Future Work With Modified Equipment

The rig should preferably be modified by automating the data output to a computer. The results from such parameters as engine speed, torque, CO_2, CO, HC and smoke emissions can be directly recorded on the data-base at fixed intervals. The experimental error would thus be kept to a minimum and a greater quantity of data recorded quickly and accurately.

[The manual recording of data could take up-to three hours for one experiment, which is both repetitive and time-consuming.]

The tests were only performed at particular times in the week since the engine was situated in a pilot plant with many other test rigs. [If all rigs were running simultaneously a high noise level resulted when the engine was started]. Enclosure of the engine within a soundproof room will provide greater flexibility in the timing of experiments.

The measurement of particulate matter e.g. PM_{10} (Particulate matter less than 10 microns) will be very useful in future work as there is concern that ordinary mineral diesel fuels emit excessive amounts, which are harmful to the public in general. Hence it would be very useful to compare the emissions of PM_{10} from bio-ultracarbofluids. A comparison of SO_2 and NO_x measurements would also be useful.

8.3.3 Other Future Work

The performance of preferred bio-ultracarbofluids formulations, selected in the light of the discussion in 7.6.6., will need to be evaluated in a range of diesel engines since compression ratio, injection timing etc. will affect performance. Extended on-the-road trials will also be required.

Nomenclature

Nomenclature

	Symbol	Units
Air/Fuel (A/F) ratio	Λ	
Revolutions per minute		RPM
Particulate matter less than 10 microns	PM_{10}	μm
European Union	EU	
Millivolt output		mV
Brake power	BP	kW
Torque	T	Nm
Bosch smoke units		BSU
Gross heat of combustion	Hg	kJ/mol
Cetane Number	CN	
Higher heating value	HHV	kJ/kg
Lower heating value	LHV	kJ/kg
Compression ratio	CR	
The heat of formation of the reactants	$\Delta H'$	kJ/g mol

Appendix

Appendix

Typical Engine Test Measurements

Road Horse Power
Brake Power and Engine Torque
Indicated Power
Friction Power
Engine Efficiency
Mechanical Efficiency
Thermal Efficiency
Volumetric Efficiency
Fuel Consumption

Road Horsepower

This is the power available at the road wheels. It is less than the power available at the engine flywheel, since some power is lost through friction in the transmission, universal joints, differential and drive axles.

Brake Power and Engine Torque

The brake power (b.p) of an engine is the power available for work at the output shaft, and is measured using some form of brake e.g. a hydraulic dynamometer .

where, $L=$ length of dynamometer torque arm (metres)
$W=$ effective load on torque arm (Newton's)

then the torque transmitted by an engine,

$$T = W \times L \quad \text{Newton metres}$$

If the engine is running at N rev/min, then,

$$\text{Engine brake power developed} = \frac{2\pi NWL}{60} \quad \text{watts}$$

$$\frac{1}{K} = \text{brake constant}$$

K is a given constant for a given dynamometer.

$$b.p = \frac{2\pi NT}{60} \text{ watts}$$

Indicated Power (I.P)

The indicated power of the engine is the power actually developed in its cylinders. It is always greater than the brake power of the engine because there will always be some power losses between the cylinders and the output shaft. The difference between the two is the friction power.

Friction Power

Friction Power = Indicated Power - Brake Power

Indicated Power >Brake Power >Road Horse Power

Engine Efficiency

Engine efficiency is the relationship between the potential energy supplied and the amount of work done. Fuel contains a certain amount of potential energy, or ability to do work. The amount of work to be done is the movement of the vehicle along the road. During each step of the process of converting fuel to mechanical energy to rotate the wheels of the vehicle, energy is used. This usage occurs in many ways, such as mechanical, thermal, engine accessories, driveline friction, rolling resistance, air resistance and acceleration.

Mechanical Efficiency

Mechanical efficiency losses can be calculated by dividing engine power by indicated power to find mechanical efficiency. The loss is the amount of potential energy used to overcome the friction of the engine.

$$\text{Mechanical Efficiency \%} = \frac{\text{brake power}}{\text{indicated power}} \times 100$$

The mechanical efficiency is the ratio of the useful power available at the output shaft to the power developed in the cylinders. An average value for a petrol engine running at normal speed would be 80%. For a diesel engine the average value is 84%.

Thermal Efficiency

Since it is the heat that creates the pressure of the power stroke, any loss of heat results in a decrease in power. If all of the energy in a fuel were used to produce pressure, the thermal efficiency of the engine would be 100%. A motor vehicle engine cannot convert all the heat energy supplied to it from fuel into useful work; even in the most efficient engine, only one-third of the heat value of the fuel is converted into mechanical work done. Energy is typically lost as follows;

HEAT ENERGY of FUEL

- 35% lost in cooling water and oil
- 35% lost in exhaust gas
- 5% lost in engine friction
- 10% lost in power train friction
- 15% Remains to propel car

The thermal efficiency gives an indication of how efficiently the fuel is being used in the engine.

Thermal efficiency is the ratio:

$$\frac{\text{Heat energy equivalent to work done/second}}{\text{Heat energy supplied from the fuel /second}}$$

Brake thermal efficiency is based on the brake power of the engine.
Thermal efficiency depends upon :

1) Mixture strength
2) Compression ratio
3) Engine speed
4) Throttle opening
5) Valve timing
6) Ignition timing
7) Type of fuel used
8) Engine dimensions
9) Combustion chamber design and dimensions
10) Inlet charge temperature
11) Cylinder temperature

Volumetric Efficiency (Ve)

The Ve of an internal combustion engine is the ratio of the actual volume of charge admitted into the cylinder at standard temperature and pressure (S.T.P) during the suction stroke to the volume swept through the piston (See Figure A.1).

Ve is sometimes defined as the ratio of the mass of charge actually admitted into the cylinder to the mass of the charge which would completely fill the swept volume S.

In an unsupercharged engine the Ve very rarely exceeds about 80%. Its actual volume depends upon a variety of factors among the more important of which are;

1) Engine speed
2) Compression ratio
3) Inlet charge temperature
4) Mixture strength.

Other influencing factors are those of induction and exhaust system layout, valve area, valve timing, throttle opening and cylinder temperature.

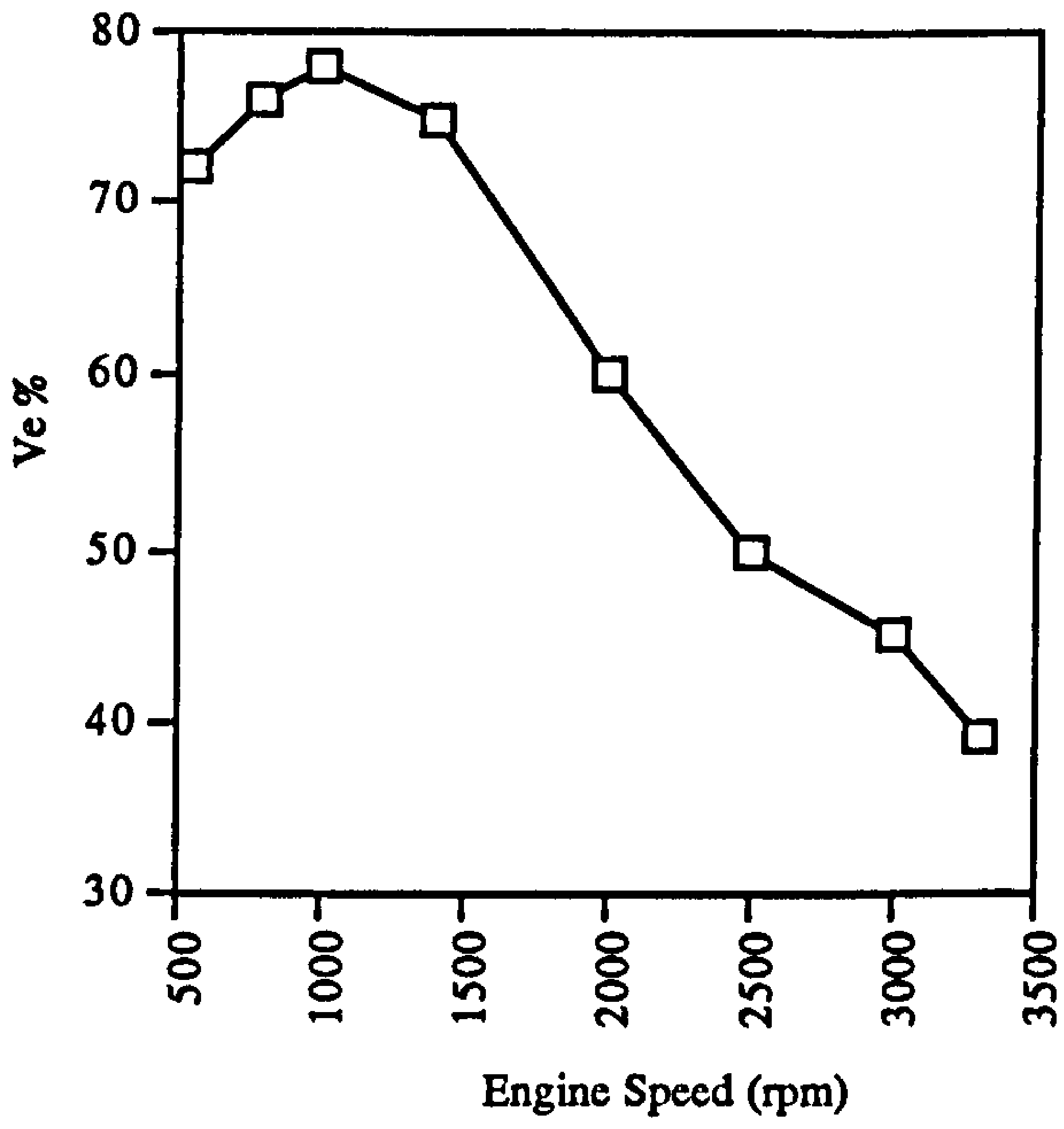

Figure A.1 Ve vs Engine Speed

Figure A.1shows that at low speeds the Ve is less than its maximum value. This is due chiefly to the valve timings being designed for a moderately high speed. Beyond its maximum value, it decreases more and more rapidly as the speed rises. This falling-off at high speeds is due mainly to increase in the frictional resistance in the inlet passages and the excessive heating of the incoming charge, resulting in a reduced mass of fresh charge entering per cycle.

From a knowledge of air consumption the Ve of an engine can be calculated.

$$Ve = \frac{\text{Actual volume of air consumed /min}}{\text{Theoretical volume of air/min}} \times 100\%$$

Theoretical volume of air consumed/min,

$$\text{Total swept volume} \times \frac{\text{rev/min}}{2}$$ --------(no of strokes consuming air out of 4)

Total swept volume of engine = Area of cylinder x Stroke x No. of cylinders

Fuel Consumption

A knowledge of the amount of fuel consumed by a motor-vehicle engine in a given time is very essential when assessing the qualities of that engine. Vehicle-users assess fuel consumption in terms of kilometres per litre, but engine designers, compare the fuel consumption of different engines by the amount of fuel used over a period at fixed load. The latter is referred to as the specific fuel consumption, and depends upon the calorific value of the fuel used.

Assuming complete combustion, the heat generated per unit mass of fuel is equal to the calorific value. This is typically 4300kJ/kg for petrol, 4000kJ/kg for diesel fuel and 5000kJ/kg for automotive gas.

$$\text{Indicated specific fuel consumption or Brake specific fuel consumption} = \frac{\text{Fuel consumed /hr}}{\text{Indicated power in kW}}$$

This gives the amount of fuel required in kg or in litres to develop an indicated power or brake power of 1kilowatt for a period of 1 hr at the load considered.

Example of Calculations

E.g. Table 7.01, experiment 1 at 1000 rpm

Total Torque = Output mV x Calibration Constant 9.92

$= 3.54 \times 9.92$

$= 35.1$ Nm

Brake Power P_b

$$\text{Brake power} = \frac{\text{Total Torque x Angular Velocity}}{\text{Brake Constant}}$$

$$\text{Brake power} = \frac{35.1 \times 1000}{9549.3}$$

Brake Power = 3.68 kW at 1000 r.p.m.

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Publications

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- **The Performance of Biomass Derived Bio-ultracarbofluids In Standard Diesel Engines**

  Paper presented at;
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  Washington D.C.
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- **Potential Applications of Biomass-Derived Bio-ultracarbofluids in Diesel Engines.**

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- **DIRECT UTILISATION OF BIOMASS-DERIVED BIO-U.C.F. (BIO-ULTRACARBOFLUIDS) IN A STANDARD DIESEL ENGINE**

  Paper presented at;
  The 4th International Symposium on Advanced Materials
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THE PERFORMANCE OF BIOMASS DERIVED BIO-ULTRACARBOFLUIDS IN STANDARD DIESEL ENGINES

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Keywords: Bio-ultracarbofluids, Diesel fuel replacement.

Introduction

The impetus for the replacement of petroleum-derived diesel fuels, whether wholly or partially, arises from the need to conserve a non-renewable energy resource and because of the significant pollutants generated by their combustion. However the use of bio-mass derived fuels may also offer strategic and economic advantages.

The majority of the world's energy resources occur in nature as solids e.g. coal and various biomass and waste materials. Bio-fuels such as wood, charcoal and agricultural residues are a major source of energy in many of the developing countries providing as much as 14% of the current world energy requirements. This is equivalent to some 25 million barrels of oil a day, the same as OPEC's current production(1). World-wide there is substantial land potentially available for growing energy crops.

The possibilities for diesel fuel replacement are;

(i) Complete replacement by a suitable vegetable oil e.g. rape seed oil(2), soya bean oil(3), esterified sugar beet extract(4). Some research is also in progress into the use of elephant grass oil (Miscanthus)(5).

(ii) Partial replacement by blending diesel with vegetable oils in varying proportions upto 20% by weight(6).

(iii) Partial replacement by blending with an aqueous suspension of a non-renewable fossil fuel e.g. coal(7).

(iv) Complete replacement by a slurry of coal in vegetable oil.

or

(v) Complete replacement by a 100% bio-renewable ultracarbofluid. This could comprise some formulation of water, charcoal and a vegetable derived oil.

The research summarised here is concerned with the last alternative.

Biomass-Derived Bio-ultracarbofluids

Typically biomass derived bio-ultracarbofluids consist of charcoal 45%-54%, oil-blend 16%-29%, water 30%-35%, surfactant 1%, plus corrosion inhibitors etc. in trace amounts. The solid constituent is of necessity finely-divided and in practice needs to be ground to <30μm particles in order to minimise erosion in the fuel system i.e. transfer lines and injectors. Clearly low ash charcoal is preferable for optimum energy efficiency but also mainly to keep residue build-up in the engine to a minimum. The higher the proportion of charcoal in the blend the greater the gross energy output.

The possible replacement of the fuel oil fraction, typically 15% to 30%, by a bio-renewable vegetable oil is of considerable interest. Several commercially available oils have been tested as fuel components. Using ordinary vegetable oils as fuel usually results in problems with severe engine deposits, ring sticking, accumulation of deposits on injector nozzles and lubricant contamination. For this reason vegetable oils for use as fuel or fuel component have to be modified by trans-esterification. Rape seed methyl ester shows great potential for use as fuel or as a fuel component for diesel engines.

The ultimate test for any fuel is to determine how well it burns over long periods of time, and the impact of its use on the combustion system and auxiliary equipment. However any blend can, of course, be characterised by conventional property measurements i.e. viscosity, cetane number, gross heat of combustion, cloud point, flash point, density, particle size and ash content.

Ultra-carbofluid (Ucf) Performance

Coal-water slurries have been studied extensively as fuels. Initial results confirmed that the main problems encountered when using coal-water slurries are, with fuel injection system operability, wear and poor combustion efficiency of the coal particles.

However, improvements have been recently been reported in reduced wear of injection components, by the addition of lubricant(8).

Bio-ultracarbofluids

Initial research on ultracarbofluids utilised a 4-stroke single cylinder, indirect injection diesel engine with a speed range of 650-800 rpm. The optimum performance has been achieved using coal 40%, water 30%, fuel oil 29%, additive 1%. The operating variables were;

-coal particle mean diameter :	8 μm
-injection timing :	42 degrees BTDC
-injection pressure :	12.5 MPa
-intake air temperature :	313 K
-intake air pressure :	0.22MPa

Specimen results in comparison with standard diesel fuel oil are given in Fig 1.

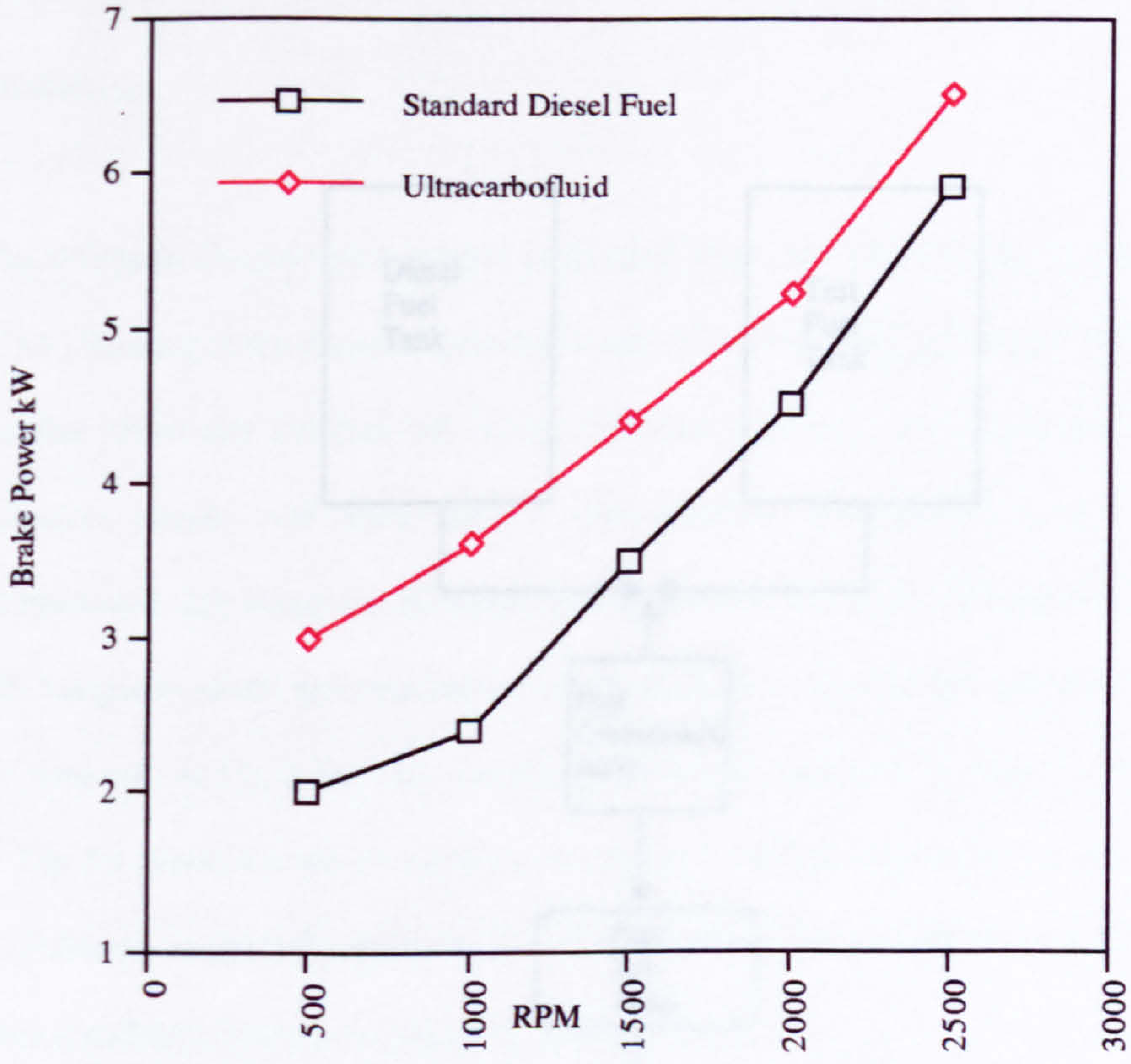


Figure 1 Brake Power Output of Ultra-carbofluid and Standard Diesel Fuel

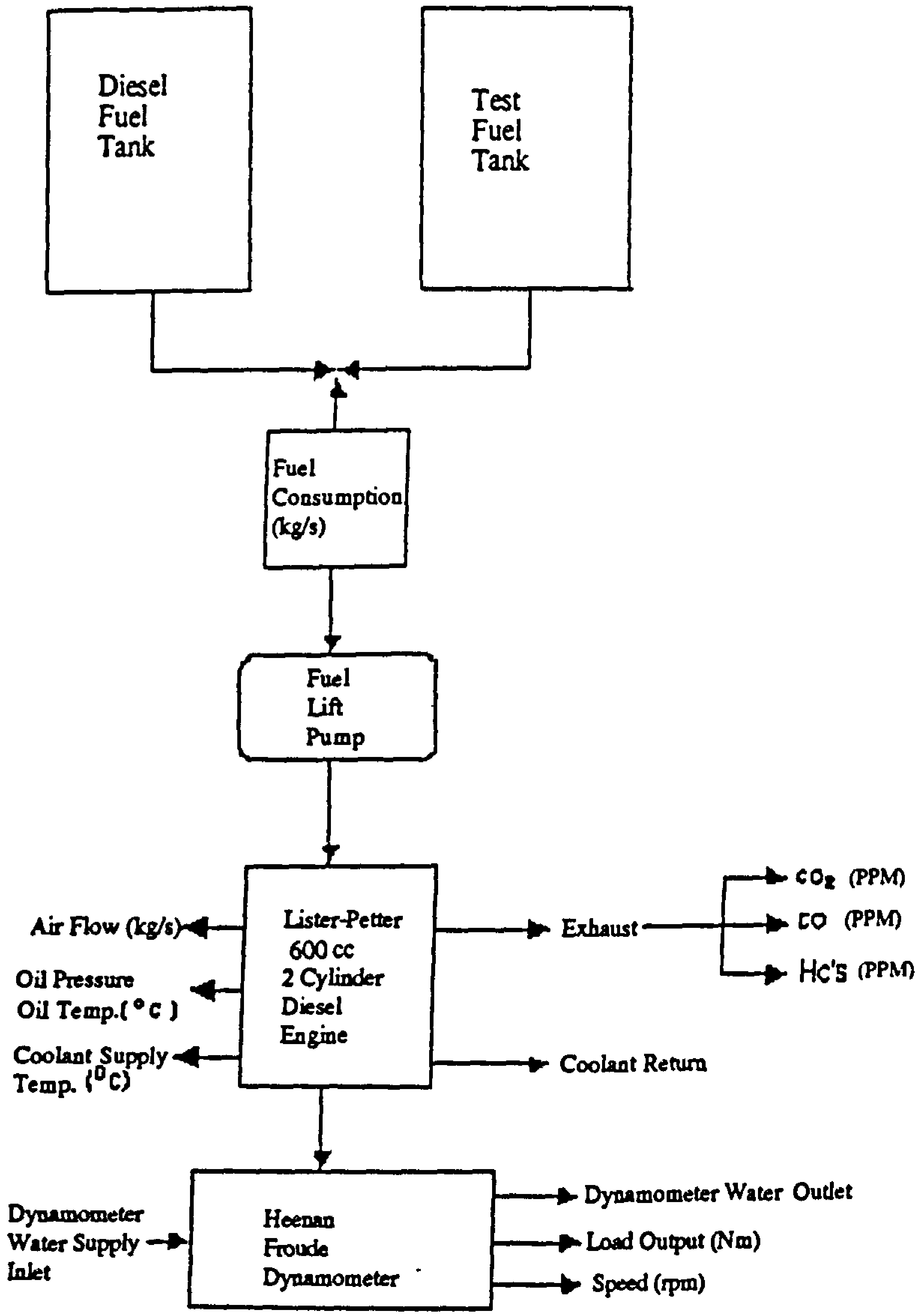
The present research utilises a 4-stroke, 2 cylinder 600cc Lister-Petter diesel engine. A Heenan Froude hydraulic dynamometer is connected to the engine, as are auxiliary data collection apparatus as shown diagrammatically in Figure 2.

The fuel formulations under investigation are based upon rape seed oil , peanut oil or sugar beet extract oil. Three different types of charcoal are under test. Also three different surfactants have been evaluated. In each case performance is compared with that of standard ordinary diesel .

The data obtained are;

engine torque	exhaust temperature
fuel consumption	oil temperature
air consumption	coolant temperature
speed	air temperature

Exhaust emissions are continuously monitored for levels of CO_2, CO and HC's levels.



<u>Engine Test Equipment Layout</u>

Economics

The European Community's interest in bio-fuel arises in part from the Common Agriculture Policy (CAP).Farming at the present represents nearly 5% of the aggregate Gross National Product of the EC member states and involves 9% of the workforce. Biomass crop production can contribute to this industrial activity and hence make a socio-economic contribution to rural development. Growing biomass will also avoid desertification of countryside. One tonne of crushed rape seed produces about 320 kilograms of oil, and charcoal is readily available commercially. Additives are more expensive but are used only as 1%. It has been calculated that bio-ultracarbofluids will cost 21p per litre as compared to 12p for diesel, on the assumption that the rape seed oil was grown on non-subsidised land. Hence preliminary estimates suggest that, with subsidies and economies of scale, the price of bio-ultracarbofluid could be comparable to diesel.

Conclusions

Results to date suggest that bio-ultrcarbofluids can be used in diesel engines without modifications. However the long term effects of corrosion, erosion and particle size on fuel handling systems require more detailed research using ASTM and EC test standards. The long term storage of the formulated fuels needs to be researched to see if this has any adverse effects such as oxidation of the oil components or settling of charcoal.

The EC is currently very keen to encourage the growing of energy crops since it will result in a reduction in the greenhouse gases, particularly CO_2, and reduce dependence on fuel imports. It would also encourage farmers to grow crops on set aside scheme. Hence there are good prospects for limited use of bio-ultracarbofluids. This would be greatly increased by direct or indirect state subsidies(9).

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Potential Applications of Biomass-Derived Bio-ultracarbofluids in Diesel Engines

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The substitution of non-renewable fossil fuels by biofuels could reduce harmful vehicle exhaust emissions, including greenhouse gases such as CO_2, and SO_2. Biofuels such as wood, charcoal and agricultural residues are already a major source of energy in many of the developing countries providing as much as 14% of the current world energy requirements(1). The potential to expand this by the replacement of diesel fuel using biomass-derived ultracarbofluids consisting of charcoal 45%-54%, oil blend 16%-29%, water 30%-35%, surfactant 1%, plus corrosion inhibitors etc. in trace amounts is discussed by reference to experimental data.

Introduction

The world's non-renewable energy resources are decreasing rapidly and may be exhausted within the foreseeable future. In response to this, and because of concern over the emission of harmful gases from vehicle exhausts and power stations into the environment, the technologically advanced countries have turned their attention to renewable energy resources. As a result, there have been significant advances in such areas as solar heating, cooling, wind generated power, ocean wave energy and biomass utilisation.

So far the discovery of fossil fuel reserves has more than kept pace with the demand. Known resources now exceed 10^{12} tonnes in total compared with just over half this amount 20 years ago(2). However alternatives will eventually be required. The current research is concerned with the partial or complete replacement of diesel fuel, which conventionally consists mainly of hydrocarbons chain length C_9-C_{11}, by a completely renewable solid-liquid fuel slurry.

Ultrcarbofluids (Slurry Fuels)

Coal-water slurries have been studied extensively as fuels for electricity generation and for diesel engines. Initial results for vehicle diesel engines confirmed that the main problems encountered with coal-water slurries are with fuel injection system operability, erosion and poor combustion efficiency of the coal particles. However, improvements have recently led to reduced wear of injection components, by the addition of lubricant(3).

Biomass-Derived Bio-ultracarbofluids

Typically biomass derived ultracarbofluids consist of charcoal 45%-54%, oil-blend 16%-29%, water 30%-35%, surfactant 1%, plus corrosion inhibitors etc. in trace amounts. The solid constituent is of necessity finely-divided and in practice needs to be ground to <30μm particles in order to minimise erosion in the fuel system i.e. transfer lines and injectors. Clearly low ash charcoal is preferable for optimum energy efficiency but also mainly to keep residue build-up in the engine to a minimum. The higher the proportion of charcoal in the blend the greater the gross energy output.

The possible replacement of the fuel oil fraction, typically 15% to 30%, by a bio-renewable vegetable oil is of considerable interest. Several commercially available oils have been tested as fuel components. Using ordinary vegetable oils as fuel usually results in problems with severe engine deposits, ring sticking, accumulation of deposits on injector nozzles and lubricant contamination. For this reason vegetable oils for use as fuel or fuel component have to be modified by trans-esterification(4). Rape seed methyl ester shows great potential for use as fuel, or as a fuel component for diesel engines.

An ideal fuel would require minimum modification to a conventional diesel engine design. However the ultimate test for any fuel is how well it burns over long periods of time, and the impact of its use on the combustion system and auxiliary equipment. However any blend can, of course, be characterised by conventional property measurements i.e. viscosity, cetane number, gross heat of combustion, cloud point, flash point, density, particle size and ash content.

Experimental

The preparation of bio-ultracarbofluids requires the homogeneous dispersion of the solid particulate fuel and the vegetable oil into water. The procedure followed in this work was;

1. Charcoal was ground to <30 µm by using a wet ball mill.

2. Charcoal and water were mixed at high speeds (2500 rpm) using a propeller stirrer.

3. Excess water was removed by decanting.

4. The oil blend (e.g. rape seed oil) and chemical additive were carefully weighed-into the charcoal water suspension. Dispersion in the charcoal suspension was achieved using high speed agitation as above.

Initial research on bio-ultracarbofluids utilised a 4-stroke Lister Petter two cylinder, indirect injection diesel engine with speed range of 800-3500 rpm. The parameters under investigation include fuel composition i.e.

component	*sample 1*	*sample 2*	*sample 3*	*sample 4*
Charcoal	35%	40	45%	50%
oil	29%	29%	29%	29%
Water	35%	30%	25%	20%
Additive	1%	1%	1%	1%

Charcoal ground to less than 30 microns was supplied by Cabot & Co. The oil was rape methyl-ester batch no. 025813 oil modified by Chemoxy Chemicals and the additive was BASF Emulan P detergent.

The optimum performance has been achieved using coal 40%, water 30%, fuel oil 29%, additive 1%. The operating variables were;

-coal particle mean diameter :20 µm -intake air temperature : 313 K
-injection pressure :12.5 MPa -intake air pressure : 0.22MPa
-injection timing :42 degrees BDC (Bottom Dead Centre)

Results in comparison with Esso diesel 2000 fuel oil are given in Fig 1.

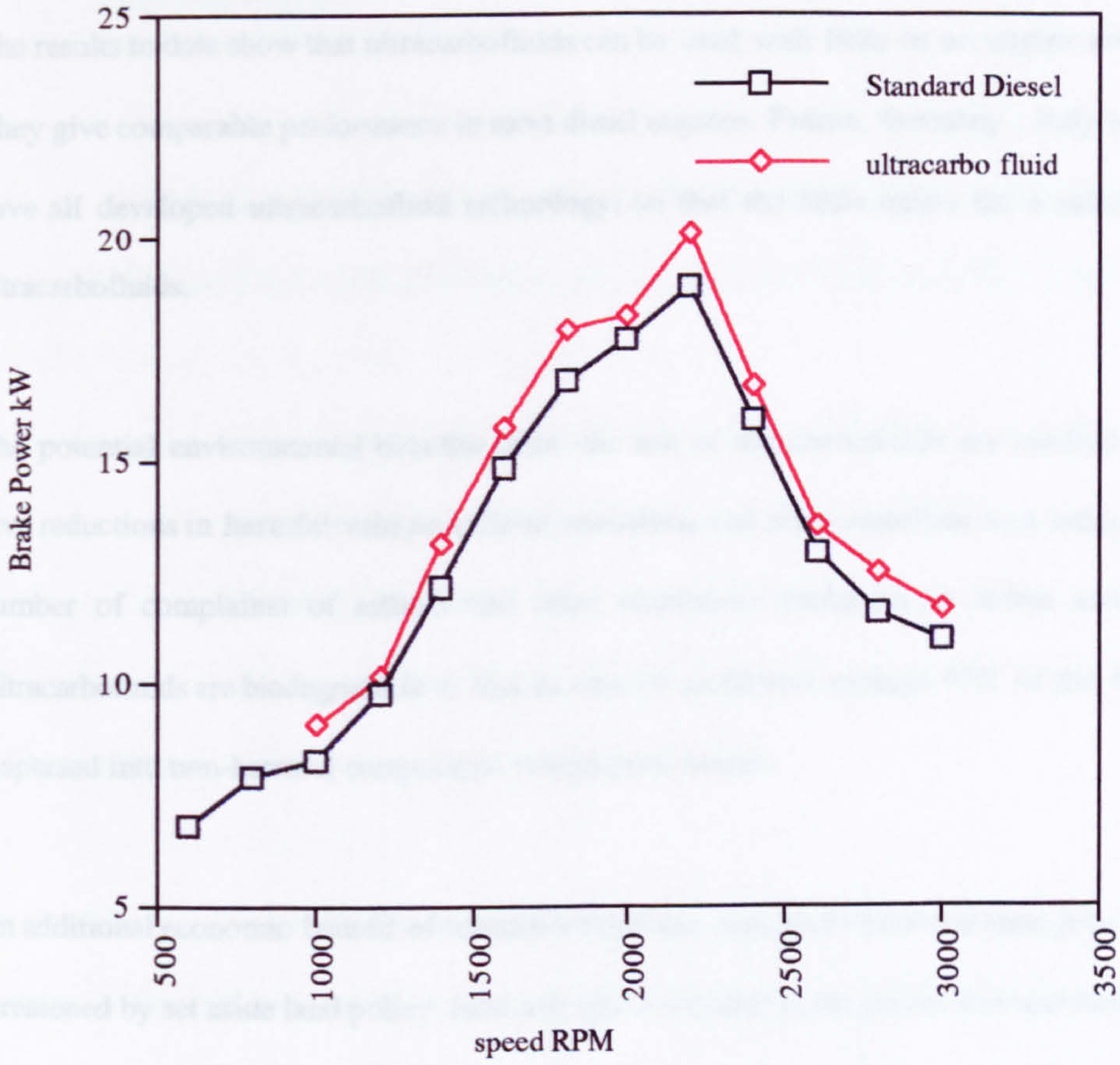

Figure 1 Speed vs Power Output of Lister Petter Diesel Engine

The emissions from a typical vehicle diesel engine are sulphur dioxide, carbon dioxide, carbon monoxide, hydrocarbons, nitrogen dioxide, smoke and particulates. Vehicle emissions in this work were measured by using Horiba Infra-red Gas Analysers.

A qualitative comparison between various samples is given in Table 1.

Sample	SO_2	CO_2	HC's	CO	Smoke*
1	Same	Lower	Lower	Lower	Lower
2	Lower	Same	Lower	Same	Lower
3	Lower	Lower	Lower	Lower	Lower
4	Lower	Lower	Lower	Lower	Lower

Table 1 Exhaust Emissions of Ultracarbofluids vs Conventional Diesel Fuel.

*(Smoke levels measured on the Bosch index)

Conclusions

The results to date show that ultracarbofluids can be used with little or no engine modification. They give comparable performance in most diesel engines. France, Germany , Italy and Austria have all developed ultracarbofluid technology, so that the basis exists for a transfer to bio-ultracarbofluids.

The potential environmental benefits from the use of ultracarbofluids are twofold. They can give reductions in harmful vehicle exhaust emissions and may contribute to a reduction in the number of complaints of asthma and other respiratory problems in urban environments. Ultracarbofluids are biodegradable so that in case of accidental spillage 97% of the fuel will be dispersed into non-harmful components within three weeks.

An additional economic benefit of ultracarbofluid use may be to preserve rural jobs, which are threatened by set aside land policy. Jobs will also be created in the production and distribution of the fuel.

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Introduction

The world's non-renewable energy resources may be exhausted within the foreseeable future. In response to this and because of concern over the emission of harmful gases, especially SO_2 and NO_x, from vehicle exhausts and power stations into the environment the technologically-advanced countries have turned their attention to renewable energy resources. As a result, there have been significant advances in such areas as solar heating, cooling, wind generated power, ocean wave energy and biomass utilisation[1].

As part of this strategy ultra-carbofluids which are typically composed of particulate charcoal, fuel oil, and water generally in the ratio of 5: 3: 2 by weight and a small amount of stabilising additive, may offer an alternative to diesel fuel in some circumstances. The charcoal may be produced by different pyrolysis techniques from various natural sources. Formulations usually contain charcoal at approximately 50% by weight and the particle size is usually in the range of <30 μm in order to remain in suspension, giving both reduced fuel delivery problems and efficient fuel combustion.

Obviously any formulated fuel oil must meet the minimum existing fuel specification standard. Progress made in assessing the technical performance and economic viability of bio-ultracarbofluids (Bio-ucf) has been reviewed by reference to experimental data. Many independent investigations [2,3] have been conducted in which slurry-fuelled engine operation was attempted.

These studies verified that the primary obstacles to coal/charcoal slurry fuelled diesel engine operation was the fuel injection system operability[4], engine wear, and poor combustion efficiency of the coal particles[5]. These may be overcome by using <20μm charcoal particulates.

The potential of bio-ucf appears to be as replacement for diesel fuel in medium speed engines. UCF can be inexpensive, safe to handle, and would utilise mainly existing infra-structure for transportation and storage. The present project was concerned with the evaluation of different bio-ucf formulae in an experimental rig consisting of a standard 600cc, 2 cylinder, 4 stroke Lister Petter diesel engine connected to a Froude dynamometer and various other data collection instruments[6] in order to monitor the performance and efficiency. The main exhaust pollutants of the UCF were monitored viz. carbon monoxide, carbon dioxide and hydrocarbon and particulates were monitored using two Horiba exhaust analysers (Mexa-321E which measured CO and HC content and the Mexa-211E which measured CO_2 content). The infrared technique allowed precise, selective measurement of individual exhausts-gas constituents process is based on the fact that infrared light is strongly absorbed by certain exhaust gas constituents at a characteristic wavelength which differs for each constituent. Particulate emissions were characterised by a Bosch Smokemeter.

Experimental/Method

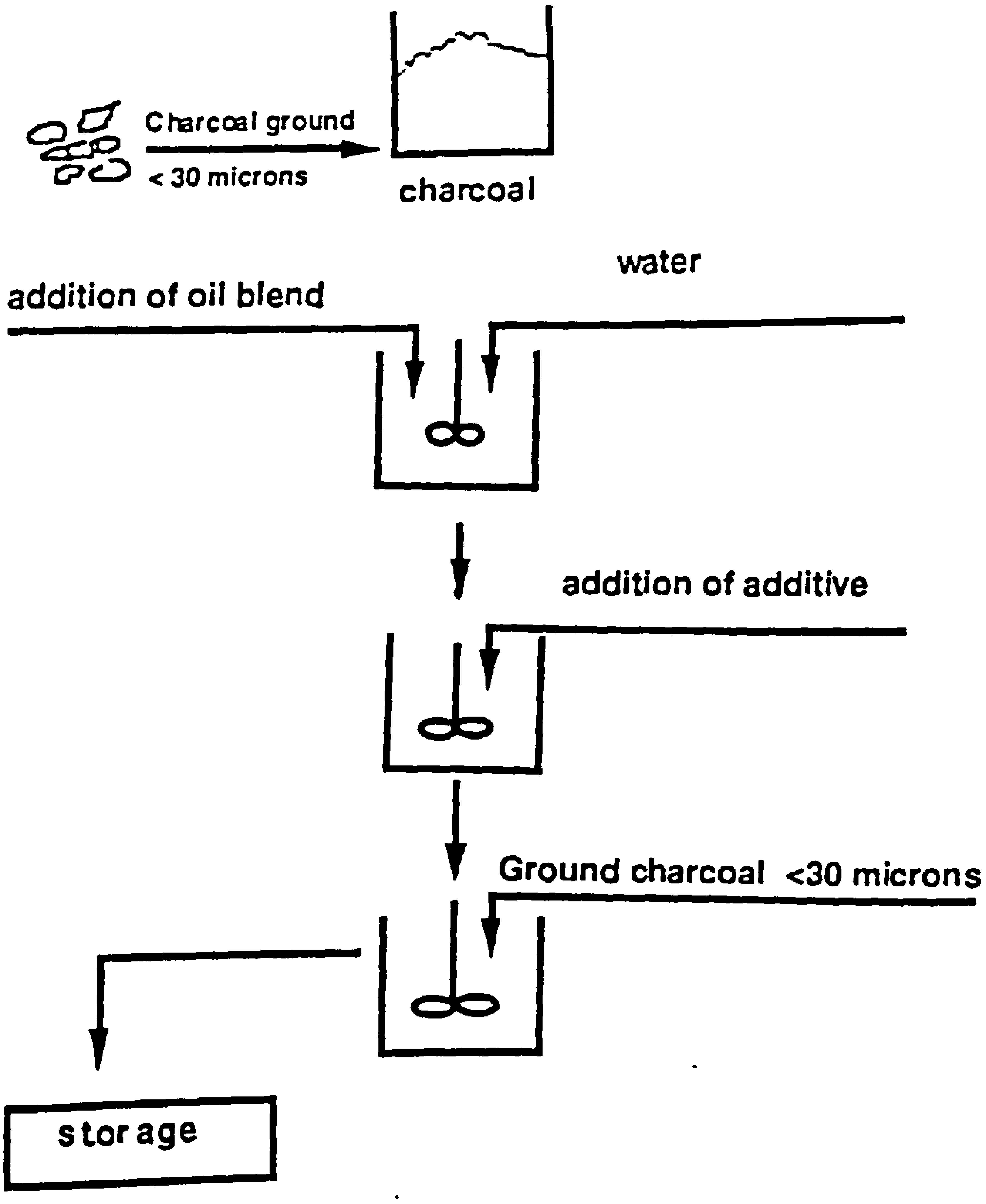
The procedure developed for bio-ultracarbofluid preparation, as illustrated in Figure 1, consisted of;

(i) Charcoal produced by Lambiotte method was ground to below <30 μm using a wet ball mill. [One of the best known processes for charcoal making is the Lambiotte method (Belgium) which uses a vertical retort which works on a continuous basis. Wood is loaded at the top and as it descends through the retort it is first dried by ascending hot gases in the top section, then carbonised by recirculating hot gases in the middle section, and finally cooled and withdrawn at the bottom].

(ii) Measured amounts (by mass) of oil blend (e.g. rapeseed, or soya etc.) and water were mixed at high speeds (2500 rpm) for 5 minutes.

(iii) A chemical dispersant (e.g. BASF Emulan-P or Albright and Wilson Colgan) was added as required to provide a stable suspension-emulsion.

(iv) Introduction of charcoal into the oil/water emulsion followed by high speed dispersion for 15 minutes.



Bio-ultracarbofluid Production Scheme

Six different formulations of bio-ultracarbofluids were made using the above method. Each formulation was tested within 24 hours of preparation. The proportion of oil and additive was kept constant while the charcoal/water ratio was varied as shown in Table 1. The viscosity of each fuel was measured using a Haake viscometer.

The test procedure was as follows:

The engine was first run using reference diesel fuel (Esso 2000 diesel) on a wide open throttle (WOT). The speed of the engine was controlled by slowly adjusting the load applied. After 15 minutes the engine was sufficiently warmed-up and the speed was set at 1000 rpm and test data recorded. The speed of the engine was increased by 200 rpm increments and further data recorded. The speed was increased upto a maximum of 3000 rpm. The engine speed was then reduced to 1000 rpm and the fuel supply switched over to bio-ultracarbofluid. The procedure was repeated for all six formulations.

Component Mass %	Charcoal	Oil	Water	Additive
Sample 1	15	30	54	1
2	20	30	49	1
3	25	30	44	1
4	30	30	39	1
5	35	30	34	1
6	40	30	29	1

Table 1 Composition of the Test Samples

Results

Typical results for the reference fuel are given in Table 2 and illustrated in Figure 2.

	Speed rpm	% CO_2	CO PP 10.000	HC's PP 10.000	Bosch Smoke No*.
1	1000	8.5	8.61	2.01	7.5
2	1200	8.7	7.83	1.95	6.4
3	1400	8.9	7.22	1.78	5.9
4	1600	9.2	6.97	1.69	5.5
5	1800	9.4	6.45	1.68	5.1
6	2000	9.7	6.91	1.7	4.2
7	2200	10.0	5.86	1.79	3.3
8	2400	10.1	5.54	1.85	3.0
9	2600	10.3	5.16	1.92	1.9
10	2800	10.5	4.73	2.01	1.5
11	3000	10.8	4.28	2.05	1.1

Table 2 Test Results for Reference Fuel

*Bosch Smoke Number: The density of smoke of the diesel engine was measured with the Bosch smoke meter. The measuring apparatus indicated the density in a range of White 0 to Black 10 according to reflection factor from a filter paper used to collect soot for a standard time.

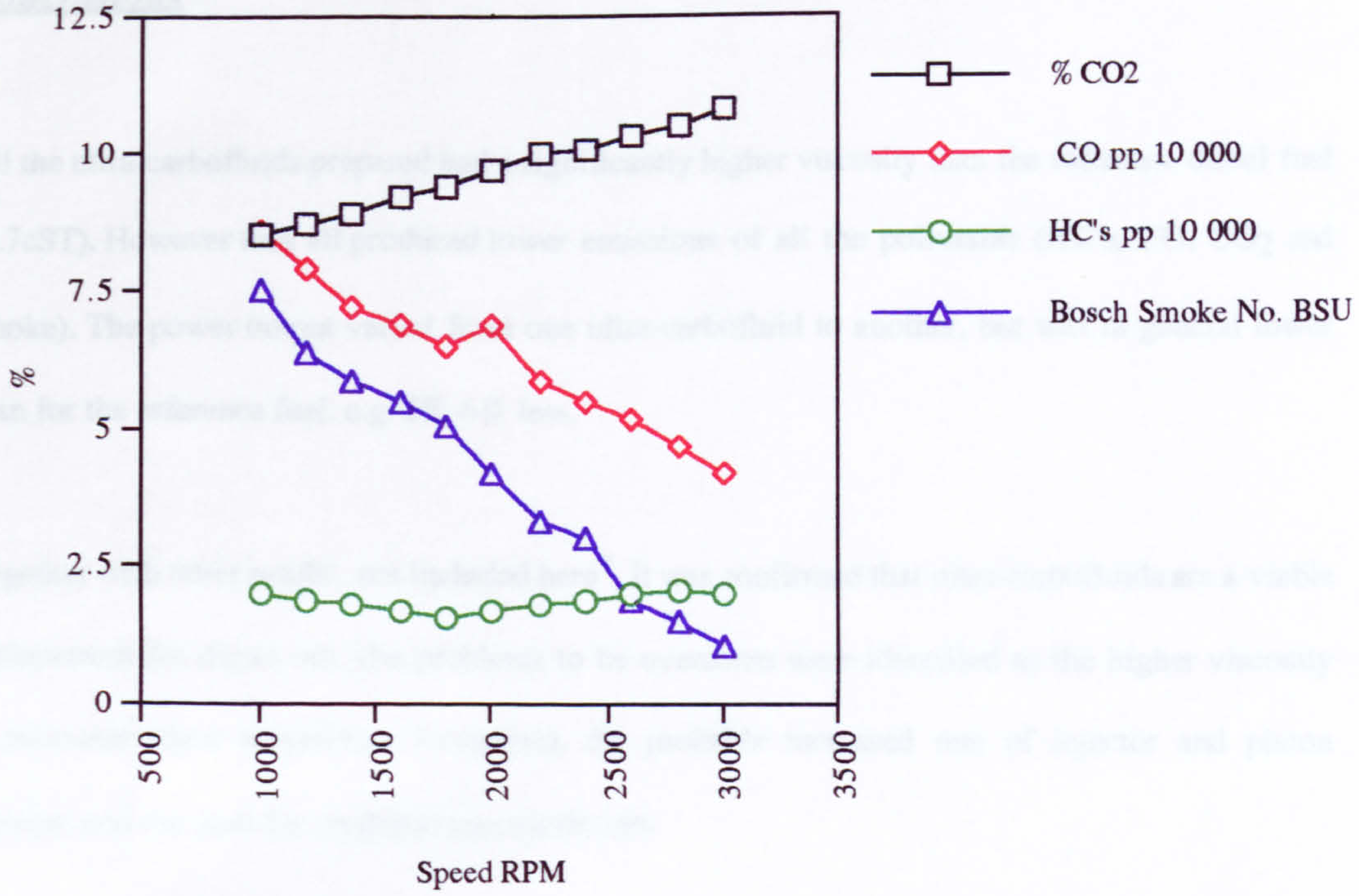


Figure 2 Plot of Test Results From Reference Fuel

These results follow the expected trends. Comparable results for the sample formulation given in Table 1 are summarised in Table 3.

Parameter	HC's	CO	CO_2	Viscosity	Torque	Smoke
Sample1	Lower	Lower	Lower	Higher	Lower	Lower
2	Lower	Lower	Lower	Higher	Lower	Lower
3	Lower	Lower	Lower	Higher	Lower	Lower
4	Lower	Lower	Lower	Higher	Lower	Lower
5	Lower	Lower	Lower	Higher	Lower	Lower
6	Lower	Lower	Lower	Higher	Higher	Lower

Table 3 Results with Bio-ultracarbofluids Formulations

Conclusions

All the ultra-carbofluids prepared had a significantly higher viscosity than the reference diesel fuel (3.7cST). However they all produced lower emissions of all the pollutants (HC's, CO, CO_2 and smoke). The power output varied from one ultra-carbofluid to another, but was in general lower than for the reference fuel. e.g. 5%-6% less.

Together with other results, not included here[7], it was confirmed that ultra-carbofluids are a viable replacement for diesel oil. The problems to be overcome were identified as the higher viscosity (consequent upon suspension formation), the probable increased rate of injector and piston erosion, and the need for modified injector design.

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