Evaporating Fuel
to Improve
Spark Ignition Engine Efficiency

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ABSTRACT

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The report first explores the various prime movers and fuels as applied to automobiles. It also suggests that conventional spark ignition engines can still be competitive. The report then shows some recent studies to improve the performance of spark ignition engines. The major objective is to propose an arrangement where liquid fuel is pumped, evaporated by exhaust gas heat then released into the intake air stream. The resulting homogeneous mixture will improve combustion efficiency.

To Dr. SABER

for his valuable support.

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CHAPTER 1

INTRODUCTION

1.1 The Automobile In The Eighties

Despite the " space age" label applied to the eighties and the tremendous technological advances, the automotive industry is still the major employer in North America. (Ref. 1) Approximately one of every seven American workers works for some aspect of the automotive industry. (Ref. 2) Indeed, the automobile is now regarded as a necessity.

Many cities have outgrown the limits of their public transportation systems and all residents of the outskirts depend on their automobiles to commute to work. They take their car out to get the groceries, take the children to school or go out for a picnic. (Ref. 3)

One could presume that the new generation cannot imagine life without cars. They may be right, since many small towns are no longer small and parks and fields are no longer a stroll away. For example, when the nearest school is ten miles away and work is thirty miles away, life without cars is inconceivable.

Cars have become a major hobby. Handy youngsters " soup up" old cars, collect antique cars or organise races and ralleys of many kinds.

1.2 Problems Facing The Automobile Industry

Because of its extensive success and its widespread use the automobile is now facing the adverse aspects of success.

1.2.a The major dependence on gasoline, which is a limited natural resource, has escalated the price of the fuel and accelerated the risk of exhausting its reserves.

1.2.b The extensive use of cars together with industrial chimneys have increased atmospheric pollutants to the point where polution became an imminent danger to the ecology. (Ref. 4) As a case, increased consciousness has promoted the creation of the EPA, the Environmental Protection Agency in the U.S. The EPA has established rules and guidelines to limit pollution both from the industry and from automobiles. (Ref. 5) The new EPA regulations have added an additional burden to the existence of the automobile.

1.2.c The need for automobiles being there, marketing competition has become fierce.

The American automobile industry, operating with expensive labour is facing competition from foreign countries with cheaper labour invading the open North American market. The inertia of the huge American auto makers throughout the past few decades, had prevented them from following the trend towards economy cars that was developing out in the rest of the world. Therefore, during recession and periods of increased fuel costs, American consumers looked for economy cars, but American auto makers were not as ready as the competition. However, is the American auto industry going to die?

We cannot predict the future, but we can suggest means to help. Although the solutions are not confined to North American auto industry.

1.3 History Of Promoting Automobiles

The American auto industry which is still major, (Ref. 1) started with mass production by Ford. Then more standardisation and automation followed.

In order to make their price more accessible, cars became lighter and started using cheaper materials and developed more compact engines, becoming more efficient. Furthermore, recent materials science advancements have allowed the Otto engine to reach higher temperatures and studies of mechanisms and lubrication have helped to decrease friction losses within the engine. In addition, regarding the combustion process itself; Ford came up with the hemispherical combustion chamber and Honda introduced the stratified charge system into the leisure vehicle market; individual carburetors for each cylinder were used to supply exactly similar mixtures and water was injected as a " third body" to increase combustion efficiency. (Ref. 6)

1.4 Dim Future?

From what we can see, the automobile is so important that it may never die because the need for it has become so strong. However, our concern is the conventional internal combustion engine (ICE), since most of the problems listed in 1.2 above aim toward the internal combustion engine more than the automobile concept itself.

Namely,

If gasoline is scarce, should it be replaced?

If pollutants are bad, how can we reduce them?

If competitors are at the door, do they have an indomitable secret weapon solving all automobile problems?

These items are discussed in following chapters, focussing on improving combustion efficiency by better mixing processes in a system that would permit transitional fuels.

The solution proposed is to preevaporate gasoline and then inject it; the internal combustion engine would enjoy a variety of proper combustible mixtures.

CHAPTER 2

THE OTTO CYCLE

The most common power process in the internal combustion engine is the Otto cycle, therefore, we wonder whether the Otto cycle can survive or not. Let us discuss that cycle and compare it to its competition.

2.1 The Otto Cycle

The Otto cycle is shown in Fig. 2.1. Theoretically, in the Otto cycle, we start with an isentropic compression of the working medium, then a constant volume heat addition followed by an isentropic expansion, then a constant volume heat rejection.

From the thermodynamics, the expression for the Otto cycle efficiency is (Ref. 7)

$$\eta_{th} = 1 - \left(\frac{1}{CR}\right)^{\gamma - 1} \qquad 2.1$$

Where CR is the isentropic compression ratio:

$$CR = \frac{\text{volume at start of compression}}{\text{volume at end of compression}}$$

This form is similar to the Carnot cycle efficiency except that the Otto cycle has to reach a higher temperature than that reached at end of compression. So, for the same temperature extremes, η_{Carnot} will always be higher than η_{Otto}. (Ref. 7)

The most noted illustration of this cycle is the gasoline piston engine, the piston being the first idea that comes to mind for compression. But we should not forget that other forms have also used the Otto cycle, like the Wankel engine. Who knows, there may still be other hidden ideas that will use the Otto cycle.

2.2 The Diesel Cycle

The main competitor for the Otto cycle is the Diesel cycle. The Diesel cycle (Fig. 2.2) starts with an isentropic compression, followed by a constant pressure heat addition, an isentropic expansion and finally a constant volume heat rejection. We can see that, for the same compression ratio and heat addition, the Otto cycle has a higher efficiency but would reach a higher temperature, impeded by material limitations. On the other hand, because of auto-ignition when compressing a flammable mixture, (Ref. 7) the Otto engine cannot reach the high CR of the Diesel engine. However, we have to recognize the physical disadvantages of a Diesel engine. (Ref. 8)

Dealing with high temperatures and pressures and needing more material strength, its power to weight ratio is low.

By the nature of its combustion, auto-ignition has no regular flame front (Ref. 3), the necessity of a high pressure fuel injection pump giving sudden " shots" creates high noise.

In practice, the Diesel is slow to start since the temperature of the compressed air has to reach the auto-ignition point for the fuel. This is compared to the Otto engine that takes an external spark.

We have to note that the Diesel started to be popular in automobiles only at high speeds. In that situation it approaches Otto cycle operation by putting some of the heat addition at constant volume. This situation is called the dual or mixed cycle. (Ref. 7)

For the sake of completeness, referring to figures 2-2 and 2-3

$$\eta_{th}\,\text{diesel} = 1 - \frac{1}{\gamma \left[\frac{CR}{1}\right]^{\gamma - 1}} \left(\frac{(vc/vb)^{\gamma} - 1}{(vc/vb) - 1}\right) \qquad 2.2$$

$$\eta_{th}\text{dual} = 1 - \frac{1}{(\frac{CR}{1})\,\gamma - 1}\left(\frac{(P_e/P_b)\,(v_c/v_e)^{\gamma}-1}{((P_e/P_b)-1)-\gamma(P_e/P_b)\,((v_c/v_e)-1)}\right)$$

CR = compression ratio

v = volume *

P = press *

* Subscripts denote key points

Reference 1 offers a theoretical comparison between Otto, diesel and dual (mixed) cycle.

2.3 The Brayton Cycle

The next competitor is the Brayton cycle. Theoretically, the Brayton cycle consists of an isentropic compression, a constant pressure heat addition, an isentropic expansion and a constant pressure heat rejection. (Fig. 2.4) We can note that it is the equivalent of the Rankine cycle except it uses gas instead of steam. Fresh air is compressed then a fuel is burnt into it increasing its enthalpy then it is expanded giving work then the hot exhaust is rejected.

The expression for its thermal efficiency is the same as for Otto and Carnot, $\eta_{th} = 1 - 1/(CR)\gamma-1$, but the maximum temperature is a more limiting factor, especially since the turbine inlet has to be continuously subjected to it.

In the automotive field the Brayton cycle was incorporated by major American auto makers, namely General Motors, Ford and Chrysler in their turbine engines. (Ref. 1) Furthermore, some manufacturers have even tried to use the Brayton cycle on a standard V-8 engine with some modifications so that four cylinders would do the compression and the four others would be used for the expansion. In that case a combustor is added between the compression and expansion parts. No striking success met the idea, so it started and ended as a bit of news in an article in Popular Mechanics magazine.

Used as an internal combustion engine for an automobile, the Brayton cycle still requires expensive fuel added to a continuous high temperature at one point compared to a cyclic high temperature for the Diesel and Otto. Despite the technology already in existence, pushing the Brayton cycle from power and pumping stations and the aeronautical field into the automotive field, the Brayton cycle has not been able to hold its head with dignity.

2.4 The Stirling Cycle

The Stirling cycle follows two isothermal processes and two constant volume processes. Fig. 2-5, The most successful Stirling cycle operates on hydrogen (reported over 3000 cycles per minute) followed by helium which is considered because it is safer than hydrogen. Historically the Stirling cycle was patented in 1816 by Robert Stirling. (Ref. 6) From 1937 to 1947 Philipps developed it for the range from 1/4 hp to 30 hp. From 1958 to 1970 General Motors was working on it. In 1971 Philipps ran a 200 hp, 4 cylinder Stirling engine in a bus. In 1975 Ford ran a Torino with a 170 hp Stirling engine but terminated the study in 1978.

The major advantages of the Stirling cycle are external combustion, which makes it a relatively clean engine with respect to E.P.A. regulations and using multiple inexpensive fuels (Ref. 9). The Stirling engine runs quietly and the predicted low end torque it develops is impressive, see Figure 2-5. Still this engine has many mechanical problems to face.

2.5 The Lenoir Cycle

The Lenoir cycle is only of historical importance from Fig. 2-6. It is a constant pressure heat rejection (d-b) a constant volume heat addition (b-c) and an isentropic expansion (c-d). (Ref. 8)

This cycle neglects the beneficial effect of high compression ratio and therefore cannot compete for efficiency. Still we have to say that in the first decade of the twentieth century Mr. Lenoir had one of the first automobiles in the world. (Ref. 1).

2.6 The Ericsson Cycle

Fig. 2-7 shows it starts with a constant temperature compression, a constant pressure heat addition, a constant temperature expansion and finally a constant pressure heat rejection. This cycle substitutes the two constant volume processes by constant pressure processes and the constant entropy processes by constant temperature processes. So, for this cycle, we should have constant temperature compression followed by constant pressure heat addition, then constant temperature expansion, followed by isothermal heat rejection. In practice the cycle is not feasible since the closest we can get to the isothermal process is a multiple intercooling compression and multiple reheat expansion. This necessitating heavy heat exchangers we can easily dismiss this cycle from competition in the automotive field.

2.7 The Atkinson Cycle

Fig. 2-8 shows that the Atkinson cycle has an isentropic compression (a-b) a constant volume heat addition (b-c) an isentropic expansion (c-d) and an isobaric heat rejection (d-a). We might say it is an overexpansion on the Otto cycle.

2.8 The Rankine Cycle

How can we neglect the first engine ever made? The steam engine following the Rankine cycle (Fig. 2-9) where we compress a liquid isentropically, then heat it until it evaporates at constant pressure, then expand it isentropically taking useful work, then cool it at constant pressure. (Ref. 10).

This engine has had all the chances to develop; it can use different fuels and be very efficient but will be bulky for a car.

Ford used " fluorinol 85" in a Rankine cycle to drive a Ford Galaxie at 107 mph delivering 146 hp at 1800 rpm. (Ref. 12).

There was another attempt by Morgan and Doyle to use the Rankine cycle with thiophene (C_4H_4S) as a working fluid in a reciprocating engine, but it failed to cope with sudden changes in load. (Ref. 13) There has even been a proposition to use Freon in a Rankine car engine with turbine.

Esso, Ford and Dodge division of Chrysler also studied different organic Rankine cycles. (Ref. 13 and 12).

Other competitors are in the race although not so seriously, if we can use the expression.

2.9 Combined Cycles

One proposed arrangement (Fig. 2-10) has a free piston engine supercharging itself and supplying high pressure exhaust to a turbine operating the load; some exhaust can be used for an additional controllable supercharger.

Since we are concerned with weight for the automotive field, we can see that this arrangement needs a combination of engines which, apart from the mechanical problems, will be heavy.

Another proposition uses a reciprocating engine whose output is coupled to the turbine output instead of a free piston engine, it is called " The piston turbine compound" also known as the D.C.E. or

" Differential compound engine" combining a piston and turbine. (Ref. 11) (Fig. 2-11)

We can also consider the widespread supercharged Diesel and the scarcer supercharged Otto engines a close combination to the Atkinson cycle except that the load is taken by the reciprocating engine, while the extra expansion work is used only for supercharging.

2.10 Current Trends

On the market now, General Motors has bet on Diesel, a strategy considered safer by observers (Ref. 3) while Ford has given up its contract with Cummings Diesel to bet on the " Proco" engine (Programmed Combustion). The Proco engine is based on a long electrode spark plug engine used in the " Ford Capri" where fuel is injected in the centre of the combustion chamber on the exact spot where the spark will occur, so we get a good stratified charge and the injection is controlled by a microprocessor. (Ref. 3)

2.11 Conclusion

The most successful competitor in the automotive field is the diesel engine. However, it is only taking over because it is approaching the Otto cycle: the heat addition is more and more taking place at constant volume; with precombustion chambers you obtain a localised ignition followed by a turbulent flame front. One could say the automotive Diesel has become a disguised Otto cycle. Because, thermodynamically speaking, the Otto cycle does not impose premixing the fuel. Thus such a Diesel can be interpreted as an Otto cycle that allows high compression ratios.

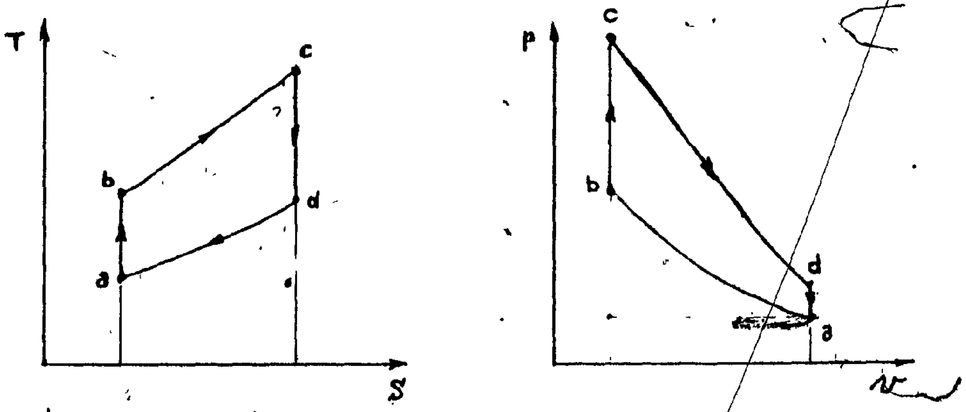


Fig: 2-I, The Otto cycle, Ref. 7

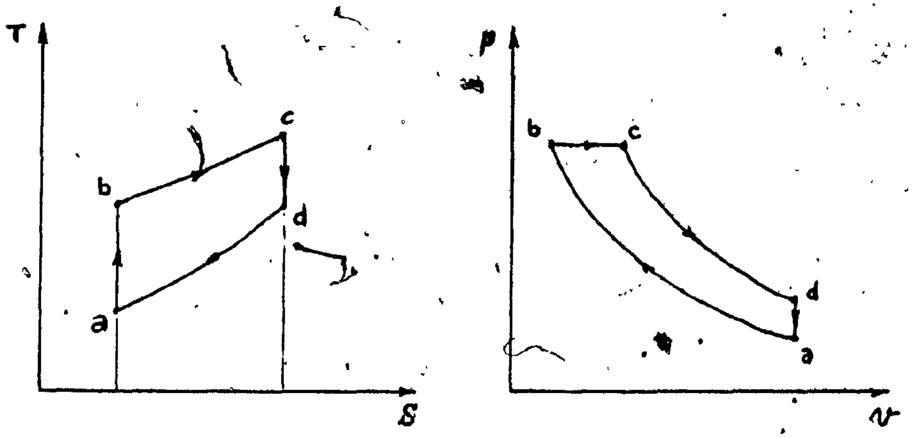


Fig: 2-2, The Diesel cycle, Ref. 7

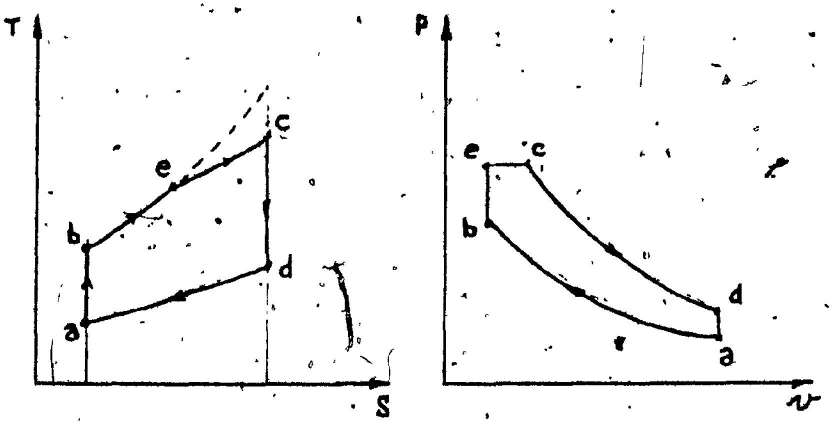


Fig: 2-3, The dual or mixed cycle, Ref. 7

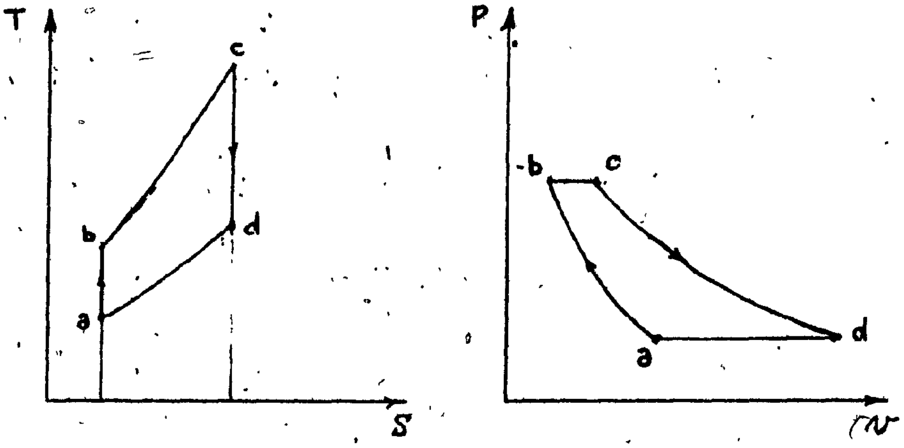
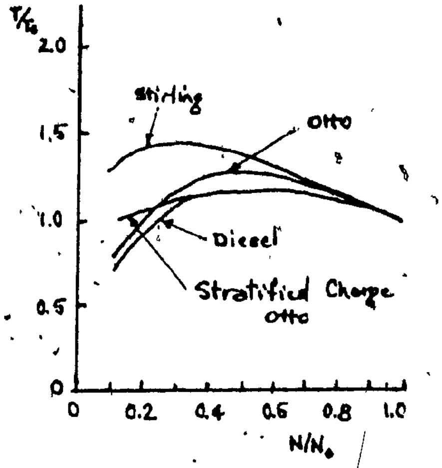


Fig: 2-4, The Brayton Cycle, Ref.7



Torque / Speed for Stirling Engine
(Referred to rated) Ref.6

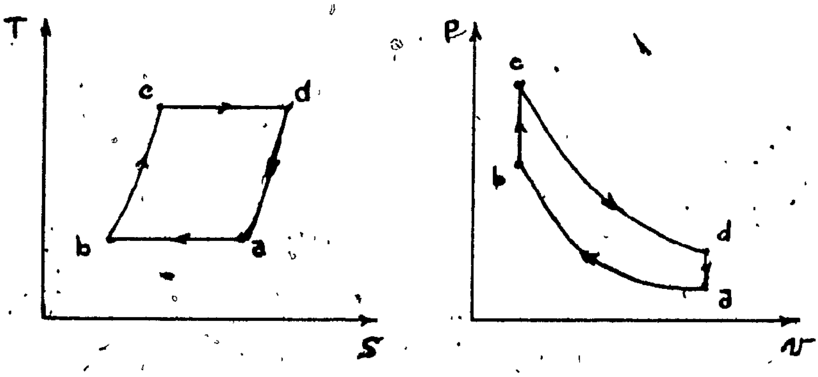


Fig: 2-5, The Stirling Cycle,Ref. 7

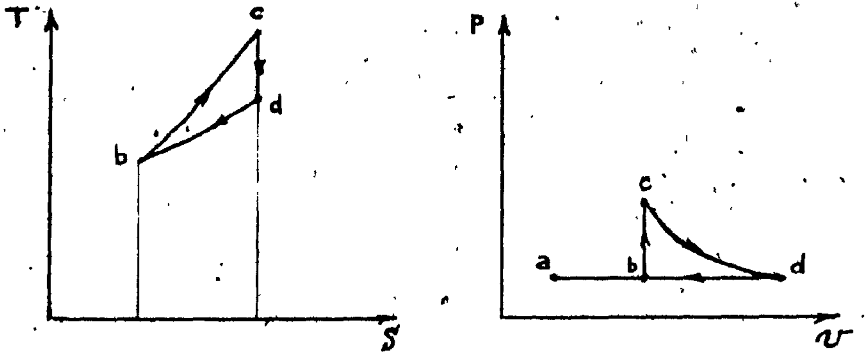


Fig: 2-6, The Lenoir cycle, Ref.7

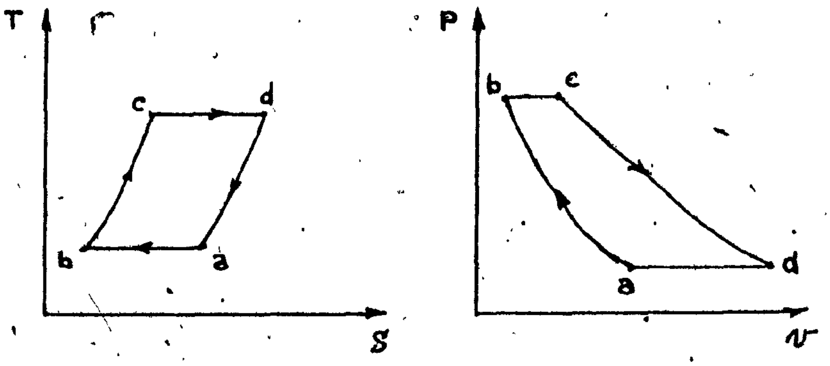


Fig: 2-7, The Ericsson cycle, Ref.7

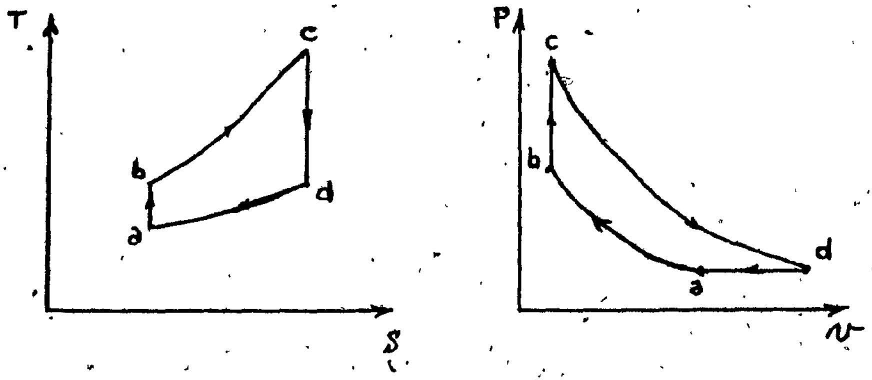


Fig: 2-8, The Atkinson cycle, Ref.7

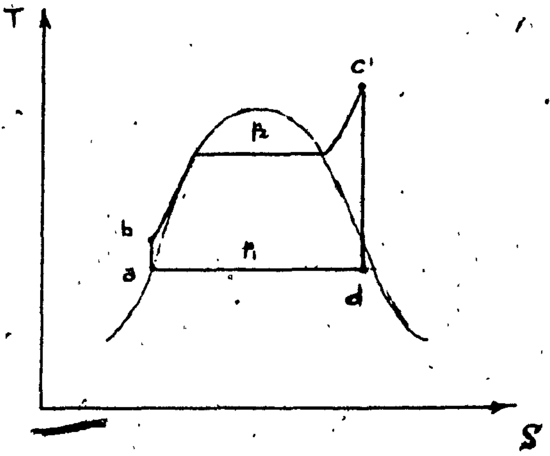


Fig: 2-9, The Rankine cycle, Ref.7

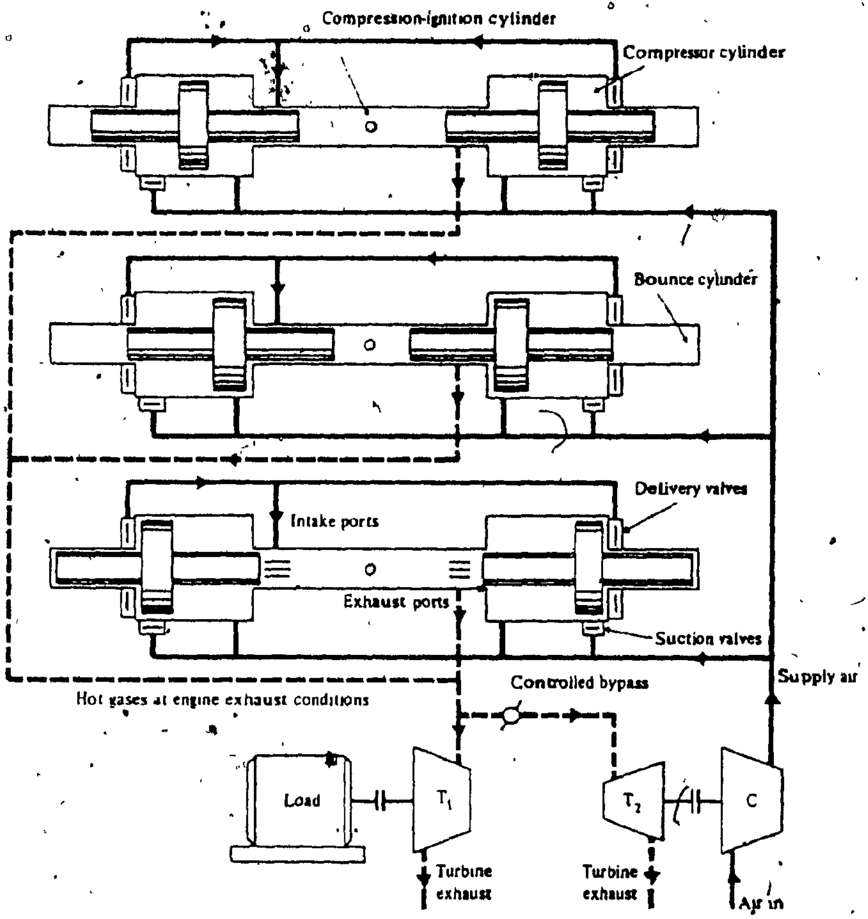
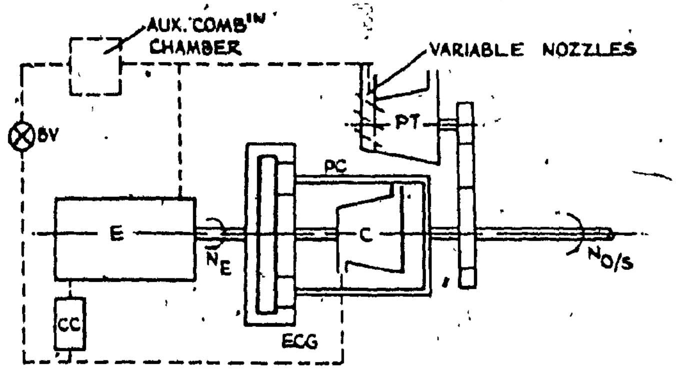


Fig: 2-10, The free piston turbine compound, Ref. 7



BV :- BYPASS VALVE
CC :- CHARGE COOLER
C :- COMPRESSOR
E :- ENGINE
ECG :- EPICYCLIC GEARBOX
PC :- PLANET CARRIER
PT :- POWER TURBINE
N_E :- ENGINE SPEED
$N_{O/S}$:- OUTPUT SHAFT SPEED

D.C.E. layout

Fig: 2-II, The differential compound engine, Ref.11

CHAPTER 3

ENGINES

3.1 Introduction

An engine is a device that transforms power from other forms into motive power. This Chapter discusses them.

3.2 The Steam Engine

It is widely accepted that steam, pushing up the cover of a boiling pot, inspired the first engine. That first engine (Newcomen 1712) was only a cylinder and a piston and a lever arm. Later, along with other improvements, Watt brought the crank mechanism giving continuous shaft rotation. From that beginning we develop our modern engine technology.

We should not be surprised to see a piston engine operating some old construction equipment in an underdeveloped country. These engines were robust, did not require much precision machining and tolerated harsh treatment. However, one inconvenience is, water has to be readily available and purified.

Thus today, for variable load applications, the piston cylinder form has been dethroned by diesel engines, thus getting rid of cumbersome boilers, Also, for steady loads, in stationary applications, the piston cylinder arrangement has been substituted by the simpler and more efficient steam turbine.

3.3 Turbine Engines

By reason of their mechanical simplicity, easy balancing and compactness, the turbine replaced the piston-cylinder arrangement in most steam applications. Examples are the axial flow turbines (Fig. 3-1), of which we can mention the impulse (Fig. 3-2) and the 50% reaction turbine (Fig. 3-3). In the impulse type turbine, the steam passes axials through a cascade of blades, changing direction without changing speed. In contrast, in the reaction type, the magnitude of the velocity is also changed. In that device, it is the change in static enthalpy through the rotor compared to the change in enthalpy through the stage that gives the motive power. (Ref. 7)

However, turbine engines which have been used extensively with steam are not practical for light automotive vehicles. Nevertheless, turbines based on the Rankine cycles are usable in stationary applications and also in turbo-prop and turbojet aircraft. (Ref. 14)

Most automotive manufacturers have tried their luck with turbine engines. (Ref. 1) Ford, GM, and Chrysler had each a turbine engine but they needed cumbersome regenerators, gearboxes and faced low efficiency at part loads. (Ref. 1) Also, since most cars run at part loads most of the time, the turbine engine was only practical for trucks for highway service. (Ref.12) We cannot even expect a breakthrough in this direction because all three automakers have given up their turbine programs. (Ref. 12)

Nevertheless there are still some combinations where a conventional internal combustion engine co-operates with a turbine engine either for supercharging as is commercially available or as in the (D.C.E.) differential compound engine,

In the differential compound engine (Fig. 3-4) a compressor supercharges a piston engine and supplies a separate combustion chamber. Together with engine exhaust, the separate combustion supplies a turbine whose output contributes to the output shaft through an epicyclic gear train. (Ref.11)

Another turbine/piston combination is the supercharged free piston internal combustion engine Fig. 3-5 shows the arrangement. The explosion between two plungers pushes larger pistons to pump a scavenging new charge between the plungers again. The large pistons obtain air from a primary supercharge and the exhaust from the plungers drives a loaded turbine. (Ref. 7)

3.4 ~~The~~ Rotary Or Wankel Engine

The rotary or Wankel engine uses the epitrochoid form. This geometry was mathematically known in the nineteenth century, but it was not until the late fifties when Felix Wankel of Germany made the news when he commercialised the epitrochoid in a revolutionary rotary internal combustion engine configuration. (Ref. 7) (Fig. 3-6)

Very compact, the engine was promising and many manufacturers worked on the problems facing it. These problems are mainly the wear of the seals on the three lobed pistons and the deformation of the casing. (Ref. 6) Nevertheless, Toyo Kogyo of Japan commercialised the Wankel engine in the Mazda. However, it was limited recently, because the engine could not be easily rebuilt or maintained.

German NSU and French Citroen had limited editions of the rotary combustion engine. Also, the major American auto makers investigated it. However, problems in the mechanical design and metallurgical construction of the engine persist. Another major disadvantage is the large quenching surface in the engine leading to higher HC emissions. (Ref.13) This adds to the reluctance of the existing auto industry, manufacturer and mechanics, to adopt it.

At this moment, we can say that the Wankel engine is an important event in the automotive history, but cannot expect any developments in its direction. It has been beaten by convention; unless as some media rumors tend to suggest, GM is elaborating it exclusively for 1984.

3.5 The Electric Motor

Electric motors have been successful in specialized applications. Such applications include public transportation where electric power is brought to the vehicle throughout its travel route.

The electric motor is reliable, environmentally acceptable and of reasonable size and weight. The motor is also reasonably easy to maintain and needs little adjustment for almost trouble free operation. (Ref. 15)

However, if we want it to power a totally independant vehicle, we shall meet many obstacles. First comes the weight of the batteries although that mass can be useful as a counterweight in fork lift trucks for example. The other obstacles are a low top speed and a short range between battery charges.

The electric motor has a lot to promote it. Chief is the fact that it is pollution-free and it can use electricity generated by any means, i.e. independant of fuel. However, until the power storage mass problem is solved, the electric motor, with its long years of existence, is not yet ready to be the major propulsion system for automotive vehicles.

3.6 Electro-Combustion Hybrid Arrangements

We have already spoken of combined turbine and free piston engines and turbocharged conventional piston engines. But the electric motor too has had its share of hybridization. For example, in 1979, Briggs and Stratton Corporation unveiled a hybrid version of the electric vehicle (EV). The unit was a four passenger sedan, powered by an 18 hp - 2 cylinder air cooled spark ignition engine coupled to a series wound D.C. electric motor 8 hp. Each motor alone or both together can run the car. However, the configuration is designed to use the electric motor to supply low speed power (under 2000 rpm), while the gasoline engine contributes higher speeds (2000 to 4000 rpm). Thus, acceleration is mainly electrical, while cruising is mainly on gasoline.

The gasoline engine is coupled to the electric motor with a standard one way clutch from Borg Warner's Duo-Cam product line. The car accelerates from rest to 30 mph (48 km/hr) in 10.5 seconds in the electric mode. The machine can reach a top speed electrically driven of 40 mph (64 km/hr) a top speed with the gasoline engine of 45 mph (72 km/hr) and a top hybrid speed of 55 mph (88 km/hr). Cruising range between battery charges varies from 30 to 60 miles (48 to 96 km) depending on the power combination the driver chooses. The weight of the battery pack, containing 12 batteries 6-V lead-acid type divided into two 36-V banks, is 1000 lb. (Ref. 3) (Fig. 3-7)

Another proposed arrangement is based on a turbine engine with regenerative braking. That arrangement aimed at optimum loading of the prime mover, which might give better promise to the use of the turbine engine. (Ref. 16)

3.7 Spring Loaded And Flywheel (Kinetic energy storage)

Wound springs and flywheels remain to be mentioned; senior citizens can tell about the rumors during World War II saying that the Japanese were commercialising a wound spring car comparable to the common toys. Recently, however, a bus with flywheel energy storage was proposed to Japanese utility services. (Ref. 17) It is the author's opinion that both ideas are of limited service.

3.8 The Stirling Engine

The Stirling engine, based on the cycle discussed in chapter 2 can be efficient, run quietly and use any fuel. (Ref. 9)

The " hot air" external combustion engine patented by the Scottish clergyman Reverand Robert Stirling in 1816 (Ref. 7) was cumbersome, and inefficient with 1/4 hp output. Between 1937 " Philipps" of Holland persued development to increase output from .25 hp to 30 hp. In 1958, under licence from Philipps, GM built several Stirling units and also built an automobile, the Stir-Lec driven by an electric motor whose power source is an onboard Stirling cycle motor generator set. (Ref. 9) General Motors was also working on a

150 hp engine when the program was cancelled in 1970. (Ref. 9)

Later, in 1971 Philipps tested a 200 hp, 4 cylinder engine mounted in a bus, Ford worked on a 170 hp unit from 1972 to 1975 and tested it on a Torino, but terminated the program in 1978. Currently the U.S. Department of Energy is sponsoring research on this subject. (Ref. 9)

Presently, most automotive Stirling engine work is concentrated on the double acting or Rinia engine. (Fig. 3-8) The hot chamber of one cylinder connects to the cold chamber of the adjacent cylinder through regenerators, coolers and heaters.The working fluid is H_2 becasue it has a very quick response to thermal changes. This quality was needed to achieve over 4000 cycles per minute. Compared to an internal combustion engine, the Rinia has very low emissions, can burn any fuel and its efficiency can go higher than 40% by using a higher maximum termpature and a lower minimum temperature. Its efficiency remains almost constant through a wide range of speed and load conditions. The Rinia also has a high torque at low speeds see Fig. 3-9, it has negligible oil consumption and has fast response to sudden load changes. (Ref. 9) Furthermore, this engine has high specific power output. However the Rinia has some problems. It needs considerable cooling to reach the necessary efficiencies and the complexity makes it costly. Furthermore, refractory materials add to the cost. It is important to note that the hydrogen needed for high-power densities causes embrittlement of ordinary engine materials. Also, sealing hydrogen at operating pressures as high as 2900 psi needs special dynamic seals and " elaborate" controls. (Ref. 9) Coupled with recent developments in fluid dynamics and heat and mass transfer, the prospects for the Stirling engine are appealing. Whether the Stirling engine will make it or not is still not clear yet.

3.9 The C-K Engine

The C-K or Cranfield-Kushul engine is shown in Fig. 3-10. The C-K has a tangential part connecting two cylinders to create a swirling motion. (Ref. 18) Tests demonstrated good economy and the possibility of using multiple fuels. (Ref. 18) Furthermore, the C-K burns a lean mixture, has low NO_x and CO emissions, but is relatively high in hydrocarbons. Finally since the C-K has rough and noisy combustion and is hard to balance (Ref. 18) its prospects for future development seem low.

3.10 The Reciprocating Piston Engine

Finally comes the familiar reciprocating engine. This engine has been used since the end of the nineteenth century. We have seen it used in spark ignition and compression ignition engines; four stroke (admission, compression, explosion (expansion), exhaust) or two stroke (compression, expansion with admission and exhaust taking place around B.D.C.).

The two stroke engine in particular has seen many modifications. These include positioning of the parts, shaping the piston as a baffle and multiple top exhaust valves. Furthermore, in both the two and four stroke engine, supercharging has been applied. The combustion chamber L shaped for a long time with both valves on one side allowing use of a camshaft down close by the crankshaft. (Fig. 3-11) These engines are robust, but have low compression ratios because of the space needed to open the valves and the distant ends causing end gas detonation. Other shapes include the T-shaped cylinder where valves were situated at the top of I shaped cyliners. However, the required pushrods and rockers added complexity with mechanical lag and friction. Also seen are wedge-shaped combustion chambers with both valves on top or the F engine: one valve on top and the other at the side pushed directly from the bottom by the camshaft. (Ref. 19)

As studies of flame propagation advanced, hemispherical combustion chamber which proved to have virtue in terms of combustion efficiency was adopted. However, the valve arrangement is complex and the camshafts had to be brought to the top to eliminate pushrods. Also, on elaborate engines, two overhead camshafts were needed (Ref. 20) adding more complexity and expense. A recent study by Ford opted for the hemispherical combustion chamber but rotated the valves to let them use different cams on the same camshaft mounted overhead with rocker arms. (Ref. 21) (Fig. 3-12)

The Diesel engine configuration introduced the concept of the air cell and the precombustion chamber. These are now used in spark ignition engines for the best stratified charge. In particular, the Honda engine (Fig. 3-13) has a pair of mixtures, one rich that goes into a precombustion chamber where the spark plug is located and the other leaner, goes into the main combustion chamber (Ref. 22) The flame front, exiting the precombustion chamber, burns in a vortex, adjusts the lean combustable mixture. The overall A/F ratio is leaner than conventional designs and less NOx CO and HC are omitted. (Ref. 23)

The Proco engine used on a Ford Capri is another variation. In the Proco, (Fig. 3-14) the fuel is injected on extended electrodes of the spark plug to start the flame in a bowl in the piston crown: flame propagation is good. (Ref. 5)

By way of comparison, the Diesel engine uses the precombustion chamber to give faster combustion allowing faster speeds and hence smaller engines. This also allows lower fuel injection pressures. In spark ignition engines, the stratified charge gives 10 to 20% better combustion efficiency (Ref. 13) but it needs either fuel injection or special cylinder heads and spark plugs.

Conventional carburation has also been elaborately studied and microprocessors are gradually taking over the control of A/F ratios, together with ignition timing according to engine temperatures and load parameters. Even the rotary engine in the Mazda had a dual mixture one rich and one lean. (Ref. 1)

The design of the engine itself went from one bank in-line to two banks of cylinders either back to back (flat engine VW) or arranged in a V, making it shorter, and hence more compact and rigid. The physical rearrangement is also easier to balance and allows improved mixture distribution through the intake manifold, due to both shorter and distances more equally spaced for the mixture to travel to the various cylinders.

New materials are also going into the construction of engines; composite engines are at the door, only the cylinder liner is still in metal on an experimental model. This will reduce engine weight and may reduce cost in the long run.

3.11 Conclusion

The piston engine is still the favorite for the major auto makers. Ford is opting for improving the spark ignition engine (Proco), while GM is going toward the Diesel engine (Ref. 8) and projects to put it on 15% of its passenger cars by 1985. (Ref. 3) GM has already put in a new injector by Lucas GB that eliminates fuel return lines and gives a better mixing and reduces emissions but still not sufficiently for 1983 emission requirements yet. (Ref. 3)

This means that the conventional SIE may still stand in good lead and deserves additional research to increase its efficiency and reduce its emissions. The options are the use of lean mixtures, air injection in the exhaust manifold, catalytic converters, exhaust gas recirculation systems, though they may add some complexity. Nevertheless, complex mechanism that everybody knows causes less concern than a probably less complex but unknown one.

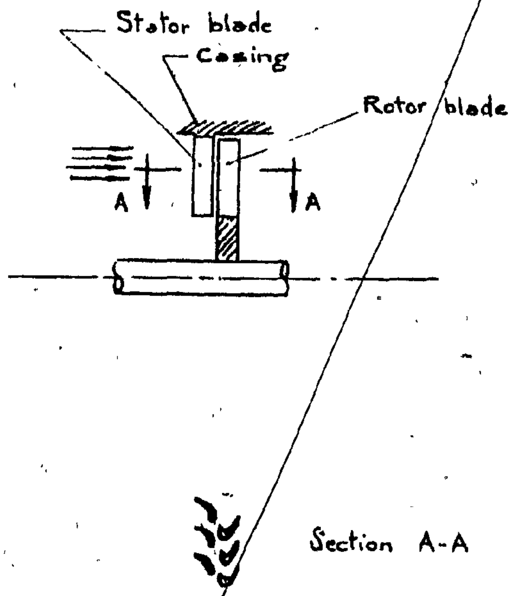
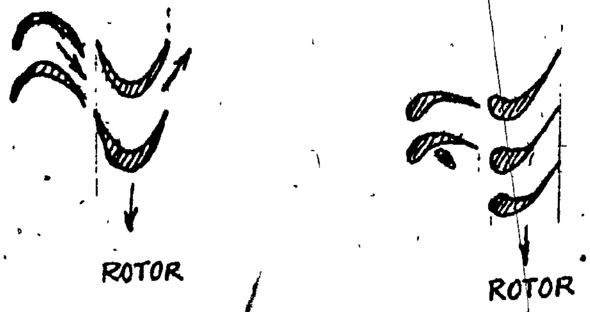


Fig: 3-1, Axial flow turbine stage.



Impulse Reaction

Fig: 3-3, Types of axial flow turbine,
Ref. 14

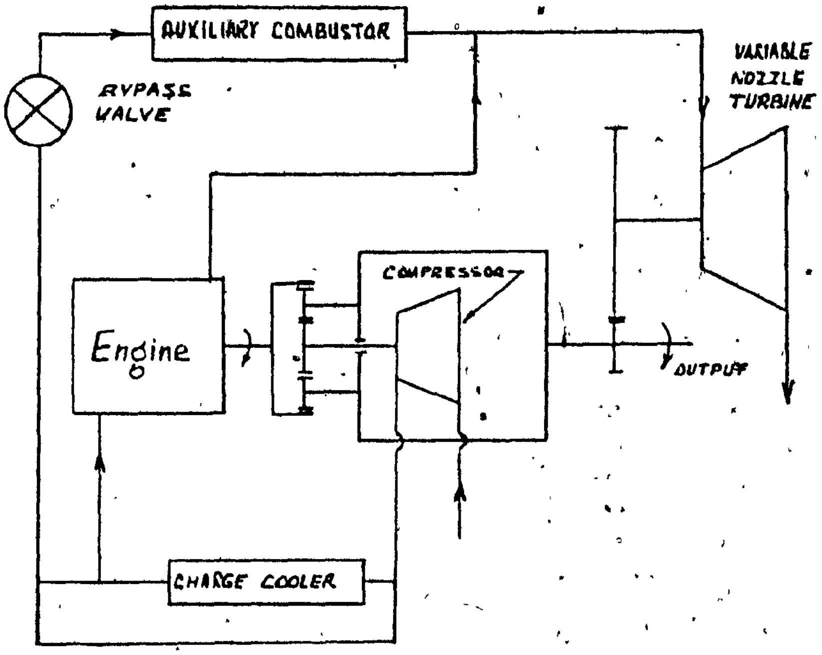


Fig: 3-4, The Differential Compound Engine, Ref. 11

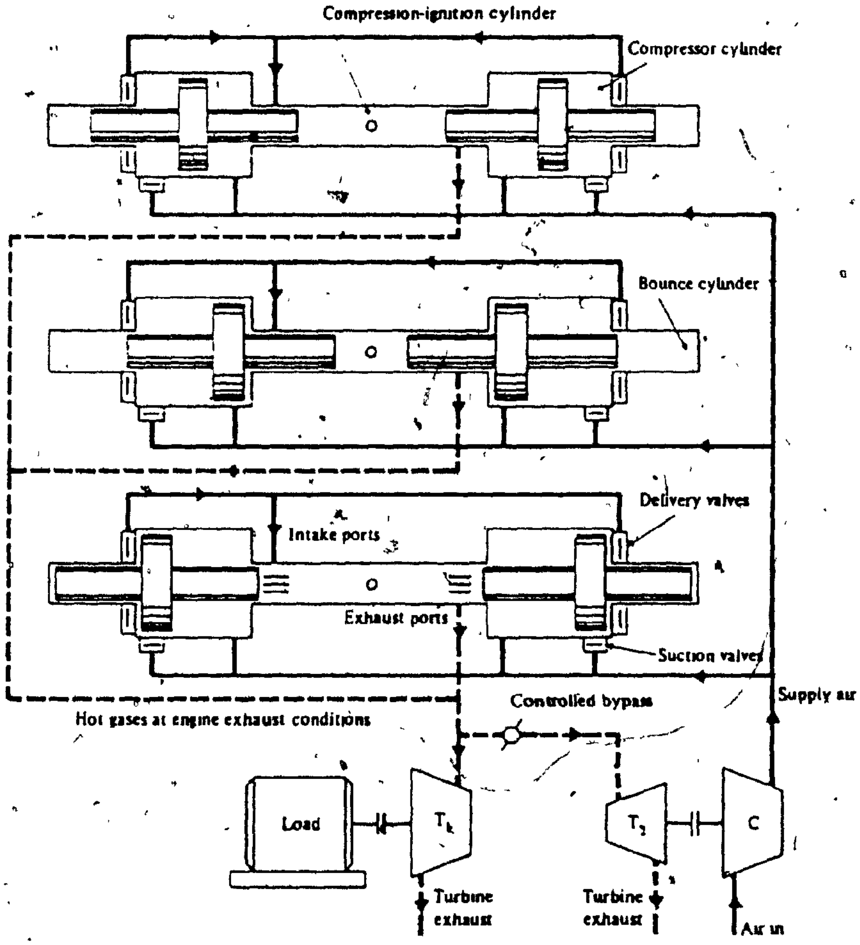


Fig: 3-5, The free piston turbine compound, Ref. 7

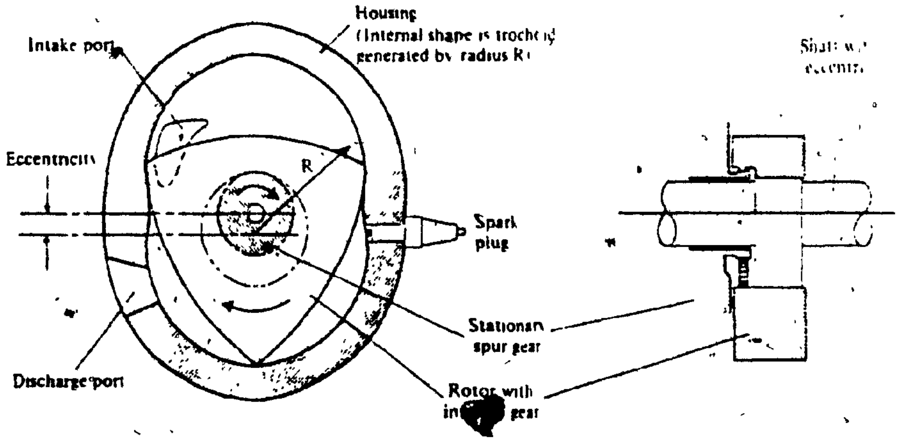


Fig: 3-6, The Wankel engine, Ref.7

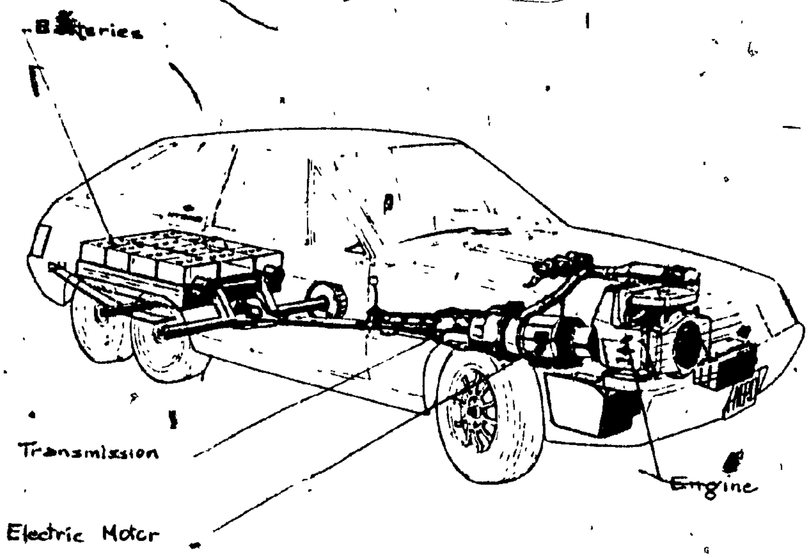


Fig: 3-7, The Hybrid Car, Ref. 3

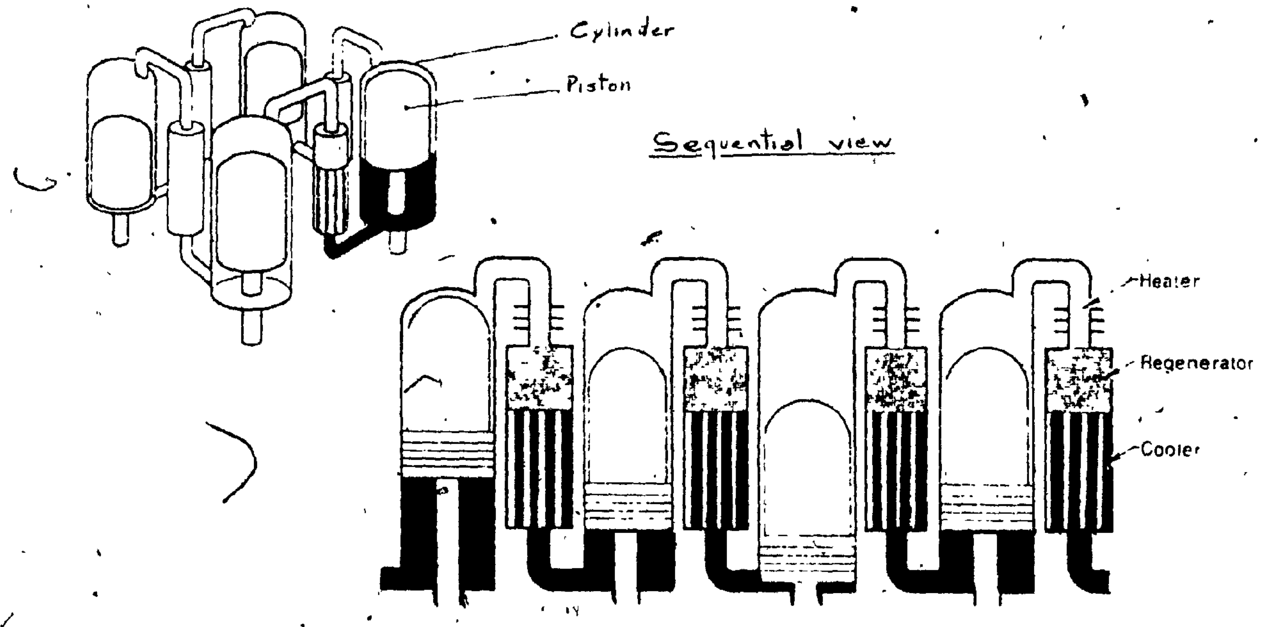
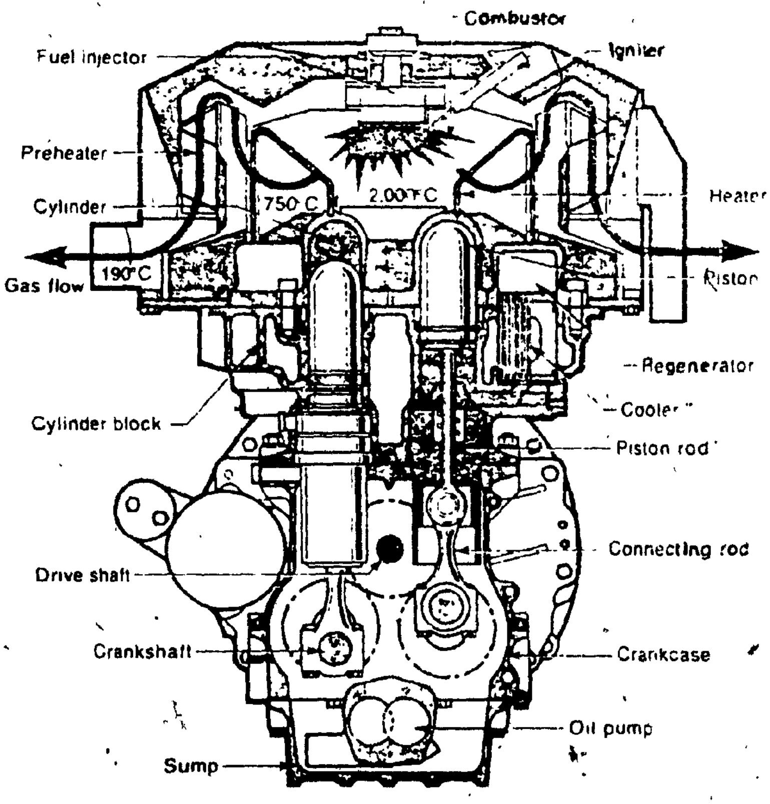


Fig: 3-8, The Rinia (Stirling) Engine, Ref. 9



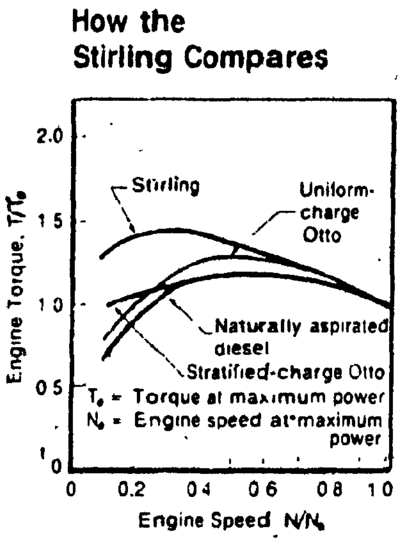
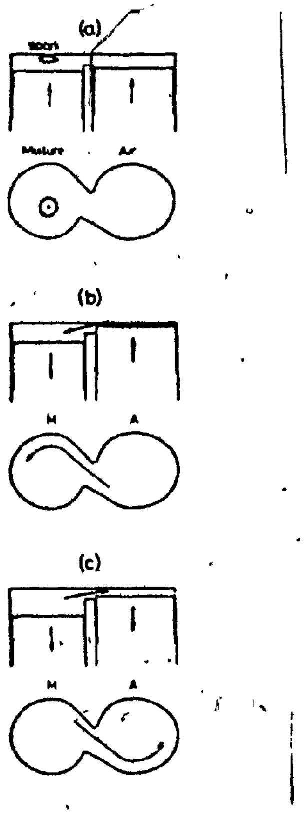


Fig: 3-9, Comparison showing Stirling engine to develop high torque at low speed, Ref. 9



Ignition

Air passes
creating swirl

Fig: 3-I0, The Cranfield-Kushel engine principle,
Ref. 18

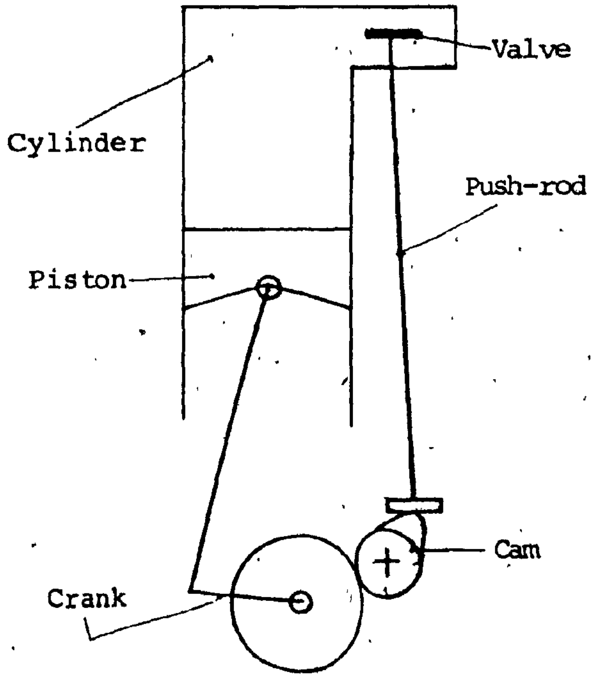


Fig: 3-11, The L-shaped combustion chamber,

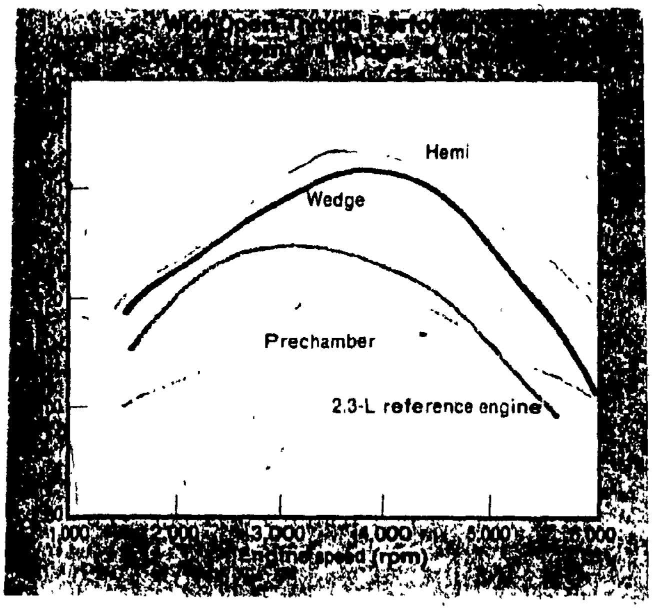


Fig: 3-I2,a, How the hemispherical combustion chamber compares, Ref. 21

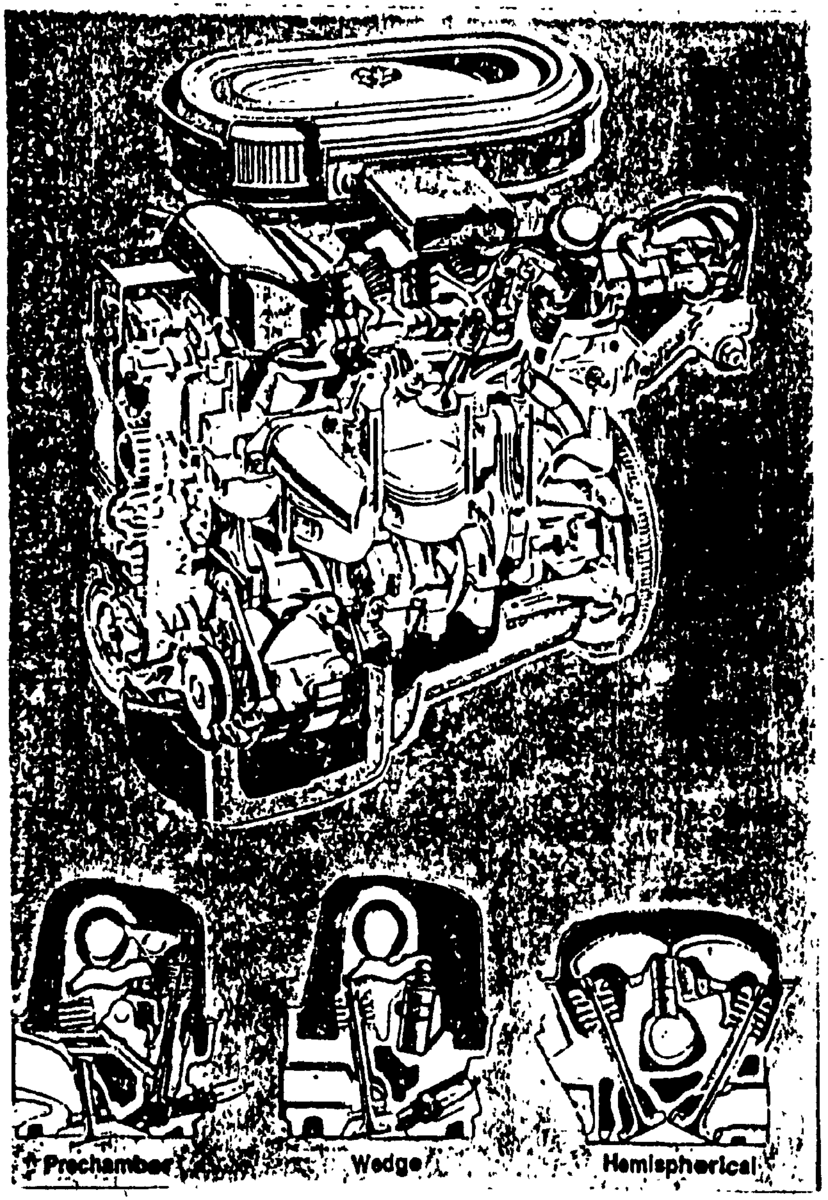
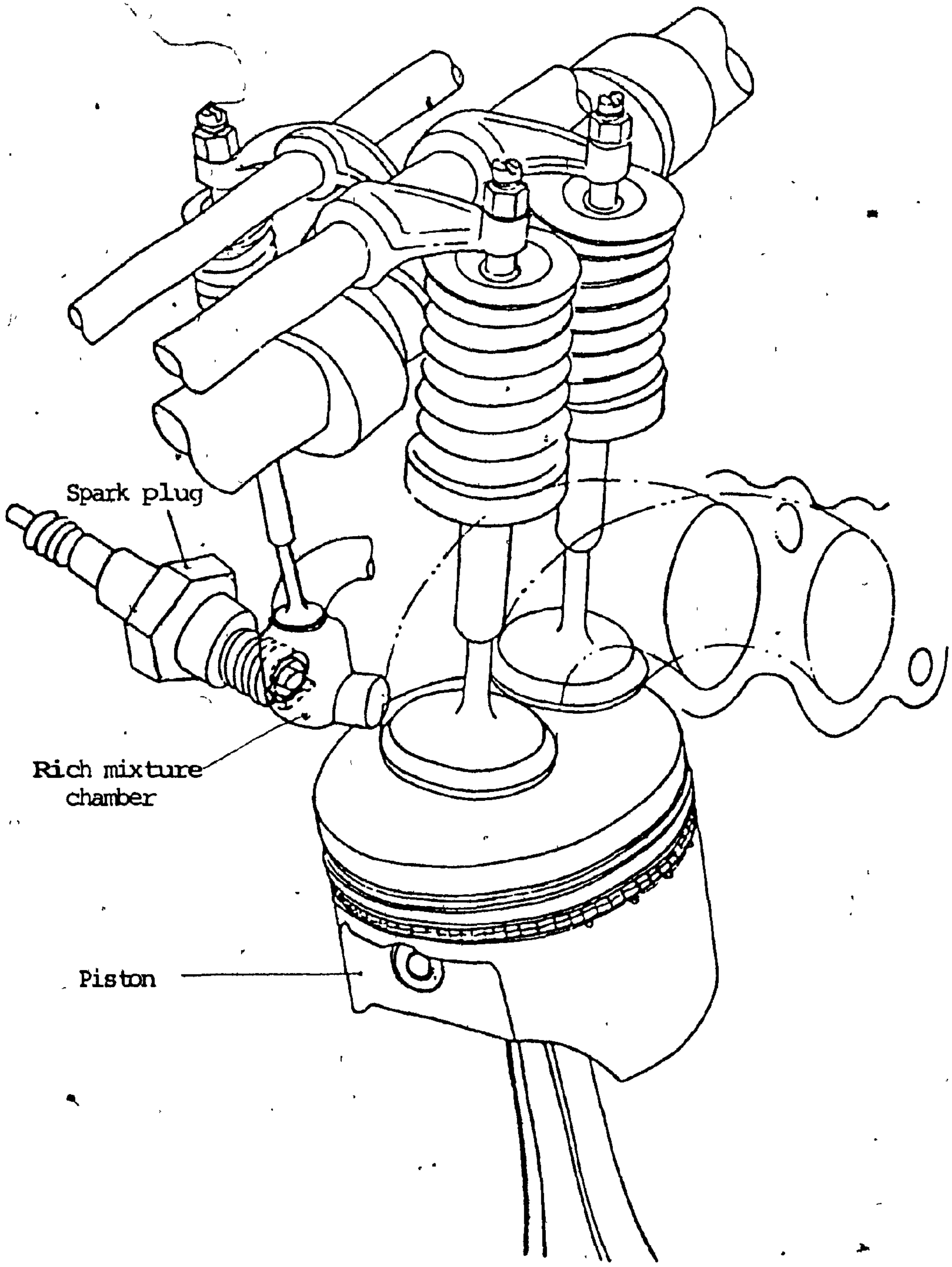


Fig: 3-I2,b, The HEMI engine as used on Lynx
by Ford Motor Co. ,Ref. 21



CVCC engine.

Fig: 3-I3, The CVCC engine by Honda, Ref. 23

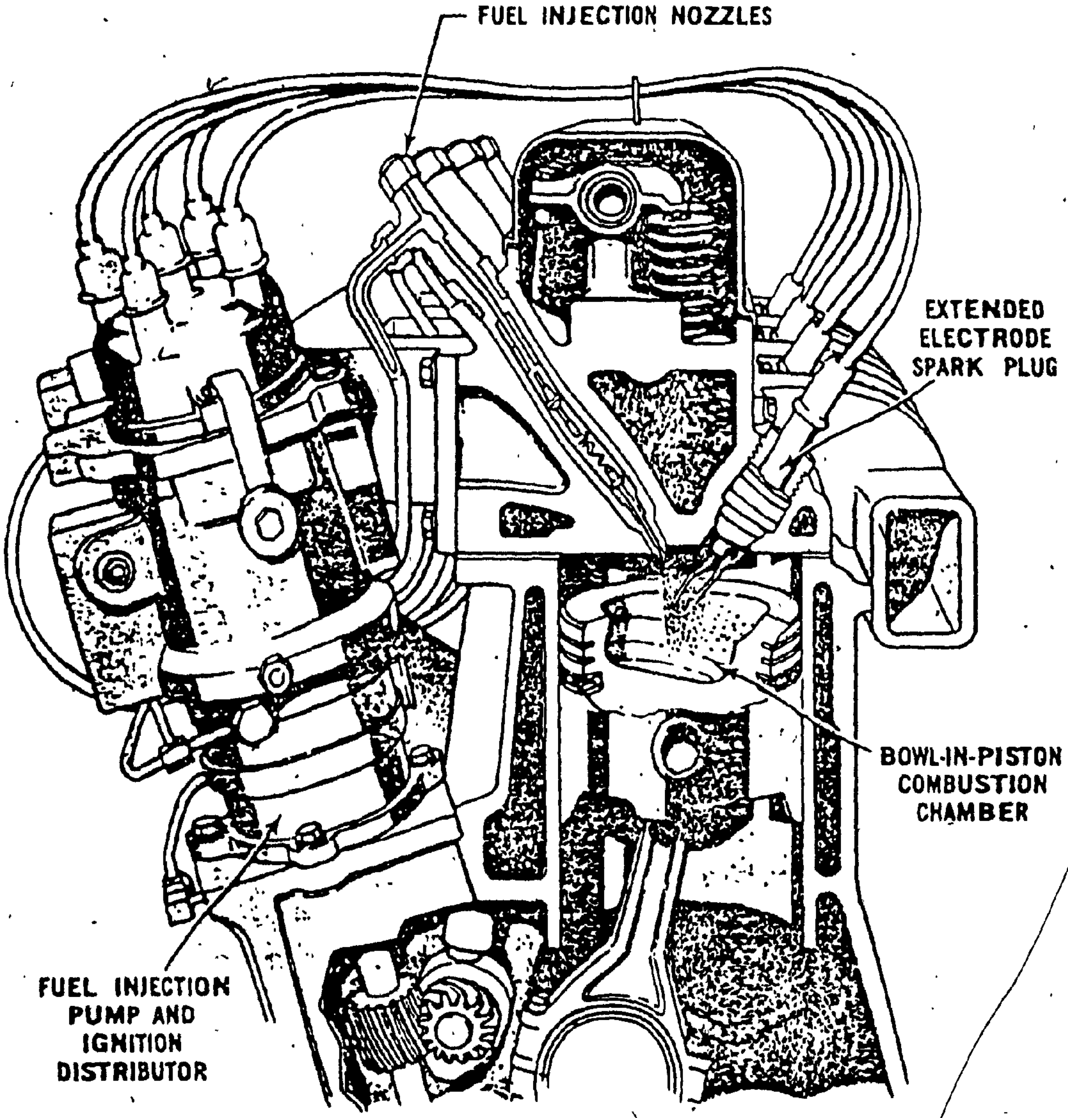


Fig: 3-14, The PROCO engine by FORD, Ref. 23

CHAPTER 4

FUELS

4.1 Introduction

It can be said that the human civilisation started when men could start a fire and maintain it.

Some of the earliest civilisations took fire as a deity and had to feed it with all sorts of things. Indeed the ultimate food used was the human being. (Ref.26) Even though the validity of the human body as a fuel is contestable, we can say that these people believed that fuel is not the only requirement for a good fire.

Most fuels are composed of hydrogen and carbon which, when burned with oxygen, usually atmospheric, will give water (H_2O) and carbon oxides (CO and CO_2) and liberate thermal energy. (Ref. 10)

However, these are not the only exothermal reactions known to man. Nevertheless, until we come up with more practical exothermal reactions, we shall keep using these two main processes.

Speaking of fuels, it would be most appropriate to follow the steps of our earliest ancestors.

4.2 Wood And Wastes

Wood is the oldest fuel, it is renewable and relatively clean. Burning it does not adversely affect the universal balance of nature since it produces no sulphur oxides and few nitrous oxides. (Ref. 27)

Since our main concern is the automotive industry, it would be appropriate to note the importance of pollution control imposed in this field. We keep reading about acid rain and it should be easy to associate acid rain with nitrogen and sulphur oxides produced from combustion.

Man has always burned logs and dry branches in open fires, stoves and fireplaces but that process was quickly forgotten when coal was discovered with a higher calorific value. Next came petroleum and natural gas. With coal and then petroleum, the so-called industrial revolution went ahead full steam. However, it has become obvious that coal, petroleum and also natural gas are exhaustible sources, so, some people went back to the old fashioned fireplaces rediscovering the cosy ambience proliferated by the harmony of nature.

Some others took a more utilitarian look at the old fuel; why not dry it to make it more readily transportable by concentrating its calorific value?

For example, California Power and Light Corp. plans to start-up a 40-50 MW electric generating plant using pelletised fuel in 1981. (Ref. 3) Other smaller installations can also be mentioned.

Another case is the Woodex pelletising process patented by Bio-Solar Research and Development Corp. starts by pulverising waste wood then drying it, in a rotary drum. Then, the dried material is extruded at 30,000 psi which drives off more moisture and produces pellets about 3/8" (.9 cm) long by 1/8" (.3 cm) diameter. The pellet water content average is 10 to 14%, compared to almost 60% in the original wood. (Ref. 27)

Another pelletising process is expected to upgrade the heating value to 13,000-14,250 Btu/lb., making it economic to ship far from production sites.

To have an idea about cost: a recent estimate puts wood at 2.35 US $\$/10^6$ btu, which is very close to natural gas (2.4 US $\$/10^6$ btu) and lower than oil now costing almost 5 $\$/10^6$ btu. (Ref. 27)

However, pelletising is not the only solution.

Liquefaction and gasification are also under way.

Wood is at the origin of fossil fuels but if we want to speak of internal combustion engines we have to transform it in someway. So, for our intents and purposes we have to use gasification or liquefaction which gives a more conventional liquid fuel. We should recall that wood as an automotive fuel was used during World War II by both the Germans and the English, where they added some wood gasifiers to their trucks. Thus wood produced a gaseous fuel of reasonable heat content to drive truck engines.

In another wood conversion process, steam is reacted with wood at 550°C and atmospheric pressure with a nickel catalyst, yielding a gas with 20-35% methane. This produced gas is later methanated to substitute natural gas. Another process converts 95% of the wood mass to gas comprising 1% CO, 20% H_2, 25% CO_2, 18% CH_4 and 8% C_2H_6 and higher hydrocarbons. (Ref. 3)

A liquefaction process gives 30 to 35 lb. of 15700 btu/lb. oil using 100 lb. of wood. The estimated cost is 6 $\$/10^6$ btu. (Ref. 3)

Wood pyrolysis is also being pursued: one process turns 1 ton/hr of wood to 13.3-16.7 gallons of oil, 1/3 ton of charcoal and 2.3-2.7 million btu in the form of combustible gas. (Ref. 27)

We can include all sorts of waste with wood. One proposition involves making briquettes of coal, garbage and sewage sludge which will be gasified at high temperature to give pollutant-free fuel gas. Another prospect uses gases from refuse after decomposing two years in a landfill site. (Ref. 28)

For an external combustion engine, wood as a fuel would stand an even better chance. However, we still wait for the liquefied product to be able to use it in the conventional way.

4.3 Petroleum

Next comes Petroleum.

There is much panic surrounding petroleum supplies, with the notion that it is an exhaustible source of energy. " How long will supplies last?", is a contraversial issue. However, we are developing alternative sources of energy in stationary applications, so we can assume that, liquid fuel availability will be extended. Furthermore, new discoveries and new processes are increasing the availability of liquid fuels or converting other fuels into petroleum-like oils. Also, liquid fuels are easy to transport. Now there is a wide variety of liquid fuels. These include fuel oil (Diesel) and gasoline, the material of interest here.

Now, petroleum yields more gasoline than diesel fuel: both have around 20,000 Btu/lb. calorific value (Ref.29) and would both suffer from petroleum shortages. However, the gasoline engine would readily accept the volatile products of gasification and liquefaction. (Ref. 12)

4.4 Coal

Coal can be considered the base fuel for the industrial revolution. However, its edifice was toppled by petroleum. Yet, now that petroleum's position is weakening, coal, with its massive remaining reserves, is finding more support.

The Western World's reserve of coal is being pulverised in furnaces and used in space heaters, etc. However, attempts to mix it with diesel fuel in fine particles is so highly abrasive so, direct use in internal combustion engines will wait. However, coal can be gasified or liquefied. Indeed, one can hardly look into a recent publication without finding coal gasification reported. There are operating plants, new processes and research going on. Such processes are working technologies such as

" In Situ" or underground gasification. Such efforts do not endanger the conventional internal combustion engines because they are adapting the fuel to the ICE use.

4.5 Natural Gas

Perhaps natural gas has not been quoted recently as a motor vehicle fuel. However, gaseous fuel was used in cars in the past. The calorific value of natural gas is about 1,000 Btu/ft^3 but the ICE can be adapted to use it. Indeed, the ICE, in its conventional spark ignition engine form, is currently using the gaseous fuel, butane in warm climates and propane in cold weather, in many applications. Such a gas gives better mixtures for combustion (Ref. 13) and no venturi effect is required since the fuel is already under pressure. Nevertheless, some " pessimists" are afraid of leaks and of the day-to-day handling of a gaseous fuel under pressure. (Ref. 13)

4.6 Geothermal Energy

Geothermal energy, by its nature, has to use heat from a stationary source, (hot springs) and so has to be transformed in order to be used in motor vehicles.

4.7 Solar Energy

Some experimental work for solar powered vehicles has been done and published as scientific curiosities, (Ref.31) and many newspaper articles mention " solar energy powered cars". However, the notion is not taken seriously.

In any case, for all practical purposes, solar energy is still used mainly for stationary plants, because of the large area and storage systems required. (Ref.31)

4.8 Winds, Tides And Waves

Tides and waves can be eliminated from the automotive field. This is because, although there is a multitude of very interesting ideas to harness such power, " Mahomet has to go to the mountain". Tides follow the moon, not the automobile.

Next, winds are eliminated for current automotive speeds, since you cannot receive more energy than you give, winds are not much more dependable than solar energy.

It is noted, however, that some sail carts have been used in sports on land, but no system has been developed with enough versatility to make a viable vehicle.

4.9 Nuclear Energy

Nuclear powered ships may suggest nuclear powered cars. However, costs are high, also size and weight of shielding are still too much for an automobile.

4.10 Hydrogen

Hydrogen is a fuel currently in vogue. Hydrogen has a very high calorific value 60,969 Btu/lb. (Ref.10), which is almost three times that of gasoline. And, its flammability limits are much wider than gasoline. This is good for the engine, but bad for safety. And storage of hydrogen is a problem because of its low molecular weight. For the same trip, a hydrogen tank would weigh 40% less than a gasoline tank but take 5 times the volume. (Ref. 10). Next these storage tanks have to be safe and the fear of the Hindenberg catastrophy has to be overcome.

Hydrogen can be stored in the form of hydrides but that is costly. (Ref. 5).One inventor pretends to generate hydrogen from water on board the vehicle, (Ref. 32) but it seems unreasonable that you dissociate water for less energy than you get by reconstituting it and be a winner.

Hydrogen can be obtained from natural gas and coal. Still, it cannot be considered a viable alternative fuel for the automotive industry (Ref. 5) even though it was tried on a Toyota and was 50% more efficient than gasoline. (Ref. 12)

4.11 Methanol

Methanol provides an alternative to gasoline and diesel fuel. Methanol has no carbon double bonds and so leaves no unburnt carbon. If pure, methanol will burn with a blue flame with little radiation. This latter effect may be inconvenient for boilers, but is good for an internal combustion engine.

The weight of methanol in a filled fuel tank for a vehicle would be 5% of the vehicle's weight. This means more load, but will pay back by a smaller, lighter engine. Also, because methanol resists detonation, the compression ratio can be 13:1. The high compression ratio implies a higher thermal efficiency i.e. higher engine output than for low compression ratio devices.

Furthermore, methanol needs less spark advance, reducing NOx emissions. (Ref. 33)

Methanol has a greater latent heat of vaporisation and has a larger mass consumption which, evaporated in air, would bring its temperature down by 20°C. (Ref. 34) The effect is to improve volumetric efficiency and lower the exhaust temperature. However, methanol has difficulties evaporating in cold weather and necessitates preheating. In a test case, Volkswagon tried methanol at 10°C and had to preheat it using a 200 watt heater from 30 to 45 seconds before the engine could start. (Ref. 33)

Now, the theoretical stoichiometric air/fuel ratio for methanol is 6.45:1 versus 15:1 for gasoline which means that the methanol injection rate must be double that of gasoline.

Coupled with these disadvantages, methanol is toxic, its mixture with air is explosive and the Volkswagon experience demonstrated that it gave bad cold idling, caused crankcase oil dilution and flooded the engine much too easily when starting.

In another case, Klockner, Humboldt and Deutz made a complex engine injecting diesel fuel first to ignite methanol from another nozzle (Methanol Diesel engine). (Ref. 35) That engine gave low pollution but was costly.

4.12 Alcohol And Gasohol

Grains can be used to make alcohol (ethanol) and hence gasohol. However, valuable proteins are concentrated from grains like corn and even slightly increased by the action of yeast in the process. Thus, the grain is available for human nutrition and the starch produces ethanol for fuel. However, if we take into consideration all the energy that goes into growing the grain, harvesting it and distilling the ethanol and compare that to the energy obtained from this ethanol in a car engine, we end up with almost 50% of the energy lost.

Currently, 75,000 Btu are required to produce 1 gallon of ethanol. (Ref. 36) However, a gallon of ethanol has 76,400 Btu. Thus there is a return of 1400 btu per gallon for a production efficiency of 2 percent. This is by no means a good return, if we disregard the byproducts. In any case, advocates of ethanol suggest that the cost of production could be reduced to 18,750 Btu/gal. If we compare this to gasoline where we obtain 4 to 6 times more energy than the energy spent in extracting and transporting it ethanol falls short. However, the mixture called gasohol has met success, because it has a higher octane number than gasoline, useful for high compression engines giving less knock. (Ref. 15) Indeed, gasohol is now used in the U.S., selling at a slightly higher price than regular gasoline.

While the U.S. auto industry is still worried about driveability, emission controls and the effect of ethanol on elastomers and various engine parts and components, G.M. Brazil modified its engines for 20% ethanol gasohol. Carburetor jets were made larger because of the larger fuel flow rate necessary
[illegible] ratio
(stoichiometric A/F = 9). (Ref. 36)

On the other hand Pontiac is modifying an engine to burn pure ethanol with some engine parts plated to protect them from contact with that fuel. The compression ratio in that engine can be over 12 and may go as high as 15 with obvious advantages. However, the intake manifold has to be always kept above the ethanol boiling point.

Yet Brazil has its reasons for pushing ethanol. The inexpensive manpower would find work, growing sugar cane for fuel. (Ref. 36)

3.13 Conclusion

As we can see, none of the competitors is strong enough to force gasoline out of the fuel race.

CHAPTER 5

PREVIOUS IMPROVEMENTS

5.1 Introduction

Three parallel routes have been developed to retain the internal combustion automobile engine concept. These routes have been directed at efficiency improvement by reducing fuel consumption. These routes are:

1. Improved Combustion Efficiency

Complete " ideal" combustion of a hydrocarbon fuel in air gives water and carbon dioxide as products, that is, there is no unburned hydrocarbons or carbon monoxide products. The ultimate aim is to achieve complete combustion without sacrifying engine performance.

2. Reduction Of " Lost Work"

To obtain usable work from the engine, some fluid and mechanical friction have to be overcome. The work spent in these frictional effects is converted to heat and is dissipated. Such effects should be reduced to a minimum.

3. Trimming Load Demands

Engine load is not usually steady, since the operational demands vary. Thus, if an engine has to cover the peak demands, it will run most of the time at part loads. The alternative is to try to synthetise a relatively uniform loading pattern and perhaps reduce the entire load.

5.2 Improved Combustion Efficiency

Combustion efficiency itself can be improved through:

a - Air-fuel mixing
b - Flame propagation in combustion chamber
c - Fuel dosage

5.2.1 Air-Fuel Mixing

The internal combustion, spark-ignition engine uses a mixture of fuel (usually liquid gasoline) and air (as an oxidiser source). In order to have complete combustion, not only does the fuel-air ratio have to be adequate, the constituents must also locate each other easily.

It is known that, between idling and full power, an automobile engine uses a wide range of air-fuel ratios. If we can obtain a perfect mixture of well evaporated gasoline and air engines could burn a mixture leaner than20:1 and still get good flammability and low pollutant emission. (Ref. 13)

In essence, a mixing process is necessary in order to bring oxidizer close to each and every fuel molecule. The goal is a homogeneous, balanced, mixture where one constituent is dissolved in the other. For liquid fuels in air, the commonly used device to achieve this situation by spraying fuel into the air is the carburetor.

Carburetors have been studied extensively. (Ref.37) However, they are made by very few manufacturers. Table 5.1 lists some of the major ones. The carburetor depends on the venturi effect that creates sufficient pressure difference to draw a spray of liquid fuel into an air stream. (Ref. 7) The bigger the pressure difference, provided the fuel nozzle is sized accordingly, the finer the spray. The consequence of finer spray is improved evaporation. However, decreasing the cross-section of the venturi throat increases the pressure difference at the expense of engine volumetric efficiency and therefore power.

Initially, multi-stage venturi passages were used in carburetors. Then manufacturers developed a moving wall venturi in an early model by Zenith and a recent proposition by Ford. Then they developed fuel injection carburetors. (Ref. 29)

One such fuel injection carburetor is used in 1980 Cadillacs (TM) by General Motors, in a system called EFI (Electronic fuel injection). The Cadillac system is shown in Fig. 5-2. The system uses two injectors operating at 60 KPa (10 psig) to give a positive fuel spray in the air passage. This pressure is much lower than the 270 KPa (39 psig) used on individual cylinder gasoline fuel injectors. (Ref. 3)

One way to improve mixing utilises the position of intake valves and, in some cases, the addition of baffles on the valves. (Fig. 5-3) This design imparts a swirling motion to the incoming mixture thus improving mixing. (Ref. 7)

Problems arise when engines are started cold particularly at low Canadian temperatures. During these cold starts only a small percentage of the fuel can evaporate in the engine intake. However, increasing the intrinsic volatility of the fuel will increase fuel evaporation losses and may contaminate engine oil, diluting it. In cold regions, winter gasoline is blended with more volatile components than the summer blend. (Ref. 1) Even if a proper mixture is prepared, it must still be conducted to the combustion chamber. The intake manifold serves this purpose. A long cold intake manifold will cause the condensation of some of the fuel. While designing an intake manifold it must be optimised for equal distribution of the mixture between cylinders. Condensation disturbs a well preportioned mixture. One interesting system to maintain mixture quality and provide good distribution is an intake manifold containing heat resistant plastic balls that vibrate generating pulses and shock waves for this purpose; its inventor claims the ball manifold arrangement saves 12 to 17% on gasoline consumption. (Ref. 38)

The next approach considered is water

injection. Water injection indirectly improves combustion efficiency. By acting as a third body in the combustion reactions and damping combustion noise. (Ref.30) Furthermore, water injection also reduces NO_X (oxides of nitrogen) formation by reducing the maximum flame temperature due to its heat capacity. (Ref. 39)

Another mixing system was used by the Cranfield Institute of Technology (CIT) which had the winning car in the Malloy Park Race for " Shell Oil Co." Super Mileage Competition 1979. Apart from minimizing air drag on the vehicle and using a carburetor with no throttle, the CIT team preevaporated the fuel by the implantation of a small electric heater to help evaporate the fuel in the intake manifold. This suggests that the CIT team recognised the importance of mixing. The Cranfield Car achieved a 914 miles per imperial gallon, i.e. 0.31 ℓ/100 km fuel consumption. (Ref. 40)

The use of such electric heaters as the one in the Cranfield Car, leads us to consider the PTC (positive thermal coefficient) materials used by Ford. These PTC's are electric heating elements whose electrical resistance rises abruptly above a certain temperature. (Fig. 5-4) This property makes the material a heater with automatic control. These PTC materials can be designed and made for different temperature limit ranges. (Ref. 6)

Additional studies have pursued ways of evaporating the fuel. (Ref. 41)

A mixture generator was used on a dynamometer mounted chassis at the Thornton Research Centre. The results encouraged evaporating the fuel for homogeneous mixing. (Ref. 41)

It is also worth noting that fuel was injected in a direction opposite to the air flow, which is better than parallel mixing. (Ref. 42) Figure 5-5 shows an electric heater that was used neglecting heat from the exhaust for that study.

One system used incorporates the heat pipe principle. The design has a contained boiler-condenser unit where liquid is pumped to the boiler section by capillary action.

At the boiler, the liquid evaporates and the vapor fills the condenser section. (Fig. 5-6) The heat pipe is used as heat conductor from the exhaust gases to the fuel, using the separate transfer medium in the heat pipe. This separate transfer medium has an evaporation temperature high enough to evaporate gasoline but not enough to crack it.

The system (Fig. 5-7) called the " Vapipe" needs some control to avoid overheating. One control method uses a thermostatic valve in the exhaust ducts. The valve diverts the exhaust gases to a bypass, away from the boiler. However, valves used in exhaust streams are troublesome since the exhaust gas at elevated temperature makes lubrication of moving parts difficult.

Another control method uses a dump heat exchanger. (Fig. 5-8). The illustration shows a three level heat pipe with the sections arranged vertically. The first lowest section is the boiler where a transfer liquid medium is evaporated by the exhaust gas heat. The intermediate section is a conventional condenser where the transfer medium vapour exchanges its heat to the air/fuel mixture.

The last section is normally occupied by an inert gas (e.g. Argon) in thermal contact with cooling water. When exhaust heat is excessive, the transfer medium vapour pressure becomes high enough to compress the inert gas, so the vapour loses the extra heat to the cooling water.

A third control system relies on varying the charge in the heat pipe. This system heats up the whole mixture; consequently, to restore volumetric efficiency, air is taken in through a bypass. (Ref. 41) Some interesting work has been done by Manford, Aung and Singh. Their primary concern was NO_x emissions. (Ref. 24) They found that a well premixed charge gave almost the same NO_x emissions as non-premixed charge at the stoichiometric mixture condition. However, in leaner mixtures, nitrous oxides (NO_x) were exponentially proportional to the fuel/air ratio and thus to flame temperature. However, the engine idles properly on lean mixtures only when it is hot. When cold, the flammability limit demands a richer mixture.

5.2.2 Flame Propagation In Combustion Chamber

Improved flame propagation is the second way to improve combustion efficiency. The improvement is achieved by using different combustion chamber shapes. The hemispherical combustion chamber shape has proved to be the best, because the quenching area is a mimimum for the volume giving less unburned hydrocarbons and no end gases to detonate in remote corners.

Ford has used the hemispherically shaped combustion chamber on the Escort - Lynx 1981. (Fig. 5-9) However, they had to incorporate a valve offset to use only one overhead camshaft instead of two. (Ref. 21)

*Stratified Charge: Another way to improve flame propagation uses a mixture that has an air fuel ratio gradient in the combustion chamber. To achieve ignition, because of flammability limits, a rich mixture is formed at the electrodes. However, to save fuel and encourage complete combustion, the remaining volume contains a lean mixture. The flame then starts well and propagates properly. The net result is good combustion of an overall lean mixture. This can be realised by fuel injection in the cylinders such as is done in the Proco (Programmed combustion) engine by Ford. (Ref. 5) The injector is shown in Fig. 5-10. The piston contains a cavity to induce a swirl in the air charge on compression, then the fuel stream from the injector is directed toward extended electrode tips. The air/fuel ratio in the vicinity of the spark is thus very low (rich mixture). Therefore, first the spark ignites the surrounding charge, the flame moves then to the peripheral leaner layers. Fuel injection stratified charge systems eliminate unreliability of ignition in air/fuel ratios higher than 15:1, it could ignite from 16:1 to 50:1 overall. (Ref. 13) The Texaco Controlled Combustion system (Fig. 5-11) (TCCS) is similar. However, the dependance on the flame front swirl motion is greater since the jet is tangent to the cylinder walls and to the air inlet. In the TCCS engine, the spark starts the flame in the rich jet zone and the flame front travels following the swirl. The advantages are the same as the Proco engine. (Ref. 13). Next comes the renowned CVCC (Compound vortex controlled combustion) engine by Honda. It also is a stratified charge system. The CVCC does not use individual injectors like the Proco and TCCS engines but has two carburetors. One carburetor prepares a rich mixture for a precombustion chamber having its own intake valve, and the other preparing a lean mixture for the main cylinder. The engine is shown in Fig. 5-12. Combustion is initiated with the spark plug in the confined precombustion chamber. Then, the flame flashes into the large combustion chamber creating a vortex burning the unburned hydrocarbons resulting from the precombustion. The resulting exhaust has a low concentration of pollutants and, because of the slower burning rate, less NO_x is produced. (Ref. 5) The CVCC system boosts fuel economy. Applied to a Chevrolet Impala, it improved fuel economy by 3.8% and power output by 10.3%. On a Vega, it improved fuel economy by 9.9% and power by 1.4%. (Ref. 23)

Azure Blue Corporation investigated fuel vapour injection but feared backfire. The corporation later tried a dual mixture with a precombustion chamber and special spark plugs. All results proved that stratified charges increase combustion efficiency by 10 to 20%. (Ref. 13)

The CVCC allows good combustion with an overall lean mixture giving less HC and CO. Furthermore, the divided chamber gives slower combustion and so limits NO_x emissions. (Ref. 18)

5.2.3 Fuel Dosage

Engine manufacturers have found that the amount of fuel delivered to cylinders depends on the distance to the carburetor. The further cylinders get leaner mixtures than the close ones. Also, to follow the automobile engine load curve, complex carburetors were demanded. Consequently, manufacturers resorted to fuel injection. Some injections occur in the manifold, immediately upstream of the intake valve. Most others inject fuel into the cylinder itself using a dosage pump. Using microprocessors, these injection systems monitor operating variables and supply a flammable mixture to insure the minimum power required by the load. Such electronic systems are used on many European and American automobiles. However, these direct fuel injection systems need complex peripherals and high pressure. The return was then to inject the fuel into the carburetor, but to meter it with an electronic system. Such a device is used on GM's EFI system where a microprocessor monitors manifold and barometric pressures, air and engine temperatures, engine speed and throttle position and doses the fuel accordingly into the carburetor. (Ref. 3)

5.3 Reduction Of Lost Work

In order to use the thermal power from the engine, we lose some of it in various ways such as:

a - Mechanical friction
b - Fluid friction
c - Heat rejection

5.3.1 Mechanical Friction

The lubrication of engines is very important in order to reduce mechanical friction losses. The number of bearings of the crankshaft is also minimized without compromising its rigidity. Some engine makers like Peugeot have used rolling element bearings on their crankshaft in passenger car engines and obtained satisfactory results. Oil companies contribute heavily in engine lubrication research. Now multigrade oils try to maintain the necessary viscosity for good lubrication and low friction losses through a wide temperature range.

5.3.2 Fluid Friction

Losses due to fluid friction in the suction passages are what causes volumetric deficiency. Carburetor manufacturers made multiple barrel carburetors and expandable venturi carburetors to reduce such losses to a minimum. Some makers also used exhaust gas in turbines to drive superchargers that will increase volumetric efficiency. Such systems use the energy of exhaust gases to overcome inlet fluid friction.

Losses in the exhaust passages are most important for two stroke engines, they have to be minimised to ensure good scavenging. In these cases the designer has to sacrify some of the muffling effect to win on scavenging.

In the case of racing cars, long individual exhaust pipes are used for each cylinder and are tuned for a certain speed so that, at that speed, the returning depression wave front helps scavenging exhaust gases from the reopened exhaust valve. However, this arrangement is noisy and non practical for passenger cars. (Ref. 29)

5.3.3 Thermal Losses

Thermal losses can also be considered, but the most common way to reduce them, i.e. regeneration, is bulky and not practical for automotive use. One might consider turbochargers to be some kind of regeneration manufacturers have been able to use.

Some thermal losses are unavoidable as per the 2nd law of thermodynamics but we are still far from Carnot's efficiency so there is still room for improvement.

If we can increase maximum cycle temperature efficiency will increase but there we meet limitations due to material strength at high temperatures and also high NO_x emissions.

Stronger, lighter and more heat resistant materials are being used in engines to increase maximum cycle temperature and output power per unit engine weight.

Plastics would be lighter and reduce conduction heat losses. Recently " Polimor Research Inc." announced an all plastic engine (except for built in cast iron cylinder liners) which is 50% lighter than conventional engines. (Ref. 24)

5.4 Trimming Load Demands

If we were to compare the automobile engine to a utility service we would say that the peak hours govern the choice of engine size and maximum output. This method of sizing lets us drag a huge reserve for the rest of the day in average driving. With this in mind many attempts were made to supply this peak power from energy accumulated during part loads or by regenerative braking.

In Ref. 16 a complex control system, combined with a low power prime move, stores energy in the form of oil pumped under pressure that will help moving the car during acceleration. Such an arrangement could help commercialise the turbine engine (having low efficiency at part loads).

The differential compound engine (DCE) (Fig. 5-13)(Ref. 11) uses a small S.I. engine combined with a free wheeling turbine engine driven at part loads by the S.I. engine exhaust and at peak loads the compressor is forced to move through an epicyclic gear train so it supercharges the engine and supplies air to an auxiliary combustor to drive the turbine, thus boosting power output for peak demand.

Other ways to trim power requirements included wind tunnel streamlining, the use of radial tires (easier to flex), cutting automobile components weight (extensive use of carbon fibers and plastics) decreases inertia thus decreasing acceleration force required; multiple speed gearboxes and overdrive systems and even an imperative slow driving to save fuel as imposed by several governments.

Some driving schools are teaching economic driving while econometer gadgets are flooding the market, one of which monitors manifold vacuum to limit intake losses and run at an average high volumetric efficiency.

5.5 Conclusion

We have a quick review of what was done in improving automotive engine performance, our main concern here is improved combustion efficiency.

Rochester products division
Holley carburetor, Division of Colt industries
Solex
Zenith
Carter carburetor, Division of ACF industries
Bendix eclipse
United Delco

Fig: 5-1, Some of the major carburetor makers.

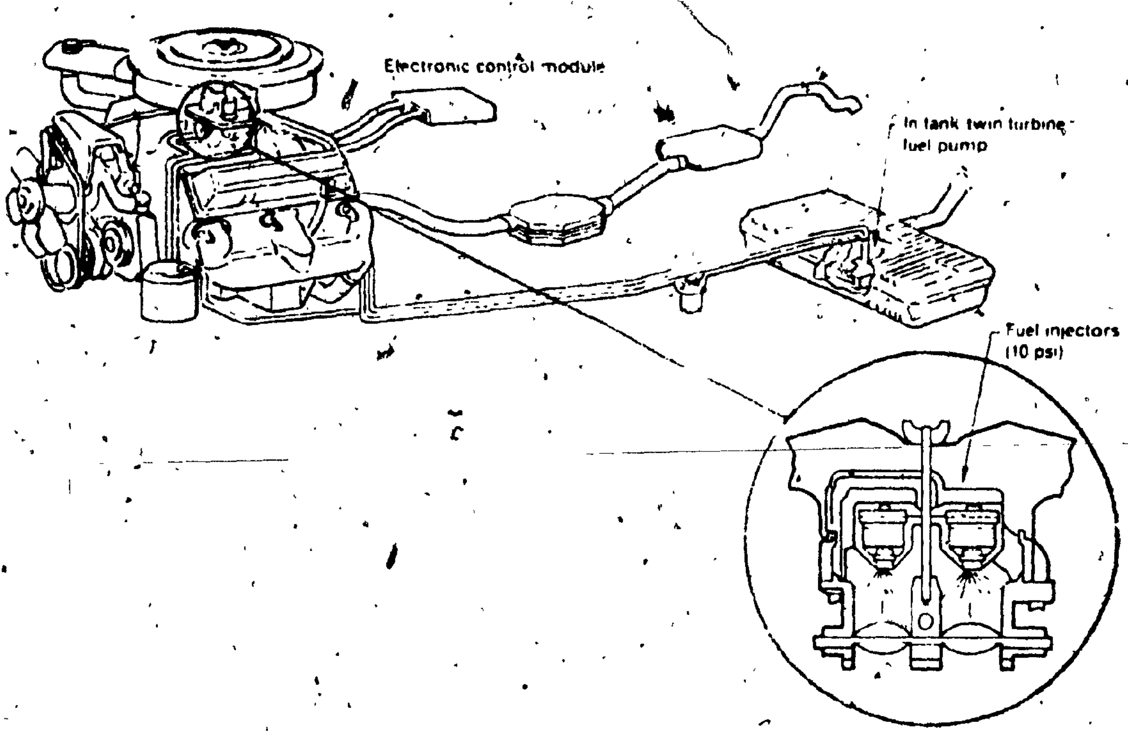


Fig: 5-2; The Electronic Fuel Injection by Cadillac division of General Motors, Ref. 3

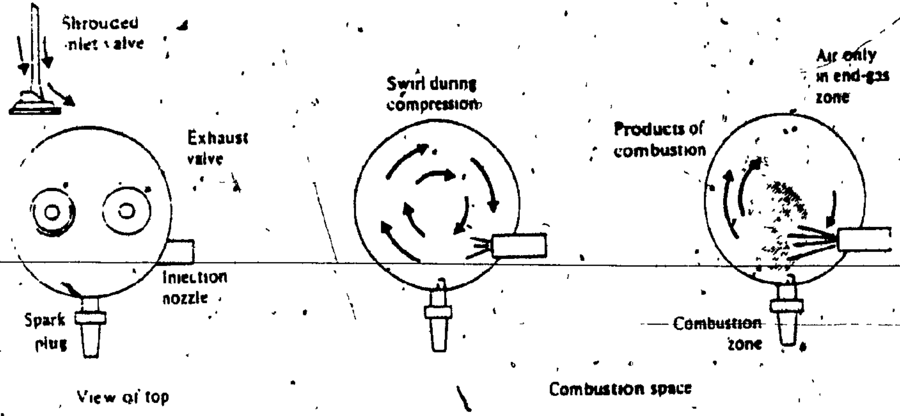


Fig: 5-3, Valve with baffle, Ref. 7

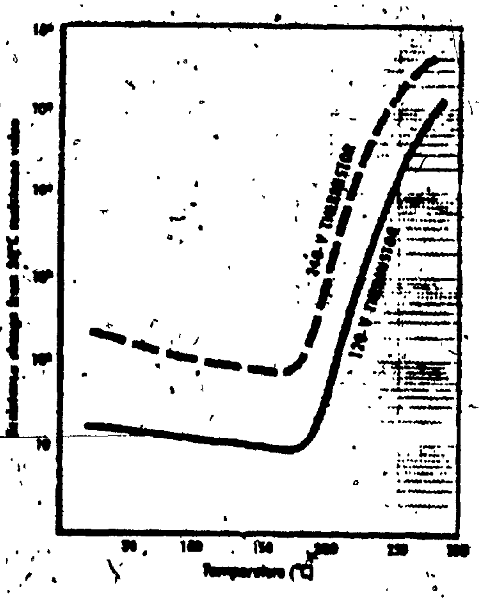


Fig: 5-4, Positive thermal coefficient material behaviour, (Ref. 48)

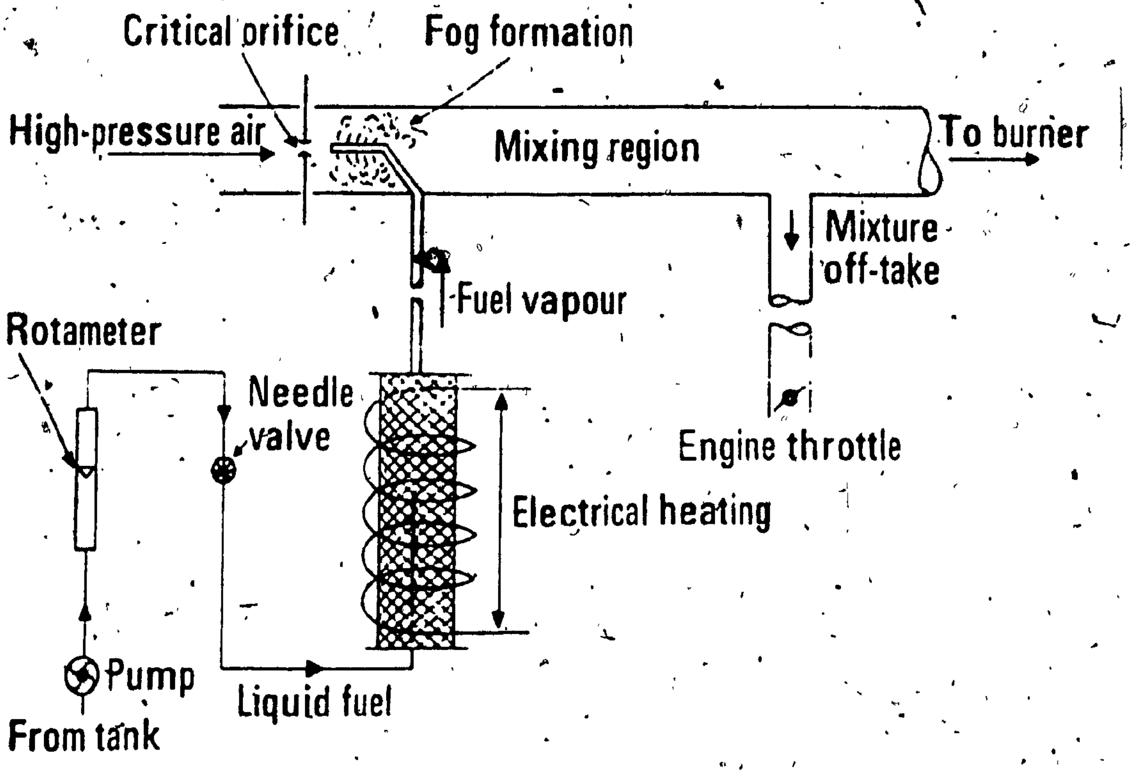


Fig: 5-5, The Thornton mixture generator,
Ref. 41

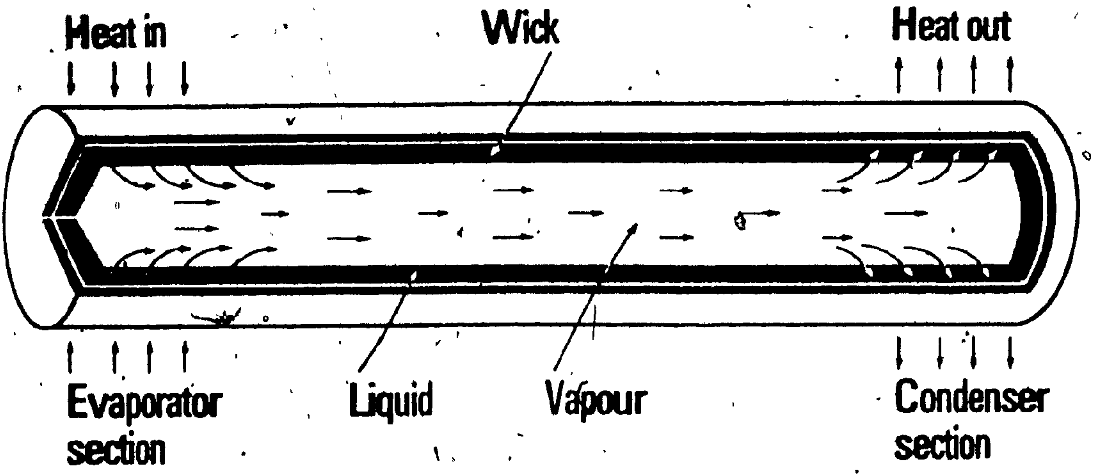


Fig: 5-6, The heat pipe principle,
Ref. 41

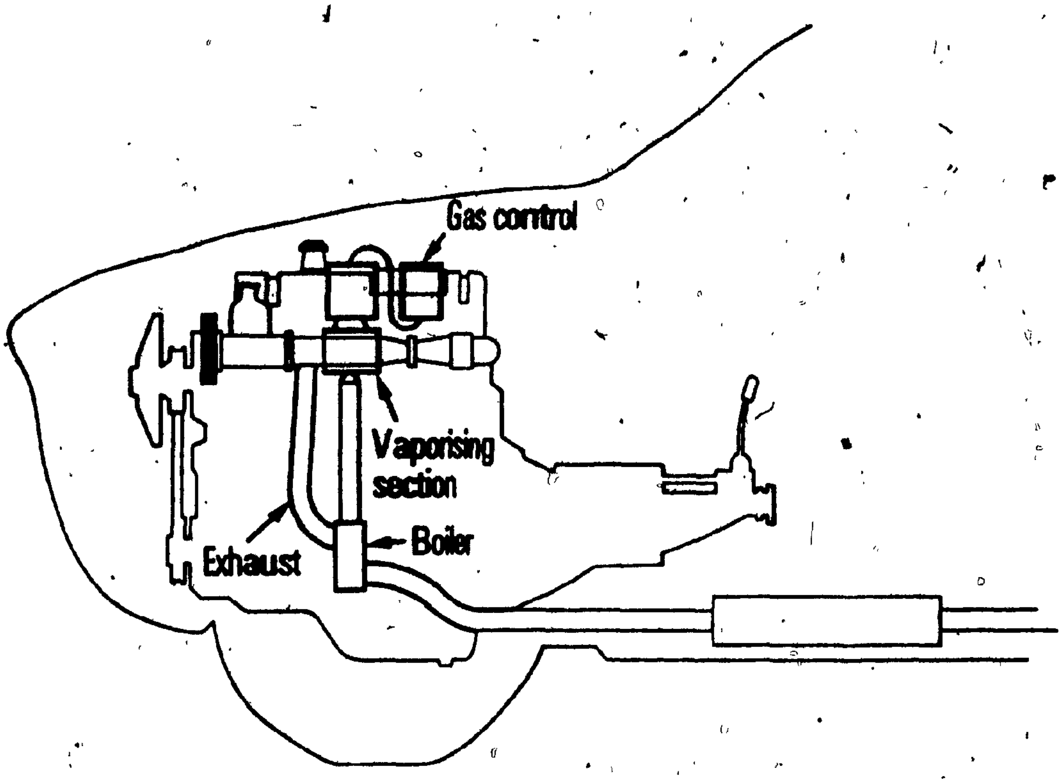


Fig: 5-7, The Vapipe arrangement,
Ref. 41

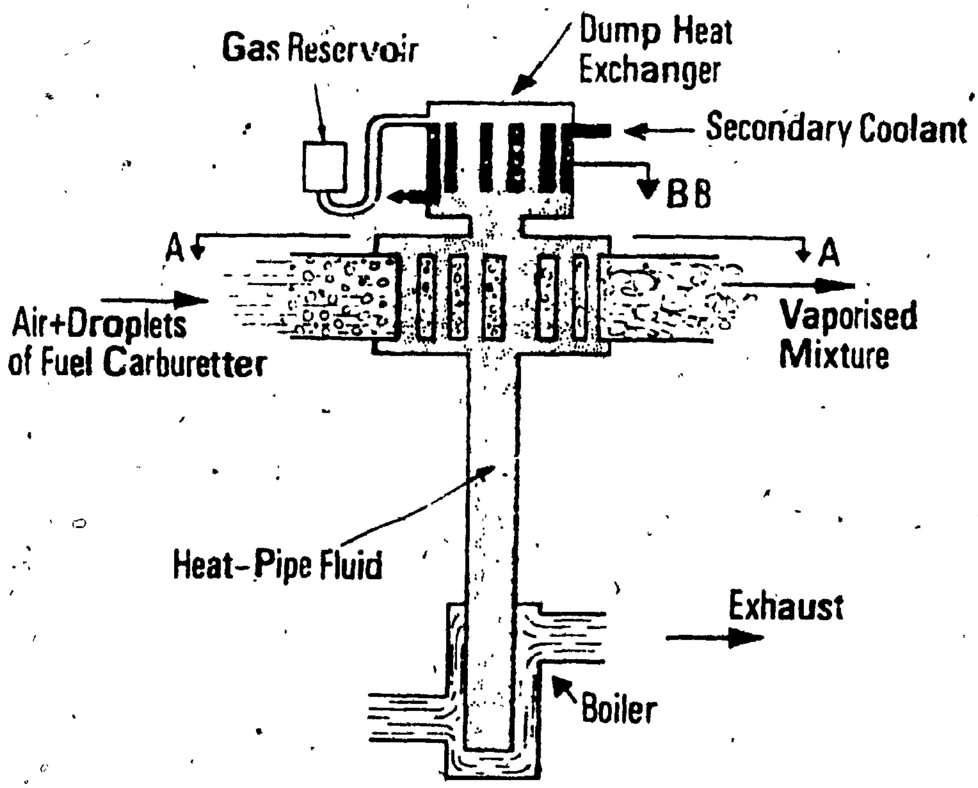


Fig: 5-8, Schematic arrangement of vaporiser with dump heat exchanger, Ref. 41

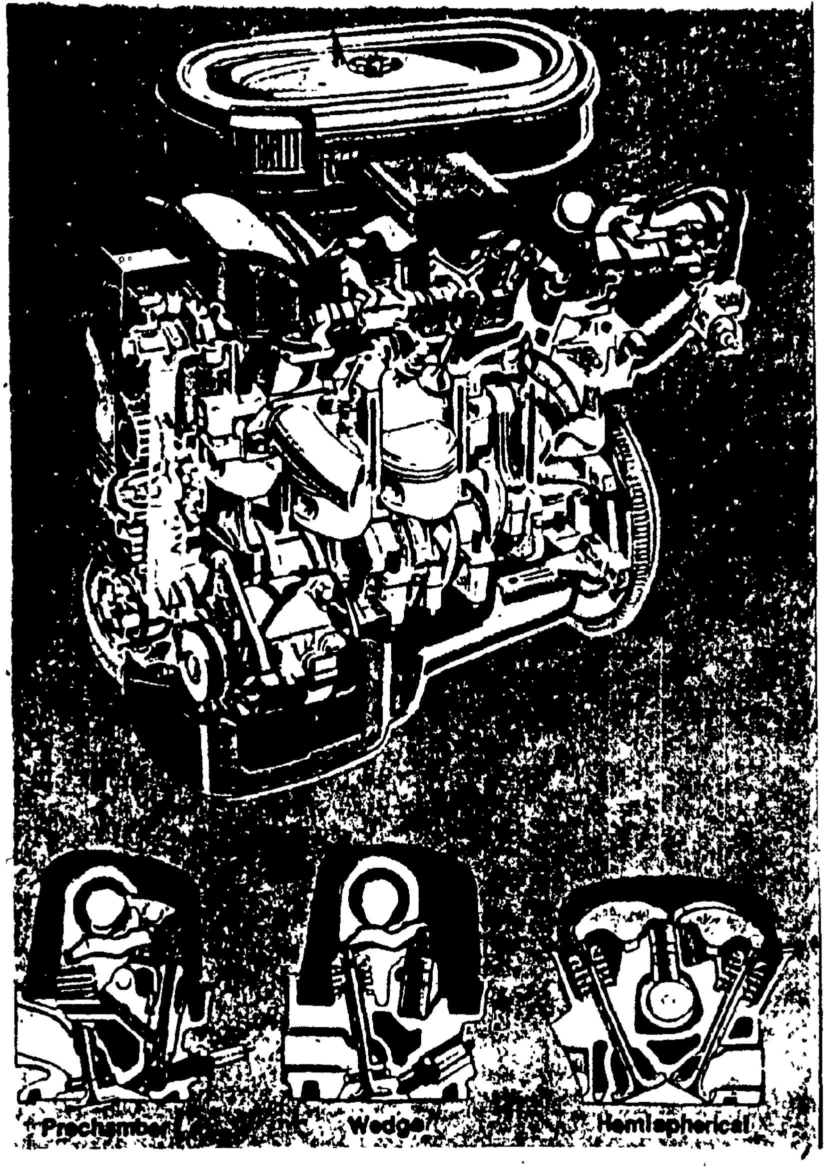


Fig: 5-9, The Hemi engine on Lynx by Ford Motor Co. , Ref. 21

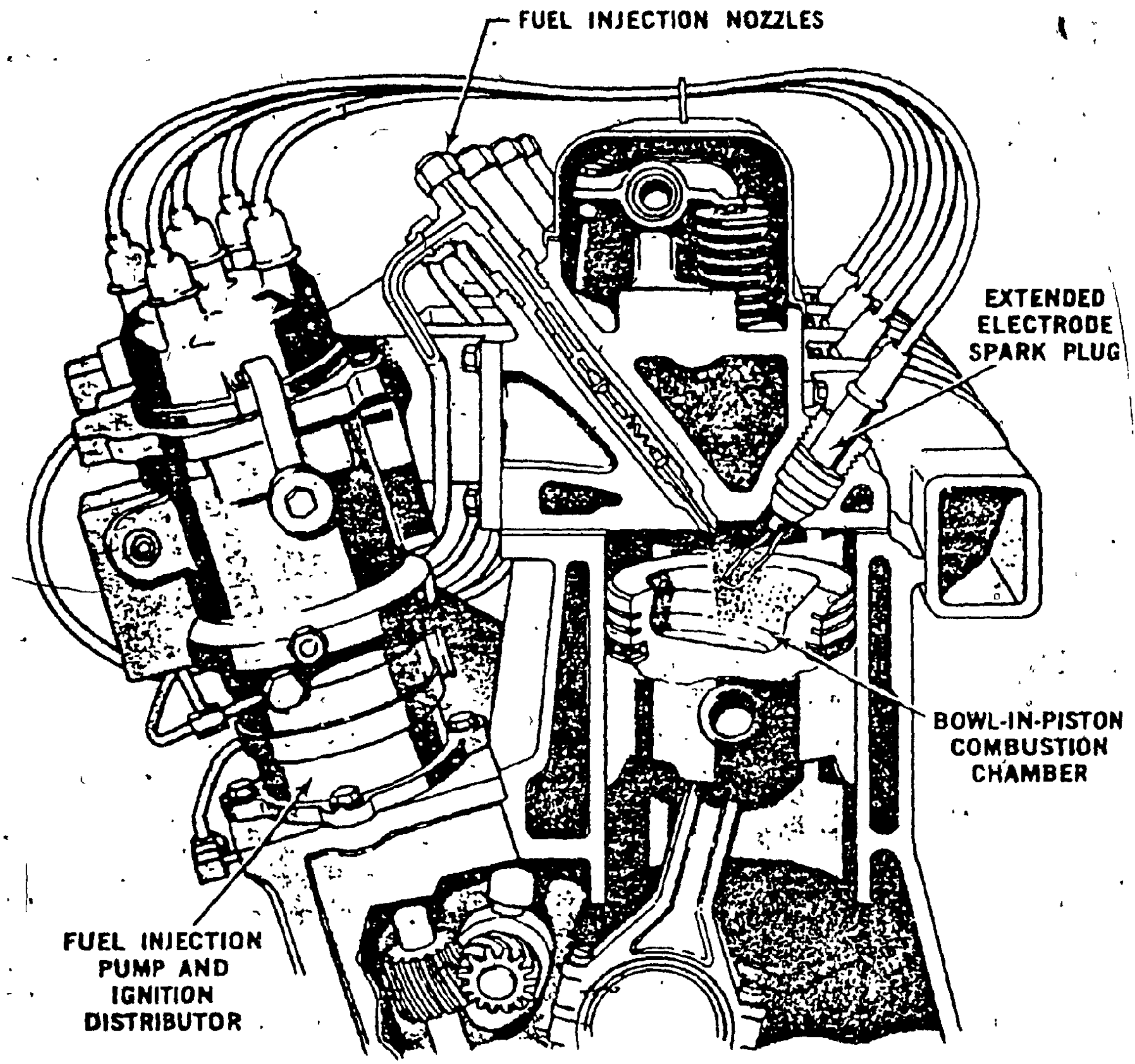


Fig: 5-10, The PROCO engine by Ford, Ref. 23

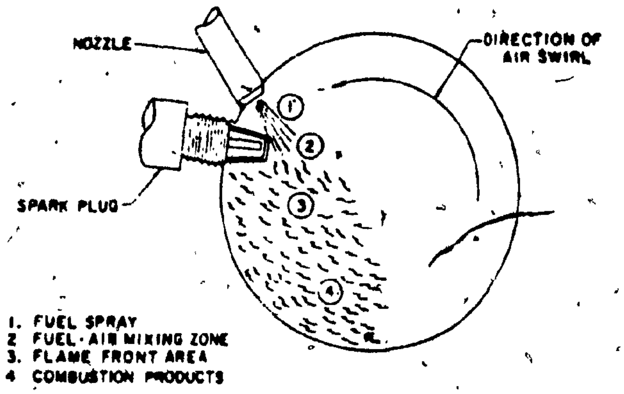
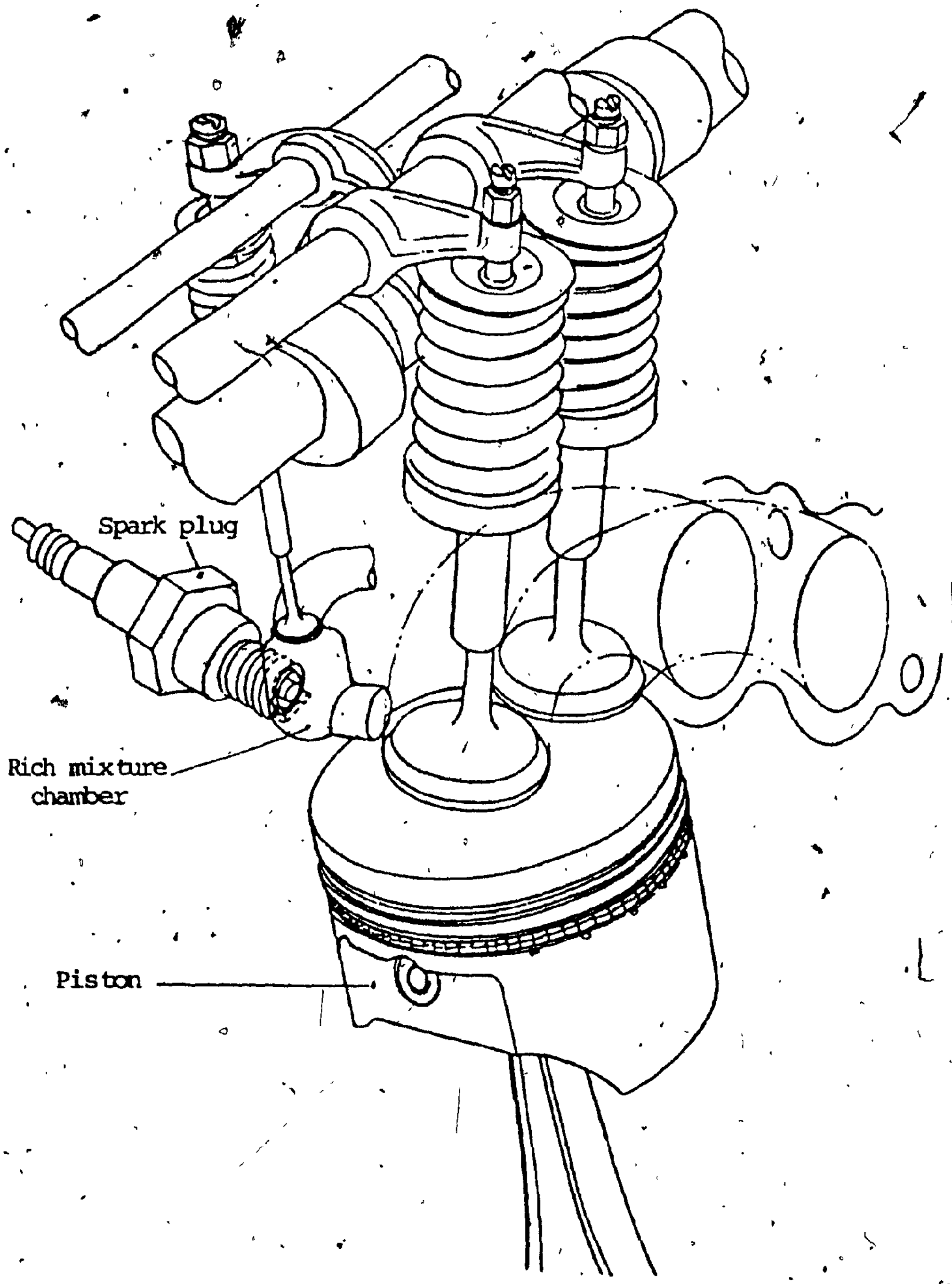


Fig: 5-II, The Texaco controlled combustion engine, Ref. 23



CVCC engine.

Fig: 5-I2, The Controlled Vortex Combustion Chamber by Honda, Ref. 23

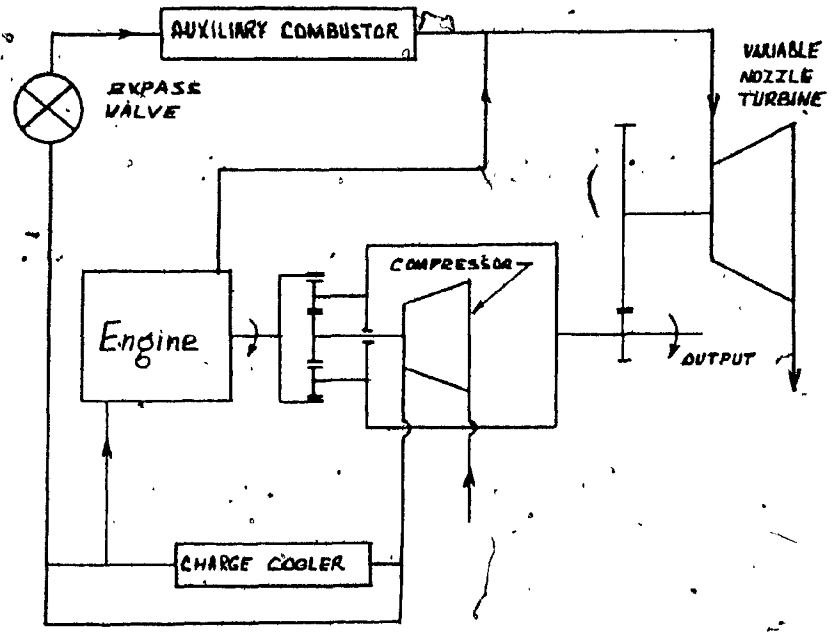


Fig: 5-I3, The Differential Compound Engine.
Ref. 11

CHAPTER 6

METHODS TO EXTEND CONVENTIONAL S.I. ENGINE EXISTENCE

6.1 Introduction

The existence of conventional S.I. engines faces two obstacles.

a) The energy crisis: imposing requirements for more efficient fuel usage. Therefore engines have to be more efficient.

b) Environmental consciousness: imposing requirements for cleaner exhaust gases.

1. Facing the requirement for cleaner exhaust, manufacturers used catalytic converters and other devices meant to eliminate or reduce pollutants in exhaust gases. We can all see charcoal canisters and catalytic converters insolently crowding today's cars.

2. To face the energy crisis the S.I. engine will need higher efficiency and this is our main topic.

6.2 Increasing S.I. Engine Efficiency

The overall efficiency of the S.I. engine is the

product of: Volumentric efficiency
Cycle efficiency
Mechanical efficiency
Combustion efficiency

The volumetric efficiency can be increased by supercharging but it faces some limitations due to detonation.

The cycle efficiency could increase with compression ratio but this again causes detonation. It could also increase by increasing the maximum cycle temperature but the construction materials of the engine would need to be exotic, besides nitrous oxides emissions would increase.

Mechanical efficiency; We cannot expect drastic improvements in this field because there is little more to be done and most researchers are heading away from mechanical research (Cybernetics keep them busy digging deeper into known systems and limiting their abstract invention ability).

Combustion efficiency is a direct contributor to engine efficiency: An increase in combustion efficiency from 70% to 80% would mean a direct reduction of fuel consumption of $(1 - \frac{.7}{.8}) \times 100 =$ 12.5%. Combustion efficiency, as we have seen in chapter 5 can be improved through many ways. We can combine good mixing with stratified charge i.e. two well mixed charges one lean and one rich. Why not evaporate fuel before preparing the mixture?

6.3 Proposed Arrangement

Two gases will mix better than a liquid and a gas. (Ref. 43) We propose to evaporate the fuel before mixing. This process would have little effect on volumetric efficiency because heat is added only to the fuel. (Ref. 43)

In the process of conceiving the system we have to note that, a quick response of the engine is a must. Therefore, the evaporated fuel must be kept in a reservoir to respond to surges in the fuel demand (maneuvrability is important for automotive application). This need for a reserve means that we cannot preheat the fuel as it flows in a heat exchanger because the response would not be prompt. Fig. 6-1 shows a sketch of the arrangement.

We should note that, increasing fuel temperature would cause less detonation than increasing the air temperature. (Ref. 43)

We shall need in this arrangement a boiler for the fuel together with a vapor reservoir as previously explained. So, why not use the boiler header as a reservoir for fuel vapor? Putting a pair of baffles at the outlet would give us dry saturated vapor. To prevent liquid overflow, we maintain the liquid level in the header with a float-operated needle valve.

In order to heat the boiler we use an arrangement similar to the famous " Babcock and Wilcox" natural buoyancy water tube arrangement. (Fig. 6-2).

The liquid tube coming down from the header will have a pressure operated (diaphragm type) control valve. This valve will allow fuel to come down and then up through the section of the tube heated by the exhaust gases. Fuel would then evaporate and make its way up to the header. When there is enough vapor in the header, its pressure will be high enough to close our special valve; no fuel would then go through the hot section. The design would incorporate in that special valve a spool that would let a small dose of water into the hot section thus expelling fuel from there to prevent pyrolysis. Besides, a small amount of steam will also improve engine sound.

A proposed design of that special valve is shown in Fig. 6-3.

For start-up we shall have to preheat this boiler electrically. We can use either a conventional heater in the boiler and have its switch temperature controlled or use a special thermistor as discovered by Ford. The thermistor is a resistance heater whose resistance jumps up after a certain point thus reducing current and hence heat produced. (Ref. 6) (Fig. 6-4) A special thermistor can be made for the temperature range needed.

The fuel outlet would be a needle valve for flow control and be operated by the throttle lever through a diaphragm type governor as illustrated in Fig. 6-5.

These controls can easily lend themselves to microprocessor monitoring and co-ordination.

But this arrangement cannot be put into operation before we study how our fuel will lend itself to the system.

6.4 Properties Of Gasoline

Since we are heating gasoline at a higher pressure than atmospheric, no sufficient data is available for accurate predictions. We also have to study the amount of gum, the volatility and especially the end point for full evaporation.

Fig. 6-6 shows a comparative table for gasoline properties. However, our boiler will operate at a higher pressure than atmospheric which means we cannot use these figures.

The information we could get was in Ref. 44, as shown in Fig. 6-7. The apparatus allowed heating gasoline and measuring the pressure while knowing the volumetric ratio between liquid and vapour.

The results were tabulated and published in Ref. 45. (Fig. 6-8).

This data can be plotted as shown in Fig. 6-9. Using this plotted graph we can extrapolate to find the pressure at a given temperature roughly corresponding to what would be the saturation pressure if we were dealing with a pure substance. The results can be checked as per Appendix I.

6.5 Theory of Operation

Looking at the plotted curve we can see that we can heat gasoline up to 380 F (193 C) and be within a reasonable pressure of about 290 psia (1996 KPa).

This pressure is within the limits of a medium duty pressure vessel. Even though the fuel feed pump would have to supply a high pressure; pumping liquid takes little energy. On the other hand the pressure driving fuel into the intake manifold would ensure evaporation by sudden expansion.

We can estimate the fuel consumption of our engine based on conventional carburetor performance test (see example in Appendix II). Based on this fuel consumption we can calculate the heat energy required to heat it:

$$Q = \dot{m}\,(cp\Delta T + L) \text{ for gasoline} \qquad 6.1$$

where

cp = specific heat of gasoline liquid

Q = Heat energy required

ΔT = Tboiler - Tambient

$\dot{m}$ = mass rate of fuel consumption

L = Latent heat of vaporisation of gasoline

The amound of gasoline circulating in the heating tube (heat exchange tube) would be depending on the driving pressure differential.

Considering that one leg of the U tube heater is filled with liquid gasoline and the other is filled with vapour while the losses in friction are computed considering liquid only through both legs.

$$(\rho liq - \rho vap)h = \frac{4fl}{d}\,\frac{Vel^2 liq}{2g}\,\rho liq. \qquad 6.2$$

Where ρ is the density of gasoline, f the friction factor in the tube, "l" and "d" length and diameter of tube, "Vel" is the circulating velocity of gasoline being heated in the tube, and h is the vertical distance between the boiler reservoir and the heater section.

Assuming a trial value for h, l and d equation 6.2 yields the velocity vel from which we can obtain the gasoline mass flow rate through the heater.

$$\dot{m} \text{ circulating} = \rho \text{liquid} \times \text{Vel} \times \frac{\pi d^2}{4} \qquad 6.3$$

If our level assumptions are correct gasoline vapour should not need to be superheated to transport the necessary amount of heat, i.e. only part of the circulating mass will evaporate when passing through the heater.

Assuming no heat losses occur from the boiler, the heat required Q per equation 6.1 must be equal to heat gained in the heater tube.

$$Q = \dot{m}' \text{circulating } (L) \text{ for fuel} \qquad 6.4$$

where L is the latent heat of vaporisation of gasoline.

If $\dot{m}'$ circulating from equation 6.4 is smaller or equal to that found from equation 6.3 the driving pressure is acceptable.

The heat Q is also equal to :

$$Q = \dot{m}_{exhaust} \times C_{pexh.} (T_{ei} - T_{eo}) \qquad 6.5$$

Where cp_{exh} is the specific heat of exhaust gases, Tei and Teo are the inlet and outlet exhaust gas temperature passing into the heater, and $\dot{m}$ exhaust is the mass flow rate of exhaust gas which can be assumed to be 16 times that of the fuel consumed. If we take an average Tei = 700 F (Ref. 29) equation 6.5 will yield Teo.

Knowing the inlet and outlet temperatures of both gasoline and exhaust gases we can find the effective-mean temperature difference for the heater as:

$$\theta = \frac{Tei + Teo}{2} - T\text{gasoline evaporating} \qquad 6.6$$

In our case this will be sensibly the same as the logarithmic mean.

To simplify the heat exchanger calculation we can use the predicted value of the overall heat transfer coefficient U as given by ref. 46 to obtain the heat exchange surface (A) required since

$$Q = UA\theta \qquad 6.7$$

Then the length of heat exchanger tube will be

$$l = \frac{A}{\pi d} \qquad 6.8$$

We can then recheck the tube length assumption.

On the other end, for vapour going out of the boiler we have to size the orifice of the controllable needle valve.

From Ref. 49 for gas flow from stagnation to a point 0 we have

$$\frac{P_{stg}}{P_o} = \left[1 + M_o^2 \frac{K-1}{2}\right]^{k/(k-1)} \qquad 6.9$$

where k is the ratio between specific heats at constant pressure and at constant volume, P is the pressure and M_o is the mach number at point 0. Subscript stg denotes stagnation condition. For a value of k between 1.1 and 1.5 and for $M_o = 1$ equation 6.9 yields a value of $\frac{P_{stg}}{P_o}$ of 1.71 to 1.95. Since the pressure ratio between the gasoline boiler and the intake will always be higher than this ratio we can safely assume choked flow at the valve with M = 1.

Hence the mass flow rate per unit area is from Ref. 49.

$$G_t^* = \left(\frac{2}{k-1}\right)^{1/(k-1)} \sqrt{\frac{2k}{k-1} P_{stg} \rho_{stg}} \qquad 6.10$$

(Equation based on lbF, slug., ft)

knowing cp, R, S and the fuel consumption m we can obtain the value orifice area

$$A = \frac{\dot{m}}{G_t^*}$$

The arrangement may still need a throttle valve for idling because of the lower flammability limit, which, with a very high volumetric efficiency would require too much fuel for idling.

(A computed example is presented in Appendix III.)

6.6 Discussion

The increase in combustion efficiency will be a direct saving in fuel consumption. The level of unburnt hydrocarbons in the exhaust will decrease thus decreasing pollution. Cold starting will also be improved.

On the negative side, it may take a little time to preheat the boiler just enough to build up about 2 psig of vapor (100°F) (Fig. 6-9). This will delay engine starting. We shall also have to worry about reducing the amount of gum in gasoline to increase boiler maintenance span.

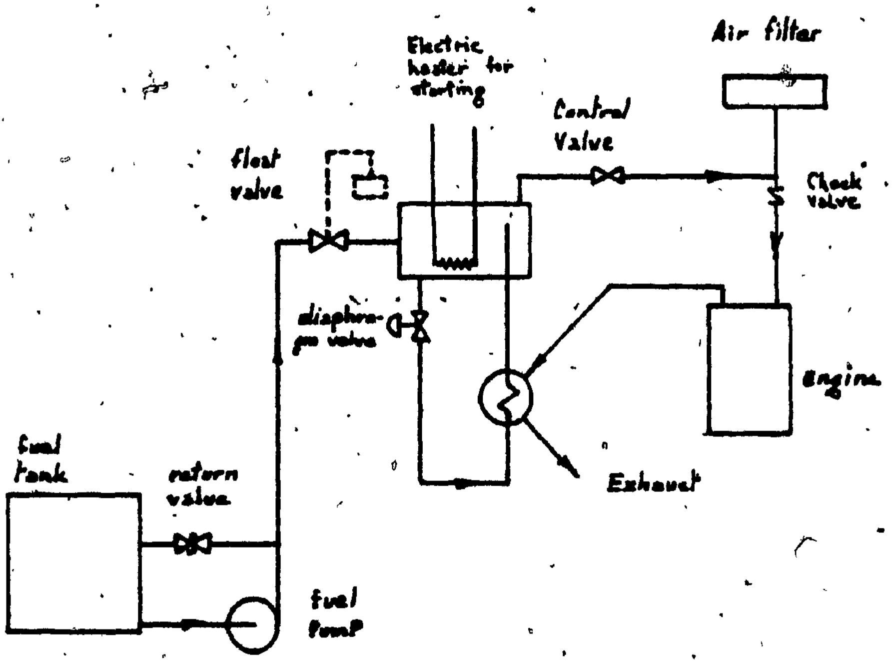


Fig: 6-I, Flow diagram of the arrangement.

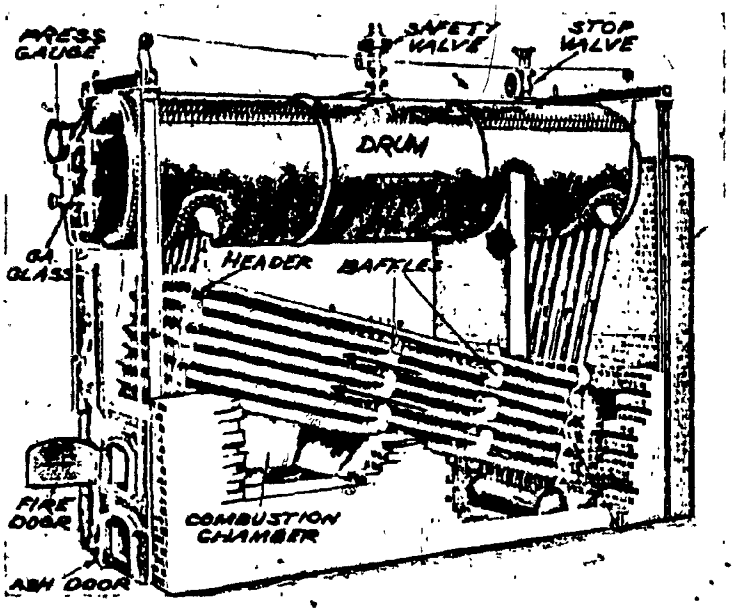


Fig: 6-2, Babcock and Wilcox boiler.

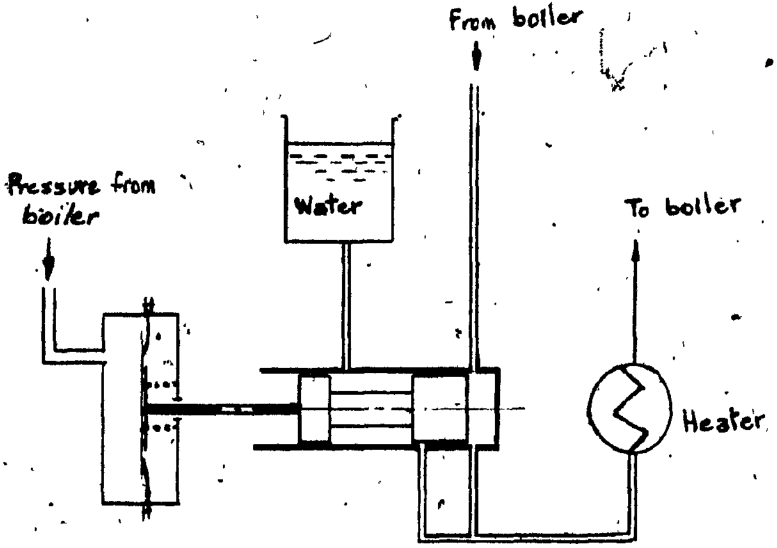


Fig: 6-3, Special diaphram operated heater control valve.

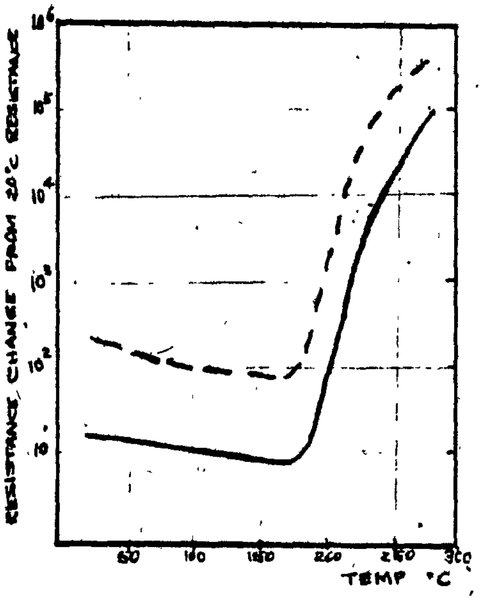


Fig: 6-4, Thermistor behaviour, Ref. 48

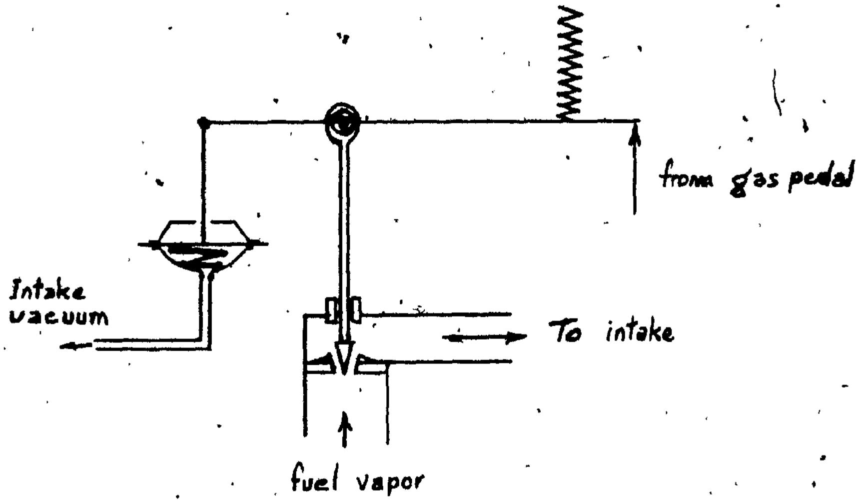
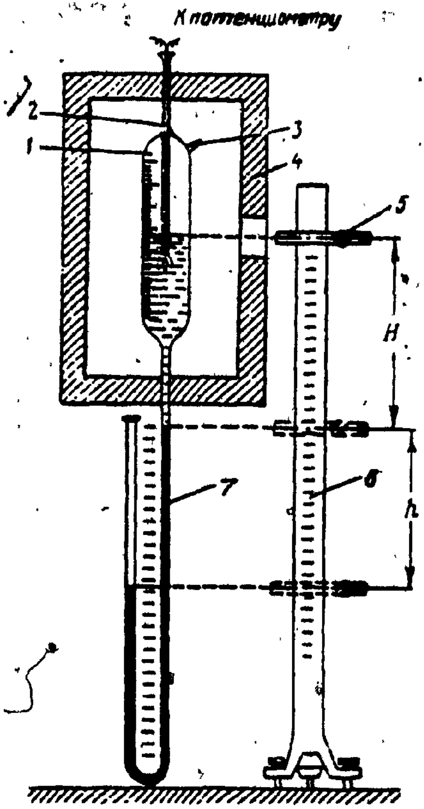


Fig. 6-5, Diaphram type governor.

Characteristic	Commercial gasolines					
	Regular		Premium		Super premium	
Octane rating	93		99.8		I02.5	
Volatility	S*	W*	S*	W*	S*	W*
I0% @ temp °F	I25	III	I25	III	I3I	I23
50% @ " "	210	201	217	210	216	211
90% @ " "	341	337	327	322	310	305
End point	413	410	406	402	389	385
Residue % " "	0.9		0.9		0.9	
Gum mg/100 ml.	1.0		1.0		1.0	

* S- summer ; W- winter.

Fig: 6-6, Gasoline characteristics,
(Internal combustion engines, by Taylor and taylor)



1. Bulb
2. Heating element
3. Filling plug.
4. Insulated compartment
5. Level viewer
6. Scale
7. Mercury U-tube manometer

H. height of gasoline column

h. height of mercury column (not necessarily as shown)

Fig: 6-7, Apparatus used to measure saturation pressure at constant dryness fraction for gasoline.
REF 44

T, °C	20	30	40	50	60	70	80	90	100	110
P, mm Hg	80	123	148	206	286	404	566	755	973	1230

Fig: 6-8, Gasoline vapour pressure (Ratio of vapour to liquid volumes v"/v 4), Ref.45

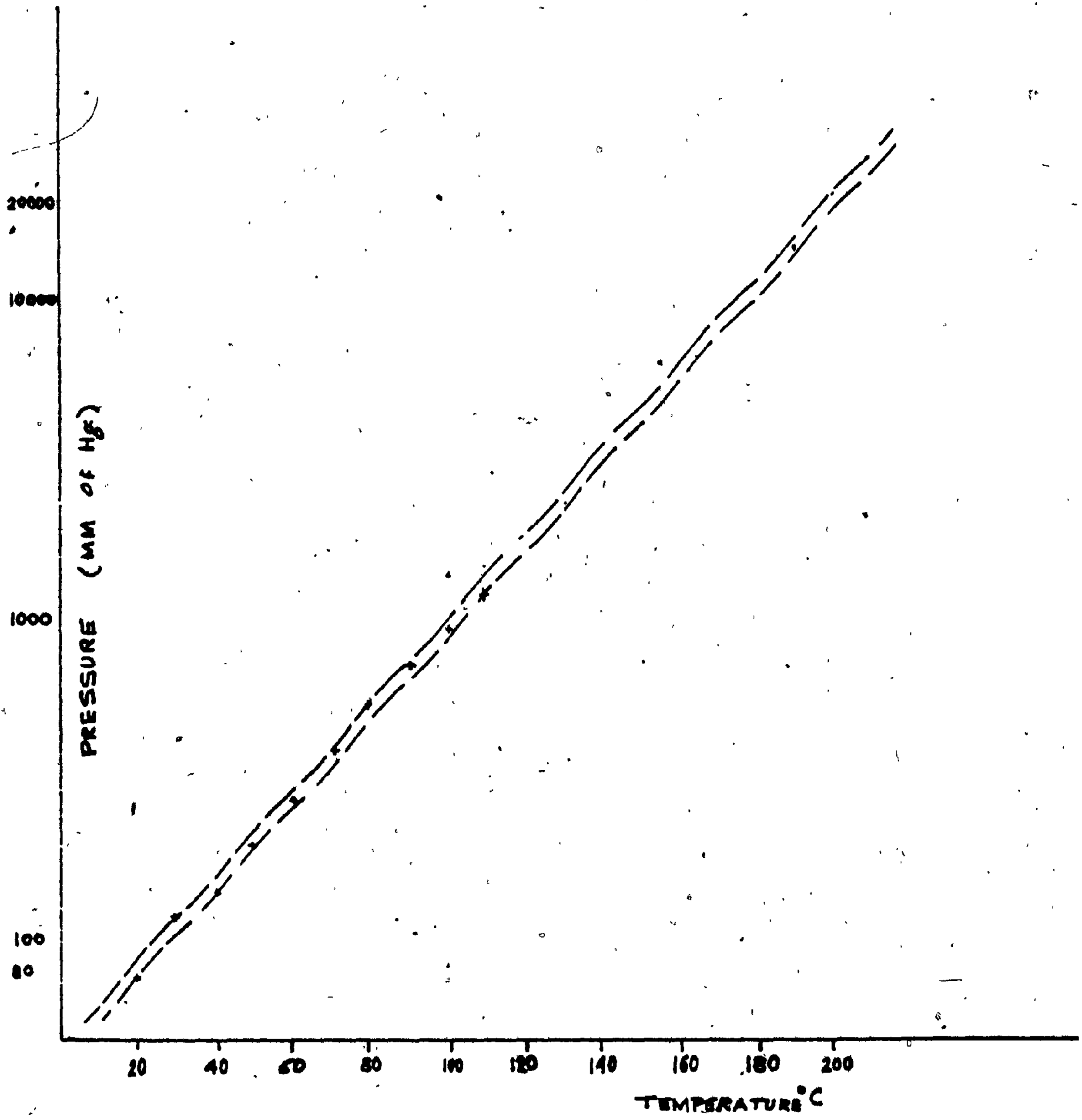


Fig: 6-9, Temp/Press. for wet gasoline vapor.
Ref. 45

APPENDICES

APPENDIX I

Proposed Test procedure to check temperature Vs pressure for gasoline vapour

Equipment required:

- Test container for high temperature and pressure
- A graph recorder with pressure sensor.
- A graph recorder with temperature sensor.
- An electric heating element with emergency shut off switch and controllable rheostat.
- For added safety, the apparatus (heater and container) can be put in a sand filled pit.

Procedure:

- Test container hydrostatically with water to 600 psi.
- Fill test container 3/4 full and close it.
- Connect pressure and temperature detectors.
- Put the heater in the hole topped with half an inch of dry sand then the container and cover the hole with sand.
- Connect the heater and control it to maintain each temperature for about three minutes or until the pressure stabilises.
- Plot pressure VS temperature readings.

Container construction:

Container should be made in accordance with ASME pressure vessel code for a minimum pressure of 300 psi (2068 Kpa) with approximate dimensions 3" dia X 4" lg (76ϕ x 102mm)

Check for Risk of Explosion

The container's total volume is (based on D = 3")

$$\frac{\pi \times 9}{4} \times 4 = 28.27 \text{ in}^3 \ (463.26 \text{ cm}^3)$$

Now if it is about half full of gasoline

$\therefore$ Weight of gasoline in container

$\text{Vol } (ft^3) \times \text{sp. gr} \times \rho \text{water} =$

$= .354 \text{ lb } (.16 \text{ kg})$

$\therefore$ Weight of air in container will be found knowing that

$\rho\text{air at } 70 \text{ F} = .0735 \text{ lb/ft}^3$

$$\therefore \frac{.0735 \times 15}{144 \times 12} = 6.38 \times 10^{-4} \text{ lb } (.003 \text{ kg})$$

This is sufficient to burn 15 times less gasoline by weight.

$$\therefore \text{Gasoline burning } \frac{6.38 \times 10^{-4}}{15} = 4.25 \times 10^{-5} \text{lb } (.00002\text{kg})$$

at 21000 btu/lb

$\therefore$ Heat released $= .0000425 \times 21000 = .89$ btu (939 J)

$= m_{\text{gasoline}} \times C_p \times \Delta T$

$= .354 \times .6 \times \Delta T$

$$\therefore \Delta T = \frac{.89}{.35 \times .6} \simeq 4^\circ F$$

which is negligible, unless there is another source of oxygen, which will then give a regular fire and not an explosion in the container.

APPENDIX II

Peformance Tests

For Engine With Standard Carburetor

The test was run on a Briggs and Stratton single cylinder, four stroke engine using a hydraulic dynamometer. The results are tabulated as follows:

Duration Minutes	Gasoline Used ml	Torque Equiv. Index	Speed rpm	Power HP	BSFC lb/ hp hr	η
8	150	3.4	2400	.816	2.301	5.2
*4 WOT	85	9.8	2600	2.548	.835	14.5
*14 WOT	320	8.5	3100	2.635	.868	13.9
*3.5 WOT	80	9.5	2300	2.185	1.047	11.5
5.5	75	6	2100	1.26	1.083	11.18
7	75	-	2350	-	-	-

We can see that we had maximum torque and maximum efficiency at a lower speed than maximum horsepower which is expected, so the test credibility is good despite the lower than expected power of the engine which can be attributed to engine system inefficiencies.

*Readings at wide open throttle

APPENDIX III

EXAMPLE

Considering the engine tested in Appendix II

Maximum power was 2.635 HP @ 3100 rpm

As tested BSFC at maximum horsepower

$$BSFC = .868 \text{ lb / HP hr}$$

We shall rate our calculation at this performance point.

Fuel flow rate

$$\dot{m}_{fuel} = \frac{.868 \times 2.635}{3600} = 6.4 \times 10^{-4} \text{ lb/sec} \quad (2.9 \times 10^{-4} \text{ kg/sec})$$

The boiler temperature will be set at 380°F (193°C) to evaporate super premium (fig 6-6). From the temperature pressure curve (fig 6-9) we can predict that, at 380°F (193°C) pressure will be 290 psia (15000 mm Hg).

Heat energy required

$$Q = \dot{m}_{fuel} \times [c_p (T_{boiler} - T_{ambient}) + L]$$

From Ref 45 between 20°C and 200°C for liquid gasoline

$$c_{pav} = 2.5 \text{ KJ/kg°C} = .6 \text{ btu/lb°R}$$

$$L = \frac{71 + 81}{2} = 76 \text{ cal/g (Ref 47)} = 136.8 \text{ btu/lb.}$$

$$\therefore Q = 6.4 \times 10^{-4} \times [.6 (380 - 70) + 136.8]$$

$$= 6.4 \times 10^{-4} \times 322.8 = 2065 \times 10^{-4} \text{ btu/sec}$$

$$= .2 \text{ btu/sec} \quad (217 \text{ J/sec} = 217 \text{ W})$$

Circulation flow

The amount of gasoline circulating in the heating tube can be found using equation 6.2.

Density of gasoline liquid at 380°F (193°C) from Ref. 45.

$$\rho = .58 \times 10^3 \text{ kg} / \text{m}^3 = 2 \times 10^{-2} \text{ lb/in}^3$$

To obtain the density of gasoline vapour we shall consider it a perfect gas with average molecular weight

$M = 114.14$ (Ref 19).

To find the density of vapour going up to the boiler assume constant pressure 290 psia (2000 KPa) and a temperature of 380°F (193°C)

$\overline{R} = 1545 \text{ ftlb}_f/\text{lb mole}°\text{R}$ (Ref. 10)

$$Pv = \frac{\overline{R}}{M} T$$

$$144 \times 290 \times v = \frac{1545}{114.14} \times (380 + 460)$$

$$\therefore v = .27 \text{ ft}^3/\text{lb}$$

$$\therefore \rho = 3.65 \text{ lb/ft}^3$$

$$= .002 \text{ lb/in}^3 \; (58.5 \text{ kg/m}^3)$$

We have to assume a heater pipe diameter of .5 in (13mm) and a pipe length of 12 in (300mm) (4" up, 4" down and 4" exchanger). The friction factor f will be assumed equal to .002 (Ref. 49).

From equation 6.2, the driving force for circulation at full evaporation

$$(\rho\text{liq} - \rho\text{vap}) \times h = 4\,\frac{fl}{d}\,\frac{\text{vel}^2}{2g}\,\rho\text{liq}$$

$$(.02 \times 12^3 - .002 \times 12^3) \times \frac{4}{12} =$$

$$\frac{4 \times .002 \times 12}{.5} \times \frac{\text{vel}^2}{2\text{x}32.2} \times .02 \times 12^3$$

$$\text{vel}^2 = 100.625$$

$$\text{vel} = 10 \text{ ft/sec } (3\text{m/sec})$$

This is the maximum velocity based on evaporation of the totality of the fuel passing through the heater. The percentage evaporated will be less so that the driving pressure will be less but the heat transfer area will govern because if the fuel circulating rate slows down, almost the same heat will be transferred and the percentage evaporated will increase and speed up the circulation.

$$\text{Maximum } \dot{m} \text{ circulating} = \rho vA$$

$$= .02 \times 10 \times 12 \times \frac{\pi \times .25}{4} = .5 \text{ lb/sec.}$$

From equation 6.4:

$$Q = \dot{m}_{\text{circulating}}\ (L)$$

$$Q = .5\ (136.8) = 68.4 \gg .2 \text{ btu/sec}$$

$\dot{m}$ circulating will be greatly reduced or interrupted often, but this only ensures that natural circulation is adequate and flow can be restricted up to the point where

$$\dot{m}' \text{circulating} = \frac{.2}{136.8} = 1.5 \times 10^{-3} \text{ lb/sec } (.68 \times 10^{-3}\text{kg/sec})$$

and still be able to heat the boiler.

On the other hand from equation 6.5

$Q = \dot{m}_{exhaust} \times c_{pexh} \; \Delta T_{exhaust}$

$.2 = 16 \times .00064 \times (700 - T_{out})$

$.2 = 0.01024 \; (700 - T_{out})$

$T_{exhaust\ out} = \frac{-.2}{.01024} + 700 = 680^{\circ}F \; (360^{\circ}C)$

Our heat transfer effective mean temperature difference for an evaporating liquid at 380°F (193°C) is

$\theta = \frac{700 - 680}{2} - 380 = 310^{\circ}F \quad (154^{\circ}C)$

and the heat transfer coefficient is expected to be

$U = 50$ btu/hr/ft^2 (Ref. 46).

$Q = UA\theta$

$.2 \times 3600 = 50 \times A \times 310$

$A = .046 \text{ ft}^2 = 6.69 \text{ in}^2 \quad (43 \text{ cm}^2)$

we had assumed .5" dia X 4" length -

$\therefore A = .5 \times \pi \times 4 = 6.3 \text{ in}^2$ which is reasonable.

To specify the size of the orifice we need equation 6.10 which in turn requires the value of k to be known.

Assuming ideal gas.

$k = \frac{cp}{cv}$

$c_v = -R + c_p$

$= c_p - \frac{\bar{R}}{M}$

for gasoline vapour at approximately 380°F (193°C)

$$C_p = 2.43 \text{ KJ/Kg degree (Ref. 45)}$$

$$= .58 \text{ btu/lb°R}$$

$$\bar{R} = 1.986 \text{ btu/mole°R} \quad \text{(Ref. 10)}$$

$$(1.986 \text{ cal/g mole°K})$$

$$c_v = .58 - \frac{1.986}{114.14} = .56 \text{ btu/lb°R}$$

$$(2.3 \text{ KJ/Kg degree})$$

$$\therefore k = \frac{.58}{.56} = 1.04$$

$$G_t^* = \left(\frac{2}{k-1}\right)^{1/(k-1)} \sqrt{\left(\frac{2k}{k-1}\right) P_{stag}\, \rho_{stag}}$$

$$= \left(\frac{2}{2.04}\right)^{1/.04} \sqrt{\frac{2.08}{2.04} \times \frac{290}{32.2} \times 144 \times 3.65}$$

$$= .6 \sqrt{4826.5} = 41.7 \text{ lb/ft}^2\text{.sec.}$$

$$\text{Area} = \frac{\dot{m}}{G^*} = \frac{.00064 \times 144}{41.7} = 2.2 \times 10^{-3} \text{ in}^2$$

$$D = \sqrt{\frac{4A}{\pi}} = .053'' \quad (1.4 \text{ mm})$$

A miniature needle valve will be needed.

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