UNIVERSITY OF BIRMINGHAM

ANIMAL FAT (TALLOW) AS FUEL FOR STATIONARY INTERNAL COMBUSTION ENGINES

by

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Abstract

Power generation is the largest single source of greenhouse gas emissions, accounting for some 40% of the world total (1). The situation can be improved by usage of renewable fuels. There is a lot of controversy and growing concerns regarding usage of so called first generation bio fuels produced from food crops. The attention of industry and researchers is moving towards second generation fuels obtained from non edible sources. Waste food or meat by-products can be processed into tallow. This thesis focuses on the suitability and feasibility of animal fat usage as a fuel for internal combustion engines. The applied approach can be characterised by acknowledging the challenges and difficulties of using untreated fat in the engine, where modifications to the fuel supply system are minimal; the consequences are described and analysed. This work is an attempt to provide guidance and minimal requirements for animal fat to be utilised as fuel.

Animal fat (tallow) has been used by humans as source of energy since the Palaeolithic age. The main area of application was combustion in various types of lamps. Tallow is obtained from animal by-products in a process called rendering. The raw material is crushed and heated. The process eliminates water, sterilises the material and allows it to be separated into fats, meat and bone meal. It may regarded to be a waste product, however, access to the raw material, such as whales washed on shore, was regulated by law from as early as the 12th century. The feasibility of alternative fuel usage may often be a critical factor affecting power plant type selection. The renewable electricity generation

subsidising system in the United Kingdom has been reviewed. A basic feasibility study for the installed generating set was prepared and the highest tallow price at which electricity generation is profitable was determined. It was proven that usage of tallow can be feasible, provided that some form of incentive for biomass or waste technology is implemented.

The properties of tallow were monitored on a weekly basis throughout a period of one year. By performing an analysis of laboratory test results, it was established whether the product quality is in statistical control. Some properties, such as acidity, moisture or ash content, showed significant variability throughout the year. Possible reasons causing variable and high acidity are given together with a proposal for an acidity removal method. The proposed method of evaporating free fatty acid under reduced pressure was tested in a laboratory installation and a promising reduction efficiency of 50 % was achieved.

The effect of storage and supply temperatures on the properties of tallow was investigated. The available laboratory facilities enabled the verification of changes in fat's viscosity, density and surface tension. Pre heating to 90°C enables reduction of all tested properties, however, the achieved results are comparable with Heavy Fuel Oil (HFO) rather than automotive diesel fuel. Lubricity of tallow was tested, to predict possible effects of its usage on the longevity of the engine fuel supply system. Elevated temperature does not have a negative impact on the lubricating properties of tallow. Storage conditions are an important factor affecting the quality of bio fuels. The impact of storage temperature on deterioration in tallow quality was investigated over a period of one month. It was proven that animal fat can be stored in a liquid form for a prolonged period of time without deterioration of its properties.

The combustion process of animal fat was compared with that of diesel fuel. Tests were conducted at three different loads. Usage of animal fat results in higher cylinder pressures, and the heat release rate for the premixed combustion phase is significantly lower. For high load operation, all measured emissions were lower for animal fat with exception of nitrogen oxides. Due to low sulphur content there is no requirement for a sulphur dioxide abatement system. The available emission control systems have been reviewed and a solution choice has been made, based on legal and economic criteria. Cooled Exhaust Gas Recirculation (cEGR) was designed and installed. Trial test results are presented and analysed. The system enabled reduction of nitrogen oxides' emissions by 75%.

A summary of two thousand hours operation of the 800 kW generating set using neat fat is provided. The performance of injectors and fuel pumps was investigated. It was proven that appropriate filtration and supply strategy can enable problem free operation of the internal combustion engine. An increased tendency for deposit formation was recorded. Two types of lubricating oil were tested. By adhering to the manufacturer's recommendation for the lubricating oil centrifuge cleaning frequency, enabled the achievement of a 1000 hours oil change interval, the same as for fossil fuel operation. Usage of tallow causes an increase in oil viscosity.

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List of Publications, Related Work and Achievements

1. **Tallow combustion in a large diesel engine and hydrogen production via tallow reforming.**

   J. Piaszyk, P. Leung, M. L. Wyszynski, A. Tsolakis, B. Williams, P. Latham, A. York, *Energy & Fuels*, submitted 2011.

2. **The economics of renewable energy generation by gas engines in the United Kingdom.**

   J. Piaszyk, M. L. Wyszynski, A. Tsolakis, P. Latham, in *Gas Engines - chosen topics,* A. Duzynski, Ed. (Wydawnictwo Politechniki Czestochowskiej, Czestochowa, 2010), pp. 404-417.

3. **Acidity of Tallow (Animal Fat) and Its Effect on Suitability of Tallow as Fuel in Electricity Generating Engines.**

   J. Piaszyk, M. L. Wyszynski, A. Tsolakis, *Archivum Combustionis* 30, 471 (2010).

4. **Possible application of animal fat as engine fuel - lubricity aspects.**

   J. Piaszyk, M. L. Wyszynski, *Combustion Engines* 147, 35 (2011).

5. **Animal fat combustion in diesel engine as a way of renewable electricity generation.**

   J. Piaszyk, M. L. Wyszynski, A. Tsolakis, B. Williams, P. Latham , poster at *Research Poster Conference 2011,* University of Birmingham (2011).

6. **Chartered Management Institute – Diploma in Management (2010).**

7. **Knowledge Transfer Partnership (KTP) Associate Certificate (2010).**

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List of Definitions and Abbreviations

AD	Anaerobic Digestion
AN	Acid Number
ANSI	American National Standards Institute
ASTM	formerly known as American Society for Testing and Materials
ATDC	After Top Dead Centre

BOTS	Ball on Three Seats
BSFC	Brake Specific Fuel Consumption
BSE	Bovine Spongiform Encephalopathy
BTDC	Before Top Dead Centre
CASS	Combustion Air Saturation System
CCL	Climate Change Levy
cEGR	Cooled Exhaust Gas Recirculation
CHP	Combined Heat and Power
CHPQA	Quality Assurance for Combined Heat and Power
CI	Compression Ignition
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COV	Coefficient of Variance
CP	Compliance Period
CPO	Crude Palm Oil
DC	Direct Current
DECC	Department of Energy and Climate Change
degCA	Crank Angle Degree
DNC	Declared Net Capacity
EfW	Energy from Waste
EGR	Exhaust Gas Recirculation
EWMA	Exponentially Weighted Moving Average

FAME	Fatty Acid Methyl Ester
FFA	Free Fatty Acid
FID	Flame Ionisation Detector
FIT	Feed In Tariff
FYP	Final Year Project
GFC	Gas Filter Correlation
HC	Hydrocarbons
HFO	Heavy Fuel Oil
HFRR	High Frequency Reciprocating Rig
HOC	Heat Obligation Certificate
HRC	Rockwell Hardness
HV	Vickers Hardness
IMEP	Indicated Mean Effective Pressure
IP	Indicated Pressure
ISO	International Organisation for Standardisation
KTP	Knowledge Transfer Partnership
LCL	Lower Control Limit
LEC	Levy Exemption Certificate
LFG	Landfill Gas
MBM	Meat and Bone Meal
MEP	Mean Effective Pressure
MFB	Mass Fraction Burned

MR	Moving Range
MWSD	Mean Wear Scar Diameter
NFFO	Non Fossil Fuel Obligation
NFPA	Non Fossil Purchasing Agency
NH_3	Ammonia
NHRR	Net Heat Release Rate
NO_x	Nitrogen Oxides
OFGEM	Office of the Gas and Electricity Markets
OH	Hydroxyl Group
PDA	Phase Doppler Anemometry
PE	Power Efficiency
PM	Particulate Matter
PP	Peak Pressure
ppm	Parts per Million
PPP	Pool Purchase Price
PV	Photovoltaics
QI	Quality Index
R_a	Profile Roughness Parameter
REC	Regional Electricity Company
RHI	Renewable Heat Incentive
RHO	Renewable Heat Obligation
RO	Renewables Obligation

ROC	Renewables Obligation Certificate
rpm	Revolutions per Minute
SAN	Strong Acid Number
SCR	Selective Catalytic Reduction
SECA	Sulphur Emission Control Area
SFOC	Specific Fuel Oil Consumption
SLBOCLE	Scuffing Load Ball on Cylinder Lubricity Evaluator
SMD	Sauter Mean Diameter
SRM	Specified Risk Material
TAN	Total Acid Number
TBN	Total Base Number
TSB	Technology Strategy Board
TSE	Transmissible Spongiform Encephalopathies
UCL	Upper Control Limit
ULSD	Ultra Low Sulphur Diesel
USV	Ultra Shear Viscometer
VAG	Volkswagen Audi Group
VOC	Volatile Organic Compound
VTT	Technical Research Centre of Finland
WID	Waste Incineration Directive
WSD	Wear Scar Diameter

Chapter 1 **INTRODUCTION**

1.1 Thesis Background

The UK Government has set strategic targets for both the energy market and industry. Documents such as the Low Carbon Transition Plan and Renewable Energy Strategy specify that emissions, expressed as metric tonne carbon dioxide equivalent ($MtCO_2e$), must be cut by 18% by 2020 (compared to the 2008 level) (2) and 15% of energy should be generated from renewable sources by 2020 (3). The targets can be achieved by extended usage of biomass as a source of renewable energy. There is a potential in using crude fats, like tallow, as fuel for internal combustion engines. By adopting the right working practices and procedures and implementing appropriate treatment methods, the rendering industry may play an important role in the renewable energy sector.

This thesis is one of the outputs of a collaborative project established between The School of Mechanical Engineering at The University of Birmingham and a leader in the UK rendering industry, Staffordshire based, John Pointon & Sons. Cooperation was in the form of a TSB (Technology Strategy Board) funded KTP (Knowledge Transfer Partnership).

1.2 Objectives

The main aim of the research process described in this thesis is to verify suitability of animal fat as fuel for internal combustion engines. The objectives of this research were to:

- identify, analyse and solve fuel flow-related problems with close attention given to the fuel supply system and fuel injection system
- study the impact of raw and treated tallow on the combustion quality, emissions, performance and economy
- study the mechanical and chemical effects of animal fat fuel on the engine components and longevity
- optimise the engine operation, prepare procedures for operation of gen-set engines using tallow fuels
- improve or modify fuel quality by varying the tallow preparation, fuel production or pre-treatment
- verify the feasibility of the usage of tallow for power generation application by conducting analysis of existing support policies for biomass/waste fuels.

1.3 Thesis Outline

The thesis is divided into nine consecutive chapters which cover various aspects of animal fat usage as fuel for reciprocating engines.

A literature review is presented in Chapter 2, which introduces a definition of animal fat (tallow), describes the production process and also provides basic information regarding how tallow is divided into grades and categories. Available information regarding neat triglycerides' usage as an engine fuel is analysed to obtain guidance for engine test trials. A short review of the emissions abatement systems available for large engines is also given. A very limited amount of published data regarding usage of animal fat as fuel for large internal combustion engines justifies the necessity of a conducted research programme.

An electricity generation feasibility study is presented in Chapter 3. It contains calculations for a small scale plant (<1MW) and also a large scale plant (20MW). The relationship that links animal fat price with fossil fuel price is analysed. The effect of fuel price change on generation feasibility is given.

The experimental set up is described in Chapter 4. It contains a description of the 800 kW research power plant located at John Pointon & Sons Ltd. premises at Cheddleton, Staffs, UK. Usage of animal fat required modification of the fuel supply system to enable dual fuel operation – the working principle is explained. The designed emission abatement system in a form of EGR with gases cooling and humidification, (cEGR), is presented together with technical drawings appended. Tests conducted at the research power plant were accompanied by laboratory tests, of which main the objective was fuel properties' testing – a laboratory facilities description is provided.

Chapter 5 presents results of an investigation that focused on the consistency of fuel properties. Changes of properties during the calendar year are statistically analysed. A possible reason for variable acidity is given together with a review of available acidity reduction methods. One of the physical methods has been tested in a laboratory scale experiment.

Chapter 6 is devoted to analysis of fuel temperature effect on its properties. The main objective of this chapter is to verify if pre heating is a correct way of animal fat pre-treatment.

Combined results of tests described in Chapters 5-6 lead to establishing a suitable fuel specification. Another outcome is the creation of an engine testing programme where operating conditions, such as fuel temperature, are considered.

Analysis of the combustion process together with emissions data are given in Chapter 7. All data is recorded for fossil fuel (diesel), hence reference data is obtained, and then compared with results for animal fat. Tests were performed at synchronous speed for three different engine loads.

The long term effect of animal fat usage on engine components' longevity is described in Chapter 8. Analysis is divided into sub sections describing fuel pumps, injectors and lubricating oil.

Conclusions and suggestions for future work constitute the final chapter of this thesis.

Chapter 2 LITERATURE REVIEW

2.1 Introduction

This chapter contains a short summary of information available in literature concerning the possible application of animal fat and other triglycerides as fuel for compressed ignition engines. Emissions abatement methods used for marine and stationary applications are briefly described.

2.2 Definition of Tallow

Tallow is an animal fat obtained by rendering animal carcases and waste from the food industry. Crude fats primarily consist of triacylglycerols but also contain non glyceride substances (unsaponifiable fraction), that affect chemical and physical properties (4). A triacylglycerol consists of a three carbon glycerol head group to which are added three fatty acid chains (5). A structure of triacylglycerol is shown in Figure 2.1. All triacylglycerols have the same basic structure, and the differences in properties and use of commercial triglycerides depend largely on the length, degree of unsaturation and other chemical modifications to the fatty acid chains (6, 7). Examples of the structures of common C18 fatty acids are given in Figure 2.2, as C18:0 (stearic acid, octadecanoic acid), C18:1 (oleic acid, 9-octadecenoic acid), and C18:2 (linoleic acid, 9,12-octadecenoic acid) (8). Typical fatty acid composition of tallow and other animal fats is given in Table 2.1.

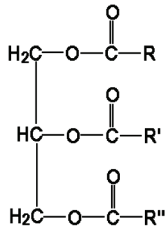

Figure 2.1 General structure of triacylglycerol, R, R', and R" indicate fatty acid groups (8)

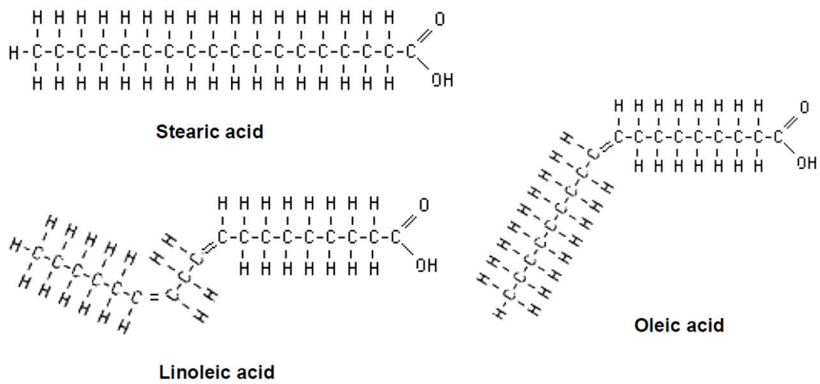

Figure 2.2 Structures of common C18 fatty acids: stearic, oleic, and linoleic acids (8)

Table 2.1 Typical fatty acid composition (%wt) of major animal fats (7). Fatty acid specification (e.g. 16:1) includes the length of carbon chain and amount of double bonds.

Fat	Fatty acid						
	14:0	*16:0*	*16:1*	*18:0*	*18:1*[a]	*18:2*	*Other*
	Myristic	*Palmitic*	*Palmitoleic*	*Stearic*	*Oleic*	*Linoleic*	
Butter[b]	12	26	3	11	28	2	18
Lard	2	26	5	11	44	11	1
Beef tallow	3	27	11	7	48	2	2
Mutton tallow	6	27	2	32	31	2	0
Chicken fat	1	22	6	7	40	20	4

Notes
[a] – including trans isomers
[b] – also 4:0 (3%), 6:0 (2%), 8:0 (1%), 10:0 (3%), and 12:0 (4%).

2.3 History of Tallow Usage

Animal fat was used not only as a fuel but also for nutritional purposes and medicines. Widespread usage of animal fats for lighting purposes can be associated with the easy controllable combustion process and feedstock availability. Proof of animal fat usage from prehistoric times was discovered. Palaeolithic humans were living in caves and caverns where flint mining required artificial lighting. The first primitive lamps were used alongside with torches and fires. In southern France, in the region of the limestone hills upon the river Vezere, at the Lascaux cave complex, small stones with little cavities were found (shown in Figure 2.3). Some of these were black as a result of a combustion process. Hollow bones filled with animal fat were also used as a light source (9). During the Neolithic Age, humans living on the Danish coast were using oval, clay lamps. Analysed samples revealed the presence of small amounts of animal fat (fish oil). Fats obtained from sea birds like cormorants and sea gulls were also used (10). Flint mines in Grimes Graves and Cissbury were lit by small lamps made from chalk (10). Animal fat burned in stone lamps was also used in one of the largest flint mines in Europe which consisted of a thousand pit shafts, located in Krzemionki Opatowskie in Poland (11).

Figure 2.3 A deer fat lamp, found in a Lascaux cave. It can be viewed in the National Prehistory Museum in Les Eyzies-de-Tayac (12)

In the polar zone, seal fat was used for heating and as a light source till modern times. Obtaining fat was inevitably linked with waste or a by-product conversion process and feedstock availability. In some cases fat was obtained from hunted animals. Whales thrown on the seashores (shown in Figure 2.4) were considered as a valuable resource. Magnus (13) listed possible ways of utilising one whale for: meat, fat for heating and lighting, leather for clothing, and bones for heating (small) and construction (large). Often people fought over it. Since the 12th century this issue was regulated by law (10).

Figure 2.4 Large Rorqual stranded at Tynemouth in August, 1532 (14)

Usage of animal fat as a source of light in mining extends even up to the 19^{th} century. Metal lamps (shown in Figure 2.5) burning with an open flame, where a textile wick was pushed into the spout, were fitted into miners' cloth caps.

Figure 2.5 Tallow lamp - 19th century (15)

Tallow was used for candle making for centuries. Even nowadays it is possible to purchase tallow candles that, according to a manufacturer, are not only a source of light and heat (used to aid lighting a fire), but in a survival situation can be eaten (16).

From this short summary it can be seen that animal fat is a resource that has been used by humans since prehistory. Sourcing fat and other products obtained from stranded whales can be seen as an exemplary way of the sustainable processing of waste. The rendering process can be seen as a modern follower of this route.

2.4 Production Process

Rendering is a straightforward process in which animal carcases and trimmings are crushed and heated. This process drives off the water, sterilises the material and allows it to be separated into the fats (tallow) and meat and bone meal (MBM). Raw materials are all the unusable parts of a carcass, including bones, internal organs and trimmings. Raw materials are collected for processing from abattoirs and from butchers and food processing sites. Two types of the process can be distinguished: batch and continuous rendering. Continuous systems are suitable for higher capacities. A process schematic diagram is shown in Figure 2.6.

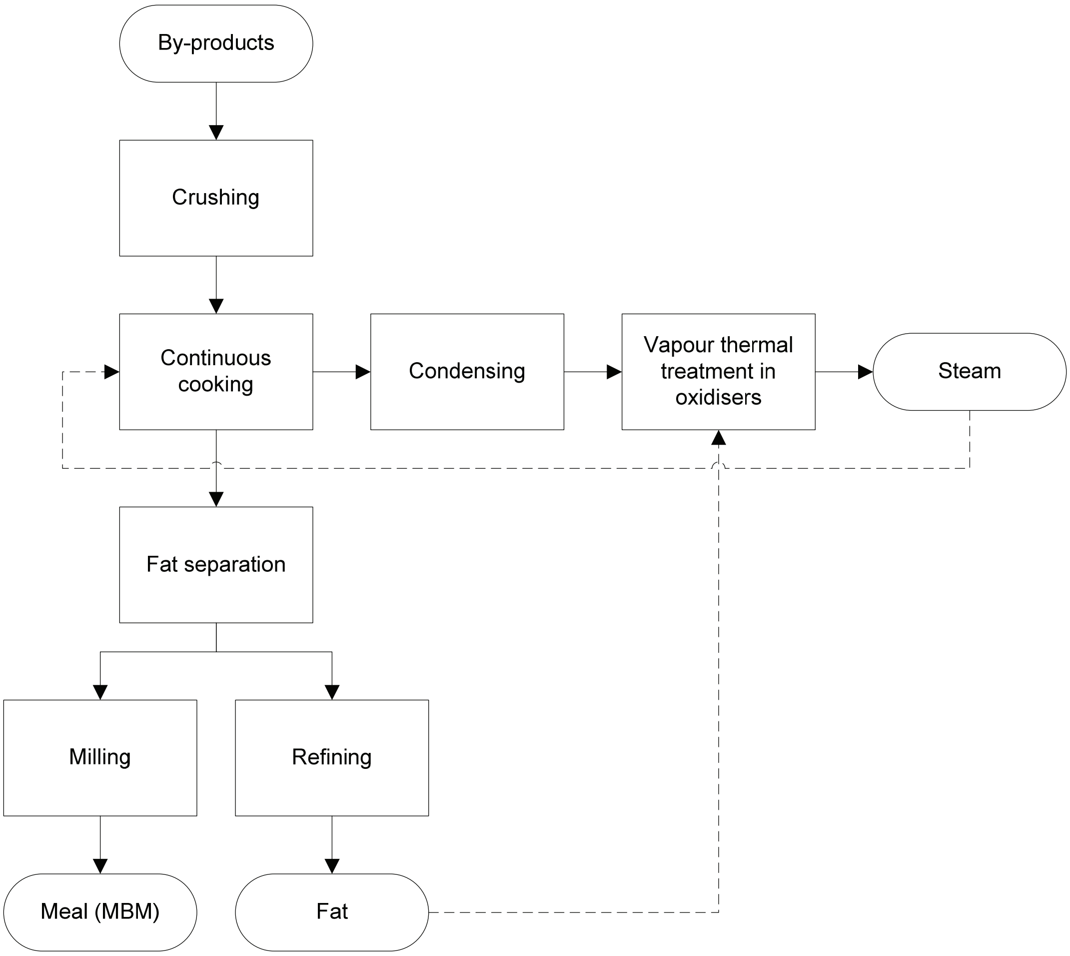

Figure 2.6 Rendering process schematic diagram

After arrival at the processing plant, by-products are placed in the hopper and then are transferred to a crusher where their size is reduced. Material is cooked in the cooker (shown in Figure 2.7) for a period of no less than 1 hour, at temperatures in excess of 150°C

Figure 2.7 Cooker used for rendering process (17)

The separation process is conducted in the screw presses, shown in Figure 2.8. As the greaves pass along the screw, the fat is pressed out, and the greaves are discharged as press cake.

Figure 2.8 Haarslev screw press (18)

Vapours from the material are diverted to thermal oxidisers, fuelled with fat, where at a temperature above 950°C all VOCs (Volatile Organic Compounds) are oxidised. Steam which is raised at the oxidisers is used for the cooking process.

2.5 Categories and Grades

Animal by-products are divided into three categories depending on their potential risk to human and animal health or to the environment. There are different rules for disposing of waste in each category (19). Categories of tallow and permitted applications were defined by Animal By-Products Regulations (20). A summary is given in Table 2.2.

Table 2.2 Tallow categories and its permitted applications (6, 19-21)

Category	Feedstock	Application
1 – very high risk	animals and materials suspected or confirmed to be infected by TSEs (transmissible spongiform encephalopathies) such as scrapie in sheep or BSE (bovine spongiform encephalopathy) in cattle, animals that have been experimented on, zoo and pet animal carcasses, catering waste from international transport, specified risk material (SRM) (tissues from cattle, sheep or goats that are, or may be, infected with BSE)	Fuel
2 – high risk	diseased animals (this excludes animals infected by TSEs), manure or animal by-products that could be contaminated with animal diseases, animals kept for human consumption, which die by means other than slaughtering, animals that die on farms that do not contain SRM	Fuel, production of tallow derivatives for technical use only
3 – low risk	raw meat and fish from food manufacturers and retailers, former foodstuffs other than catering waste, this includes manufacturing or packaging defects, eggs and other by-products that do not show signs of transmissible disease, raw milk, fish and other sea animals	Fuel, pet food production, production of tallow derivatives

Tallow is also graded in terms of quality. The two key grades for the UK market are:

- grade 2 – high quality, low colour, used for demanding applications such as soap;
- grade 6 – low quality, highly coloured, used for technical applications (6).

Specifications for various tallow grades are given in Table 2.3.

Table 2.3 Properties of technical tallows and animal greases (22)

Grade	FFA max.	Moisture and dirt	Unsaponifiable matter	Titre	Iodine number
	max % (m/m)	*% (m/m)*	*max % (m/m)*	*min °C*	*max*
1	3.0	0.5	0.5	40.0	55
2	5.0	1.0	1.0	40.0	55
3	8.0	1.0	1.0	40.0	55
4	12.0	1.0	1.5	40.0	58
5	15.0	1.0	1.5	40.0	58
6	20.0	1.0	2.0	40.0	58
Animal greases	20.0	2.0	2.0	36.0-40.0	61

2.6 Legal Status

According to current legislation, in the UK, animal fat is treated as waste (23). Therefore, the Waste Incineration Directive applies. One of the requirements is that exhaust gas resulting from the process is raised to a temperature of 850ºC for 2 seconds (23). For the purpose of this research project – a Knowledge Transfer Partnership, the Environment Agency issued a permit to operate a generating set fuelled with animal fat (24).

Products of the animal fat esterification process conducted in accordance with quality requirements described in Quality Protocol (25) are not classed as waste.

The rendering industry is working on developing End of Waste Test criteria so tallow will be excluded from the Waste Incineration Directive.

2.7 Usage of Triacylglycerols as Engine Fuels

Usage of triacylglycerols as fuels for internal combustion engines interested researchers in the earliest stages of engine history. Attempts, described as successful, were conducted by Dr Diesel (26). In the performed tests, earth nut oil has been used; however, potential for usage of other vegetable oil or animal fat is also mentioned. Due to lower prices of crude oil distillation products, oils and fats were not given much attention until the fuel shortages during the second world war and after the fuel crisis in the 1970s-80s (27). Some properties of oil and fats, important for substances designed to be used as fuels, are listed and described below.

Density

Density of the fuel has an impact on the fuel atomisation, for higher densities atomisation is worse (28, 29). Higher density results in increased formation of particulates, especially for higher loads (30, 31). As for the majority of injection systems, a fuel dose is controlled on a volumetric basis or based on timed events; a change in fuel density will affect the injection strategy (27, 32, 33). Density of triacylglycerols is on average, 10% higher than ULSD and approximately 10% lower than HFO.

Viscosity

Fuel viscosity is another parameter affecting atomisation of fuel; its contribution towards change in the SMD is approximated to be around 90% (28). For heavier fuels viscosity is an important parameter used to determine the appropriate design of auxiliary fuel supply systems such as centrifuges and pre-heaters. Changes in viscosity have an impact on the efficiency of the fuel pumps, for higher viscosities leaks are reduced resulting in increased efficiency accompanied with larger fuel dose (27, 34).

Surface Tension

Surface tension affects fuel atomisation. For higher tensions, droplet radius increases and atomisation is worse (35, 36).

Contamination

For road fuels a contamination is defined as all un-dissolved substances retained on a filter after filtration under test conditions (37). For residual fuels contamination is called a sediment and is a sum of insoluble organic and inorganic material, separated from the bulk of the sample by filtration through a specified filter, and also insoluble in a predominantly paraffinic solvent (38). The standard specific for the rendering industry includes also a mineral matter combined as soaps (22). Particles present in the fuel will increase wear of the injection system elements.

For fuels of vegetable origin potential for contamination is lower than for crude fuels, however, in the case of fats, contamination with finely divided particles of protein, bone and fibre requires close monitoring (31, 39).

Water Content

Water content in the fuel despite lowering its calorific value may lead to corrosion of the fuel system elements. The problem of corrosion applies especially to crude fuels that may be contaminated with sea water containing salt (31, 40). Water presence reduces lubricating properties of fuels. At lower temperatures, ice crystals together with solid impurities are the nucleus of crystallisation for waxes and paraffins (27). In the case of bio fuels, water can speed up the biodegradation of the fuel. For animal fats moisture content characterises the efficiency of the filtration and separation processes. It is desirable to keep moisture at low levels. High moisture content may encourage hydrolysis and increase acidity as a result (39).

Carbon Residue/Ash Content

Ash represents solid contaminants as well as metals bound in the fuel (e.g. vanadium and nickel). Part of the ash could be catalyst particles from the refining process for mineral fuels. Solid ash should be removed to the widest possible extent by centrifuging, and cleaning can be improved by installing a fine filter after the centrifuge (e.g. 50 μm) (40).

The carbon residue is measured as Conradson Carbon or Microcarbon. Carbon residue is an amount left after evaporation and pyrolysis to provide some indication of relative coke forming propensity (41). Fuels with a high carbon residue content could cause increased fouling of the gas ways, necessitating more frequent cleaning, especially of the turbocharger (40).

Acidity

Acidity is expressed as an Acid Number (AN) [or Total Acid Number (TAN)] and measured in mg KOH/g or Free Fatty Acid content (in %). FFA results may be expressed in terms of acid value by multiplying the FFA percent by 1.99 (4). Monitoring of this parameter is important due to the corrosive impact of high acidity fuels on the fuel injection systems (31, 42).

Acid number (AN) – the quantity of base, expressed in milligrams of potassium hydroxide per gram of sample, required to titrate a sample in the solvent from its initial meter reading to a meter reading corresponding to a freshly prepared non-aqueous basic buffer solution, or a well defined inflection point, as specified in the test method (43).

Strong acid number (SAN) – the quantity of base, expressed as milligrams of potassium hydroxide per gram of sample, required to titrate a sample in the solvent from its initial meter reading to a meter reading corresponding to a freshly prepared non-aqueous acidic buffer solution, or a well defined inflection point, as specified in the test method (43).

Iodine number

Properties of oils and fats depend on the ratio of saturated and unsaturated acids. Iodine number is the parameter describing the unsaturation level of the fat (4, 7).

Sulphur

All sulphur entering the engine combustion chamber is oxidized to SO_x, which is emitted into the atmosphere with the exhaust gases. The SO_x emissions from the engine depend on the fuel sulphur content and fuel consumption (44, 45). Low sulphur content is one the most significant advantages of bio fuels.

Calorific Value

The upper (higher or gross) calorific value is the heat of combustion, calculated assuming that all of the water in the products has condensed to liquid. Lower (or net) value is obtained in the case where none of the water is assumed to condense (46).

The use of gross or net calorific value varies with type of industry. Engine and gas turbine manufacturers, for example, use net calorific value, whereas UK boiler manufacturers use gross when stating the efficiency of their plant (47).

The calorific value for oils and fats is lower when compared to mineral fuels due to the oxygen content.

Flash Point

Flash point temperature is measured to assess the tendency of the fuel to form a flammable mixture with air. The flash point can indicate the possible presence of highly volatile and flammable materials in a relatively non-volatile or non-flammable material (48). Crude bio fuels have a higher flash point compared to mineral fuels (31).

Cetane Number

The cetane number characterizes the time between injection and combustion in a diesel engine. The higher the number, the more flammable the fuel. The cetane numbers obtained for most vegetable oils are between 29 and 43 as opposed to 45–55 for diesel (32).

It has been noted that a cetane number is not applicable for heavy residual fuels as an indicator of ignition quality. The concept of an ignition index based on viscosity and density was developed (31, 32). The CCAI (Calculated Carbon Aromaticity Index) is a unit-less number allowing ranking the ignition qualities of different residual fuel oils: the lower the number, the better the ignition characteristics. The CCAI does not give an absolute measure of ignition performance since this is much more dependent upon engine design and operating conditions (49).

Due to the complex structure and composition of tallow, a cetane number or calculated indexes may not be appropriate criteria for assessment of its ignition quality.

Table 2.4 Standard fuels and triacylglycerols as fuels for CI engines - comparison of selected properties

CI Engine Fuel	Density	Viscosity	Carbon residue	Iodine number	Lower calorific value	Flash point	Cetane number	Sulphur content	Ref.
	kg/m³ @25°C	*mm²/s@30°C*	*% w/w*	*gI₂/kg*	*MJ/kg*	*°C*	*-*	*mg/kg*	
Diesel	820-845[a]	2.0-4.5[c]	0.30	N/A	41.4-42.7	55	46-50	10	(37, 50-52)
Diesel – Class A2	820[a]	1.5-5.5[c]	0.30	N/A	42.3	56	Min 45	0.2 [%]	(53)
FAME	860-900[a]	3.5-5.0[c]	0.30	120	37.1	101	47-51	10	(27, 54)
HFO – RMA 30	960[a]	30[b]	10	N/A	39.8-41.5	60	-	3.5 [%]	(31, 40, 55)
HFO – RMK 700	1010[a]	700[b]	22	N/A		60	-	4.5 [%]	(31, 40, 55)
Coconut	915-920	32-40	-	7.5-10.5	35.0-35.8	228	37	0.01-4	(4, 27, 31, 32, 51, 56, 57)
Corn	915-920	60-64/35[c]	0.24	118-128	37.8-39.5	277	38-42	0.01	(4, 31, 50)
Cotton	916-918	50-73/34[c]	-	98-118	36.7-39.7	234-243	38-41.8	0.01	(4, 31, 50)
Jathropa	901-940	25-53[c]	0.20-0.40	94	38.9	180-280	33.7-51	0.01	(31, 32, 58, 59)
Palm	915/889[b]	95-106/39.6[c]	-	46-56	36.5-36.9	280	42	<1	(4, 31, 60, 61)
Rapeseed	915	34-39[c]	0.30	98	36.8-37.4	320	37.6	0.01-2.6	(27, 31, 62)
Soybean	917-921	58-63	0.27	123-139	37.3	330	37.9	0.01	(4, 31)
Sunflower	918-923	55-62/34[c]	0.23	125-136	36.5-37.8	316	37	0.01	(4, 31, 50, 63)
Waste Oil	910-940	72.6	-	107-115	39.2-39.6	312-314	36-37	0.02	(64, 65)
Animal fat	890-920	40-55[c]	0.36	40-49	36.5-39.8	268	~40	<0.01	(52, 66-68)

[a] – at 15°C [b] – at 50°C [c] – at 40°C

A comparison of selected properties of various vegetable oils and animal fat is given in Table 2.4. Many of the physical and chemical properties of liquid vegetable oils are similar to those of fossil fuels. However, there are also differences that affect engine operation. The main differences are (27, 69):

- The energy content is about 8–14% lower.
- The flash point is very high.
- The sulphur content is very low.
- The acidity of certain vegetable oils is higher.
- The cloud point / cold filter plugging point of certain vegetable oils is higher.
- The viscosity and surface tension are higher
- Vegetable oils have a different distillation curve – up to 250°C little volume of vegetable oil can be distilled, above that temperature, oil can be thermo cracked and follows a decomposition process.

Researchers from Wartsila (69) recommend paying attention to the following issues when comparing the properties of liquid bio fuels and fossil fuels:

- Solidification properties - the fuel injection equipment and fuel system must be designed to avoid filter clogging and breakage.
- Acidity corrosion should be avoided.
- Contents of ash constituents fouling the exhaust gas system, combustion chamber components, and the catalyst elements in the SCR and oxidation catalyst, should be avoided.

- Lower energy content - an adequate flow capacity in the fuel injection system is needed.

Usage of tricylglycerols as engine fuels has several considerable advantages (32):

- They are produced in rural areas and can contribute to the local economy.
- They are biodegradable and they are a renewable fuel with a short carbon cycle period (1–2 years compared to millions of years for petroleum fuels) and are environmentally friendly.
- They have physical and combustion characteristics similar to those of pure diesel oil.
- They have a low sulphur content compared to pure diesel oil.
- They have a flash point higher than that of diesel oil thus are safer for use.

Some manufacturers allow usage of crude biofuels in their engines. Guiding specifications are given for two stroke engines (Table 2.5) and four stroke engines (Table 2.6).

Table 2.5 Guiding biofuel specification for MAN B&W two-stroke low speed diesel engines (40)

Designation	**Unit**	**Limit** [1)]
Density at 15°C	kg/m^3	1010
Kinematic viscosity at 100°C [2)]	cSt	55
Flash point	°C	$\geq$60
Carbon residue	% (m/m)	22
Ash	% (m/m)	0.15
Water	% (m/m)	1.0
Sulphur [3)]	% (m/m)	5.0
Vanadium	ppm (m/m)	600
Aluminium + Silicon	mg/kg	80
Sodium plus potassium	ppm (m/m)	200
Calcium	ppm (m/m)	200
Lead	ppm (m/m)	10
TAN (Total Acid Number)	mg KOH/g [4)]	<25
SAN (Strong Acid Number)	mg KOH/g	0

1) Valid at inlet to centrifuge plant
2) Pre-heating down to 15 cSt at engine inlet flange is to be ensured
3) Iodine, phosphorus and sulphur content according to agreement with emission controls maker
4) Experience shows that a high Total Acid Number has influence on the time between overhaul of the engine fuel system and, therefore, need to be adjusted accordingly

Table 2.6 Liquid biofuel specification for Wärtsilä 4-stroke engines (69)

Property	Unit	Limit	Test method reference
Viscosity, max.	cSt @ 40 °C	100	ISO 3104
Viscosity, min.	cSt	1.8 - 2.8 1)	ISO 3104
Injection viscosity, max.	cSt	24	ISO 3104
Density, max.	kg/m^3 @ 15 °C	991	ISO 3675 OR 12185
Ignition properties		2)	FIA test
Water, max. before engine	% V/V	0.20	ISO 3733
Carbon residue (micro method),max.	% m/m	0.30	ISO 10370
Flash point (PMCC), min.	°C	60	ISO 2719
Pour point, max.	°C	3)	ISO 3016
Cloud point, max.	°C	3)	ISO 3015
Cold fi lter plugging point, max.	°C	3)	IP 309
Total sediment existent, max.	% m/m	0.05	ISO 10307-1
Sulphur, max.	% m/m	0.05	ISO 8754
Ash, max.	% m/m	0.05	ISO 6245
Phosphorus, max.	mg/kg	100	ISO 10478
Silicon, max.	mg/kg	10	ISO 10478
Alkali content (Na+K), max.	mg/kg	30	ISO 10478
Copper strip corrosion, (3 hrs @ 50°C) max.	Rating	1b	ASTM D130
Steel corrosion (24/72hrs @ 20, 60, 120°C), max.	Rating	No signs of corrosion	LP 2902
Acid number, max.	mg KOH/g	5.0	ASTM D664
Strong acid number, max.	mg KOH/g	0.0	ASTM D664
Iodine number, max.		120	ISO 3961

1) depends on the engine model
2) To be equal or better than the requirements for fossil fuels, i.e. CI min. 35, CCAI max. 870
3) To be at least 10 °C below fuel injection temperature

2.8 Potential of Tallow for Biodiesel Production

Usage of tallow for biodiesel production has been described by other researchers (70-79). High and variable acidity level (free fatty acid - FFA content) required a two stage transesterification process. The FFA removal stage has an impact on yield and feasibility of biodiesel production. Therefore, this use of tallow has not been described in this thesis.

2.9 Combustion of Neat Fat in Internal Compressed Ignition Engine

The majority of researchers focused on the combustion of triacylglycerols of vegetable origin. Animal fat, due to its different chemical composition and production process may present challenges in application as fuel, hence should be described separately.

Some researchers attempted to use preheated animal fat as fuel for automotive scale engines. Takayuki (66) used a 411cc Mitsubishi engine and animal fat preheated to 60°C. A decrease in NO_x emissions by 10-15% is reported accompanied by an increase of CO and HC emissions, especially for low loads. PM emissions were higher than for diesel fuel at high load. Lower cylinder pressure and shorter ignition delay was recorded for animal fat. Decreased engine output is associated with lower calorific value of the fat.

Kleinova (80) presented results of tests conducted on VAG engines – 1.9 TDI (rotary pump) and 2.5 TDI (pump injector unit). Decrease in engine performance is explained as being related to the lower energy content of bio fuels (lard and chicken fat). Very low CO and HC emissions are reported; also the NO_x level is lower when compared to results obtained for engines fuelled with diesel. The authors suggest than problematic operation of engines fuelled with triglycerides can be associated with poor fuel atomisation and low injection pressure. It is claimed that in the case of using a high pressure common rail system, it is possible to achieve good results for bio fuels. Paper contains a conclusion to disregard results obtained for triglycerides fuels in engines equipped with fuel supply systems different from common rail.

Kumar (52) ran a series of tests on a Lister Petter TS1 – 630cc engine. Animal fat was preheated to 30, 40, 50, 60 and 70°C. Peak pressure and rate of pressure rise are lower with animal fat at low temperature as compared to diesel. Increasing fuel temperature results in an increase of both measured parameters. Ignition delay is higher for animal fat at all tested loads. Ignition delay depends on fuel temperature, for higher temperatures reduced delay has been reported. Heat release rates are lower for animal fat with a tendency to increase for elevated fuel temperatures. Operation on bio fuel resulted in an increased exhaust temperature. Emissions of CO and HC are higher with animal fat as compared to diesel. However, fuel pre heating reduces these emissions. Emissions of NO_x were lower with a tendency to increase with elevated fuel temperature. Obtained results were confirmed by another member of the same research team – Kerihuel (81).

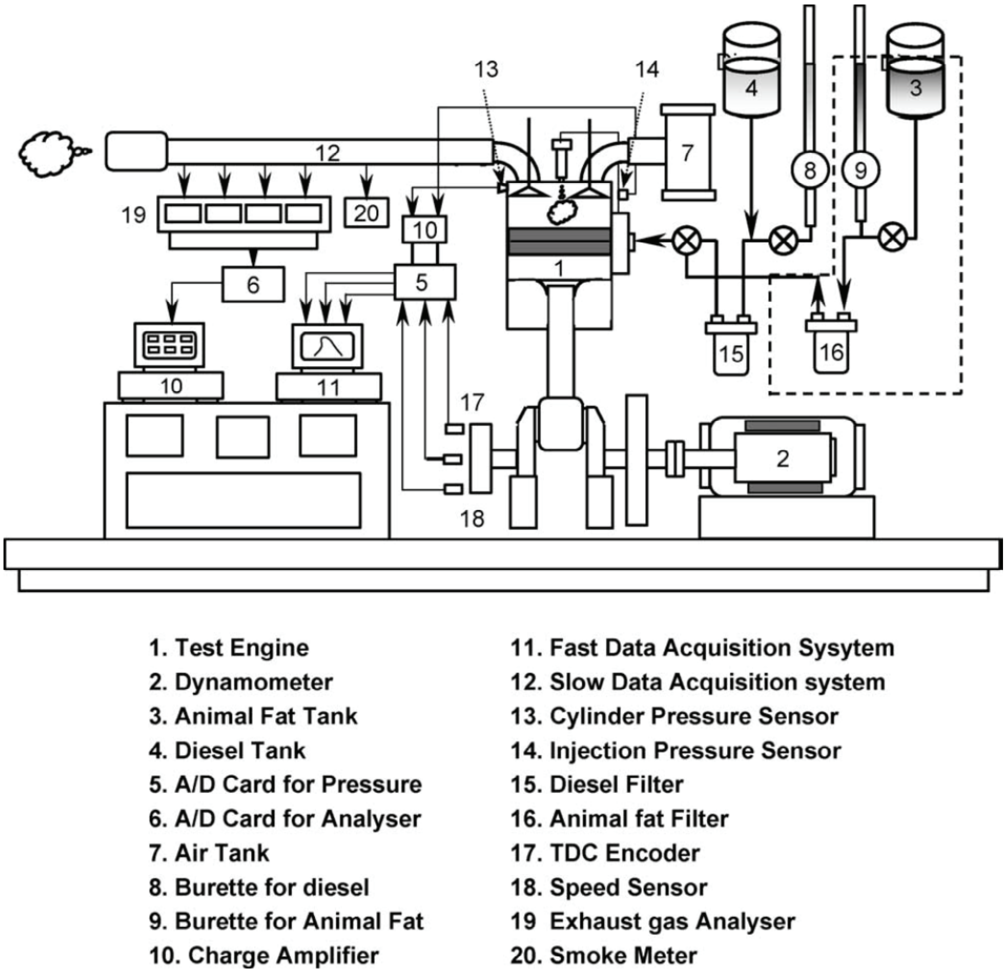

Figure 2.9 Typical engine test bed with dual fuel supply system used for triacylglycerol fuels testing (52)

Research published by Mormino (67) was conducted at a test bed incorporating a four stroke turbocharged diesel engine without charge air cooler .A Volvo TD 60 B six cylinder engine has a swept volume of 913 cc per cylinder. The combustion process and resulting emissions from diesel, vegetable oils and animal fat were compared. Animal fat was preheated to 70 ^{o}C. Ignition delay for animal fat was shorter; the difference was more significant for lower test speeds (rpm). The lower emissions of nitrogen oxides were explained by a limited premixed combustion phase and lower temperature in the combustion chamber. Lower emissions of soot were reported, the difference was associated with the oxygen content and lack of aromatic compounds in fat. Hydrocarbons' emissions were higher for oils and fat when compared to diesel as a result of less effective atomization.

Kapusta (68) briefly described research conducted by Wartsila with regard to potential usage of various bio fuels for large generating sets. Tests were performed at two research power plants (VTT and Pieksamaki) equipped with Wartsila 4R32LN and 6L20 engines. A view of the Pieksamaki research power plant with a description of its main components is given in Figure 2.10. Significant reduction in soot emissions was observed for animal fat (up to 60%). While emission of nitrogen oxides was comparable for all tested fuels, a slight increase in hydrocarbons' emission was detected. Researchers concluded that fuel quality and preparation is crucial for problem free engine operation.

Figure 2.10 Pieksamaki research power plant (69)

Reported results are combined together and presented in Table 2.7. It has to be noted that conclusions made by other researchers are not consistent. For example, in the case of nitrogen oxides' emissions, the assessment varies from a significant reduction in the case of a small engine fuelled with animal fat supplied at low temperature, while on the other hand, for a large engine with a fuel preheating system, an increase of those emissions is reported.

Table 2.7 Comparison of combustion characteristics and emissions obtained at a range of testing conditions for engines fuelled with animal fat with values obtained for fossil fuels

Ref	Test Conditions			Combustion Characteristics			Emissions				Specific Fuel Consumption
	Engine	*Load*	*Fuel temp*	*Peak Pressure*	*Ignition delay*	*Heat Release Rate*	*NO_x*	*CO*	*HC*	*Smoke*	
Takayuki (66)	Mitsubishi D800	LL	60	-	-		-	+	+	~[a]	+
		HL	60	-	-		-	-	-	-	+
Kleinova (80)	VW 1.9 TDI & 2.5 TDI	LL[b]					-	+	~	+	+
		HL[c]					-	~	+	+	+
Kumar (52)	Lister Petter TS1	LL	30				- -	+	+	-	+
		LL	70				-	~	~	-	+
		HL	30	- -	+ +	- -	- -	+ +	+ +	-	+
		HL	70	-	+	-	-	- -	~	- -	+
Mormino (67)	Volvo TD60B	Range	70	-	-	-	-		+	[d]	+
Kapusta (68)	Wartsila 6L20	LL					+	+	~	- -	
		HL					+	+	+	- -	

Where:
'+' – increase, '+ +' - significant increase, '-' – decrease, '- -' - significant decrease, '~' – comparable result, LL – low load, HL – high load, a – decrease in PM emissions was also reported, b - at speed of 60 km/h, c - at speed of 120 km/h, d – decrease in soot emissions also reported, not significant difference for low speeds

There is no full set of test results (including emissions and combustion characteristics) for a large diesel engine, which may be used by the rendering industry to offset part of their electricity demand by utilising animal fat for renewable electricity generation. Hence, conducting a research programme, as described in this thesis, which aims to investigate various aspects of neat animal fat application as fuel for internal combustion engines, is justified.

2.10 Emissions Abatement Methods for Large Engines

The research power plant described in this thesis was granted special permission by the Environment Agency to conduct a trial test of the animal fat combustion in a large diesel engine. At the end of the trial, an abatement system enabling compliance with given limits should be proposed and installed. Review of available methods typical for large diesel engines is presented in following section.

2.10.1 Nitrogen Oxides Emissions Abatement

2.10.1.1 Classification of Abatement Methods

There are various method classification criteria. Wartsila segregates methods as ‘dry’ or ‘wet’. ‘Dry’ methods can be characterised by modification and optimisation of engine operation through fuel injection strategy alteration and modification of combustion chamber shape. NO_x reduction in ‘wet’ methods is achieved thanks to water presence in the combustion chamber. MAN B&W divides methods into ‘primary’ – where modifications prevent NO_x formation and ‘secondary’ where exhaust after treatment needs to be applied.

2.10.1.2 Exhaust Gas Recirculation

The Exhaust Gas Recirculation method’s working principle is the feeding of a portion of the exhaust gas back to the cylinder. Nitrogen oxides emission depends on partial pressure of reagents – oxygen and nitrogen. The partial pressure can be altered by modification of charge composition in the cylinder. NO_x emission can be reduced if oxygen concentration is lowered (dilution effect). Exhaust recirculation results in increased heat capacity of the cylinder charge (thermal effect). Carbon dioxide and water, present in the exhaust, can potentially, dissociate at high temperatures and take part in the combustion process (chemical effect) (82). EGR cooling is necessary to prevent soot emissions from rising to unacceptable levels and to avoid a significant drop in engine efficiency. The need for EGR cooling is more evident at high EGR rates and low engine speeds (83).

Possible layouts of the EGR system are shown in Figure 2.11. Exhaust gas can be fed back before (case 1) or after (case 2) the turbocharger. Other researchers point out that charge dilution should be applied in circumstances where clean gas with low oxygen content is available (case 3) (44). For this reason, the EGR is disregarded as a NO_x abatement method for marine applications by Wartsila (45). However, high reduction potential has to be noted, according to (44, 84), 5% recirculation can reduce NO_x emission by 30%. Results of tests conducted by MAN B&W on a 4T50MX engine are given in Figure 2.12.

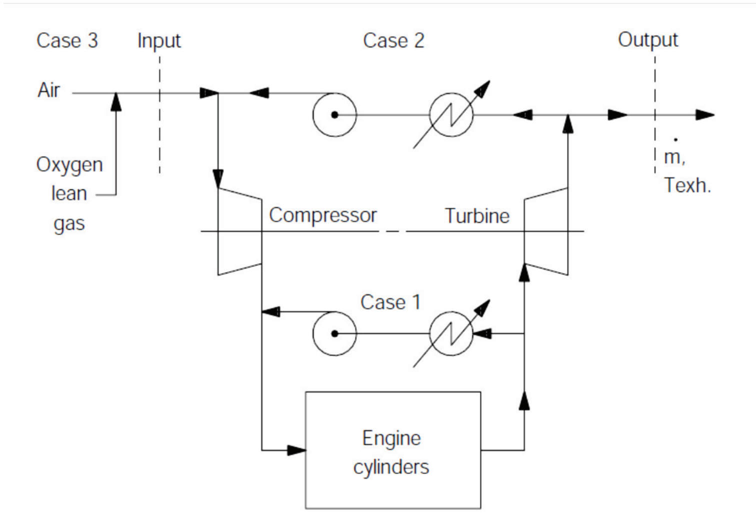

Figure 2.11 Different layouts for EGR system; case 1 – high pressure EGR, case 2- low pressure EGR, case 3 – charge dilution (44)

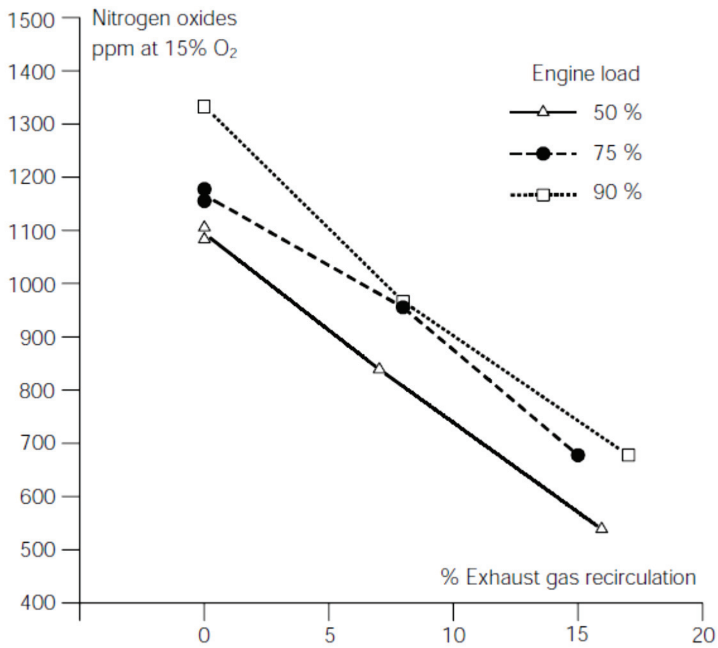

Figure 2.12 Effect of EGR on the 4T50MX engine emission (44)

2.10.1.3 Optimisation of Injection Strategy

NO_x emissions can be lowered by alteration of injector type. Large engine manufacturers implemented various solutions to improve fuel atomisation and provide better injection control. Wartsila introduced the RT-flex engine family equipped with a common rail injection system. MAN B&W introduced the ME engine family equipped with an individual electronic module responsible for fuel injection for each cylinder and a hydraulic exhaust valve actuator. The ME engine control system layout is shown in Figure 2.14.

Figure 2.13 presents a development process, starting with basic injection flow (InFl basic) optimised for low fuel consumption and used in production engines (Standard MC). Injection strategy management can lead to NO_x emission reduction by even 20% (fuel consumption penalty of 3%) – for example via pilot injection introduction (pre-injection).

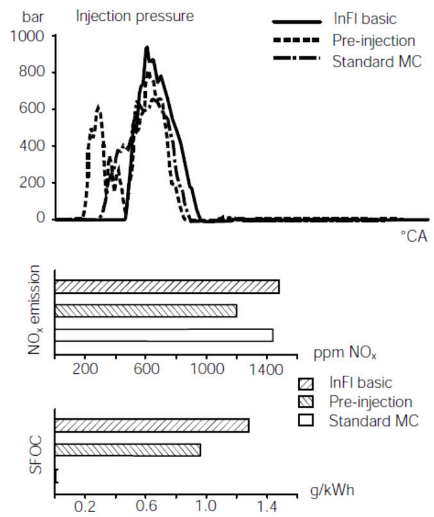

Figure 2.13 Fuel injection patterns, including pre-injection and the effects on SFOC and NO_x emissions (44)

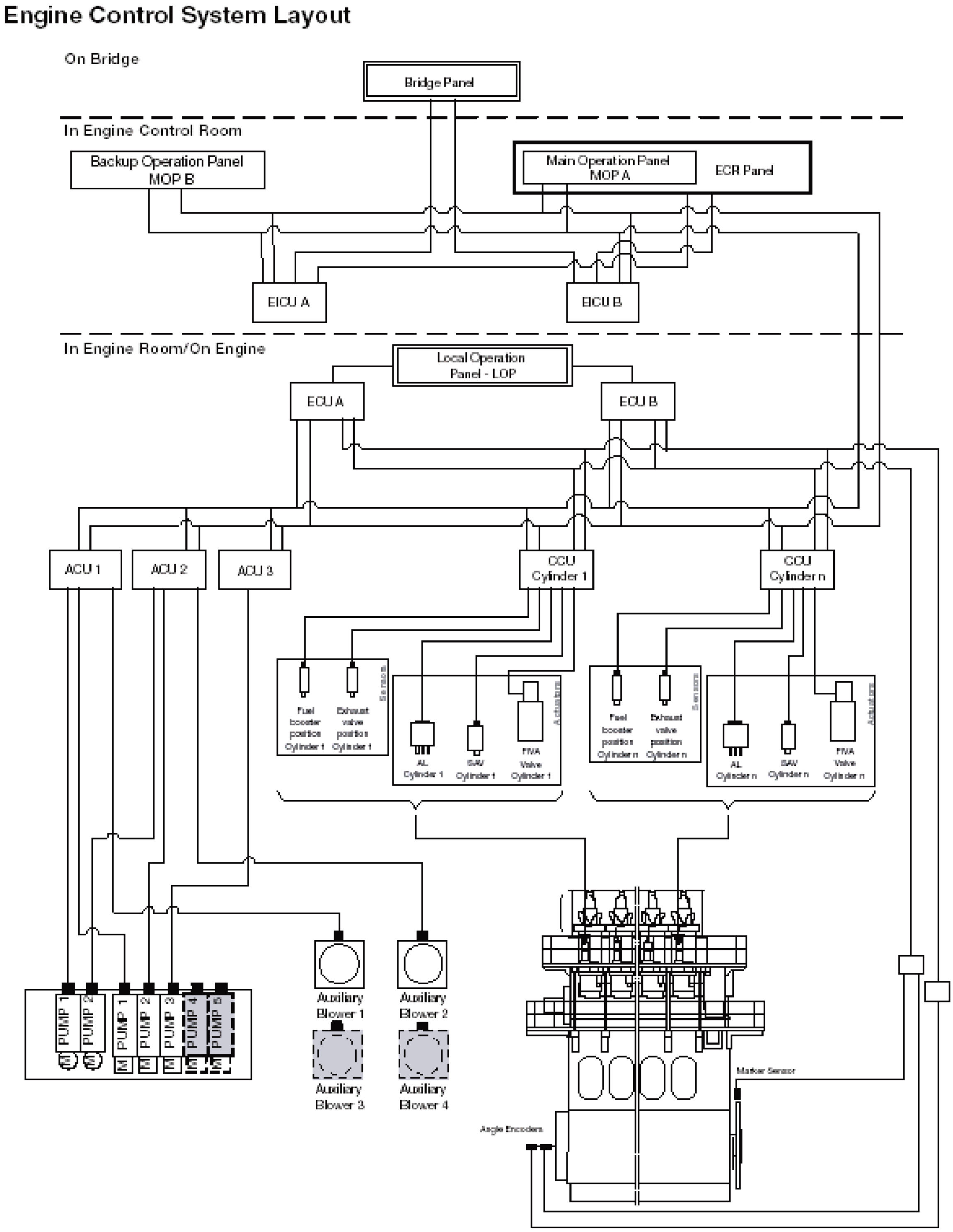

Figure 2.14 MAN ME engine control system layout

2.10.1.4 SCR – Selective Catalytic Reduction

The working principle of the method is mixing exhaust gases with ammonia NH_3, typically supplied as urea, and passing it through a catalytic reactor where nitrogen oxides are reduced to N_2 and H_20 at a temperature of 300 – 400°C. The following reactions occur once the urea has been decomposed and hydrolysed (85, 86):

$$4\,NO + 4\,NH_3 + O_2 = 4\,N_2 + 6\,H_2O \qquad \text{(NO SCR)}$$

$$6\,NO_2 + 8\,NH_3 = 7\,N_2 + 12\,H_2O \qquad \text{(NO}_2\text{ SCR)}$$

$$NO + NO_2 + 2NH_3 = 2N_2 + 3H_2O \qquad \text{(Fast SCR)}$$

The main advantage of this method is very high efficiency, reaching even 98%. Complicated installation, shown in Figure 2.15, resulting in higher capital expenditure and maintenance cost is a disadvantage. Despite the reaction of NO_x reduction – a reversion process occurs as well. Calculation of both reaction coefficients at various temperatures can determine the appropriate operational temperature for the reactor. For low temperatures the reactor will not achieve its desired reduction efficiency. For higher temperatures ammonia will be burned before reduction reaction occurs. NO_x reduction depends also on the amount of added ammonia – for higher concentrations, ammonia slip may occur – therefore a precise dosing system is required for efficient SCR operation. Another variable that may have impact on the SCR system reduction efficiency is location and type of ammonia injectors (44, 84).

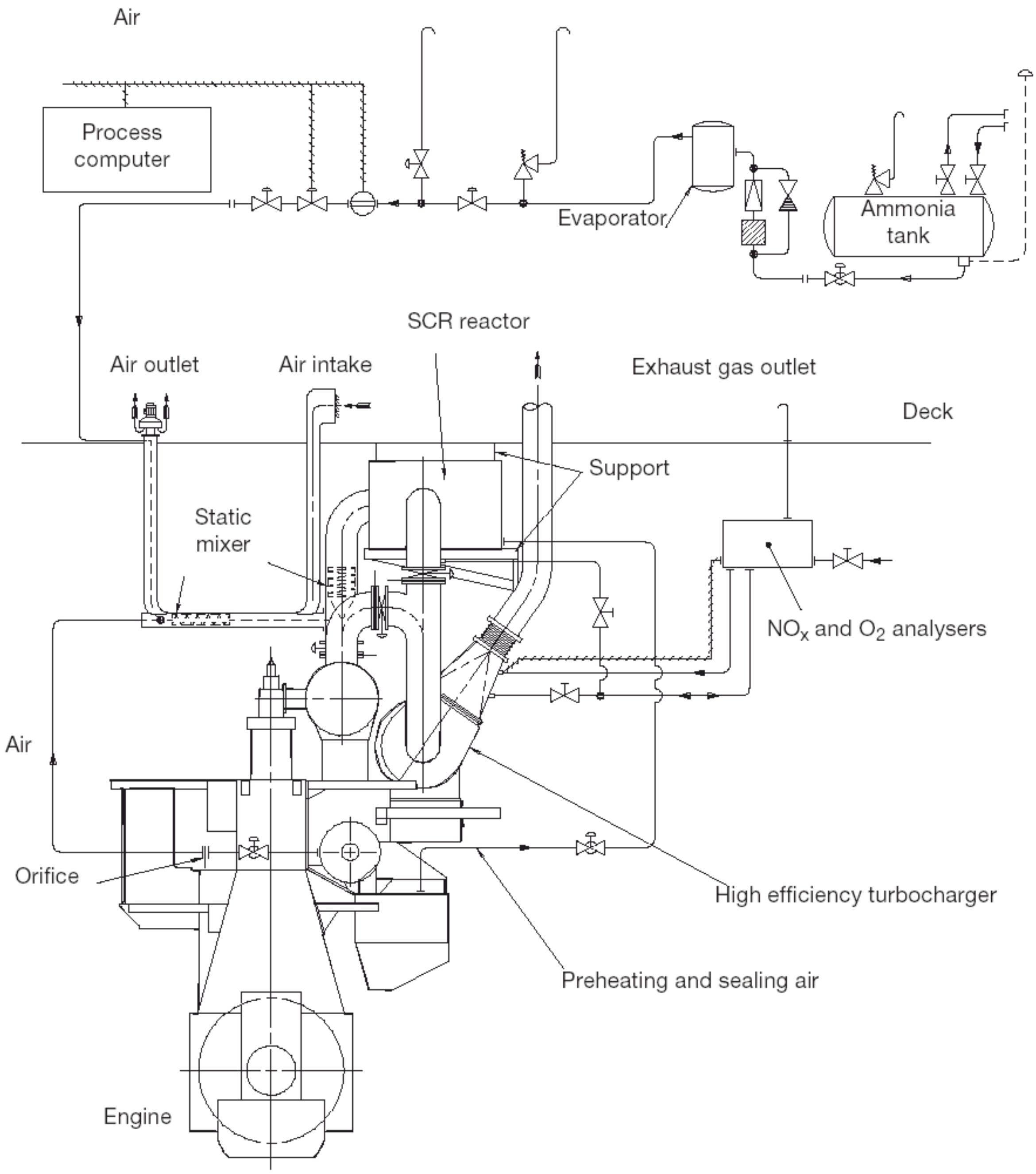

Figure 2.15 SCR system layout for MAN B&W S46 MC-C engine (87)

2.10.1.5 Usage of Water

The combustion process in a CI engine can be characterised by high local air excess ratios. Formation of nitrogen oxides can be reduced by lowering the temperature in the combustion chamber. It can be achieved through introduction of water, which absorbs heat via evaporation. Water can be delivered to the combustion chamber in various ways: with an additional water injector, through injection into the engine intake, supply the engine with water-fuel emulsion (88). CASS – (Combustion Air Saturation System) is an example of a system using water injection into the engine intake. A reported high reduction efficiency of 50-60% with no fuel penalty is accompanied by high fresh water consumption. Lower water consumption can be achieved through direct water injection (45).

2.10.2 Reduction of Sulphur Oxides Emissions

Sulphur present in fuel is oxidised to sulphur oxides in the combustion chamber. Sulphur oxides' emission is proportional to sulphur content in the fuel (45). The only viable method of SO_x emission is usage of low fuels with low sulphur content. It is reflected in the introduction of SECAs (Sulphur Emission Control Area) (89-91) where ships have to use low sulphur fuels.

2.11 Summary

The following conclusions and predictions can be made based on the presented literature review:

- Animal fat atomisation can be affected by its physical properties.
- Atomisation can be assessed by optical methods – changes in Sauter Mean Diameter (SMD).
- Emission of carbon monoxide can be used as an indicator of atomisation quality.
- Atomisation can be improved by:
    - Increase of fuel temperature
    - Increase of injection pressure.
- For good atomisation the benefit of the oxygen content may lead to a decrease of CO, HC and soot emissions.
- Emissions of NO_x may increase for high fuel temperatures.
- Calorific value of the tallow is lower – it may decrease the engine performance (max power).
- High acidity may lead to corrosion of the fuel supply system.
- No abatement system for SO_2 should be required due to low sulphur content of the animal fat.

Chapter 3 FEASIBILITY OF ELECTRICITY GENERATION WHEN USING AN INTERNAL COMBUSTION ENGINE FUELLED WITH TALLOW AS THE PRIME MOVER

3.1 Factors Affecting Feasibility of Electricity Generation

In this chapter renewable electricity and heat production support in the UK is described. Tallow prices recorded in 2009 are given. Fuel price, combined with additional subsidies available in 2009, are used to calculate the feasibility of a research power plant operation.

The feasibility of electricity generation from animal fat in power plants using reciprocating engines depends on the following factors:

- Electricity price (selling price)
- Fuel price
- Subsidies for renewable electricity/heat producers.

3.2 Supporting Legislation for Renewable Electricity Generation

3.2.1 The History of Renewable Energy Support System

3.2.1.1 Fossil Fuel Levy and Non Fossil Fuel Obligation

Fossil Fuel Levy

In the late 1980s the UK Government decided to privatise and deregulate the energy industry. Privatisation of the nuclear energy sector turned out to be a challenge. Private investors refused to accept all the risks and liabilities linked with nuclear power. Energy generated by nuclear plants was more expensive than energy derived from fossil fuels.

The government thus kept the nuclear energy sector in public hands. To cover additional costs and protect the generators, a Non Fossil Fuel Obligation together with a Fossil Fuel Levy system, were then introduced in 1989 (92).

Energy distributors were forced to purchase electricity generated by nuclear power stations. The levy was imposed on fossil fuel based power, and was set by an independent electricity regulator. Through this mechanism, the government made all consumers pay the extra costs for the 'benefits' of nuclear production by applying a broad carbon tax on the rest of the sector (93). The Fossil Fuel Levy Rates are given in Table 3.1.

Table 3.1 Fossil Fuel Levy rates (94)

Dates			Rates (%)
1 Apr 1990	to	31 Mar 1991	10.60
1 Apr 1991	to	31 Mar 1993	11.00
1 Apr 1993	to	30 Sep 1996	10.00
31 Oct 1996	to	31 Mar 1997	3.70
1 Apr 1997	to	31 Mar 1998	2.20
1 Apr 1998	to	31 Dec 1998	0.90
1 Jan 1999	to	30 Sep 1999	0.70
1 Oct 1999	to	31 Mar 2002	0.30

NFFO process

Under the 1989 Electricity Act, the Secretary of State made five Orders requiring the Regional Electricity Companies (RECs) in England and Wales to contract for certain amounts of electricity generating capacity from renewable sources. The first Non Fossil Fuel Obligation Order (NFFO 1) took place in 1990, with the others following in 1991, 1995, 1997 and 1998. The European Commission ruled that the NFFO constituted a state subsidy to the nuclear industry and thus they had to end in 1998 (93).

Each Order specified the generating capacity for each technology band. These bands were: large wind projects, small wind projects, hydro, landfill gas, waste to energy and biomass. Project developers were then asked to bid for contracts. Winning offers were selected by the Non-Fossil Purchasing Agency (NFPA) based solely on bid price (94). A winning project was then rewarded with a long term (typically 15 years (95)) contract to supply electricity to the National Grid. The energy was purchased by the NFPA and then sold to one of the RECs at the price set by the market regulator. The funds collected under the Fossil Fuel Levy were used to cover the difference between the sale price and the contracted cost (93).

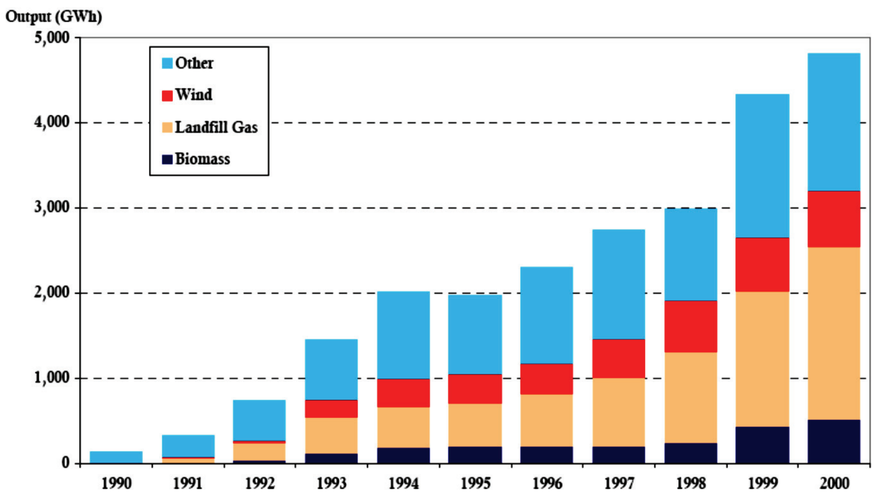

Figure 3.1 Total output by year and technology (GWh) (96)

Figure 3.1 presents total output by year and technology. The output includes the generation of NFFO contracted projects. NFFO 1 and 2 contracts ended at the end of 1998. The output produced from NFFO 1 and 2 contracts during 1998 have been added to the 1999 and 2000 output from NFFO 3, 4 and 5 contracts. This may overstate generation if these projects did not continue to produce at NFFO contracted levels.

The key aspects of the NFFO concept can be identified as follows:

- The UK Government would theoretically secure the largest amount of renewable generating capacity for a given cost.

- By giving developers secure long-term contracts, financing would be relatively easy to come by and also cheap.
- The price of each technology would be revealed, and through successive competitions, driven down (93).

The Impact of NFFO

The Department of Trade and Industry asked the Frontier Economics and Byrne O'Cleirigh consultancy companies to evaluate support for renewable energy under the NFFO. The final report has been prepared (96) and its results can be summarised as follows:

The NFFO has encouraged the uptake of renewable technologies, especially in landfill gas and onshore wind. In total, over 3200 MW capacity has been contracted through the NFFO in England and Wales. It has been estimated that nearly 24000 GWh have been produced by the NFFO contracted plants. The competitive NFFO process has helped to identify competitive prices for renewable energy and has enabled the government to maximise contracted capacity at the lowest cost. Electricity from NFFO contracted plants has replaced a significant amount of fossil-fuel production (96).

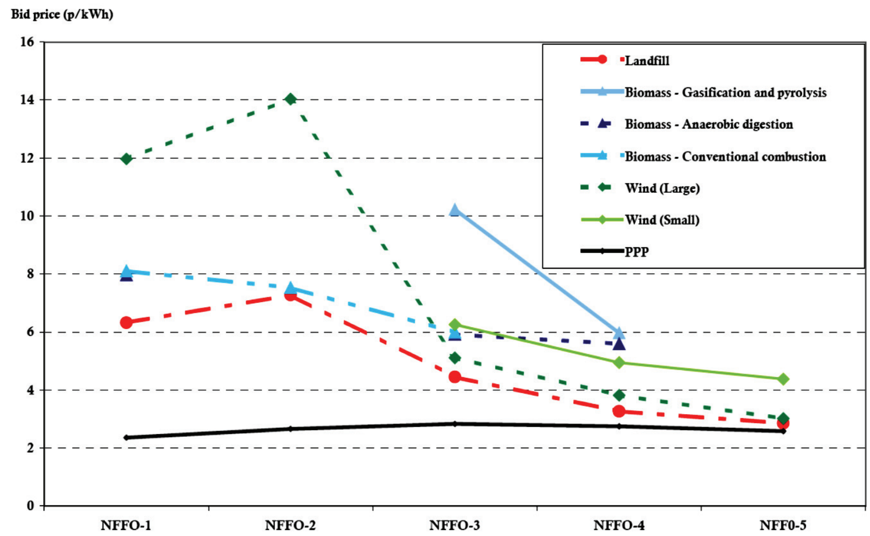

Figure 3.2 Real average contracted price for each technology (2000 prices). The average is a capacity-weighted average of the contracted price and does not account for the length of the contract. PPP is the Pool Purchase Price in the electricity market (96)

Figure 3.2 presents contracted prices for different technologies. Lowering the prices of the renewable energy is regarded to be one of the largest successes of the NFFO system (93, 94, 96). Data given in Figure 3.2 show those technologies such as landfill gas (LFG) and onshore wind could be developed in the future without additional funding.

3.2.1.2 Renewable Obligation

The Renewable Obligation support system was introduced on 1 April 2002 by the Renewable Obligation Order. Each MWh of electricity generated from eligible renewable sources is entitled to receive a special certificate – the ROC (Renewable Obligation Certificate). At that stage no technology banding was introduced. Certificates were introduced as tradable instruments. Therefore renewable energy generators had two main sources of revenue, sold energy and sold ROCs.

The licensed electricity suppliers must provide a certain percentage of sold energy that originates from renewable sources. The percentage is set by the government, as shown in Table 3.2. If a supplier is unable to present the required amount of ROCs, it has to pay a buy-out price. Funds raised this way are then divided between suppliers who comply with the obligation.

Table 3.2 Renewables Obligation percentage and buy-out price for different obligation periods (97)

Obligation period			Obligation (%)	Buy-out price (£/MWh)
1 Apr 2002	to	31 Mar 2003	3.0	30.00
1 Apr 2003	to	31 Mar 2004	4.3	30.51
1 Apr 2004	to	31 Mar 2005	4.9	31.59
1 Apr 2005	to	31 Mar 2006	5.5	32.33
1 Apr 2006	to	31 Mar 2007	6.7	33.24
1 Apr 2007	to	31 Mar 2008	7.9	34.30
1 Apr 2008	to	31 Mar 2009	9.1	35.76
1 Apr 2009	to	31 Mar 2010	9.7	37.19
1 Apr 2010	to	31 Mar 2011	10.4	-
1 Apr 2011	to	31 Mar 2012	11.4	-
1 Apr 2012	to	31 Mar 2013	12.4	-
1 Apr 2013	to	31 Mar 2014	13.4	-
1 Apr 2014	to	31 Mar 2015	14.4	-
1 Apr 2015	to	31 Mar 2016	15.4	-

As the amount of ROCs is limited due to the small number of accredited generators, ROCs are traded through auction systems. The electronic auction system is administrated by the Non-Fossil Purchasing Agency (NFPA). Figure 3.3 presents the historic record of auction ROCs prices.

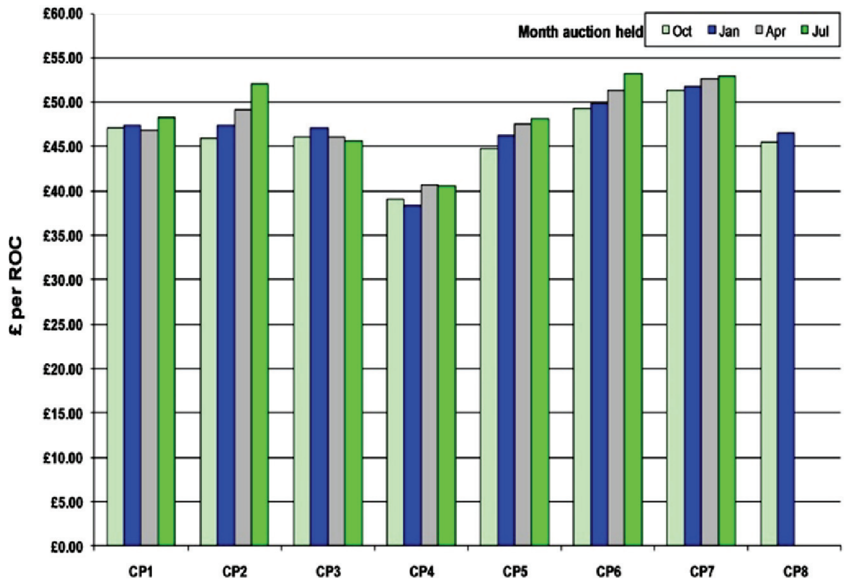

Figure 3.3 Track record for ROC auction prices by Compliance Period (CP) (98)

As no technology banding was introduced, all power plants using internal combustion engines fuelled with gaseous fuels such as sewage gas, landfill gas or biogas are entitled to the same level of support. However, plants using bio fuels have to agree to and accredit the Fuel Measurement and Sampling procedure. Since 2007 'own use' electricity is also entitled for support within the RO scheme (95). Different rules apply to micro generators (DNC less than 50kW).

3.2.2 Existing Support Policy

3.2.2.1 Climate Change Levy and Levy Exemption Certificates

Climate Change Levy (CCL)

The Climate Change Levy (CCL) is an environmental tax that came into force on 1 April 2001. The levy is chargeable on the industrial and commercial supply of taxable commodities for lighting, heating and power used by consumers in the following sectors of business:

- industry
- commerce
- agriculture
- public administration, and
- other services.

The levy does not apply to taxable commodities used by domestic consumers, or by charities for non-business use (99). The tax is applied as a rate per unit of energy. Each category of commodity has a specific rate of the tax .

Table 3.3 Climate Change Levy rates (99-102)

Taxable commodity	Rate			
	1 April 2001 – 31 March 2007	*1 April 2007 – 31 March 2008*	*1 April 2008 – 31 March 2009*	*1 April 2009 – 31 March 2010*
Electricity	£0.00430 /kWh	£0.00441 /kWh	£0.00456 /kWh	£0.00470 /kWh
Gas supplied by a gas utility or any gas supplied in a gaseous state that is of a kind supplied by a gas utility	£0.00150 /kWh	£0.00154 /kWh	£0.00159 /kWh	£0.00164 /kWh
Any petroleum gas, or other gaseous hydrocarbon, supplied in a liquid state	£0.00960 /kg	£0.00985 /kg	£0.01018 /kg	£0.01050 /kg
Any other taxable commodity	£0.01170 /kg	£0.01201 /kg	£0.01242 /kg	£0.01281 /kg

The CCL should deliver estimated annual carbon dioxide savings of over 3.5 million tonnes of carbon in 2010 (in the UK). It was also estimated to lead to an increase of good quality heat and power capacity by 1.2 Gigawatts of electricity by 2010 (103). The CCL policy was reviewed in 2006 and it was calculated that it resulted in cumulative savings of 60.5 million tonnes of carbon (103, 104).

Levy Exemption Certificates (LECs)

Energy generated from qualified renewable sources is exempt from the Levy where certain conditions can be met.

Renewable source technologies eligible for exemption include:

- wind energy

- hydro power (up to 10 MW)
- tidal power
- wave energy
- photovoltaic cells
- photo conversion
- geothermal hot dry rock
- geothermal aquifers
- municipal and industrial wastes
- landfill gas
- agriculture and forestry wastes, and
- energy crops (105).

The Generators must be accredited by Ofgem (market regulator) for the renewable electricity they generate. Exemption certificates (LECs) are then issued for each monthly qualifying output. Certificates can be traded separately from the electricity for which they were issued (106).

CHP stations are regarded to be one of the most effective ways of reducing the carbon footprint. Therefore output from such plants may qualify for CCL exemption.

Whether a CHP Station qualifies for CCL exemption on its entire energy inputs and outputs will be determined under the CHP Quality Assurance (CHPQA) programme administered on behalf of the Department of Energy and Climate Change (DECC). Under the programme rules, the Quality Index (QI), and Power Efficiency (PE) of a CHP station are calculated from the fuel used, electricity generated, and heat supplied (107).

3.2.2.2 Renewable Obligation

The Renewable Obligation Order 2009 introduced several changes to the RO scheme. The most important is technology banding, introduced to support more advanced technologies. Banding details are given in Table 3.4. The Renewable Obligation scheme will remain operational as support for large scale renewable projects. The Renewable Obligation Order will implement few changes to the system. The lifetime of the scheme will be extended to 2037. The Generators will not be entitled to receive support for more than 20 years (108, 109).

Table 3.4 Renewable Obligation scheme technologies banding (95)

Technologies	Level of support ROCs/MWh	Number of MWh to be generated for 1 ROC to be awarded
Landfill gas	0.25	4
Sewage gas, co-firing on non-energy crop (regular) biomass	0.5	2
Onshore wind; hydro-electric; co-firing of energy crops; co-firing on non-energy crop (regular) biomass with CHP; EfW with CHP; geo pressure; the use of fuels made using standard gasification or pyrolysis; other not specified	1.0	1
Offshore wind; co-firing of energy crops with CHP; dedicated regular biomass	1.5	2/3
Wave; tidal stream; fuels made using anaerobic digestion, advanced gasification or pyrolysis; dedicated biomass burning etidal impoundment; micro generation;	2.0	½

3.2.2.3 Feed-in Tariffs

During the consultation regarding the 2008 Renewable Energy Strategy, many replies indicated Feed in Tariffs (FITs) as the most appropriate support mechanism for distributed and small scale electricity (109). Key characteristics of the mechanism are:

- Each kWh generated from an eligible source will receive a fixed payment depending on the type of technology used (the 'generation tariff').
- Generators will be guaranteed a market for their exports at a long-term guaranteed price (the 'export tariff'). However, generators are entitled to individually negotiate the price for exported electricity with suppliers.
- electricity can be used on-site (109).

The FITs were introduced on 1 April 2010 and cover generators with declared net capacity (DNC) lower than 5MW (110). FIT supports generation technologies such as: anaerobic digestion (AD), hydro, micro CHP, photovoltaic cells and wind turbines.

3.2.2.4 Renewable Heat Incentive

Choosing from many available support models the government has decided to introduce the Renewable Heat Obligation as a support scheme for renewable heat. According to the Ernst and Young (Consultants) report (111) the key characteristics of an RHO mechanism would be:

- Suppliers of heat guarantee a minimum percentage of heat demand to be met by renewable heat applications ('Obligation'), with the percentage increasing over time to achieve a specific future target for renewable heat supplied as a proportion of total heat demand.
- Suppliers either pay a penalty if they fail to achieve their Obligation ('Buy-Out'), or obtain Heat Obligation Certificates (HOC) for metered renewable heat generation that contributes to their Obligation.
- Revenues from supplier penalties are recycled to compliant suppliers who meet their obligation (111).

The RHI was introduced in April 2011 (112). The incentive is promoting various technologies, including:

- heat pumps,
- solar thermal
- biomass boilers
- renewable CHP
- use of biogas and bio-liquids
- bio-methane injection into gas grid (112).

3.2.3 Combined Heat and Power

A CHP scheme must be accredited within the Good Quality CHP programme. The accreditation process is conducted to prove that a particular plant provides significant 'environmental and other benefits' compared to best available energy supply alternatives (113). Projects are assessed by analysing the Quality Index (*QI*). This factor was introduced to compare the CHP schemes with other projects that generate power or heat only. To calculate the *QI* the following formula (1) is used:

(1) $$QI = X \times \eta_{Power} + Y \times \eta_{Heat}$$

(2) $$\eta_{Power} = CHP_{TPO} / CHP_{TFI}$$

(3) $$\eta_{Heat} = CHP_{QHO} / CHP_{TFI} ,$$

Where: Total Power Output (CHP_{TPO}) is the total registered annual power generation from a CHP Scheme (MWh_e) as measured at the generator terminals; Qualifying Heat Output (CHP_{QHO}) is the total registered amount of useful heat supplied annually from a CHP Scheme (MWh_{th}). Total Fuel Input (CHP_{TFI}) is the total registered annual fuel input to a CHP Scheme (MWh). All numbers are based on Gross Calorific Value (GCV)

For the proposed plants the following conditions must be met: $QI > 105$ and $\eta_{Power} > 20\%$ (113). The *X* and *Y* coefficient values for new CHP schemes are given in Table 3.6.

Table 3.5 Coefficients for the calculation of QI for various sizes and types of new CHP scheme (113)

Technology	Size [MWe]	X	Y
Natural Gas (IC engines incl.)	≤1	249	115
	1 – 10	195	
	10 – 25	191	
	25 – 50	186	
	50 – 100	179	
	100 – 200	176	
	200 – 500	173	
	> 500	172	
Oil	≤1	249	115
	1 – 25	191	
	> 25	176	
Coal	≤1	249	115
	1 – 25	191	
	> 25	176	
Fuel Cell		180	120

Techno-logy	Size	X	Y
By-Product Gases	≤1	294	120
	1 – 25	221	
	> 25	193	
Biogas	≤1	285	120
	1 – 25	251	
	> 25	193	
Waste Gas or Heat	≤1	329	120
	1 – 25	299	
	> 25	193	
Liquid Biofuels	≤1	275	120
	1 – 25	191	
	> 25	176	
Liquid Waste	≤1	275	120
	1 – 25	260	
	> 25	176	

Techno-logy	Size [MWe]	X	Y
Biomass or Solid Waste	≤1	370	120
	1 – 25	370	
	> 25	220	
Wood Fuels	≤1	329	120
	1 – 25	315	
	> 25	220	

3.2.4 Summary

It is very important to correctly determine all sources of revenue for a feasibility study of a planned generating station. The majority of the data required to prepare a good feasibility study is specific for the chosen engine and fuel type. Moreover, the revenue from the sale of energy or offset, depends on agreement with the regional electricity supplier, thus it is different for each project.

The RO banding introduced in 2009 resulted in reduced support for proven technologies like landfill gas or sewage gas. Anaerobic digestion (AD) was granted a double value ROC band. Landfill gas and sewage gas will not be supported under the new FIT scheme designed for plants with DNC < 5MW. Small and medium scale biogas (AD) projects will be supported with the highest subsidy reaching even £115/MWh.

Animal fat combustion can be supported only in the case of large (> 5MW) projects within the RO scheme. Generating plants equipped with reciprocating engines can be used also as sources of heat – combined heat and power – therefore additional support can be granted from the RHI scheme.

3.3 Tallow Prices

The tallow market in the UK is limited to a few types of organizations, such as rendering companies (producers), oleo chemical companies, biodiesel production companies, pet food industry (clients). There is no open market for tallow – trade is done via direct contracts between companies. Therefore data regarding tallow consumption and prices is commercially sensitive. It corresponds with AEA findings presented in their report (6). For the purpose of the project described in this thesis, the up to date price for Grade 6 Category 3 tallow has been obtained weekly. The data have been used for an electricity generation feasibility analysis. Crude oil prices were obtained from BP (114, 115) – those reported are weekly average prices of Brent crude oil. Comparison of tallow and crude oil prices is shown in Figure 3.4. It has to be noted that animal fat price is given in GBP per tonne while oil price is reported in USD per barrel. The presented data proves that to some extent animal fat prices are linked with fossil fuel prices. The lack of consistency in the last few weeks of 2009 can be explained by the higher availability of animal fat during the winter, this could have stopped the price from rising along the trend line which was visible during the earlier months of the year.

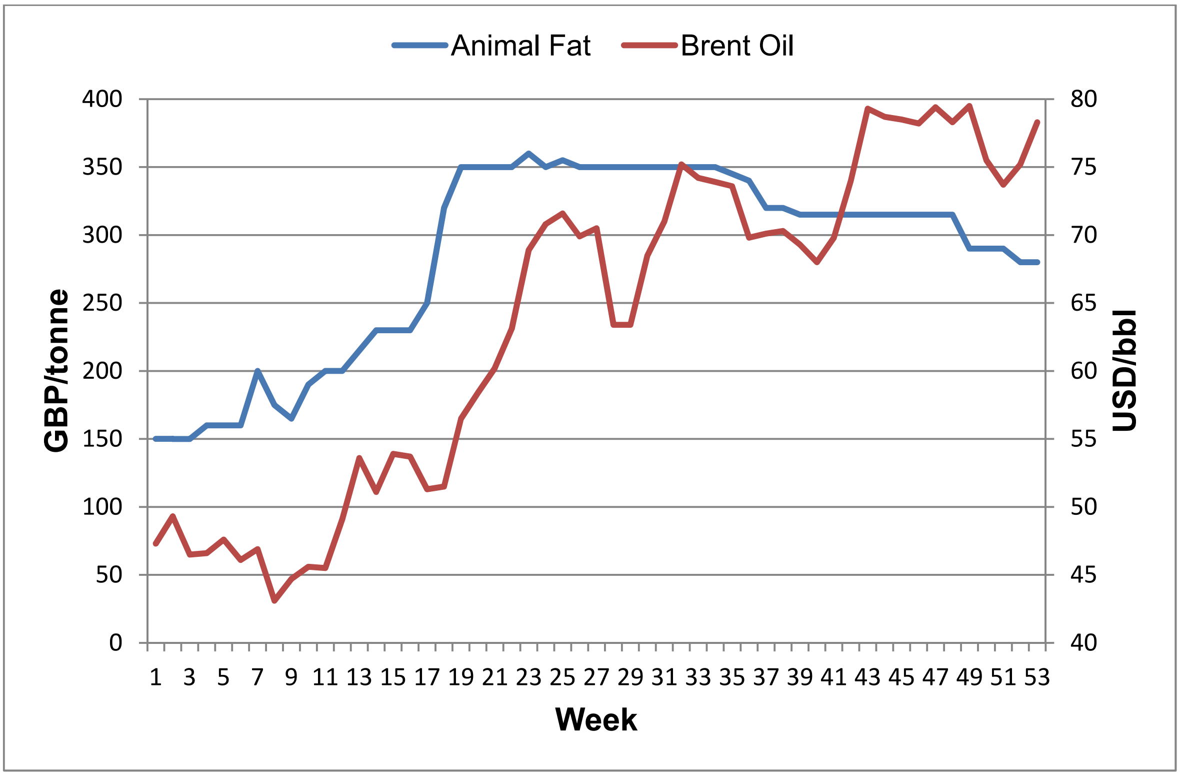

Figure 3.4 Comparison of animal fat (grade 6) and crude oil (Brent) prices in 2009 (114, 115)

3.4 Feasibility Study of 0.8 MWe Generating Plant

The following approach has been followed to assess a feasibility study of the research power plant installed at the host company premises at Cheddleton, Staffs, England.

Each kWh of energy generated by the test generator results in a lower electricity bill for the host company. As the company has signed a long term contract, the price of energy units can be treated as constant.

Energy is generated from a renewable source so it is entitled to be supported by the Renewable Obligation System. The amount of money is related to the amount of MWh generated. Therefore:

$$Income = MWh * (A + B)$$

Where:

A – Electricity price (£/MWh)

B – Subsidy (£/MWh)

Fixed costs such as: emission monitoring system hire (£/week) or engine servicing cost (£/year) were identified. The main variable cost is the price of fuel:

$$Expenditure = MWh * C$$

Where: C – fuel price (£/tonne)

The used model does not take depreciation into account as the engine used for the study was not an up to date model and it was difficult to correctly estimate the cost of replacing it. Analysis of animal price effect on generation feasibility has been conducted. Results are given in Figure 3.5. It can be seen that for the given engine, at prices of animal fat exceeding 300 GBP/tonne electricity production is not feasible. Only additional support in form of ROCs can make electricity production from animal fat profitable, however, in the case of a fuel price rise above 500 GBP/tonne, even subsidised production is not profitable. Depending on the price, the fuel forms between 80-90% of total production cost.

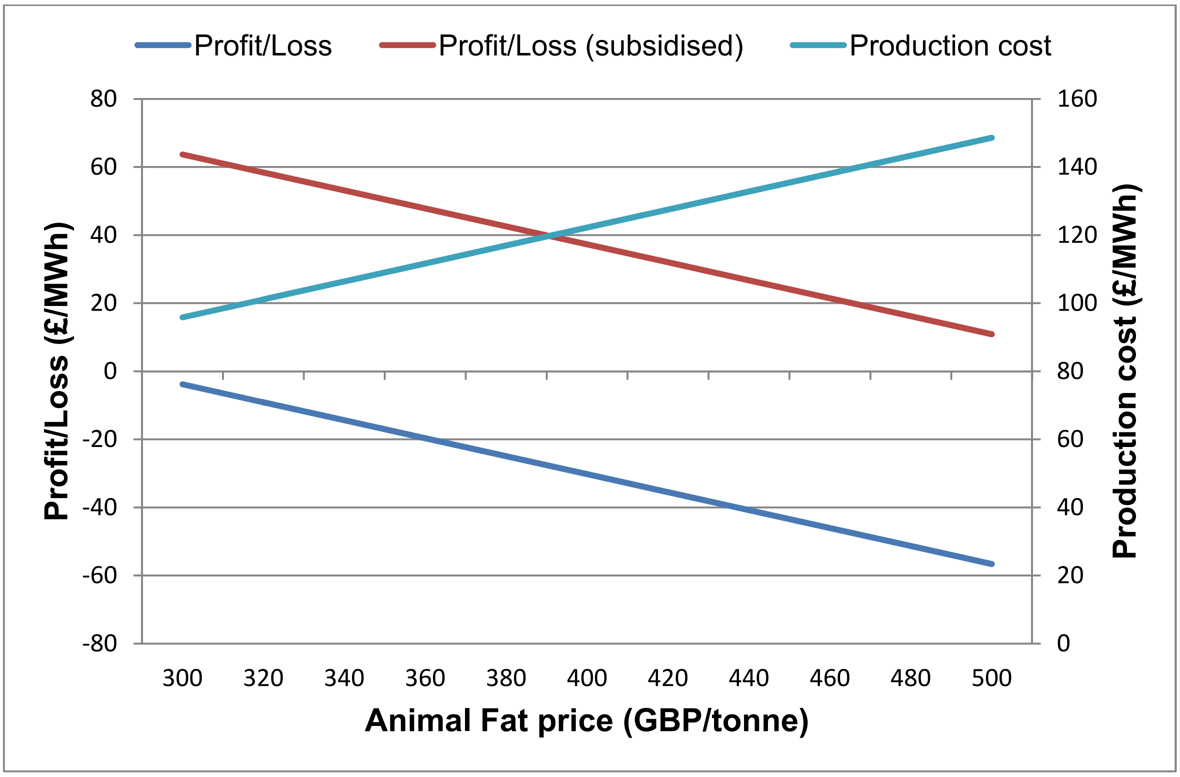

Figure 3.5 Impact of animal fat price on electricity generation feasibility. Assumptions: electricity selling price - 92 £/MWh, ROC price - 45 £/MWh

3.5 Feasibility Study of Large Scale 20 MWe Generating Plant

A feasibility study for a proposed large (20 MW) power plant fuelled with animal fat has been prepared. Two documents: Electrical Production Cost Study and Feasibility Calculation, have been prepared by MAN B&W in cooperation with the Author for the host company – John Pointon & Sons Ltd. The electrical production cost analysis gives a total description of the economic flow in the financial period. The electricity, heat production and the running costs were assumed to be constant throughout the financial period. The sensitivity analysis covers the most important economical parameters, in order to show the influence the changed values on the comparison between the plant alternatives.

The findings can be summarised as follows: electricity production from animal fat even in a high efficiency (48%) two stroke reciprocating engine driven plant is not feasible without additional support in the form of ROC or another scheme. Fuel price is responsible for approximately 85% of the total running cost (including staff costs, servicing and maintenance etc.). For a long payback time (25 years), electricity generation cost does not fall below 85 £/MWh. At the time of the study preparation, price paid to electricity generators was approximately at a level of 40 £/MWh.

3.6 Economics of Electricity Generation

Currently power plants using engine driven generators and fuelled with animal fat are entitled to government subsidies in the form of Renewable Obligation Certificates. This scheme supports the production of electricity in large (>5MW) stations using biomass. Animal fat is currently classed as biomass. Each MWh receives a virtual certificate that can be traded with other generators and suppliers. Heat generated by a CHP plant fuelled with tallow can be classed as output enabling the generator to obtain Climate Change Levy

Exemption Certificates (LECs). The recently introduced RHI creates another possible source of income by subsidising heat production.

The analysis of animal fat prices was a difficult task as there is no open market for this commodity trade. The collected data showed that a link between animal fat and fossil fuels exists, in consequence it makes tallow price very volatile which can possibly lead to the wrong process of feasibility assessment. On the other hand, animal fat price can be predicted to some level of accuracy by the usage of similar methods which are used for fossil fuel prices' prediction.

The feasibility analysis prepared for the research plant showed that fuel price can constitute up to 90% of total electricity production cost. Therefore, animal fat price has a major impact on feasibility. Electricity generation was only profitable in the case of receiving support in the form of ROCs. For tallow prices above 500 £/tonne it was not feasible to operate the plant.

Similar findings are included in the feasibility study for the proposed large power plant. Very efficient two stroke diesel engines were proposed for this particular application but still fuel price contributes to approximately 85% of the total generation cost. Also in the case of the proposed plant, feasibility is very sensitive to fuel price change. Electricity production from animal fat can be profitable only when additional support such as the Renewable Obligation or Renewable Heat Incentive is available.

Chapter 4 **EXPERIMENTAL FACILITIES**

4.1 Introduction

This chapter describes facilities used in the research process. It can be divided into two areas: facilities located at the hosting company premises, such as the engine-generating set together with monitoring equipment (in cylinder pressure sensor, shaft encoder etc.), emission monitoring, modified fuel supply system and developed emission abatement system; and laboratory facilities located at the University of Birmingham, where fuel properties have been tested. It has to be noted that the engine used in this research was designed and manufactured in the 1960s – therefore obtained results shouldn't be directly compared with those gained from modern facilities.

4.2 Engine Facility

4.2.1 Engine Specifications

A Ruston 6AR has been modified for the research described in this thesis. Modifications included installation of a new heated fuel supply system, installation of an electronic control unit enabling engine speed control, operational parameters monitoring and also synchronising with the grid. The engine has been equipped with cylinder pressure sensors, a shaft encoder and emission monitoring system. A new emission abatement system has been designed and installed. The 6AR (shown in Figure 4.1) is a six cylinder, four stroke, direct injection diesel unit of 260.5 mm bore and 368 mm stroke. The engine is equipped with a turbocharger and water cooled air cooler. The cylinder liners are of the wet type. Separate cylinder heads are provided for each cylinder carrying two inlets, two exhaust valves, fuel injector and air starter valve. A chain driven camshaft, through a set of cams, operates valves and individual fuel injection pumps. The engine is water cooled with two circuits of raw and fresh water. The engine is started with a compressed air system. The air for the starter is raised by a diesel powered compressor. Engine technical data is given in Table 4.1.

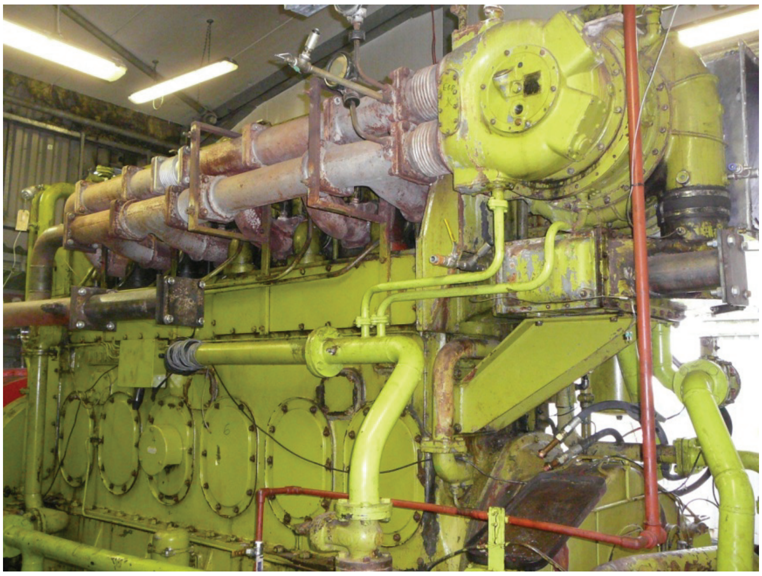

Figure 4.1 Ruston 6AR engine installed at John Pointon and Sons Ltd. premises at Cheddleton

Table 4.1 Engine technical data

No. of cylinders	6	-
Nominal speed	600	rpm
Power	809	kW
Bore	260.5	mm
Stroke	368	mm
MEP	1.4	MPa
Compression ratio	12.3:1	-
Injection pressure	200	Bar
Injection commences	22	ºBTDC

The engine is mechanically coupled to a Brush 11 kV alternator and exciter. The generating set has been installed at the hosting company premises at Cheddleton, Staffordshire, England and registered with OFGEM as 'Pointon_gen4' station. A single line diagram showing the local electrical grid configuration with the newly designed metering system is given in Figure 4.2.

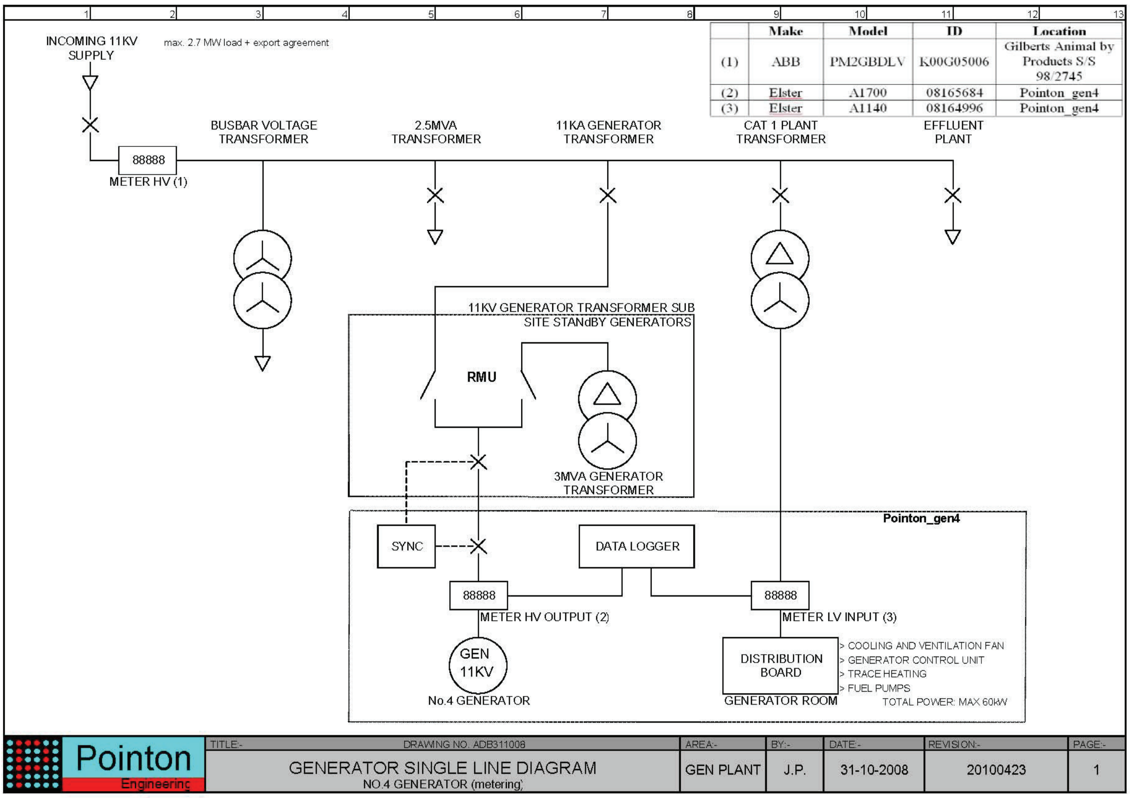

Figure 4.2 Generating station single line diagram showing Ruston 6AR engine (Gen 11kV) and dedicated electricity metering system complying with OFGEM requirements

4.2.2 Monitoring Equipment

<u>Cylinder pressure monitoring equipment</u>

The cylinder pressure monitoring system consists of:

- pressure transmitter
- shaft encoder
- data acquisition PC card
- data acquisition software

Pressure transmitter

The pressure transmitter Kistler 6613CA, shown in Figure 4.3, contains a piezoelectric sensor and an integrated charge amplifier. The pressure transmitter is made for continuous cylinder pressure monitoring of large engines. The integrated charge amplifier provides a uniform output and can be connected directly to a data acquisition unit. There are no individual sensitivity adjustments necessary, since the output has uniform sensitivity. The sensor has a voltage output of 0 - 5 V with a zero line of 2 V (if pressure is 0 MPa) (116). The sensor can record pressure within two ranges: the first up to 25 MPa, and the second up to 10 MPa with sensitivities of 100 mV/MPa and 250 mV/MPa respectively.

The calibration of the pressure transducer was performed on an oil weight bench machine in the range of 0MPa/1.5V to 9MPa/2.5V. The obtained characteristics of the pressure transducer were applied to the data acquisition software as a tuned coefficient.

Working principle

The cylinder pressure is acting on the diaphragm. The diaphragm converts the pressure in proportional force on the sensor element. The piezoelectric sensor element converts the force into a charge. The charge is converted by a charge amplifier into a voltage. The complete measuring chain is designed for easy operation and very long life time.

The advantages of the piezoelectric principle are:

- It operates safely up to high temperatures and therefore is ideally suited for accurate measurements in harsh conditions.
- It has a very small sensitivity change over a temperature range.
- Its high stiffness results in small diaphragm stress.
- It has high reproducibility since the piezoelectric constant of the measuring element is a constant of nature and does not change over time (116).

Figure 4.3 Kistler 6613CA pressure transmitter (116)

<u>Data acquisition software</u>

The software used is a LabView based programme developed at the University of Birmingham. The cylinder pressure signal is recorded and then various parameters can be calculated, for example:

- maximum pressure (comparison between cycles)
- heat release rate

- IMEP (indicated mean effective pressure)
- compression and exhaust polytrope factor – k
- pressure vs. crank angle
- pressure vs. volume.

Emission monitoring system

The emission monitoring system was provided by CBISS Ltd. The system consisted of:-

- MIR9000 – an infra red spectrophotometer that uses a Gas Filter Correlation technique. The advantage of the GFC technique is that it uses a pair of narrow band pass interference filters, specific to each gaseous species, to establish and remove any cross interference from other gases (117).
- FID – Flame Ionisation Detector – Gas is sampled with a heated pump and led to the burner supplied with pure hydrogen and air filtered and purified through an internal generator. The separation of the hydrocarbon molecules at high temperature in the cone of the flame provides an ionizing current, the strength of which is directly proportional to the number of carbon atoms of the analysed mixture (117).
- PCME LMS 181 probe - The LMS181 measures the scattered forward light from a laser source. The measurement volume in the sensor probe is positioned in a representative location within the stack. The scattered light response is directly proportional to soot concentration. The instrument optimises its resolution and zero drift characteristics (118).

The emission data was recorded continuously and stored in the system memory. The daily report contained half hourly averages and the daily average of the following exhaust components and parameters: sulphur dioxide – SO_2, nitrogen monoxide – NO, nitrogen oxides – NO_x , carbon monoxide – CO, carbon dioxide – CO_2, flow, temperature, soot, hydrocarbons – HC.

4.2.3 Fuel Supply System

According to the engine manual (119) the standard fuel supply system comprises of the following items:

- Daily service tank
- Fuel filters: before fuel pumps and edge filters in each injector
- Individual fuel pumps for each cylinder
- Injectors
- Interconnecting piping.

A standard fuel system diagram is given in Figure 4.4.

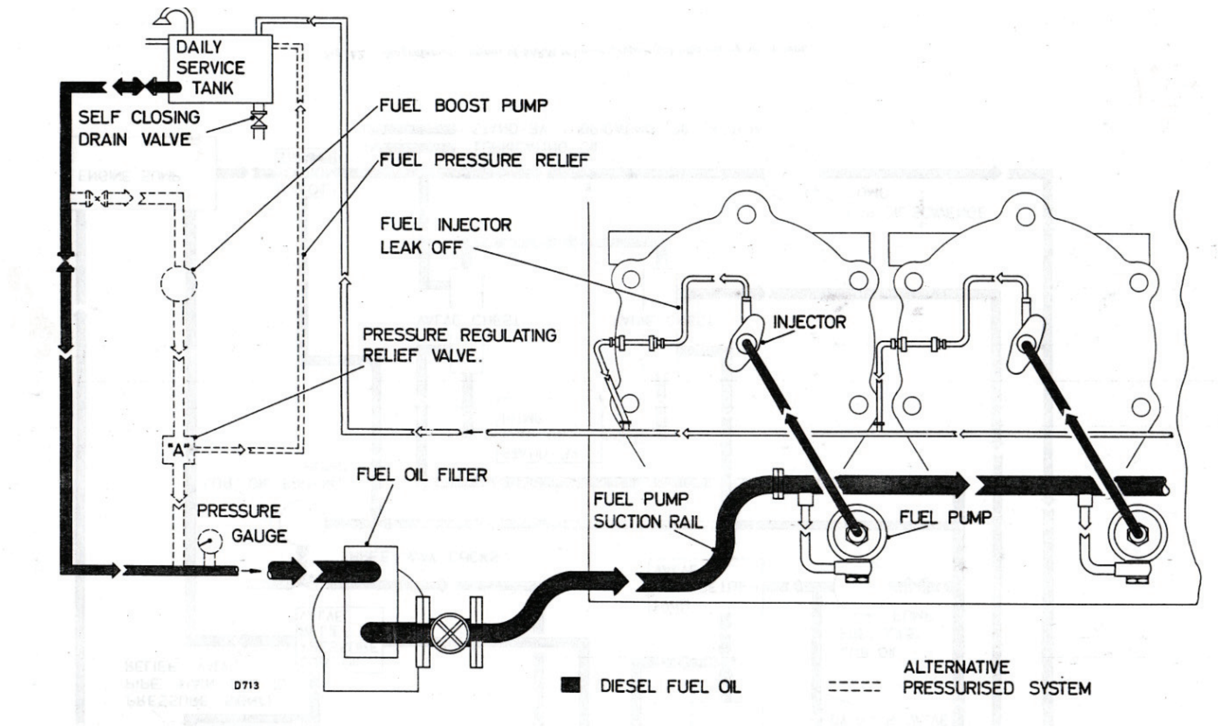

Figure 4.4 Standard fuel system layout (119)

As animal fat is solid at room temperature, the fuel supply system had to be modified to enable operation on alternative fuel. The following assumptions were made:

- The engine should start and stop on diesel fuel
- The fuel supply system should be able to switch back to standard fuel in case of an alarm condition such as grid voltage loss, engine overheating, synchronisation loss etc.

The fuel system has been modified by adding a second fuel tank with a heating coil for animal fat storage. Pipe work connecting the tank with the fuel supply panel has been fitted with trace heating preventing fat from solidification and non return valves were also fitted. The fuel supply panel consisted of two fuel boost pumps, one for diesel and another for liquid fat, powered by electric motors, four sets of filters, where two were preliminary filters located before the boost pumps, and main filters located before the engine inlet. Three interlinked valves, one for diesel supply, second for fat supply and third for fuel return, were operated by a pneumatic actuator. The described arrangement enabled smooth transition between the fuels. The system layout is given in Figure 4.5. The valve arrangement and the fuels' flow patterns for diesel operation (engine start up and warm up or alarm state) are given in Figure 4.6. The system state for animal fat operation is given in Figure 4.7.

Fuel consumption has been measured with two flow meters. Coriolis mass flow meter, Promass 83F supplied by Endress+Hauser, has been used for animal fat consumption measurement. The flow meter was linked to a PC with a data acquisition software package installed. Diesel consumption was recorded with a positive displacement type flow meter, MP 025S supplied by Trimec.

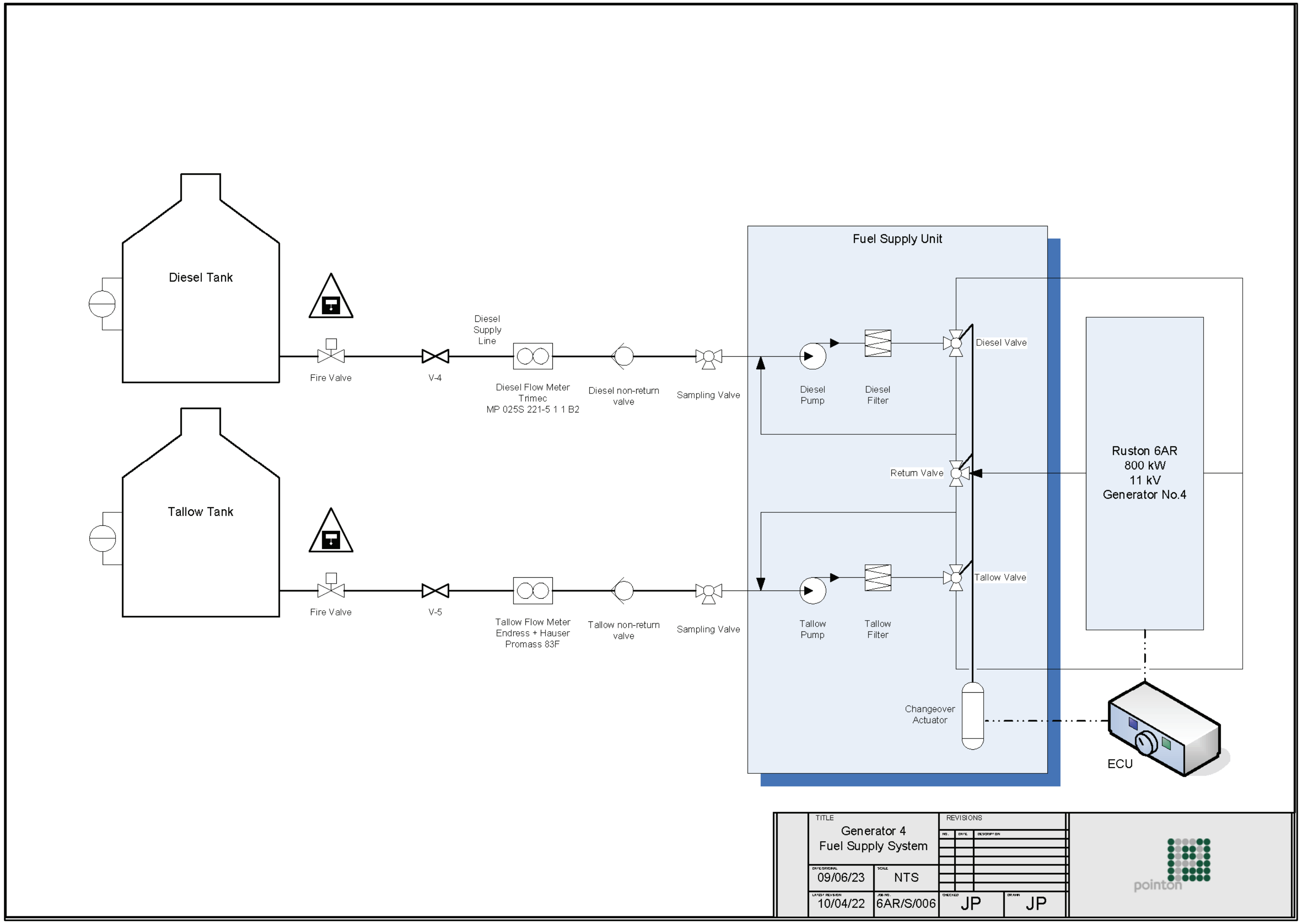

Figure 4.5 Fuel supply system layout

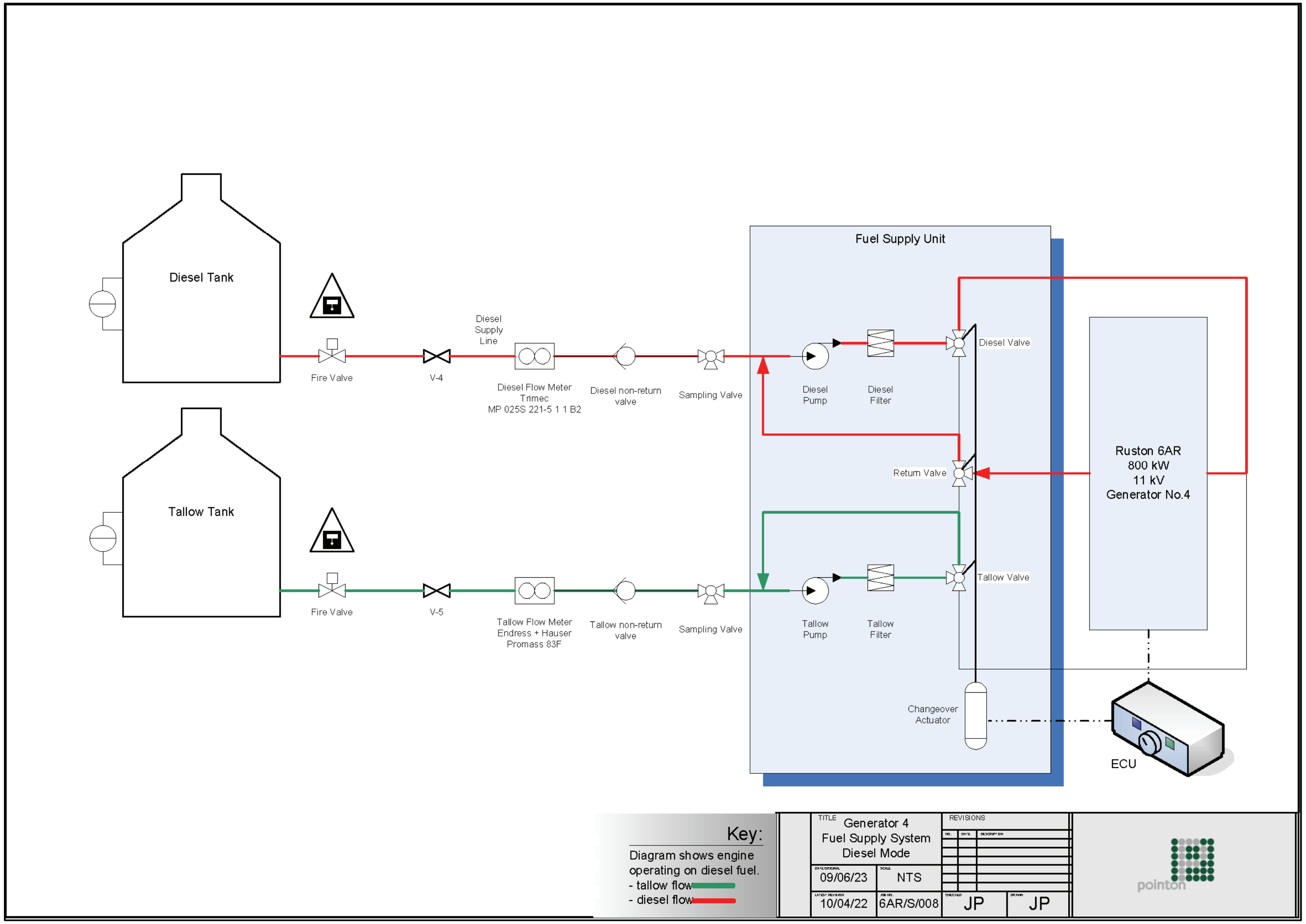

Figure 4.6 Fuel supply system - diesel mode

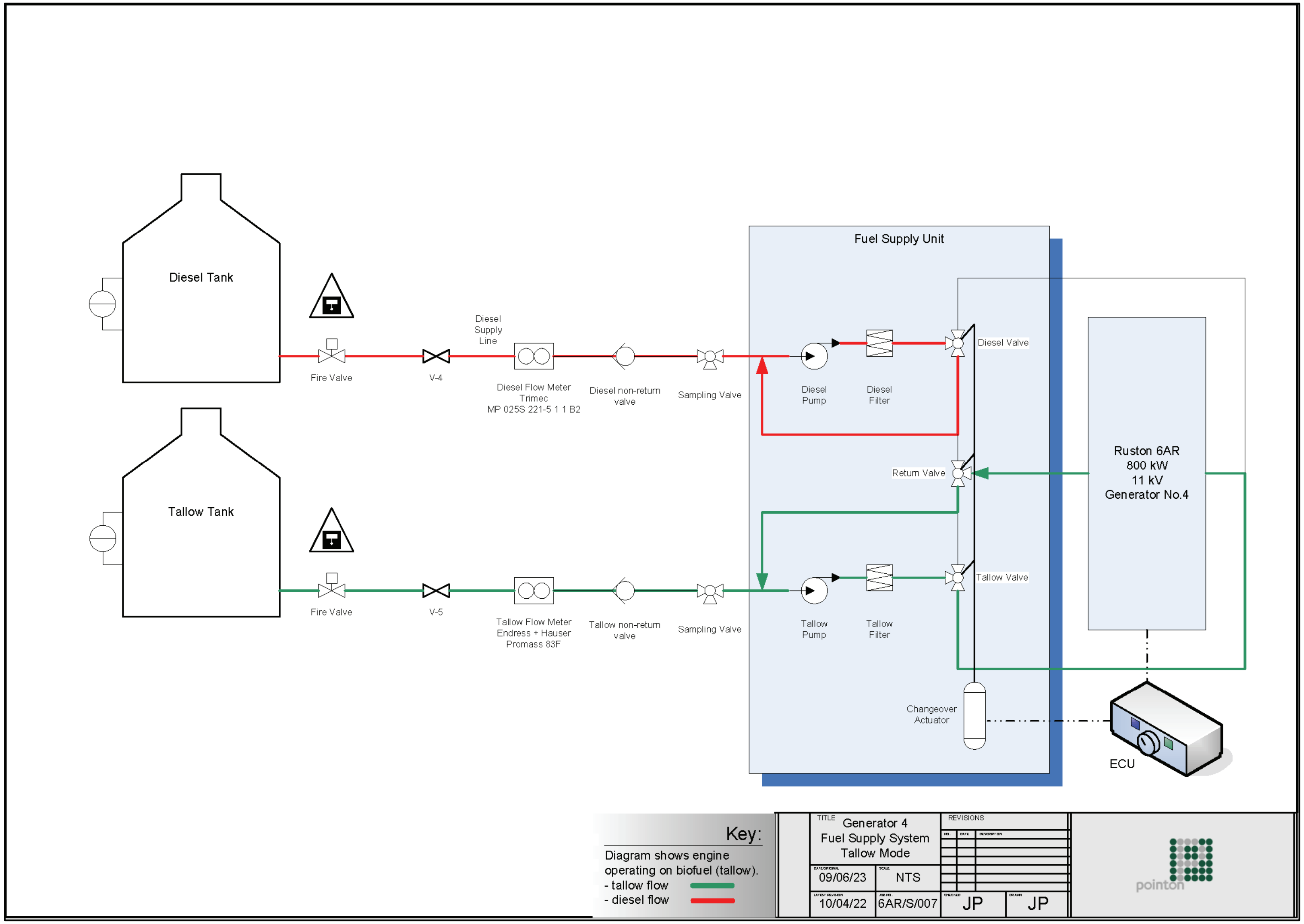

Figure 4.7 Fuel supply system - tallow mode

4.2.4 Emissions Abatement System

The main reason for the EGR testing was to reduce NO_x emission from the generating set. The limit was set by the local authorities at the level of 450 mg/m^3 (concentration in dry air at a temperature of 273K at a pressure of 101.3 kPa and with an oxygen content of 11% dry) (24). Method efficiency should reach 75-80%. An abatement system combining the effects of exhaust gases recirculation and introduction of water to the combustion chamber was designed and installed. Figure 4.8 shows the EGR system with gases cooling and humidification installed on the engine. Usage of water for an abatement system was carefully considered and was found acceptable for the purpose of this particular installation, because of reclaimed water availability within the rendering plant.

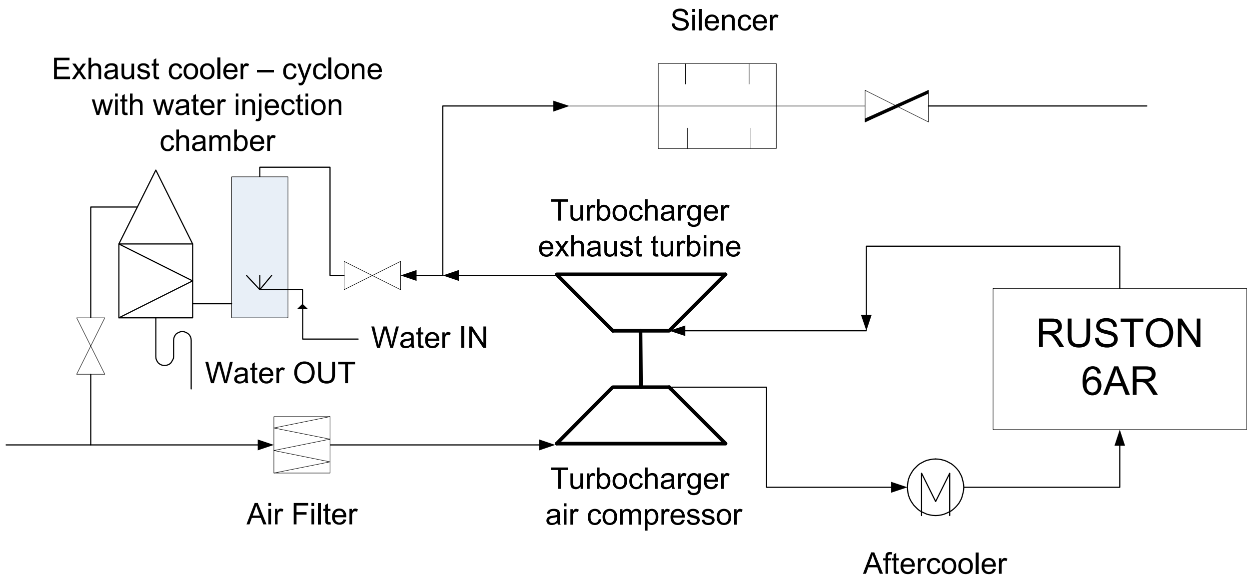

Figure 4.8 cEGR system layout - including gas cooling and humidification chamber

The proportion of recirculated exhaust can be controlled by a set of manually operated valves. EGR percentage was determined by comparison between two CO_2 concentrations. One was measured at the engine intake, the second at the stack outlet. To achieve higher NOx emissions' reduction efficiency, the EGR was cooled (cEGR) and humidified. Exhaust was diverted to a spray chamber where water was injected through a set of nozzles, shown in Figure 4.9. The mixture should be free of water droplets, therefore a cyclone chamber, shown in Figure 4.10, was installed to spin the gases. Any excess water was flowing down the walls of the chamber. Water injection can be switched off; the engine operates then with typical gas recirculation (EGR). Technical drawings of the cEGR system form Appendix 1.

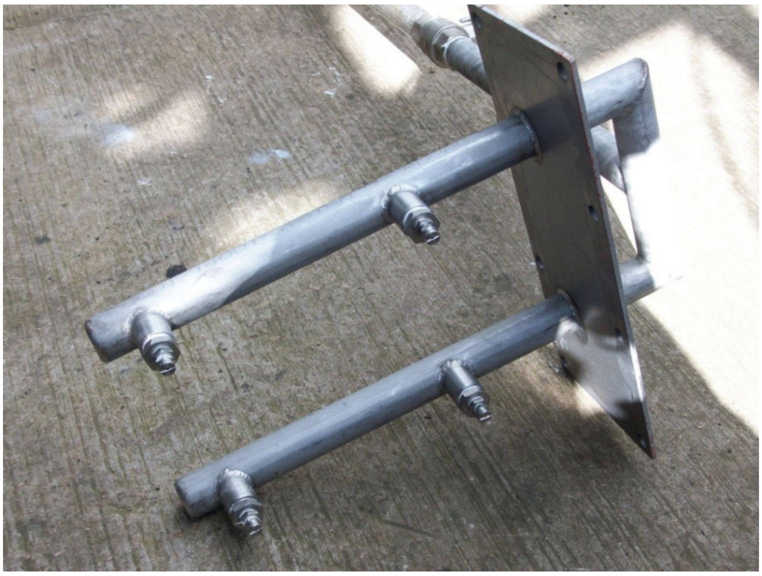

Figure 4.9 Water injecting nozzles

Figure 4.10 EGR cyclone chamber

4.3 Fuel Laboratory Facilities

4.3.1 Density Test

The hydrometer method has been used for determination of animal fat density. A tested fuel sample was placed in a water bath with a thermostat to minimise sample temperature variation. Animal fat is an opaque liquid in all conditions, therefore the scale reading method described in ASTM standard D1298-99 (2005) (120) and shown in Figure 4.11, was used.

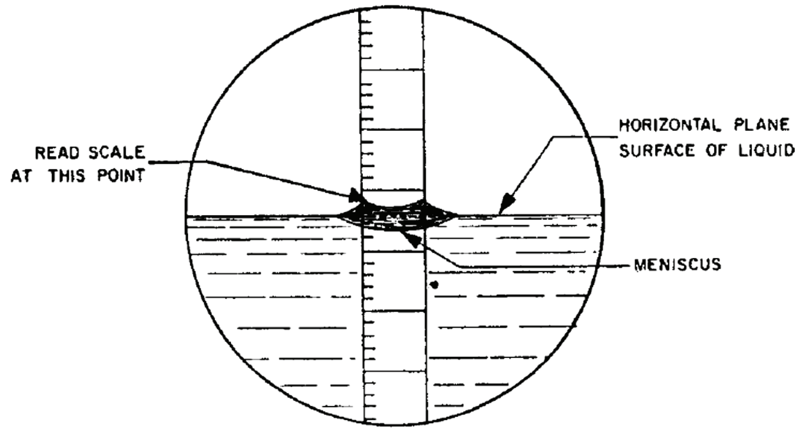

Figure 4.11 Hydrometer scale reading for opaque fluids (120)

4.3.2 Surface Tension Test

A maximum bubble pressure method has been used to measure surface tension of various fuels. A Sita Proline T15 tension meter was used and technical data are given in Table 4.2. Sample temperature was controlled by a water bath.

Table 4.2 Sita Proline T15 technical data

Surface Tension	
Measuring range	10 - 100 mN/m (dyn/cm)
Resolution	0.1 mN/m (dyn/cm)
Bubble Lifetime	
Controlled range	15 - 15000 ms
Resolution	1 ms
Liquid Temperature	
Measuring range	0 - 100°C
Resolution	0.1 K

Variable bubble lifetime makes obtaining results comparable with static methods possible. Bubble pressure method suitability, for measurement of viscous fluids, has been positively verified by Fainerman (121).

4.3.3 Viscosity Test

Fuel viscosity has been analysed with an Ultra Shear Viscometer provided by PCS. The Ultra Shear Viscometer can carry out fully automated viscosity measurements over a shear rate range from $10^6\ s^{-1}$ to $10^7\ s^{-1}$ and temperatures between 40 and 150°C. The meter is fitted with a DC servo motor capable of speeds of over 20,000 rpm and an electromagnetic clutch which engages the rotor for only a very short period of time (typically 30 ms). This brief shearing interval minimizes the shear heating in the lubricant (122). The viscometer is shown in Figure 4.12 and its main parts are shown in Figure 4.13.

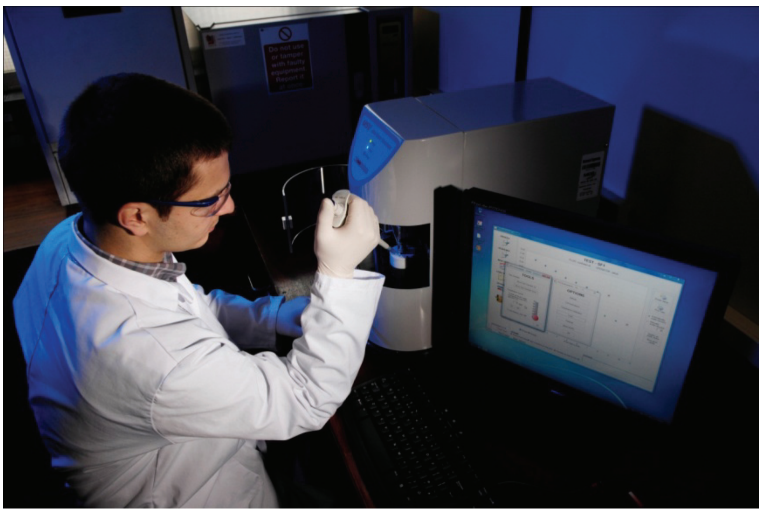

Figure 4.12 PCS Ultra Shear Viscometer

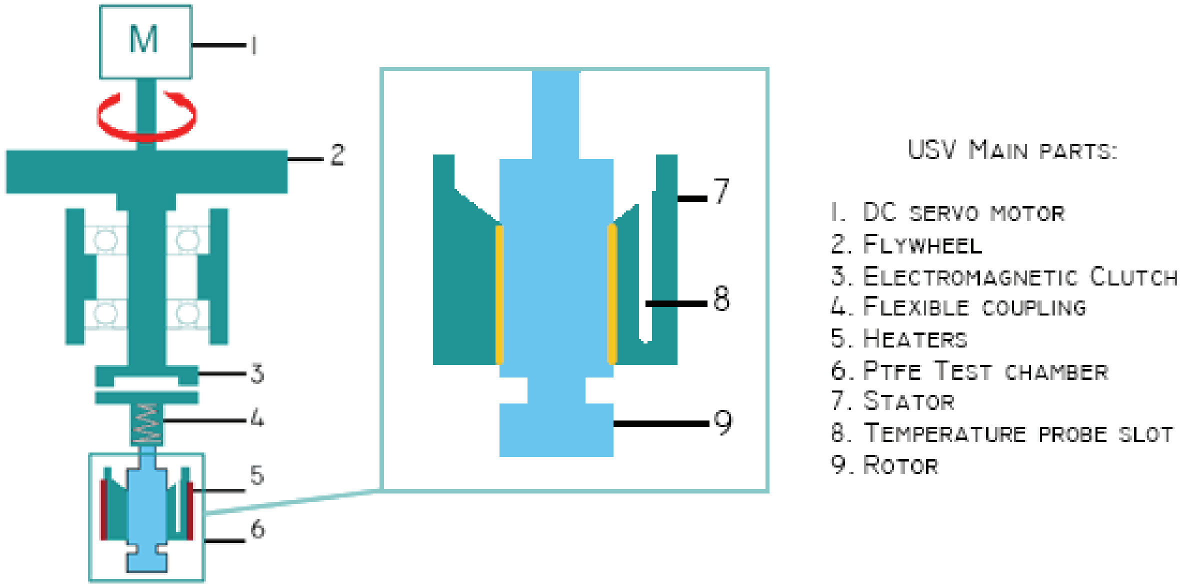

Figure 4.13 USV main parts (122)

4.3.4 Lubricity Test

Several methods have been developed to assess fuel lubricity. These include: the Scuffing Load Ball on Cylinder Lubricity Evaluator (SLBOCLE), the High-Frequency Reciprocating Rig (HFRR), and the Ball on Three Seats (BOTS). More detailed description and discussion of correlation between full scale injection pump systems and laboratory methods can be found in the literature (123). High Frequency Reciprocating Rig (HFRR) method has been used in this study to assess lubricating properties of animal fat. The rig has been provided by PCS Instruments Ltd. London, UK. A schematic diagram showing the working principle is given in Figure 4.14 . The technical specification is given in

Table 4.3.

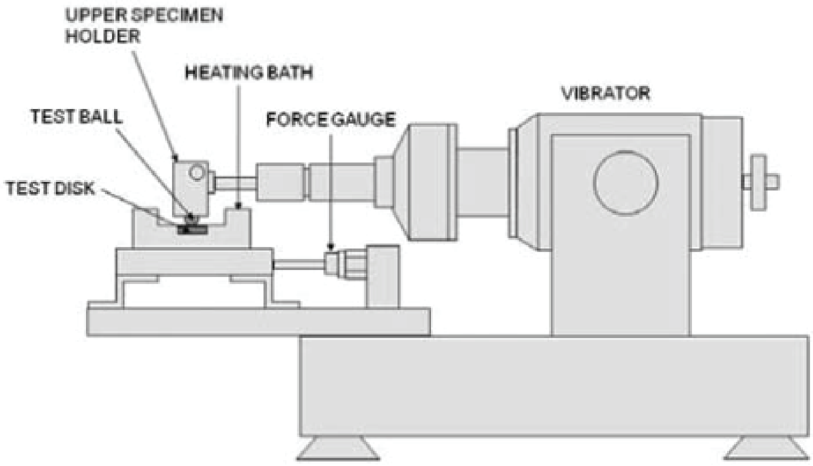

Figure 4.14 Schematic diagram of HFRR (124)

Table 4.3 PCS HFRR technical specification

Frequency	10 – 200 Hz
Stroke	20 μm – 2.0 mm
Load	0 – 1.0 kg
Max. friction force	10.0 N
Temperature	Up to 400 °C
Upper specimen	6.0 mm diameter ball
Lower specimen	10.0 mm diameter x 3.0 mm thick disc
Camera resolution	2048 x 1536 pixels

To increase test repeatability and reduce scatter the rig has been fitted with a temperature and humidity controlled cabinet so tests can be carried out at constant temperature and relative humidity. The wear scar diameter is measured with a Meiji metallurgical microscope equipped with a digital measurement camera. Test conditions were based on ISO 12156 standard (refer to Table 4.4).

Table 4.4 Test conditions based on ISO 12156

Fluid volume	2 ± 0.2 ml
Stroke length	1 ± 0.002 mm
Frequency	50 ± 1 Hz
Fluid temperature	60, 75, 90 ± 2 °C
Applied load	200 ± 1 g
Test duration	75 ± 0.1 min
Bath surface area	6 ± 1 cm^2

Certified specimens provided by PCS were used for testing. The upper specimen is a 6.0 mm diameter ball that is loaded into the upper specimen holder. The upper specimen is specified to grade 28 (ANSI B3.12), ANSI E-52100 steel, with a Rockwell hardness "C" scale (HRC) number of 58-66 (ISO 6508), and a surface finish of less than 0.05 µm R_a. The lower specimen is the disc that is loaded into the lower specimen holder. The lower specimen is specified to ANSI E-52100 steel machined from annealed rod, with Vickers hardness "HV30" scale number of 190-210 (ISO 6507/1). It is turned lapped and polished to a surface finish of less than 0.02 µm R_a (122).

4.3.5 Free Fatty Acids Removal

One possible method of acidity reduction is free fatty acid (FFA) evaporation under reduced pressure. FFA removal is described in more detail in sections 5.3 and 5.4.

A small scale laboratory test rig was designed to run the trial with tallow fuel. A sample of animal fat was put in a beaker; the outlet was connected to a vacuum pump. The pump is capable of reducing pressure down to 6.5 - 9.5 hPa. The beaker, prepared as described above, was placed in a liquid bath. The temperature was set to 100°C and 220°C. The sample was exposed to the raised temperature over one and three hours. The experimental set up is presented in Figure 4.15.

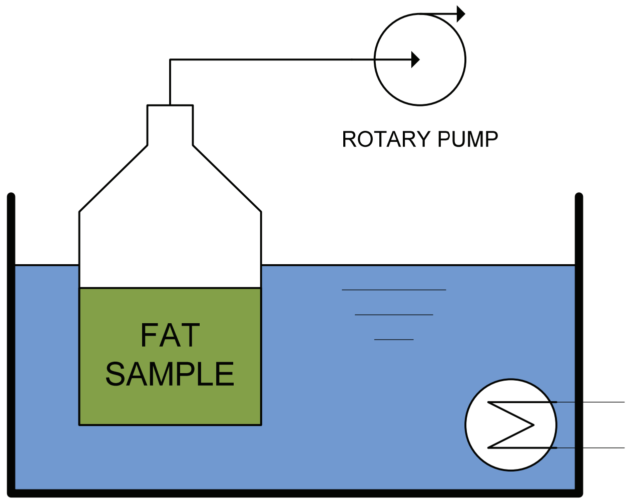

Figure 4.15 Test rig for FFA removal via evaporation at reduced pressure

Chapter 5 **CONSISTENCY OF TALLOW PROPERTIES**

5.1 Introduction

There are properties that are widely used to determine tallow quality and suitability for applications within the chemical and food industry. Usually the free fatty acid content, polyethylene contamination, moisture, insoluble impurities, ash and iodine values are measured. Those properties are tested on a regular basis in the host company's on-site laboratory. Analysis presented in this chapter is based on test results obtained there.

The amount of free fatty acid an animal fat contains is a good indication of whether the fats were properly handled before rendering. Meat tissues contain fat-splitting enzymes, which start to hydrolyze the fat to form free fatty acid as soon as the animal dies. Rendering must be performed as soon as possible after the animals are slaughtered for a minimum of free fatty acid development (4). The raw material is usually contaminated with polyethylene that will melt and disperse in the tallow during the rendering process. Polyethylene may solidify as the tallow is cooled and contaminate pipe work and valves or damage the fuel injection system. Moisture content characterises the efficiency of tallow filtration and separation processes. It is desirable to keep moisture at low levels. High moisture content may encourage hydrolysis and increase acidity as a result. Insoluble impurities are usually small particles of protein, bone and fibre. Animal fats are highly saturated and the iodine value is a parameter describing the level of saturation.

Industrial requirements for grade 6 tallow and crude bio-fuel specifications for two- and four-stroke heavy fuel oil engines are given in Table 5.1.

Table 5.1 Required tallow properties

Property	Limit value		
	Grade 6 tallow	4-stroke engine spec (69)	2-stroke engine spec (42)
Free fatty acids (FFA)	<15 %	<10%	<15%
Polyethylene	<200 ppm	-	-
Moisture	<0.03%	0.2%	1.0%
Insoluble impurities	<0.05%	0.05%	-
Ash	<0.02%	0.05%	0.15%
Iodine value	<60	120	-
Calorific value	36-40 MJ/kg	-	-

5.2 Long Term Monitoring Programme

A category 3 grade 6 tallow batch was prepared on a weekly basis and pumped to a heated tank supplying the test generator. Samples were taken weekly throughout 2009 and tests were also conducted on a weekly basis with the exemption of density and calorific value, where monthly composite samples were tested.

Results were statistically analysed to determine whether the data came from a process which is subject to statistical description. A two stage approach was chosen. The first step was to check if the data values follow the normal distribution. A test for data normality consisting of Chi-square, Shapiro-Wilks statistics and Z scores for skewness and kurtosis was used and P-values were calculated. It can be assumed that data are adequately modelled by a normal distribution if the P-value is greater than 0.05 (125, 126). As the sample size used for process monitoring is n=1, a control chart for an individual unit should be used during the second stage of the data analysing process. If the data values follow normal distribution then a moving range control chart for individual measurements (MR chart) can be used. In case the data values do not follow normal distribution an exponentially weighted moving average control chart (EWMA chart) can be used. The exponentially weighted moving average is defined as:

$$z_i = \lambda x_i + (1 - \lambda) z_{i-1}$$

Where $0<\lambda<1$ is a constant and the starting value is the process target (126).

Montgomery (126) claims that a EWMA with lambda parameter $\lambda = 0.05 - 0.10$ and an appropriately chosen control limit will perform very well against both normal and non normal distributions.

To check if the acidity of the fuel depends on the ambient temperature, it has been recorded at hourly intervals. The weekly average temperature was then calculated.

Calculated annual mean values were compared with industrial requirements for grade 6 tallow and bio fuel specification for large four and two stroke engines used for power generation.

5.2.1 Results

Results of tests for weeks 6-8 are excluded due to a failure of the filtration system which resulted in 'off spec' fuel provided for the research engine. Other data are graphically presented in Figure 5.1 and Figure 5.2. Acidity test results are presented in Figure 5.3 together with the weekly average ambient temperatures. Monthly composite samples results are presented in Figure 5.4.

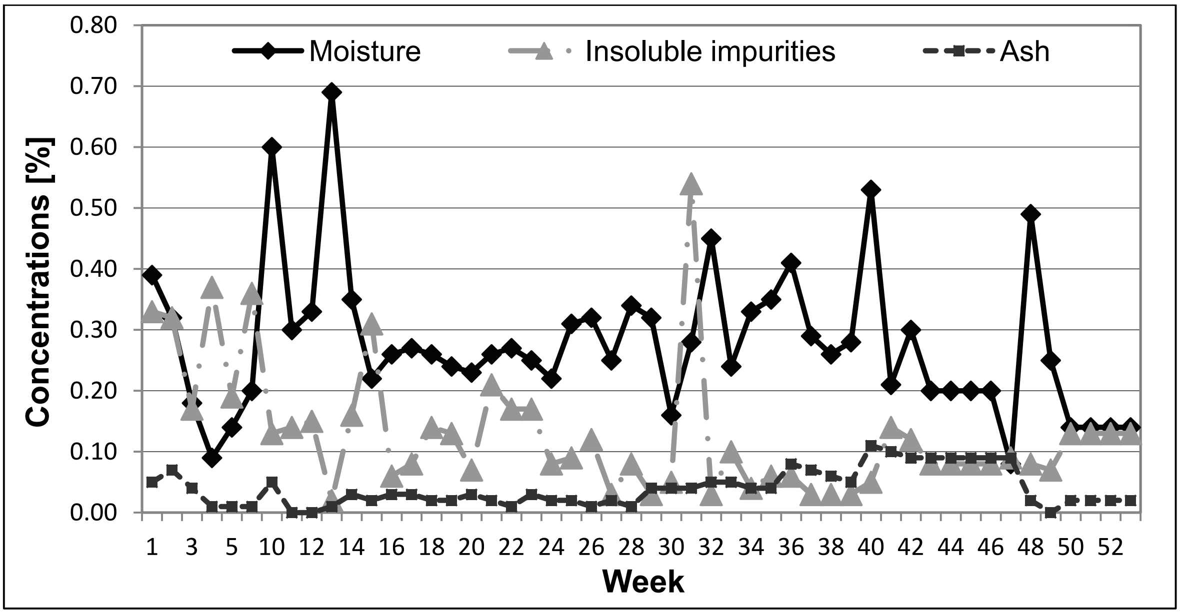

Figure 5.1 Moisture, insoluble impurities, ash levels in tallow during 2009

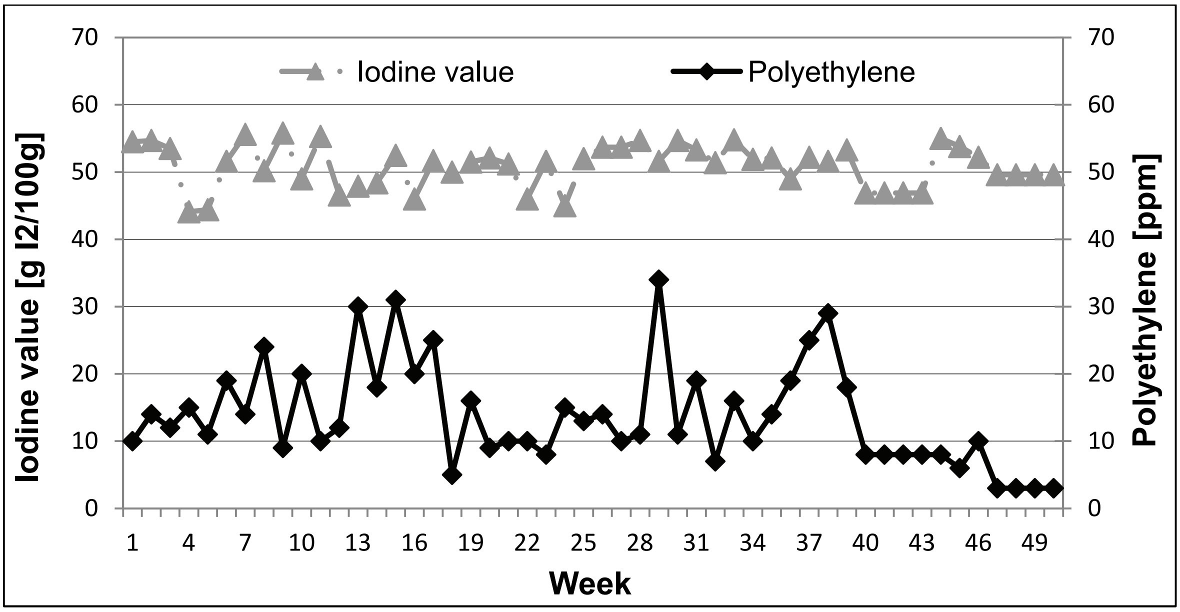

Figure 5.2 Iodine number and polyethylene levels in tallow during 2009

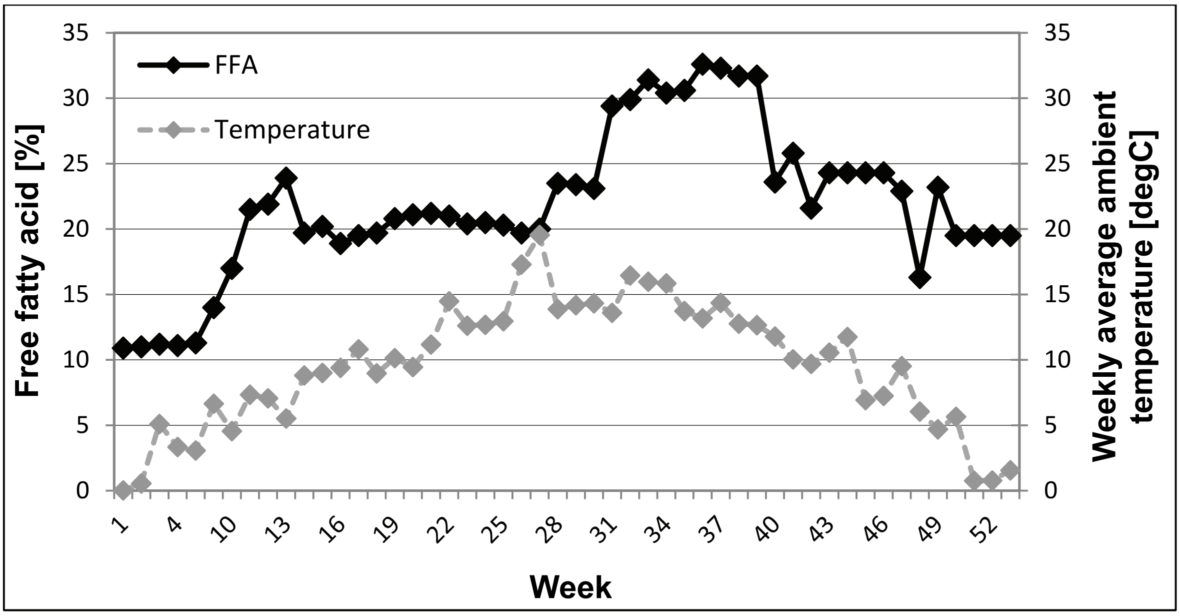

Figure 5.3 Free fatty acids (FFA) level in tallow and weekly average ambient temperature during 2009

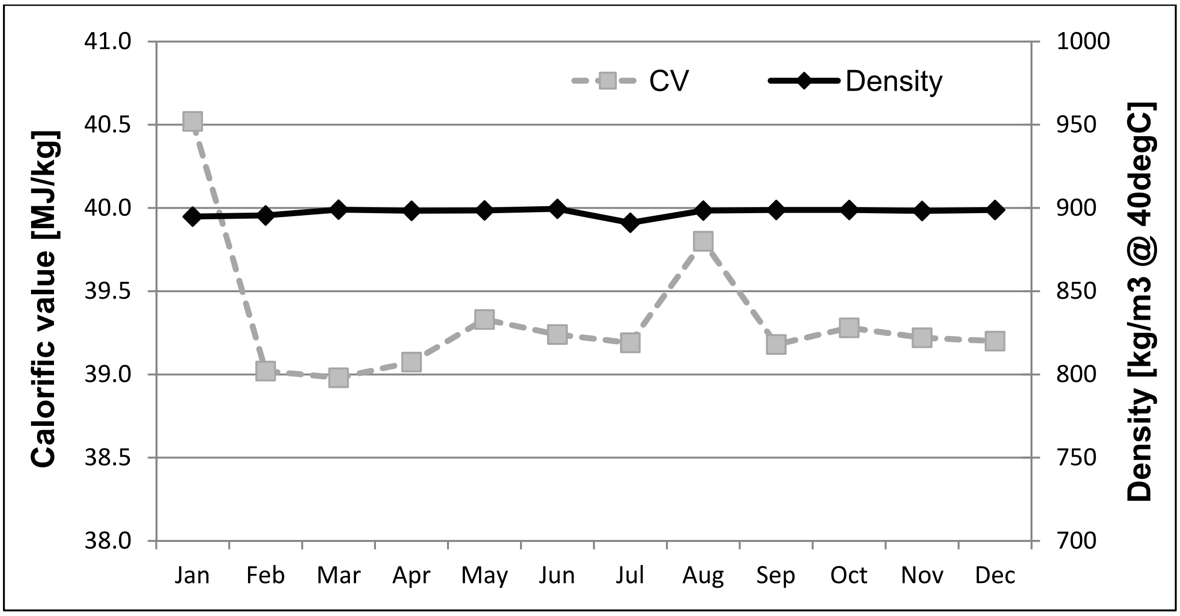

Figure 5.4 Calorific value (higher) and density of tallow during 2009

Statistical analysis shows that the majority of measured properties are not within the statistical model. In Figure 5.5, EWMA control charts prepared with the Statgraphics® software package for all the measured properties are presented. Graphs include the plotted moving average value together with upper and lower control limits (UCL and LCL). The process centre line was approximated by the data arithmetic average. Lack of consistency in the data can be seen for acidity and the ash data series. For calorific value results only one point is outside defined control limits. The significant variation detected for January and August samples can be explained by different feedstock used for fat production. During those months demand for meat is higher, hence the amount of meat by-products in the mix is higher than for other months, where a large proportion of the feedstock is food waste. A summary of statistical analysis is presented in Table 5.2. In the second column the smallest P-values of four conducted tests for data normality are given. If the value is smaller than 0.05 then it can’t be assumed that that particular data series follows normal distribution. The process is within statistical control if the obtained results are within designed limits – EWMA upper and lower control limits (UCL and LCL) in the case of the analysis presented in this paragraph. In the fourth column it is stated whether a particular tested property is within statistical control. A comparison of the calculated annual average and highest recorded values with three specifications (grade 6 tallow, 4- and 2-stroke engines) is also included; Y – means that the calculated/measured value complies with the specification, N – means that the calculated/measured value does not comply with the particular specification. It can be concluded that although some properties, like polyethylene contamination, are not consistent during the sampling period, they do not prevent the tallow from being used in industrial applications, as calculated averages exceed the required specification (grade 6). The only parameter that disqualifies the tested tallow from being used as a fuel in any available combustion engine is the acidity expressed as free fatty acids level. The highest measured value of FFA exceeds the specification for a two stroke low speed engine by 100%. Moisture content in the tested fuel seems to be within the statistical limits, however, the mean value does not meet requirements of grade 6 tallow and bio fuel for a four stroke engine.

As shown in Figure 5.3, there is a relationship between ambient temperature and free fatty acids' level. Acidity is considerably higher during the summer period. The collected data are very random so it was difficult to create a detailed model or equation linking ambient temperature with acidity level. However, a very coarse approximation can be formulated: increase of ambient temperature by one degree can increase acidity of tallow by 0.75%. Acidity level depends on the intensity of the decomposition process and fat hydrolysis by enzymes. Clearly, the ambient temperature is one of the factors affecting the reaction rate.

Table 5.2 Summary of statistical analysis and compliance with various specifications

Data series	Smallest P-value	Normal distribution	Process in statistical control	Annual average	Highest reading	Unit	Compliance with specification		
							G6	4S	2S
Moisture	0.0008	No	Yes	0.28	0.69	%	N/N	N/N	Y/Y
Insoluble impurities	$1.05*10^{-8}$	No	No	0.13	0.54	%	N/N	N/N	-
Ash	$1.77*10^{-13}$	No	No	0.04	0.11	%	N/N	Y/N	Y/Y
Iodine value	0.0150	No	Yes	50.9	55.8	gI_2/100g	Y/Y	Y/Y	-
Polyethylene	0.0017	No	No	13.7	34.0	ppm	Y/Y	-	-
FFA	$5.11*10^{-6}$	No	No	21.9	32.6	%	N/N	N/N	N/N
Density	0.0008	No	Yes	897.4	899.5	kg/m^3	-	Y/Y	Y/Y
Calorific value	0.0005	No	No	39.34	38.98	MJ/kg	Y/Y	-	-
Where: G6 – grade 6 specification, 4S – four stroke specification, 2S – two stroke specification									

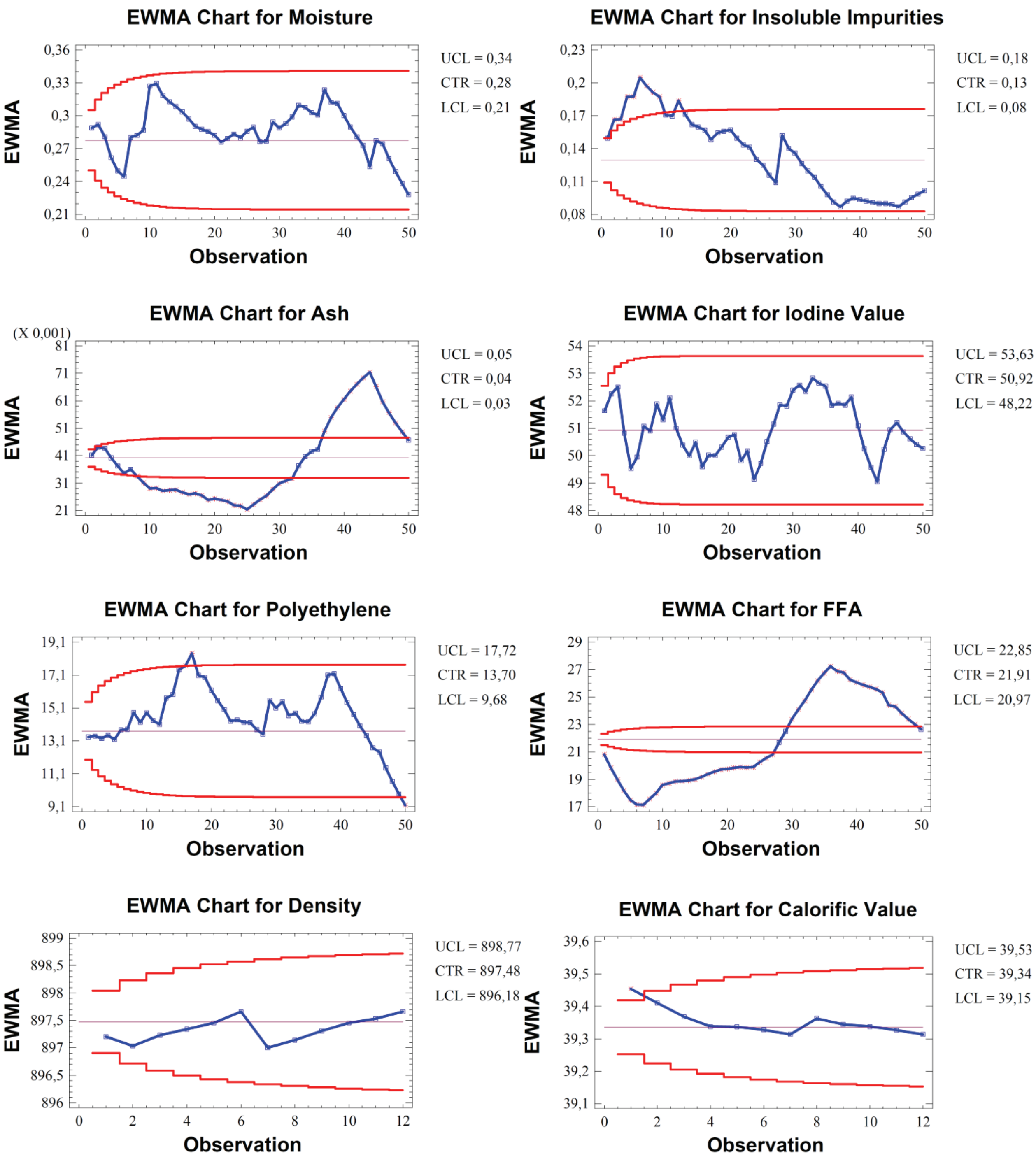

Figure 5.5 EWMA control charts for monitored tallow properties

5.3 Available Acidity Reduction Methods

Acidity can be lowered in many ways. Bhosle et al. (127) describe three main groups of methods: chemical, physical and miscella deacidification. The chemical method of lowering acidity comprises of the addition of an alkali to degummed oil, thereby turning the FFA into soap, which is then removed by mechanical separation from the neutral oil. This method has been widely researched by Zheng et al. (78) and Meher et al. (128) and applied in first generation biodiesel production by Canakci et al. (129). An alternative approach is presented by Cmolik et al. (130), where advantages of physical methods like lower environment pollution due to lack of chemicals, higher yields achieved, are described. The most common physical methods are steam refining and inert gas stripping. Further investigation is required to determine the best solution for deacidification technology that can be implemented in the case of tallow used as fuel in engines.

5.4 Acidity Reduction by Evaporation – Trial Test

5.4.1 Preliminary Information

In the case of the project described in this thesis, it was desirable to find an acidity lowering method that will not involve the usage of chemicals. Chemical FFA removal is a well known process and is already used in the biodiesel production industry, even for treatment of the fat sourced from the host company.

All physical methods are based on the fact that free fatty acids evaporate at lower temperatures if the pressure is reduced. The main goal is to lower the temperature to avoid polymerisation and fat decomposition. One of the physical method variations is thin film evaporation. The industrial scale method is described below. A Laboratory scale experiment has been conducted to ensure that fat specific for this project can be treated with this method – as there is no experience in dealing with grade 6 feedstock (correct at 2010, experience in yellow grease treatment – FFA of 25%).

5.4.2 Large Scale Plant Utilising Rothoterm® Technology by Artisan Industries Inc.

A technology description accompanied by a process flow diagram is attached as Appendix 2.

5.4.3 Small Scale Test Results and Discussion

Average acidity reported in Table 5.3 has been calculated based on three consecutive tests. Tallow samples were tested on the rig described in paragraph 4.3.5.

Table 5.3 FFA evaporation at low pressure – 6.5 – 9.5 hPa

Test duration [hours]	Test temperature [ºC]	
	100	*220*
0 [ref]	9.38 %	
1	9.63 %	4.26 %
3	9.21 %	7.53 %

It can be seen that heating animal fat at low pressure will encourage evaporation of free fatty acids. In the case of prolonged heating, high acidity can probably be explained by hydrolysis reaction affected by the higher temperature. As expected, the acids' removal process should be fast – in industrial applications it is achieved either by supplying fats to stripping columns in the form of spray or in the case of evaporators in a thin film layer. The conducted test proves that fat produced by the host company can be potentially treated with one of the physical deacidification methods. No negative impact of the treatment on fat has been detected.

5.5 Conclusions

Data collected throughout the duration of the project proved that acidity of the tallow is high and does not meet any requirements given by engine manufacturers. An appropriate method of deacidification must be implemented to modify tallow properties to enable its usage as fuel for engine driven power plants. Moreover, high variability of acidity was detected. Ambient temperature affects the speed of the decomposition process, hence the acidity level. Observations proved the possible suitability of tallow as a fuel, due to high calorific value, which is consistent during the year. The quality of the fuel preparation process must be improved so that moisture content can be lowered. Tallow can be treated as a potential fuel for renewable energy power plants, however, its quality and pre-treatment have to be developed and improved.

Chapter 6 DETERMINATION OF APPROPRIATE STORAGE AND SUPPLY TEMPERATURES

6.1 Effect of Temperature on Properties of Animal Fat

This chapter describes an attempt to establish the appropriate temperature for animal fat to be supplied as a fuel for reciprocating engines. Tallow is solid at ambient conditions and melts in temperatures above 35 °C. The following aspects have been discussed in this part of the study; elevating temperature will reduce the fat's viscosity and surface tension thus improving spray characteristics. At the same time, high temperature may have an impact on the lubricating properties of the fuel. In the light of findings presented in Chapter 5, acidity seems to be one of the fuel properties that need close monitoring; therefore the possible contribution of high storage temperature towards increased acidity was also investigated. The main objective of this part of the study was to determine optimal feed and storage temperature for animal fat.

The investigation concluded in Chapter 5 focused on properties' consistency. Despite acidity variation associated with ambient temperature influencing the decomposition process, other properties presented some level of consistency, enabling the establishment of a set of typical values for animal fat. The next step was to establish limits – the internal specification when fuel would be rejected and not used for engine trials. Fuel used for tests presented in the current chapter was within the limits given in Table 6.1.

Table 6.1 Animal fat typical specification, tested sample properties

Data series	Annual average	Limit	Sample	Unit
Moisture	0.28	0.5	0.16	%
Insoluble impurities	0.13	0.4	0.15	%
Ash	0.04	0.1	0.06	%
Iodine value	50.9	55	54	gI_2/100g
Polyethylene	13.7	35.0	15	ppm

6.1.1 Viscosity

Tallow contains high levels of saturated fatty acids, which give it a solid consistency at room temperature (4). Fuel pre heating was reported by numerous researchers (32, 66, 131, 132) as a potential way of utilising neat triglycerides as engine fuels. The importance of viscosity reduction was noted by Ejim et al. (28) as it has the largest contribution, about 90%, to change in the SMD. Therefore, viscosity reduction should be prioritised to achieve better fuel atomisation.

Figure 6.1 presents a comparison of dynamic viscosity of two fuels – animal fat and ULSD – measured at a range of temperatures. The presented results are calculated averages of four consecutive tests performed at USV. The first condition measured was a temperature of 40 ^{o}C – often used in fuel specifications as a reference. A temperature of 60 ^{o}C is often regarded to be the temperature of fuel in the supply system and is used as a reference for example in the lubricity HFRR test. It was impossible to perform a test for animal fat at lower temperatures and higher shear rates as viscosity values were reported to be too high. The impact of temperature on the viscosity of animal fat is significant; raising the temperature from 40^{o}C up to 60^{o}C results in viscosity reduction from approximately 40 cP down to 20 cP. Further heating up to 90^{o}C reduces viscosity to 9 cP (for low shear rate) and 8 cP (for high shear rate). It has to be noted that even heating up to 90^{o}C does not reduce viscosity to levels comparable with ULSD. However, calculated kinematic viscosity (presented in Figure 6.2) of 13.5 cSt (for 80^{o}C) and 10.8 cSt (for 90^{o}C) is lower than the limit of 15 cSt at the engine inlet flange defined for large two stroke engines (133). Therefore, it should be possible to use animal fat as fuel in large engines equipped with a fuel supply system capable of handling viscous fuels such as HFO or crude oil. The engine used in trials presented in this thesis can be supplied with fuel of viscosity limited to 14.5 cSt at 40^{o}C (119).

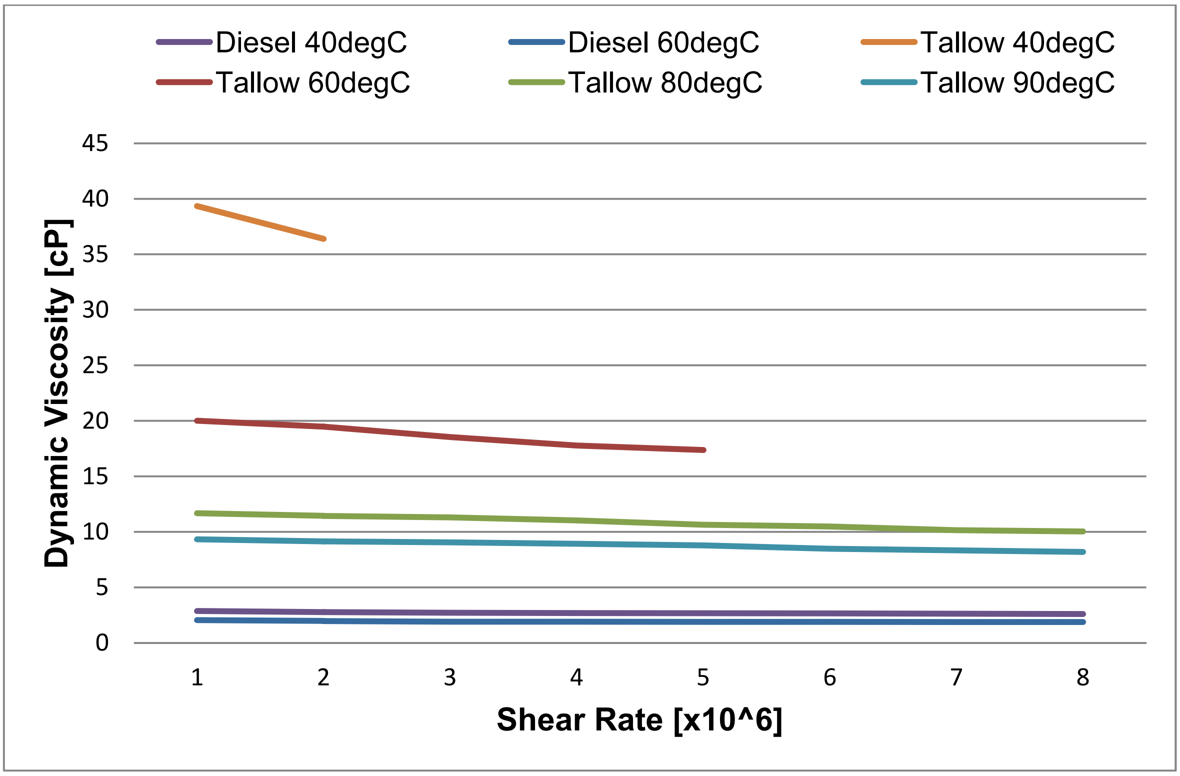

Figure 6.1 Comparison of dynamic viscosity of animal fat and ULSD at range of temperatures

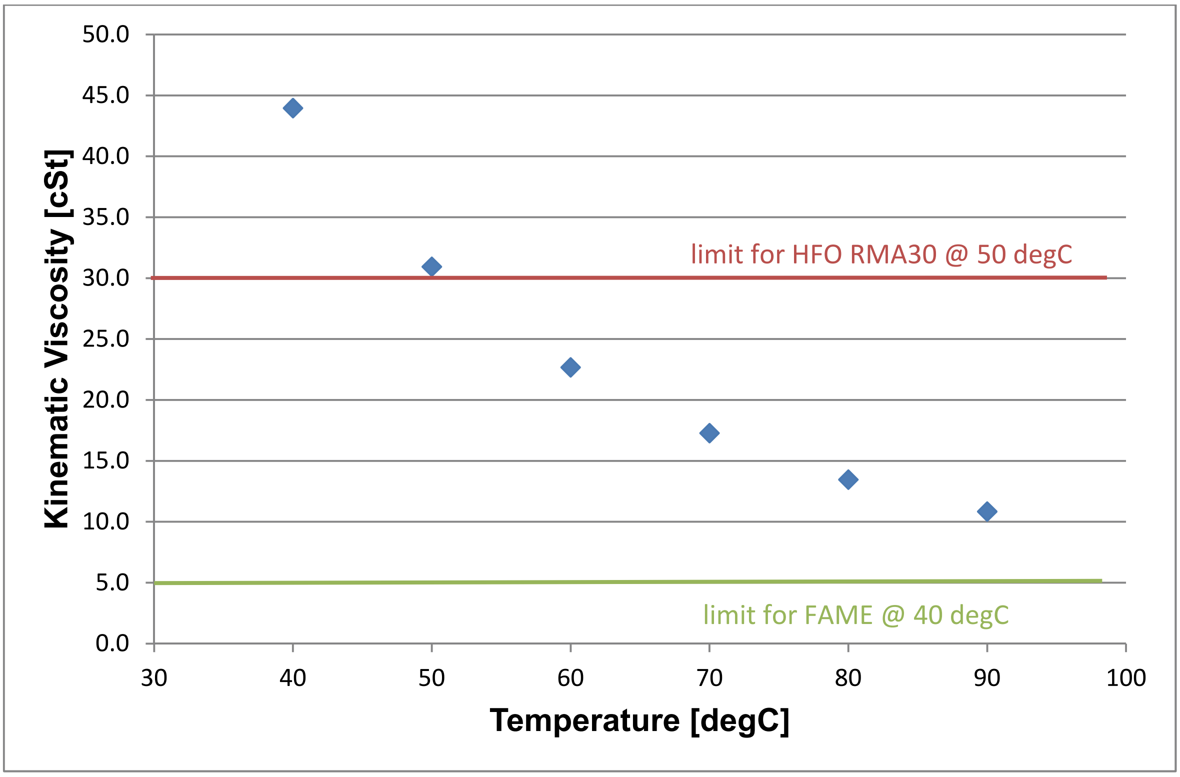

Figure 6.2 Effect of temperature on animal fat kinematic viscosity

Presented results prove that pre heating above 80°C is required to reduce viscosity to a level comparable with that required by the engine manufacturer.

The character of animal fat as a fluid can be determined by analysis of the relationship between stress and shear rate. Shear stress for animal fat and ULSD at various temperatures is shown in Figure 6.3. For ULSD at both tested temperatures a linear relationship between shear stress and shear rate was observed. A similar conclusion can be drawn for animal fat for temperatures of 80 and 90°C. It proves that tallow is Newtonian fluid. For lower test temperatures animal fat shows minimal signs of shear-thinning as curve gradient (viscosity) reduces with increasing shear rate.

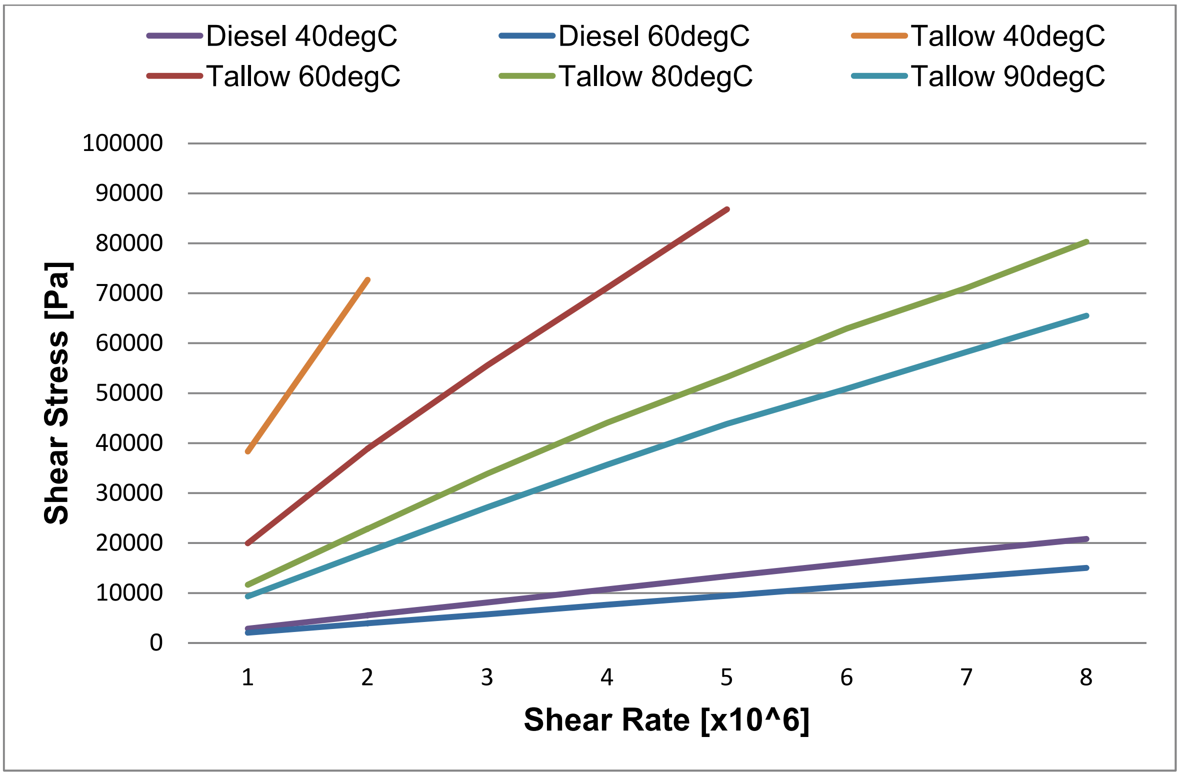

Figure 6.3 Relationship between shear stress and shear rate for animal fat and ULSD at a range of temperatures

6.1.2 Lubricity

Verification of lubricating properties initially applied only to fuels used in the aviation industry (123). Introduction of low sulphur diesel fuels resulted in fuel injection pump and distributor pump failures, particularly in Sweden (134). Low sulphur fuels possess poorer lubricity than non-desulphurised fuels, mainly due to the removal of polar oxygen and nitrogen containing compounds (135, 136). Products of the triglycerides' transesterification process are regarded to be good lubricity enhancers, especially when blended at a level of 1-2% with ULSD (136-138). Lubricity of neat fatty compounds depends on various features such as saturation, oxygen presence, number of OH groups (136).

The test for each temperature has been repeated three times, calculated averages are reported in Table 6.2. The wear scar measured for ULSD is shown in Figure 6.4. The measured diameter of 320 µm is consistent with values available in literature (138, 139).

Table 6.2 HFRR test results

Fuel	Temperature	MWSD	WS1.4	Avg. Film	Avg. Friction coefficient
	[degC]	*[µm]*	*[µm]*	*[%]*	*[-]*
ULSD	60	315.0	320.0	83	0.176
Fat	60	85.5	102.3	100	0.069
Fat	75	86.5	104.2	100	0.078
Fat	90	89.5	108.9	100	0.082
Where: MWSD – uncorrected mean wear scar diameter; WS1.4 – corrected wear scar diameter					

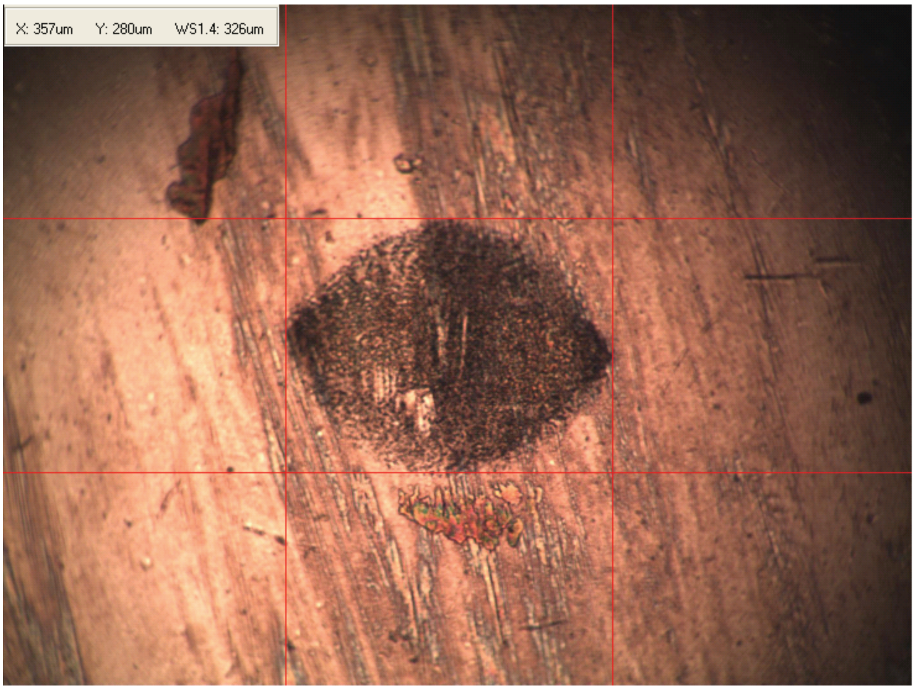

Figure 6.4 Wear scar captured by digital microscope; ULSD at 60°C

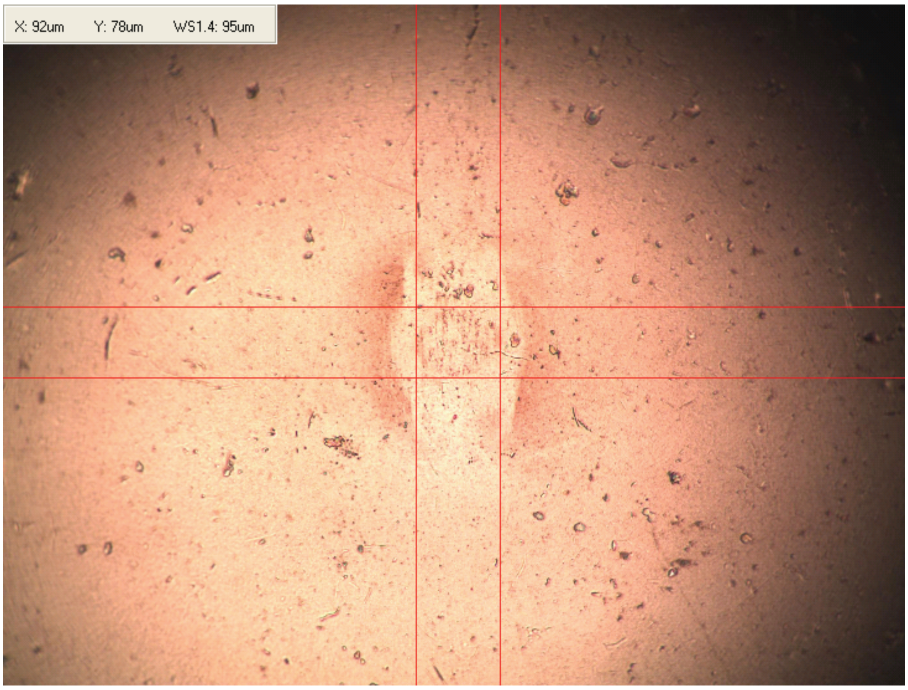

Figure 6.5 Wear scar captured by digital microscope; Animal Fat at 60°C

As expected wear scar diameter is significantly lower for animal fat than for diesel fuel. The measurement result is shown in Figure 6.5. It can be explained by high unsaturation of animal fat - presence of double bonds, indicated by a iodine number. Animal fat contains 10% oxygen which improves lubricity. According to Knothe et al. (140) oleic and linoleic acids have excellent lubricating properties, as no wear scar has been recorded. These two components constitute more than 50% of animal fat composition (7). Differences in lubricity of animal fat and ULSD are even more significant if film thickness is compared. For animal fat, film is developed after less than 5 minutes of the HFRR test, whilst for ULSD it never exceeds 85% of thickness. Comparison of film thickness for both analysed fuels is given in Figure 6.6 and a more detailed comparison focusing on the first 5 minutes of the test is given in Figure 6.7. Better lubricity of animal fat can also be proved by lower friction coefficients; in all cases the difference is significant. Comparison is given in Figure 6.8.

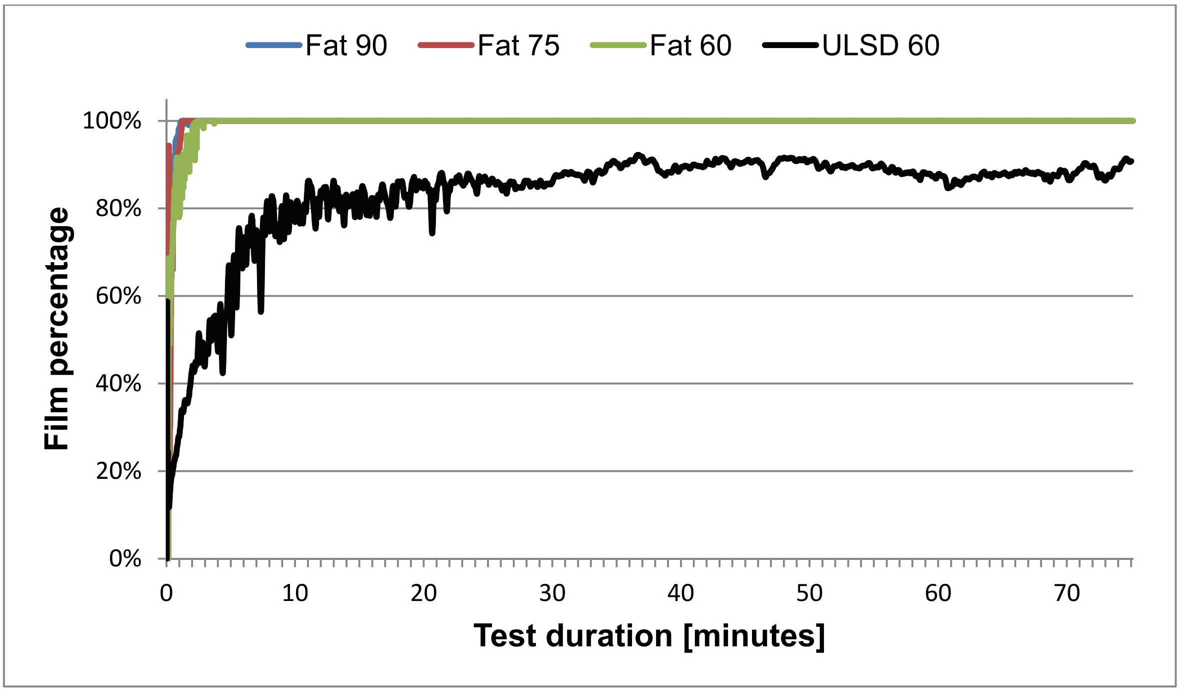

Figure 6.6 Film percentages for ULSD and animal fat at a range of temperatures.

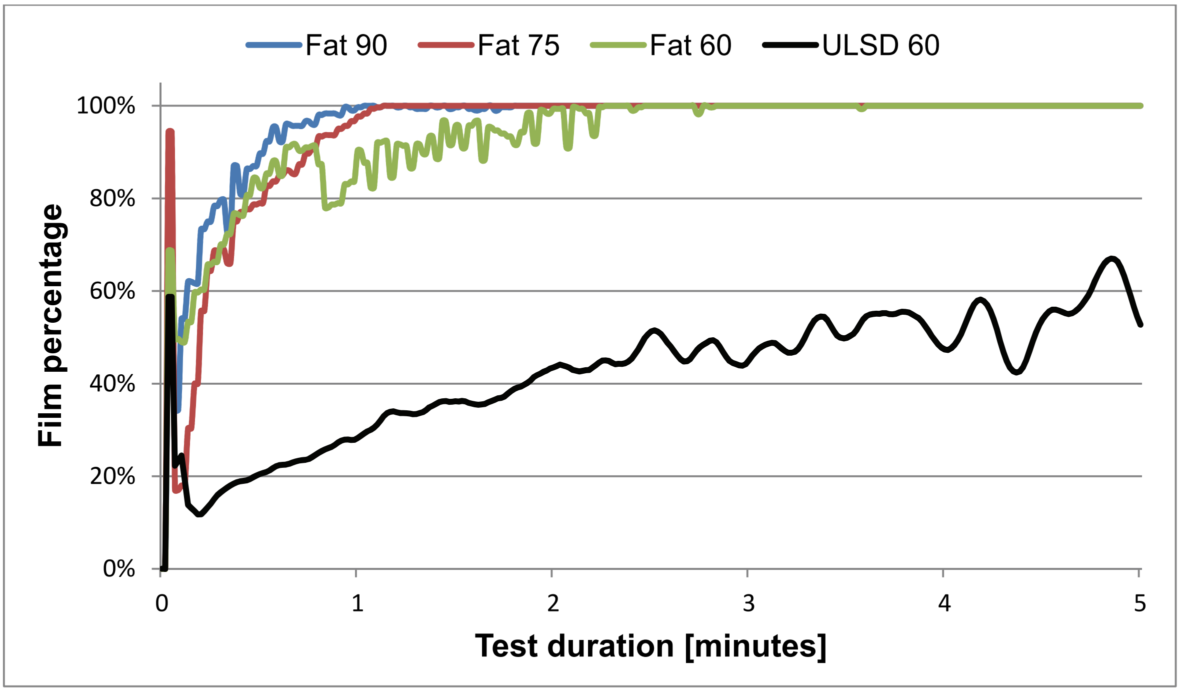

Figure 6.7 Film percentages for ULSD and animal fat at a range of temperatures - first 5 minutes of HFRR test

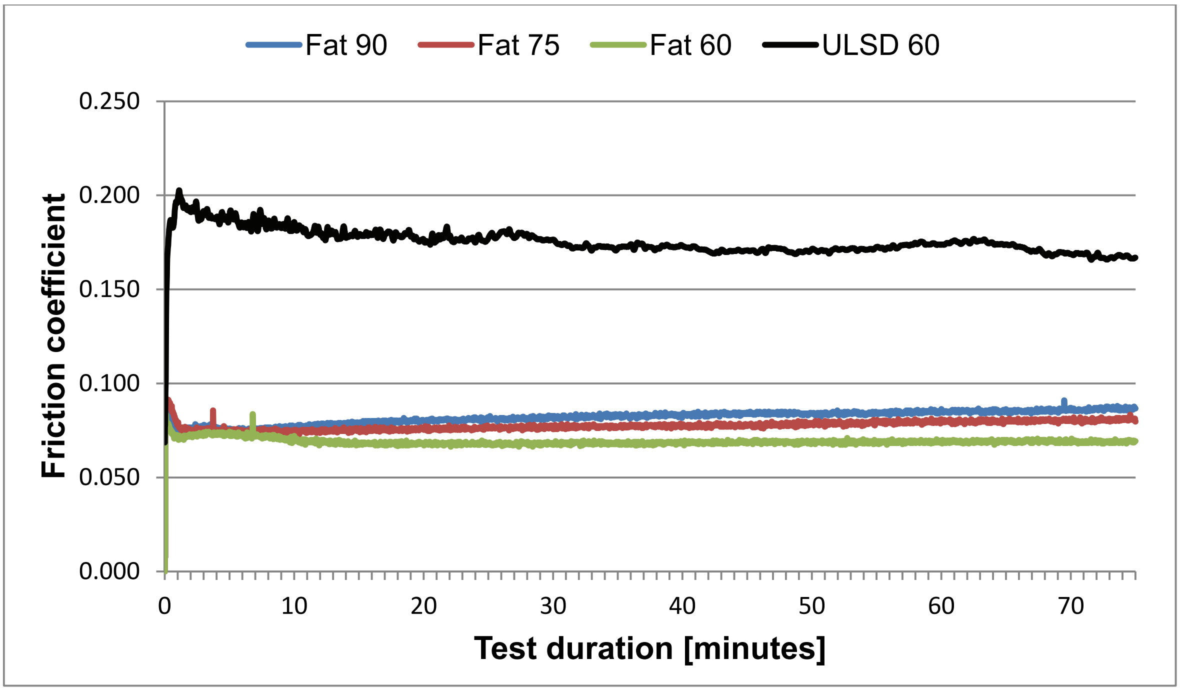

Figure 6.8 Friction coefficients for ULSD and animal fat at a range of temperatures

No significant impact of elevated temperature on lubricating properties has been detected. The wear scar diameter increased for the highest test point (90^{o}C) by 7 μm; the wear scar is shown in Figure 6.9. Friction coefficient increased by 0.013 indicating worse lubrication. HFRR test results are consistent with those expected from the literature review. Further investigation is required to find correlation between the HFRR test parameters and the working conditions of the injection equipment of stationary engines. Conducted tests proved that impurities present in fuel prepared for engine trials do not affect lubricating properties. Lack of significant increase of wear scar diameter for the high temperature test ensures that fuel pre heating, necessary for viscosity reduction, will not have a negative impact on fuel pumps' wear. This conclusion was verified by long term tests of fuel pumps which are described in section 8.3.

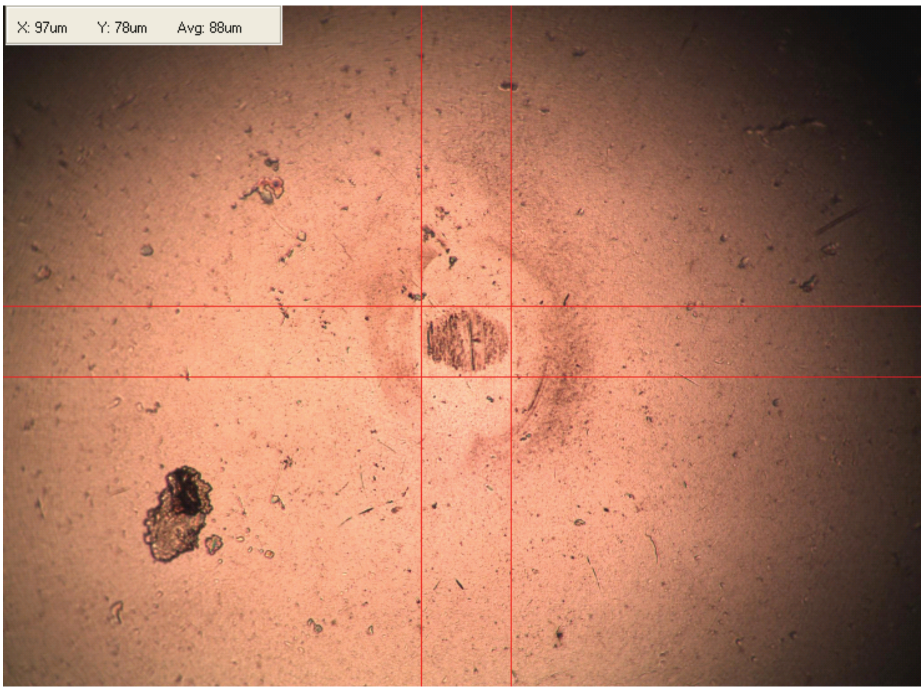

Figure 6.9 Wear scar captured by digital microscope; Animal Fat at 90^{o}C

6.1.3 Surface Tension

Fuel surface tension is one of the parameters that have significant impact on fuel atomisation. For hydrocarbon fuels it increases together with viscosity and density and decreases when temperature and pressure rises.

Surface tension has been measured with a bubble pressure tension meter at a range of temperatures, starting at 60°C going up to 90°C with intervals of 10°C. Diesel fuel (ULSD) has been tested at a temperature of 60°C. Each reading has been repeated three times – results are shown in Figure 6.10. The maximum bubble pressure method enables the recording of changes of fuel surface tension influenced by hydrodynamic effects (121). To compare results obtained with the bubble tension meter with data available in literature and obtained with static methods, long bubble lifetimes should be used. If results obtained for animal fat are considered, it can be seen that for bubble lifetimes longer than 5 seconds, measured surface tension remains constant. Significant impact of bubble lifetime on animal fat surface tension was recorded. It can be expected that hydrodynamic effects may have a negative impact on the atomisation process.

Pre heating of animal fat reduces its surface tension. Raising the temperature to 90°C lowers the value down to 25.8 [mN/m] from 31.0 [mN/m] recorded at 40°C. The surface tension is still considerably higher than for mineral fuel – 23.4 [mN/m].

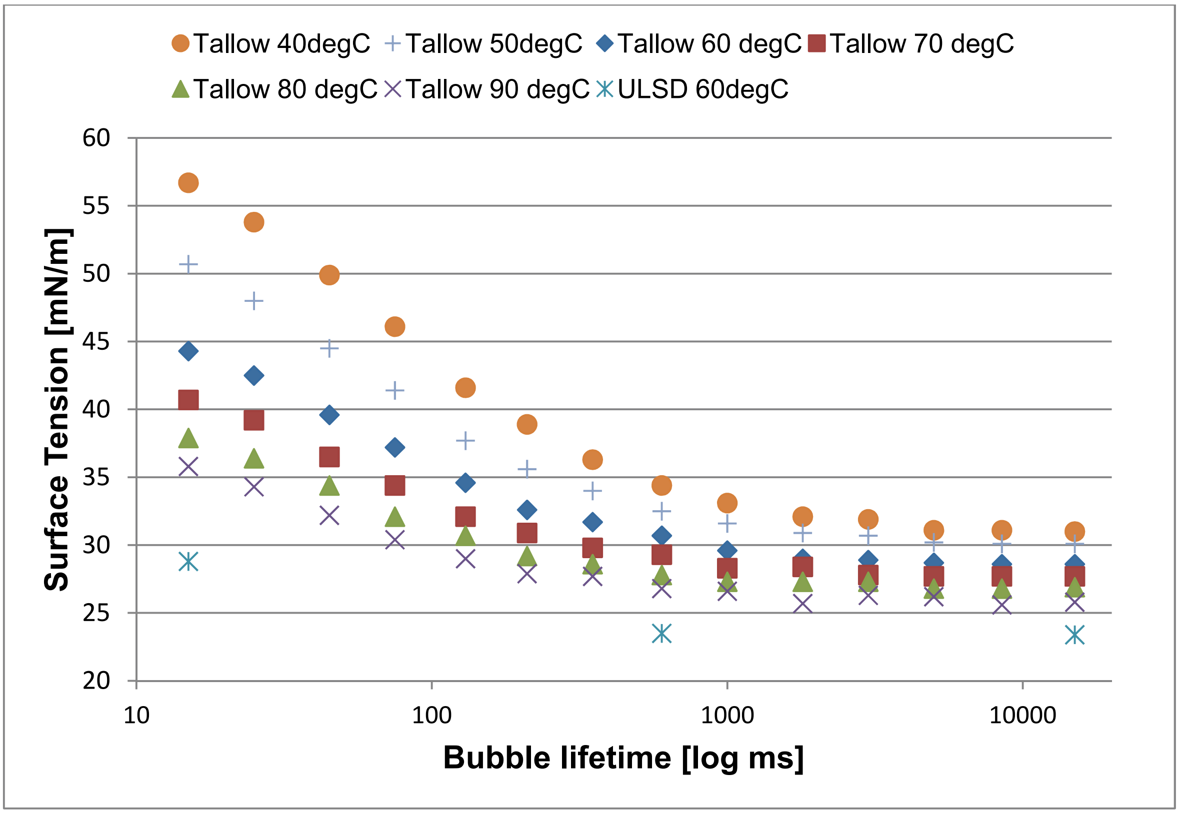

Figure 6.10 Comparison of surface tension measured at a range of temperatures for ULSD and animal fat

6.1.4 Density

A sample of animal fat was tested with accordance with ISO 12185 standard,- as the standard test temperature is 15°C, the fat was solid. To investigate the impact of elevated temperature, the sample was put in a water bath with a temperature control. Density was tested with a hydrometer at temperatures between 40 and 90°C with intervals of 10°C. Each test was repeated three times; calculated averages are reported and shown in Figure 6.11.

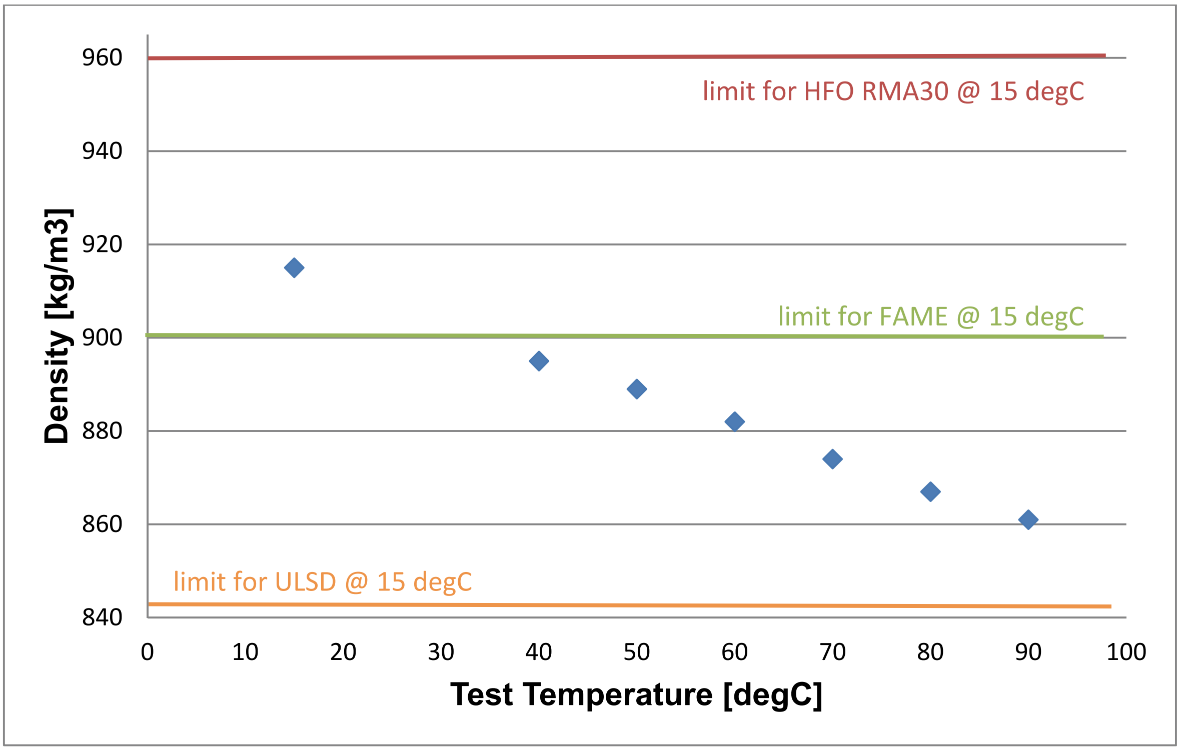

Figure 6.11 Impact of fat temperature on density

The obtained results present a linear trend where density decreases as temperature rises. The measured density at standard conditions (temperature 15ºC) – 915 kg/m^3 – is higher than the maximum density for diesel fuels (800 – 845 kg/m^3 (37)) and FAME (860 – 900 kg/m^3 (54)). The density is similar to values reported in the literature (4).

6.2 Maximum Allowable Long Term Storage Temperature

Animal fat is usually stored in a solid state and preheated before transportation or usage. In a small generating station with power below 1 MW, this regime does not seem to be practical as a multiple tank arrangement will increase installation and maintenance costs. For large plants, where fuel is transferred from storage tanks to daily service tanks, animal fat can possibly be stored for prolonged periods of time in a solid state. Due to its composition, tallow can easily oxidise (4). Nitrogen blanketing can be used to prevent fat oxidation. Multiple heating and cooling should be avoided due to potential fat polymerisation. In the case of the research plant described in this study, the size of the tank was determined to be approximately 20 tonnes. The tank would fulfil weekly fuel demand.

Rice et al. (141) and the host company staff reported the potential impact of the storage temperature on animal fat acidity. As acidity of the tested fuel is already high (please refer to Chapter 5) any potential cause for its increase should be avoided. It should be noted that both findings apply to fat of higher quality (Grade 2). Due to lack of literature data it was decided to investigate the impact of storage temperature on tallow acidity.

An experiment was set up at the hosting company. On that basis, a Final Year Project was established at The University of Birmingham – Mr Paik Seng Teoh conducted experiments and produced final report (142). Tested fuel samples were stored at a range of temperatures (ambient, 20, 60, 85, 105°C) for four weeks. Free fatty acid content was tested on a weekly basis.

The findings can be summarised as follows; animal fat storage in liquid form at elevated temperatures does not increase its acidity, refer to data given in Table 6.3 and graphically presented in Figure 6.12. An increase has been detected for room and ambient temperature – however, due to a large error margin, it cannot be regarded as significant.

Table 6.3 Animal fat acidity - long term storage

Temp (^{0}C)	Content of Free Fatty Acid (%)				
	Reference	*Week 1*	*Week 2*	*Week 3*	*Week 4*
Ambient	9.4	9.1	9.3	9.1	9.7
20	9.4	9.1	9.3	9.1	9.3
65	9.4	9.1	9.3	9.3	9.7
85	9.4	9.2	9.1	8.9	9.0
105	9.4	9.0	8.7	8.6	7.9

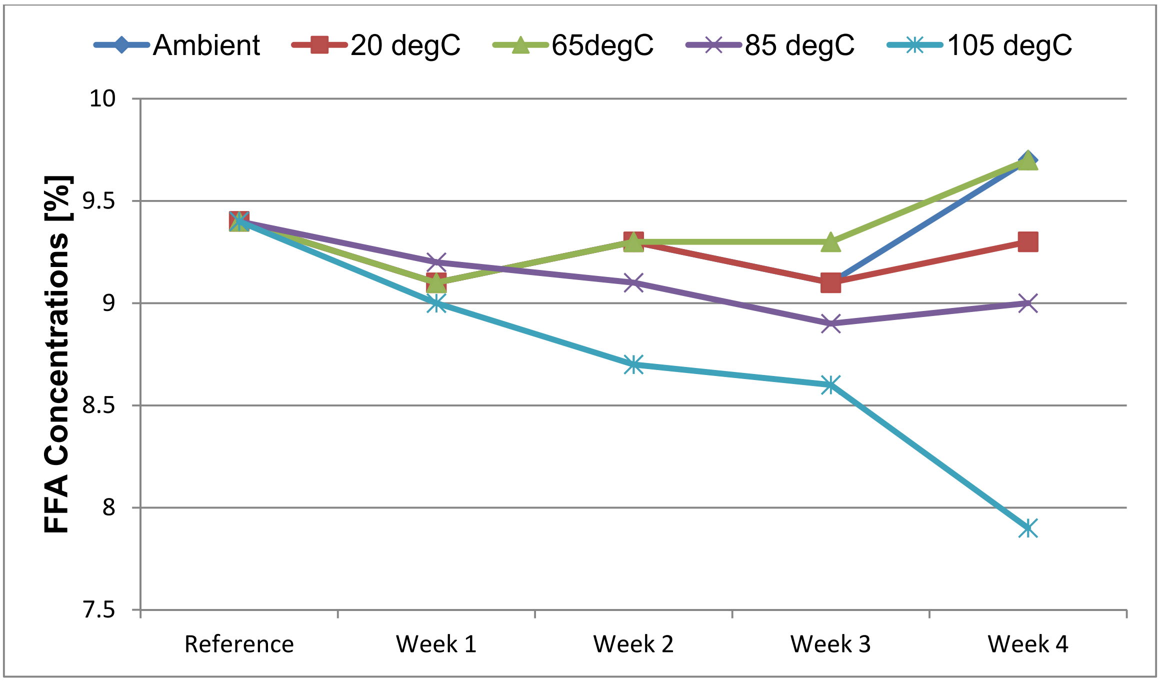

Figure 6.12 Free fatty acids content in animal fat stored for four weeks at various temperatures

6.3 Conclusions

The investigation presented in this chapter can be summarised as follows. Animal fat viscosity can be reduced by pre heating, however, even raising the temperature up to 90^{o}C does not bring the viscosity down to a level comparable with conventional diesel fuel. For lower temperatures, like 40^{o}C, when viscosity is high, a shear heating effect was observed. A linear relationship between fat temperature and its density was proved. The measured density is higher than conventional fuel and FAME, despite elevating the fuel temperature. A similar relationship was detected for fuel surface tension where pre heating reduces fat surface tension for various bubble lifetimes. The applied method – maximum bubble pressure – enabled detection of a significant difference between diesel fuel and fat, especially for short bubble lifetimes. Investigation of the hydrodynamic effect on fuel atomisation requires further analysis. Lubricating properties were tested at HFRR. Tests proved the excellent lubricity of animal fat at a range of temperatures. The impact of elevating the temperature up to 90^{o}C was studied and no significant change in the wear scar diameter was detected. Acidity dependence on storage temperature was another area investigated in this chapter. Results of tests performed as part of FYP proved that animal fat storage at higher temperatures does not have an impact on fuels' acidity.

Two samples of tallow were sent for more detailed analysis to external laboratories. Certificates of analysis form Appendix 3.

The general conclusion of the tests presented in this chapter is that pre heating can be used as a method of altering physical properties to match those of conventional fuel. It has to be noted that raising fuel temperature even above 90^{o}C does not result in achieving properties similar to ULSD. Animal fat should be treated as an alternative to heavy fuel oil (HFO). As no negative consequences of pre heating were detected, fat temperature of 80-90^{o}C was chosen for engine trials.

Chapter 7 **COMBUSTION PROCESS ANALYSIS**

7.1 Combustion Characteristics

Heat release analysis is conducted in a way proposed and described by Stone (143). Net heat release rate is calculated with the following equation:

$$\frac{dQ_n}{dCA} = \frac{k}{k-1} p \frac{dV}{dCA} + \frac{1}{k-1} V \frac{dp}{dCA}$$

where k is approximated to be the polytropic exponent of compression and expansion, for which a different value is calculated for the respective parts of the cycle. Presented results are averages obtained from 100 cycles.

The in-cylinder pressure and heat release rate patterns, accompanied by cylinder pressure rise rates for three rated loads from the engine operation on diesel and animal fat, are shown in Figures 47-52. A summary of combustion analysis is given in Table 7.1. Fossil diesel fuel has a higher calorific value than animal fat, thus the mass flow of animal fat was increased on average by 10-15 %, whereas volumetric flow rose by 5-7 %. The peak engine load for animal fat fuelling was reduced by 10%, as the fuel injection system was not modified to deliver higher quantities of fuels.

Figure 7.1 presents pressure and heat release patterns for diesel and tallow combustion at high load (75%). It can be seen that peak pressure for tallow combustion is higher and occurs approximately two crank angle degrees later than for diesel. The difference in heat release patterns is evident. Net heat release rate (NHRR) during the premixed combustion is higher for diesel compared with tallow. Mixing controlled combustion heat release tends to dominate in the case of tallow (period between -5 deg BTDC and 15 deg ATDC). The peak of the heat release rate for diesel was recorded at -9 deg BTDC and 5 deg ATDC for tallow. Late burn heat release is greater for diesel. Pressure increase for animal fat is slower than for mineral fuel (Figure 7.2).

Figure 7.3 shows a comparison of the combustion process at medium load (50%). Again, recorded peak pressure for tallow is higher and occurs later; however, the difference is not as evident as at high load. The peak of heat release for diesel was recorded at -7 deg BTDC and -8 deg BTDC for tallow. For medium load it was noted that pressure rise, although lower for animal fat, occurs earlier – it may indicate shorter ignition delay (Figure 7.4).

The comparison for combustion at low load (25%) is shown in Figure 7.5. Peak pressure for tallow is slightly lower but again delay was recorded. The peak of heat release for diesel was recorded at -6 deg BTDC and -7 deg BTDC for tallow.

Heat release rate patterns for the premixed combustion phase at various loads for both fuels, are shown in Figure 7.7. For all three loads compared, more heat was delivered in the premixed mode for diesel fuel. However, recorded patterns show that combustion begins earlier for tallow and local maxima were noted approximately one crank angle degree earlier. Ignition delay increases for lower loads. The shorter ignition delay in the case of tallow combustion can be explained by chemical composition. As tallow contains unsaturated fatty acids, a chemical reaction, such as carbon double bond cracking could have produced light volatile compounds (131). Shorter ignition delay for a high temperature of fat has been reported by Kumar (52). The larger amount of heat released in the diffusion combustion phase can be associated with multiple reasons. Firstly, polymerisation of triglyceride at the high temperature spray core, could have produced heavy low-volatility compounds (131). Heavy compounds are difficult to combust; therefore the process extends to the late phase. Physical properties of tallow, such as high viscosity (even at elevated temperature) and increased surface tension, affect the spray formation, leading to poor atomisation compared to diesel. Higher fuel viscosity can lead to a decrease in leaks in fuel pumps (34). Therefore it can be assumed than injection commences earlier. In the case of animal fat usage, diffusion combustion phase is the predominant form of combustion process. Lower heat release rate during the premixed combustion phase can be explained by limited availability of combustible mixture due to the higher viscosity and surface tension of animal fat. Therefore more time is required for the fuel droplet to evaporate and combust. It results in peak pressure occurrence delay by 1-2 degCA for animal fat combustion. The coefficient of variance for IMEP, regarded to be a combustion stability evaluation criterion, is lower than 5% for high and medium loads for both fuels. At low load combustion stability is worse, most likely due to poor atomisation of animal fat. Lower calorific value of tallow requires more fuel to be injected per cycle through an unmodified injection system.

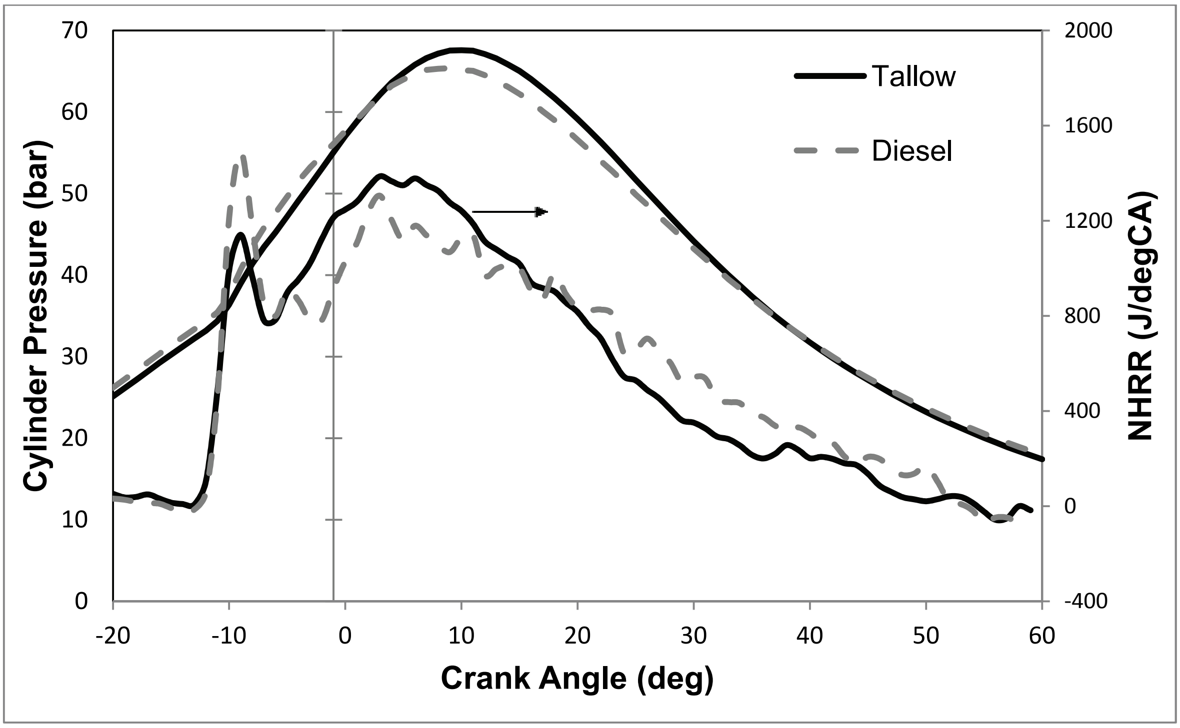

Figure 7.1 Combustion process comparison – 75% load

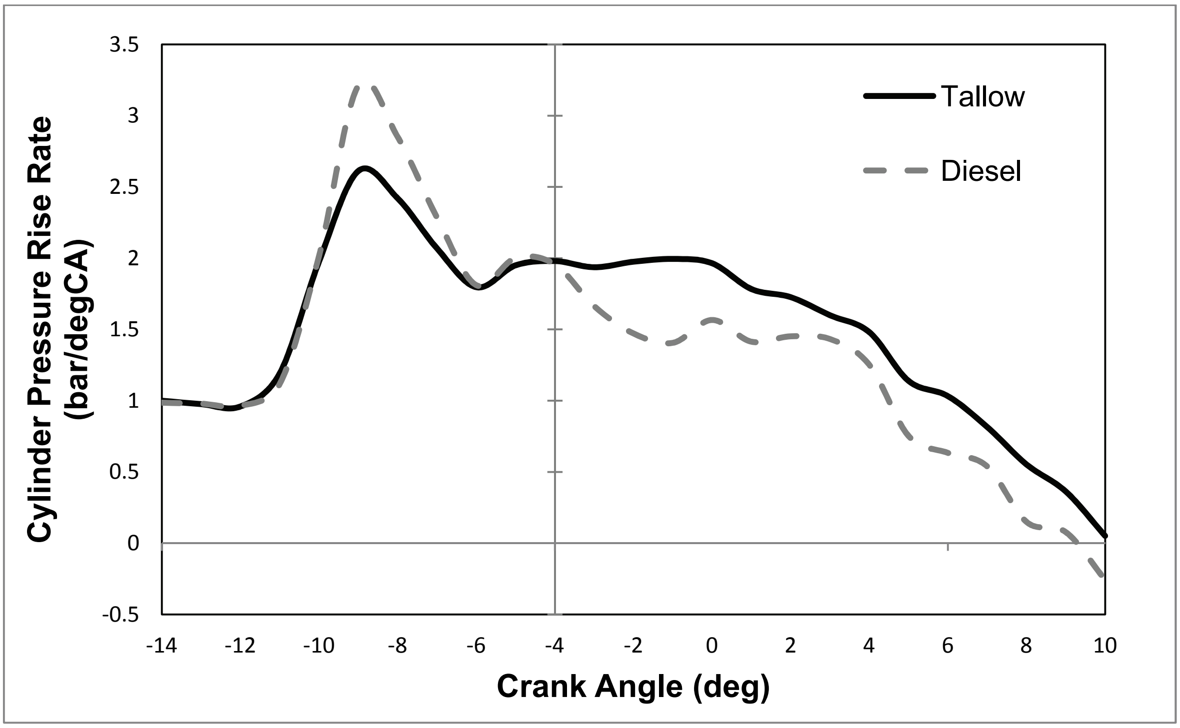

Figure 7.2 Cylinder pressure rise rate – 75% load

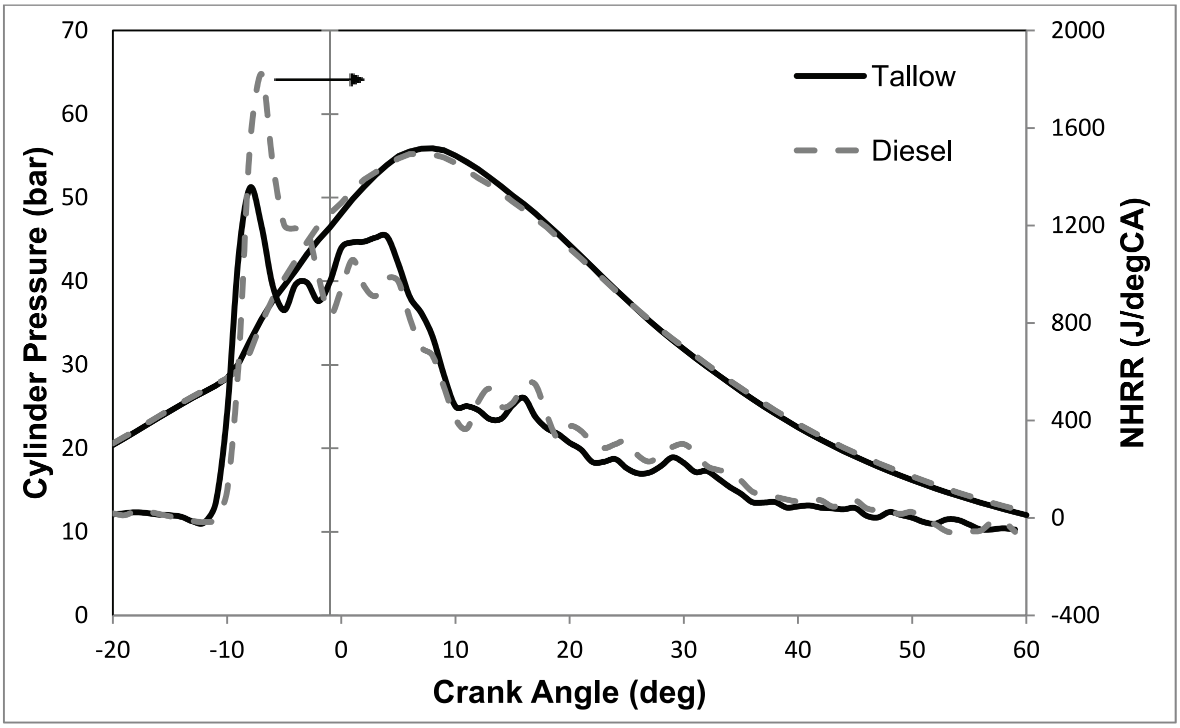

Figure 7.3 Combustion process comparison - 50% load

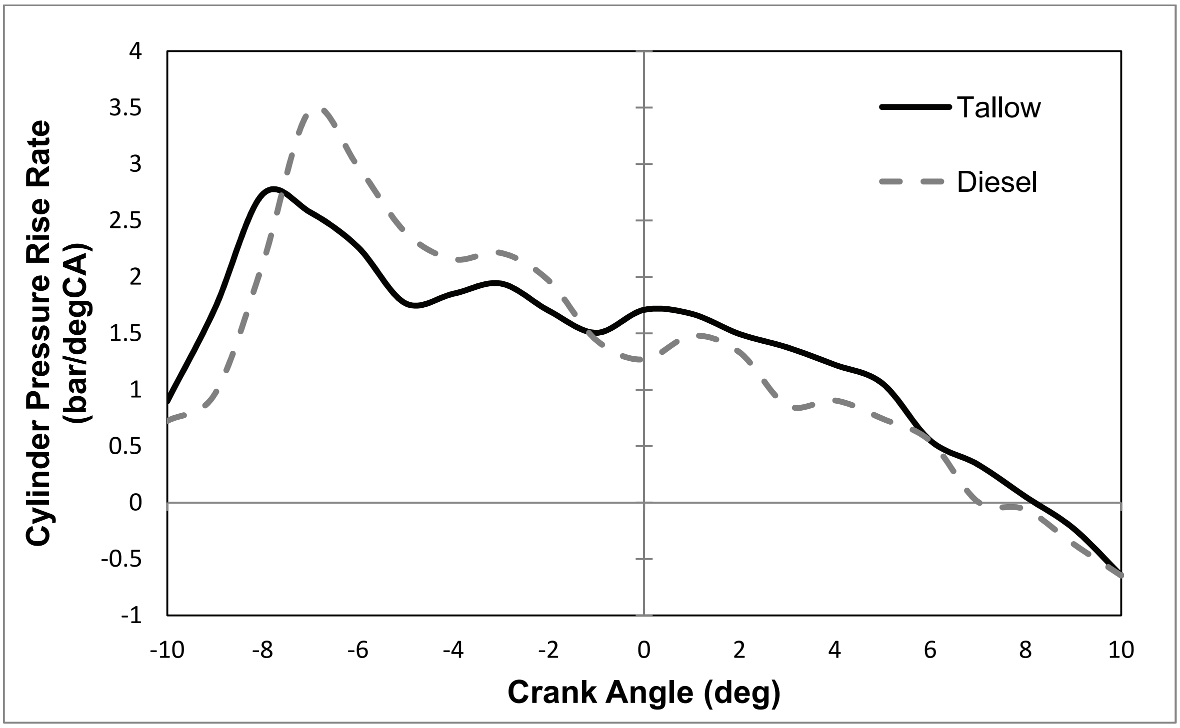

Figure 7.4 Cylinder pressure rise rate - 50% load

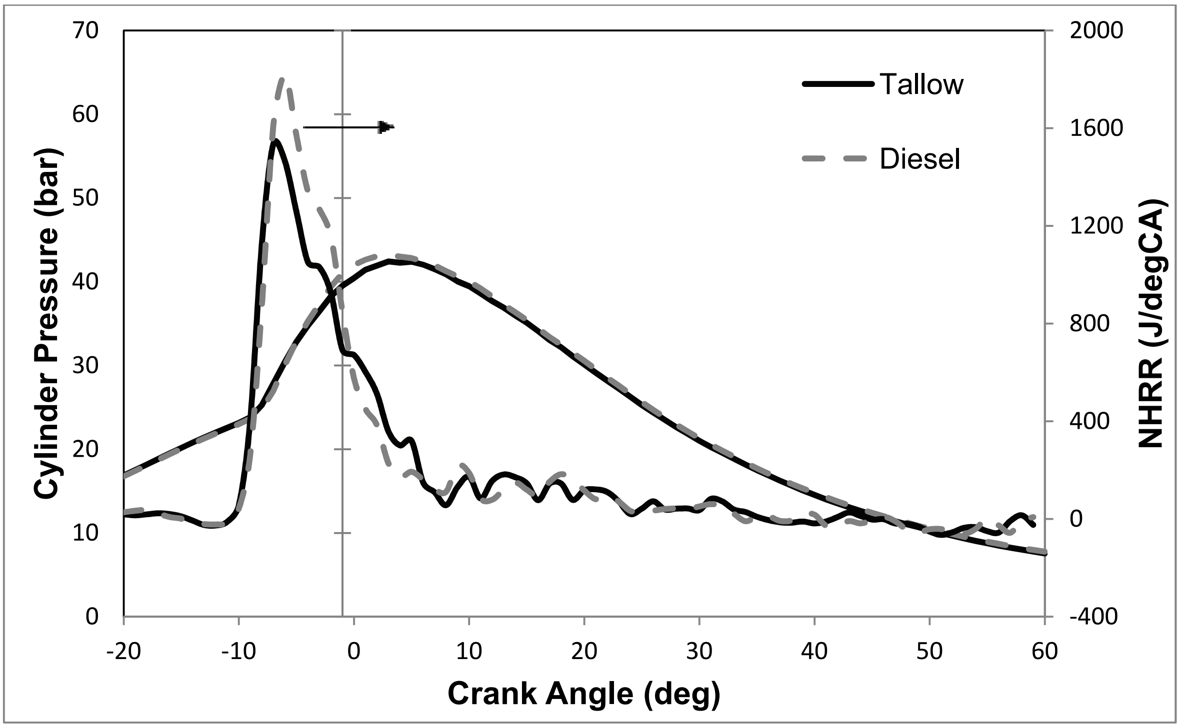

Figure 7.5 Combustion process comparison - 25% load

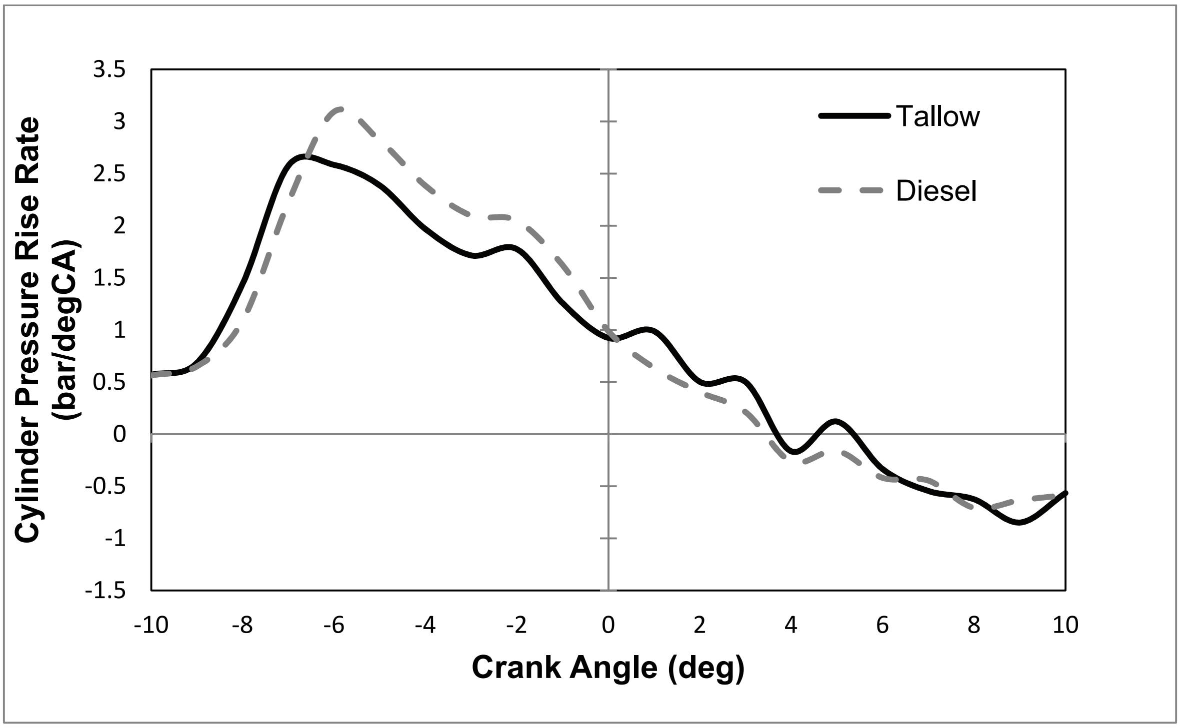

Figure 7.6 Cylinder pressure rise rate - 25% load

Table 7.1 Combustion analysis results

Parameter	Unit	Test condition					
		D75	T75	D50	T50	D25	T25
Ignition delay	deg CA	12	12	12	12	13	13
25% HR @	deg CA	0	0	-4	-4	-6	-6
50% HR @	deg CA	10	8	3	3	-3	-3
95% HR @	deg CA	40	36	32	30	19	20
Total duration (Injection -95% MFB)	deg CA	61	57	53	51	40	41
Avg. PP	bar	64.5	66.7	54.5	55.0	42.5	41.6
Avg. IP	bar	102.1	103.0	69.1	67.3	36.1	34.6
Avg. IMEP	bar	10.1	10.2	6.8	6.6	3.6	3.4
COV PP	%	2.7	2.2	1.8	2.1	2.8	1.5
COV IP	%	2.0	1.2	1.8	2.5	1.7	5.1
COV IMEP	%	2.0	1.2	1.8	2.5	1.7	5.1
Fuel Mass Flow	kg/h	145	160	100	110	60	65
Fuel Vol. Flow	l/h	175	185	120	125	70	75
Where: HR – heat released, PP – peak pressure, IP – indicated pressure, IMEP - indicated mean effective pressure, COV – coefficient of variance							

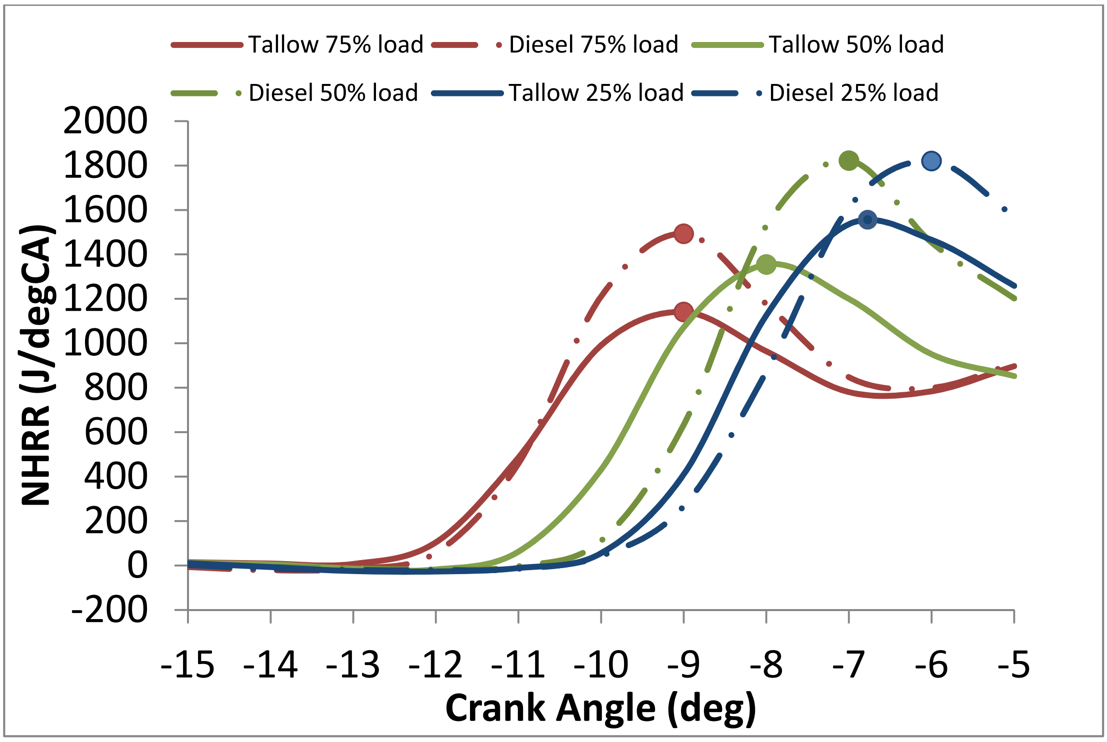

Figure 7.7 Premixed combustion net heat release (NHRR) patterns for both tested fuels at three tested loads. Local maxima for premixed combustion phase are marked.

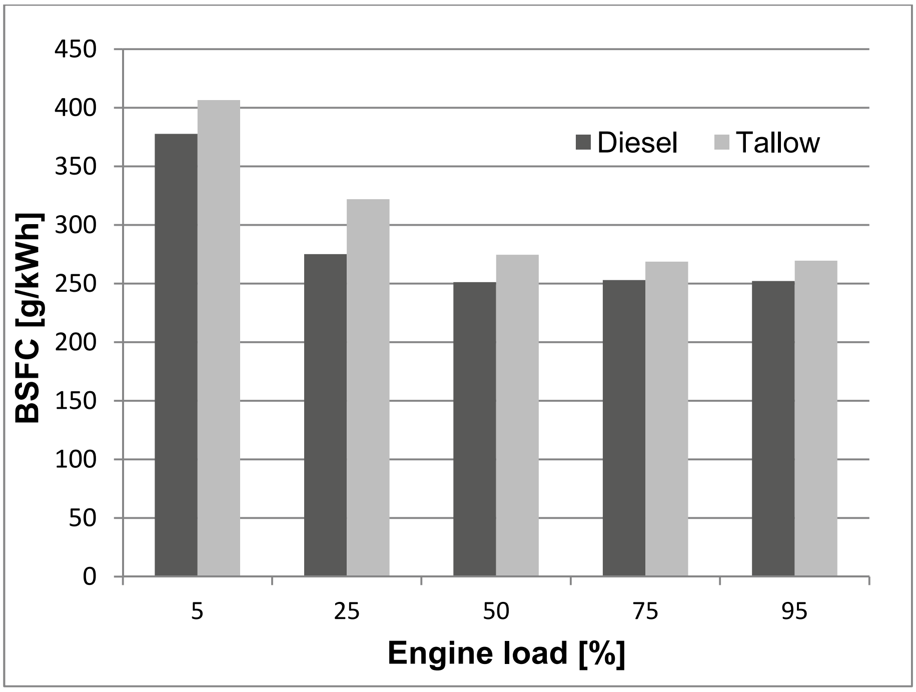

Figure 7.8 Effect of fuel on the specific fuel consumption (not adjusted for calorific value)

Figure 7.8 shows the variation of the specific fuel consumption for the tested engine when fuelled with tallow and diesel. Tallow consumption is higher than diesel consumption by 10 – 15%. Specific fuel consumption remains constant at loads varying between 50 and 95 per cent for both tested fuels. Table 7.1 contains a comparison of fuel volumetric and mass flows.

Fuel consumption has been recorded during the trial. Tallow consumption was recorded by a mass flow meter with data acquisition module and software. The permit for the trial specified a limit on tallow throughput to be $\dot{Q}_{\max} = 270\left[{}^{kg}\!/_{h}\right]$. Prior to starting the engine and switching to tallow, the fuel supply system permeability was checked by draining for a few seconds. It resulted in high fuel flow spikes being recorded by a flow meter. In Figure 7.9 typical daily fuel consumption data is presented together with a fuel temperature curve. A weekly tallow consumption graph is shown in Figure 7.10.

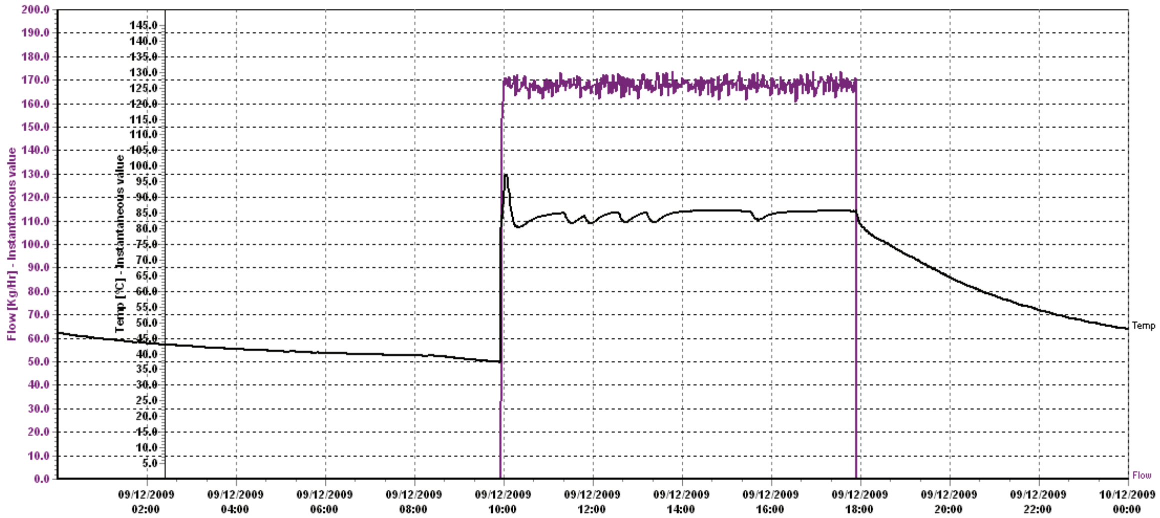

Figure 7.9 Daily fuel consumption curve

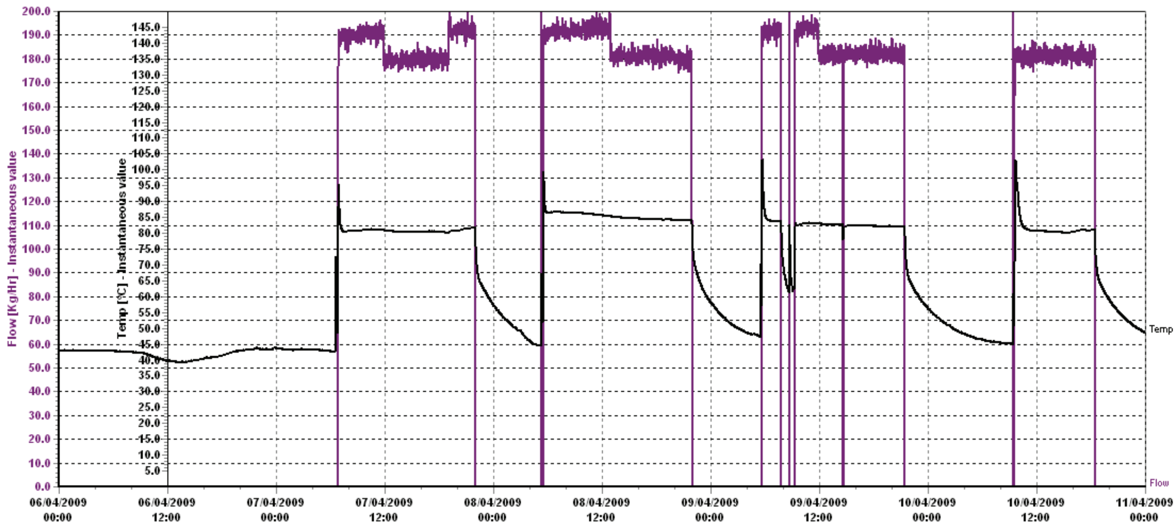

Figure 7.10 Weekly fuel consumption curve

7.2 Emissions Comparison

Engine emissions were measured for three loads and two tested fuels. Figure 7.11 contains a comparison of emissions for the high load operation. One of the main advantages of animal fat is its very low sulphur content resulting in sulphur dioxide emissions complying with WID standards for all three tested loads. It eliminates the necessity of a SO_2 abatement system.

As animal fat does not contain nitrogen, all nitrogen oxides are formed at high temperature in the combustion chamber. Higher NO_x emissions corresponds with higher cylinder peak pressure and a prolonged combustion process (Figure 7.1). Higher exhaust temperature for animal fat combustion has been recorded. Oxygen content in the animal fat improves the combustion process, as a result, emissions of carbon monoxide and unburned hydrocarbons are considerably lower.

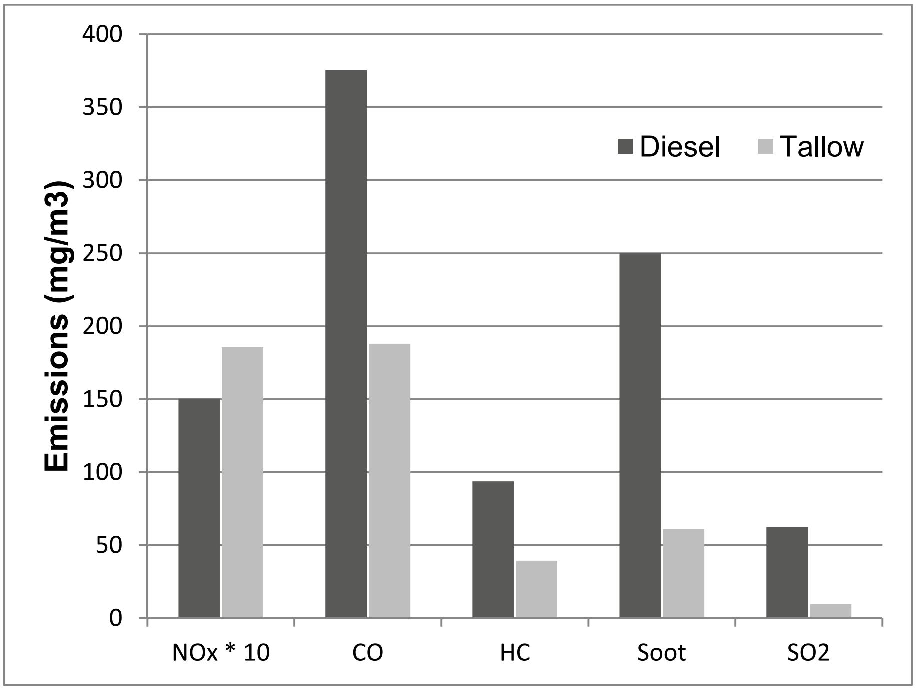

Figure 7.11 Effect of fuel type on the engine exhaust emissions - 75% load

For the medium load, nitrogen oxides emissions are higher for animal fat (Figure 7.12), however, the measured difference is not as significant as for the high load. Carbon monoxide emissions are higher for animal fat. A similar observation was made for the low load operation, but the differences in emissions' levels are more significant. For the low load operation (Figure 7.13) nitrogen oxides emissions are lower due to lower peak pressure and lower temperature for fat combustion.

Increasing formation of carbon monoxide, accompanied by descending concentration of nitrogen oxides for tallow combustion at the medium and low load operation, can be associated with multiple reasons. Firstly, the physical properties of tallow cause poor atomization, despite the presence of oxygen in the fuel molecule. Secondly, it can be explained by the characteristics and efficiency of the turbocharger. The Ruston 6AR is equipped with a Napier turbocharger with a constant geometry setting optimised for high load operation. Therefore cylinder filling and scavenging is worse for low loads. Finally, implications of the engine design type may affect the atomization process and tallow combustion. For a direct injection engine with a low compression ratio, the air temperature before start of the injection will be lower than for high loads.

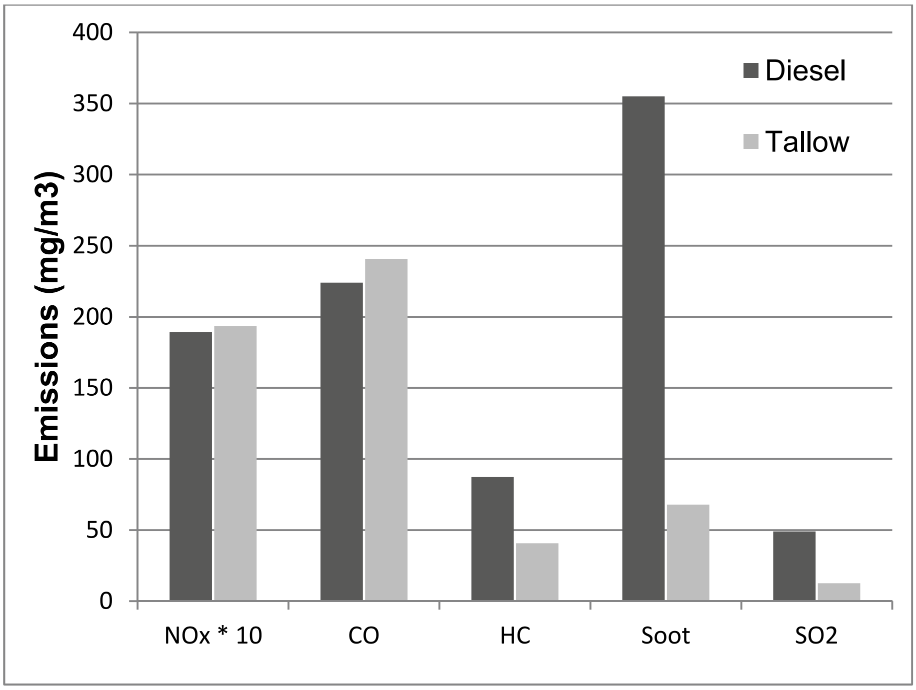

Figure 7.12 Effect of fuel type on the engine exhaust emissions - 50% load

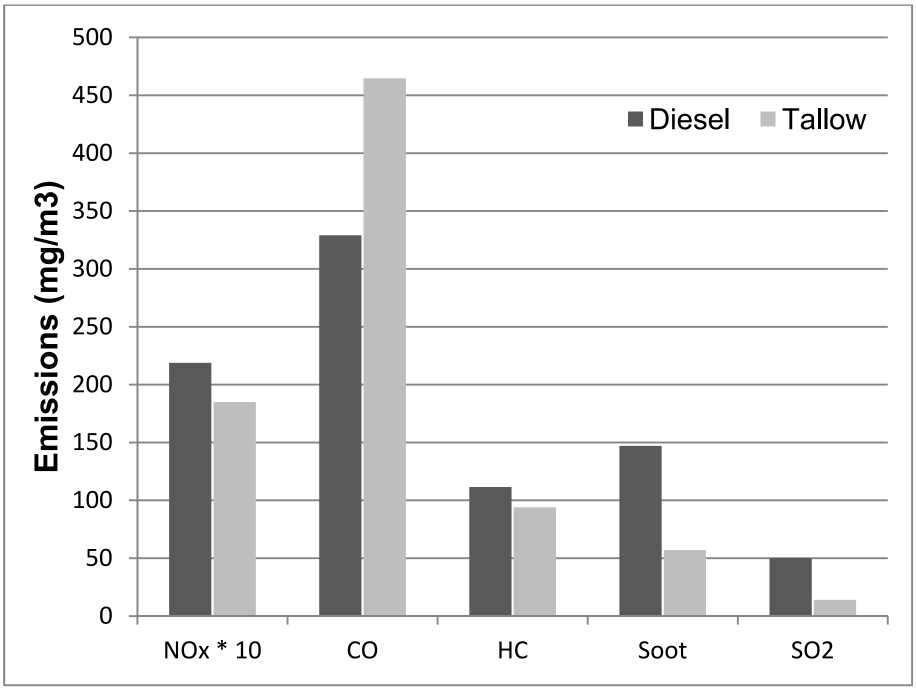

Figure 7.13 Effect of fuel type on the engine exhaust emissions - 25% load

7.3 Use of EGR

The effects of various EGR concentrations on tallow combustion have been tested, with and without water injection. Results for the standard EGR configuration combustion analysis are given in Figure 7.14. As expected, peak pressure decreases with increased proportions of recirculated gases. The addition of exhaust gas prolongs the duration of the combustion process. For low recirculation rates there is no significant impact on the combustion process. Figure 7.15 shows the impact of cooled exhaust gas recirculation on the tallow combustion process. Addition of more than 20% of EGR results in a significant drop in peak pressure.

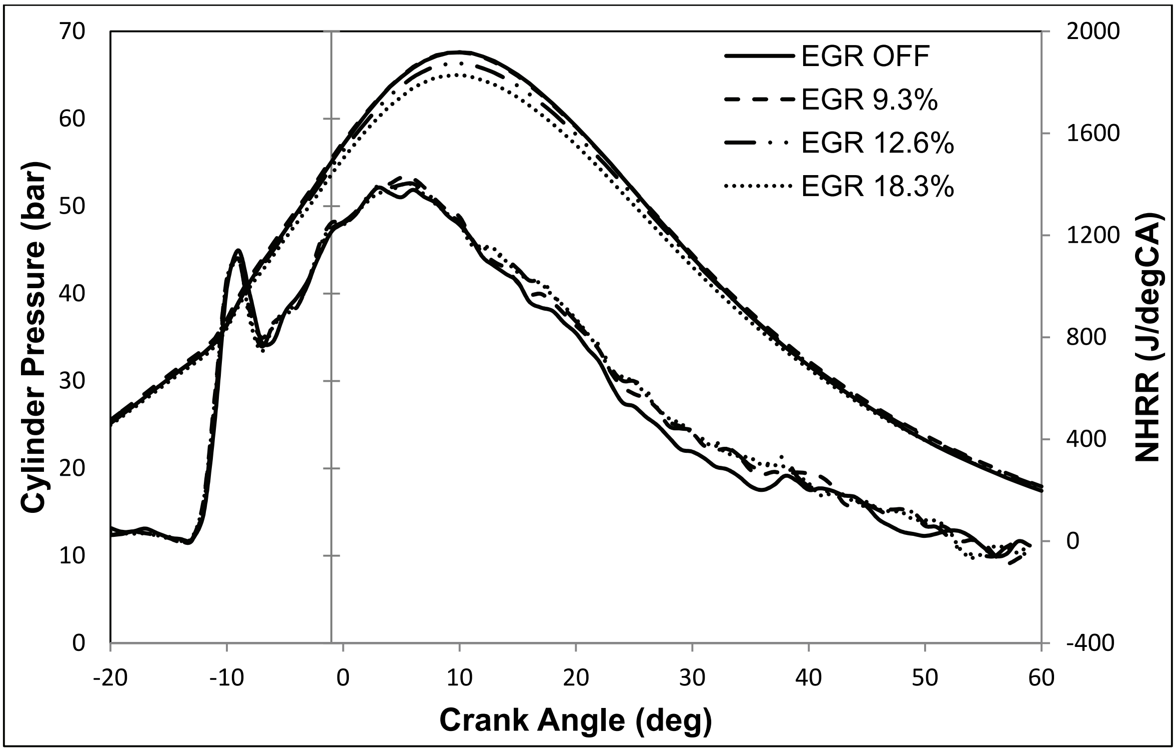

Figure 7.14 Impact of the EGR on tallow combustion

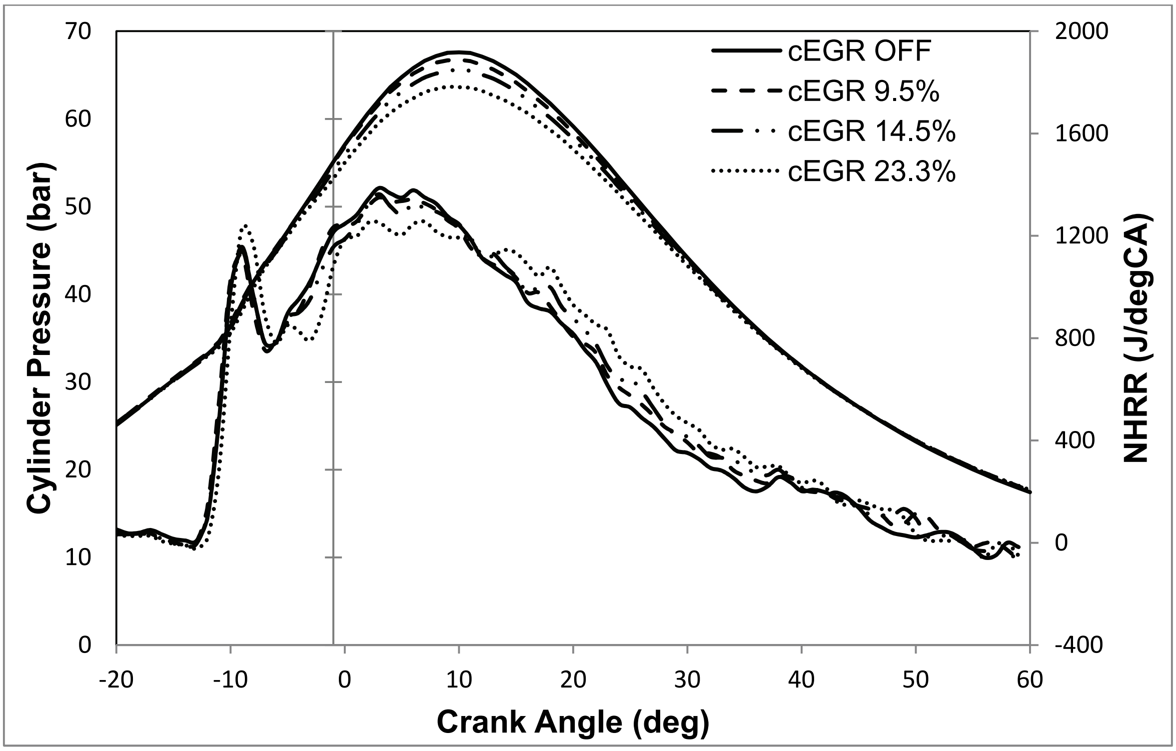

Figure 7.15 Impact of the cooled EGR (cEGR) on tallow combustion

Figure 7.16 presents an emissions' comparison for various EGR concentrations. As expected, increasing the recirculation rate results in an increase of carbon monoxide. For cooled EGR, (Figure 7.17), more gases can be recirculated without an increase in exhaust temperature; better NO_x reduction has been achieved. Emission of nitrogen oxides has been reduced by 75%, below the required 450 mg/m^3, compared with the 0% EGR case. At the same time, carbon monoxide emission increased by 280%, and soot emission increased by 300%. It should be noted that the reference level for animal fat combustion is already low compared to fossil fuels. However, hydrocarbons emission decreased by 25%. This can be explained by the scrubbing effect of water sprayed into the exhaust and spun in the cyclone chamber. Visible carbon containing deposits were found in the excess water. Addition of water cooling and gas humidification improved the efficiency of the NO_x reduction process (Figure 7.18). EGR concentrations higher than 18% were not achieved without cooling, due to an increase of exhaust temperature above 450°C and charge air temperature above 50°C. Gas cooling and water injection enabled the desired NO_x reduction efficiency, at the same time charge air temperature did not increase above 40°C and exhaust temperature was stable at a 450°C level. Specific fuel consumption increased by 7%. The results obtained are consistent with those obtained on a low speed two stroke engine by MAN Diesel (84).

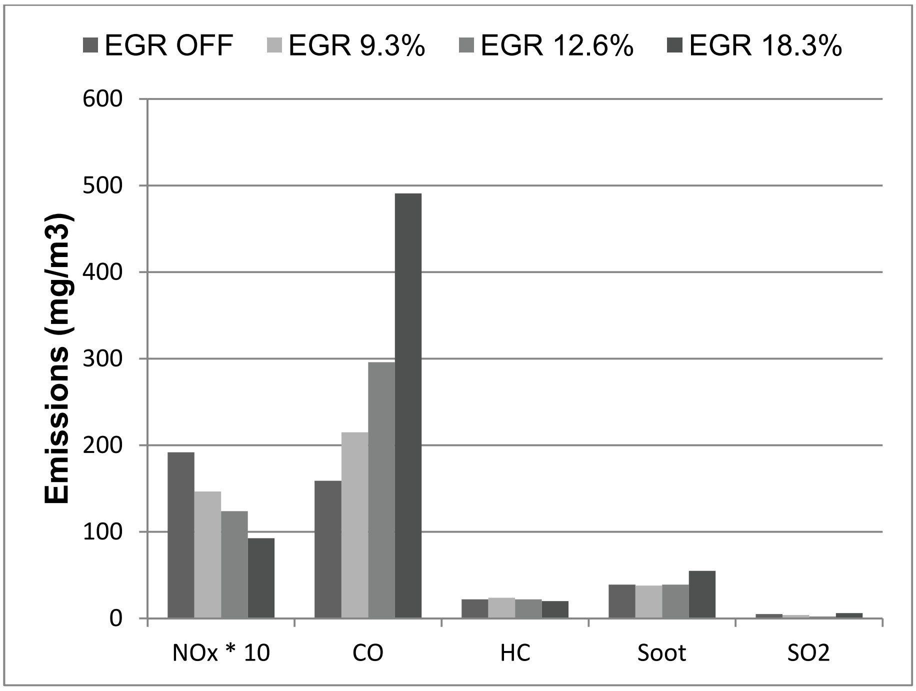

Figure 7.16 Impact of EGR concentration on engine emissions when fuelled with tallow - 75% load

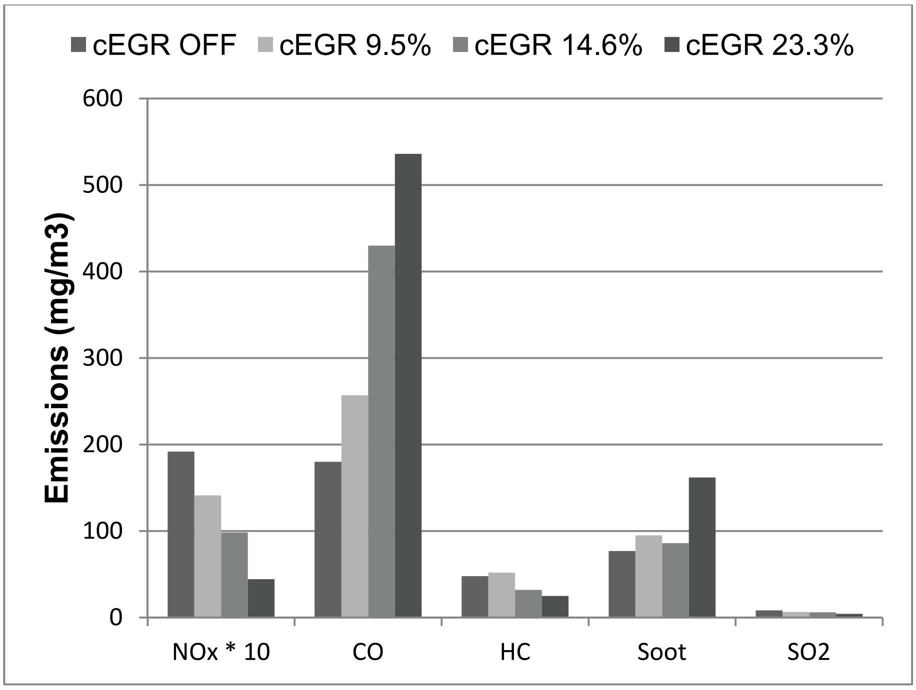

Figure 7.17 Impact of cooled EGR concentration on engine emissions when fuelled with tallow - 75% load

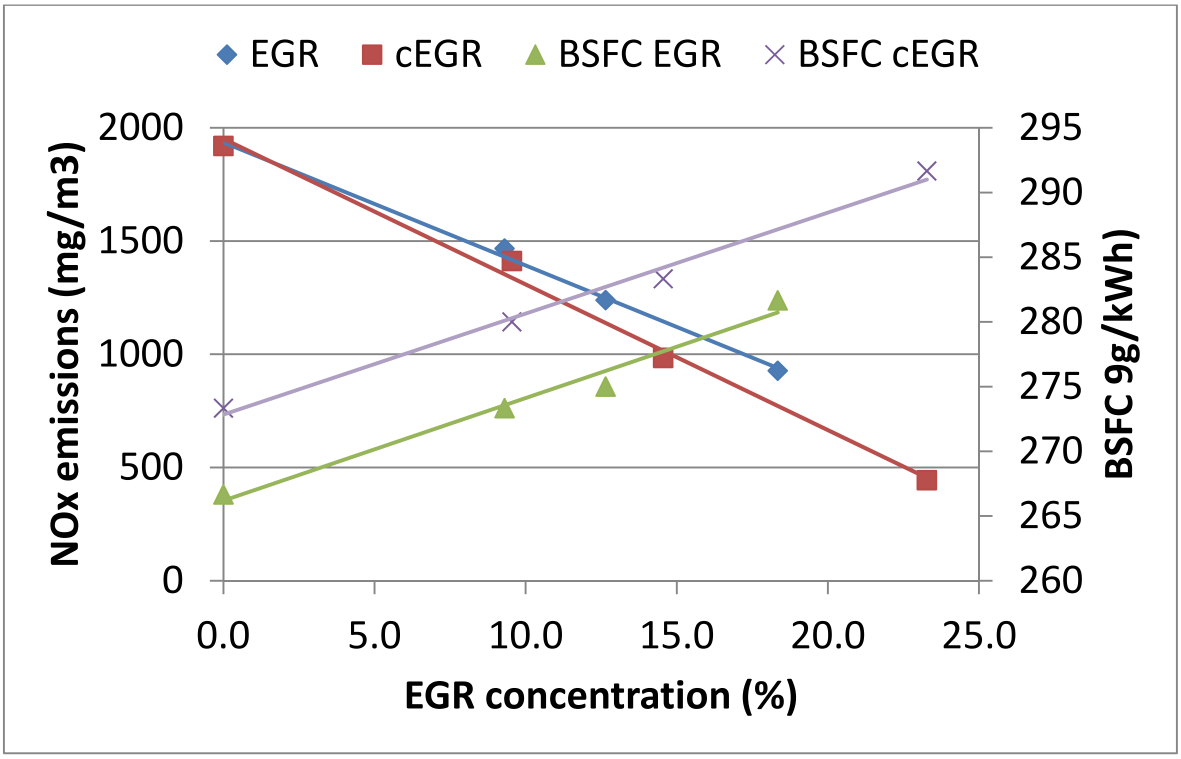

Figure 7.18 Effect of EGR and cEGR concentration on nitrogen oxides reduction potential and fuel consumption at 75% load

7.4 Conclusions

Physical properties of animal fat such as density, viscosity and surface tension are much higher compared to mineral fuel. Preheating was chosen as a way of bringing them closer to values typical for light fossil fuels. However, the engine fuel supply system must be capable of handling higher viscosity fuels, such as HFO or CFO. In the case of a supply system conversion, larger fuel pumps have to be implemented due to the lower calorific value of fat requiring a higher mass flow. These results are consistent with findings reported by Gotfredsen (42).

Combustion of animal fat results in achieving higher peak pressures; emissions of NO_x increase as a result. The ignition delay was shorter for animal fat; the difference is evident for low load operation. Pressure rise rate for the animal fat was lower for all tested loads. Specific fuel consumption for the tested engine increased when fuelled with tallow. Animal fat contains oxygen, it leads to a more complete oxidation process, as a result emissions of carbon monoxide, hydrocarbons and soot are considerably lower at high loads. At medium and low load conditions the negative effect of the physical properties of the fuel on fuel atomization seem to prevail the benefits of the oxygen content, resulting in increased CO emissions. Emissions of sulphur dioxide were very low, complying with limits set by the local authority. Application of animal fat as fuel eliminates a necessity of SO_2 abatement system.

As described in the literature review - Table 2.7 - increased emissions of CO and HC accompanied with lower NO_x emissions for animal fat were reported. It has to be noted that the described tests were conducted at a relatively low fuel temperature – 60 ºC. Considering the fact that animal fat temperature for the current test was set above 80 ºC, obtained results seem to confirm the positive effect of higher triacylglycerol supply temperature on the combustion characteristics and emissions.

The suitability of exhaust gas recirculation as a nitrogen oxides' reduction method for stationary engines operating at high loads has been tested. Introduction of gas cooling and humidification increased the method's efficiency enabling a 75% reduction in NO_x emissions.

The impact of the reported higher fuel consumption on generating station feasibility has to be considered. Combining the effect of lowering oxygen concentration by exhaust gas recirculation with the presence of water vapour, can be considered as a feasible method of NO_x abatement, even for stationary engines designed to operate on high loads for prolonged periods of time.

Chapter 8 LONG TERM EFFECT OF USING TALLOW

8.1 Introduction

This chapter presents the consequences of using neat animal fat in a medium speed, four stroke diesel engine. The impact on the fuel supply system, injectors and lubricating oil is described. A preliminary assessment of the possible impact of animal fat on the fuel supply system has been conducted by analysis of the lubricating properties. Lubricity has been measured at an HFRR (High Frequency Reciprocating Rig). As high acidity of fuel was detected it was decided to verify the capability of the upgraded lubricating oil to withstand an operation of the engine when fuelled with animal fat. Two lubricating oils were compared.

8.2 Lubricating Oil

8.2.1 Requirements for Lubricating Oils Used in Generating Sets

A modern engine needs a wide range of oil qualities. Oil acts in the following processes:

- Separation of moving surfaces with oil film
- Engine cooling by combustion and friction heat dissipation
- Combustion chamber sealing
- Cleaning the engine from deposits.

Juoperi (144) listed demands for medium-speed diesel engine lubricating oils:

- Excellent thermal stability
- Excellent oxidation stability
- Effective capability to neutralize acid compounds entering lube oil
- Slow viscosity increase rate (influence of insoluble matter and oxidation)
- Excellent water shedding properties (removal of water also from used lube oil)
- Excellent compatibility with fuels preventing:
    - deposit formation into piston cooling gallery
    - deposit formation on piston ring groove area
    - black sludge / deposit formation on cold engine component surfaces
    - sticking of fuel injection pumps

8.2.2 Testing Programme

Two types of lubricating oils were used in the research plant described in paragraph 4.2. The oil properties are given in Table 8.1. The main purpose of this part of the research was to verify what kind of impact on oil properties is caused by the usage of animal fat as a fuel. The first oil, Fuchs Titan 30 – SAE 30 grade, complies with the engine manufacturer's recommendations. After 1000h of operation the oil grade was altered to Fuchs Titan Marine 30, which can be characterised by higher TBN and increased detergency. The oil type was chosen after the fuel properties' testing, described in Chapter 5, which showed a very high TAN of tallow, reaching even 70 mgKOH/g fuel.

Table 8.1 Lubricating oil properties (145, 146)

Characteristics	Unit	Test Method	Titan TXE 30 Oil	Titan Marine 30 Oil
SAE	-	-	30	30
Kinematic Viscosity				
@100ºC	mm^2/s	IP 71	11.2	12.3
@40ºC			96	107
Viscosity Index			102	106
Flash point	ºC	IP34	220	210
TBN	mg KOH/g	-		14
Sulphated ash	%wt.	-		1.7
Specific gravity at 20ºC	kg/dm^3	IP160	0.893	0.890
Pour Point	ºC	IP15	-20	-15

The oil was sampled directly from the sump by a vacuum sampling pump and then tested against a set of criteria, including viscosity, soot content and chemical composition. The testing interval was set to be 100 hours or 1 month. The engine lubricating system, shown in Figure 8.1, has been modified to avoid the possibility of oil contamination with fuel that may leak from the fuel pumps' supply lines. The oil lubricating rocker gear, delivered by pipe No. 22 and returning via pipe No. 21 was originally going back to the sump through the drip tray. In the modified arrangement this oil was diverted to the waste oil tank.

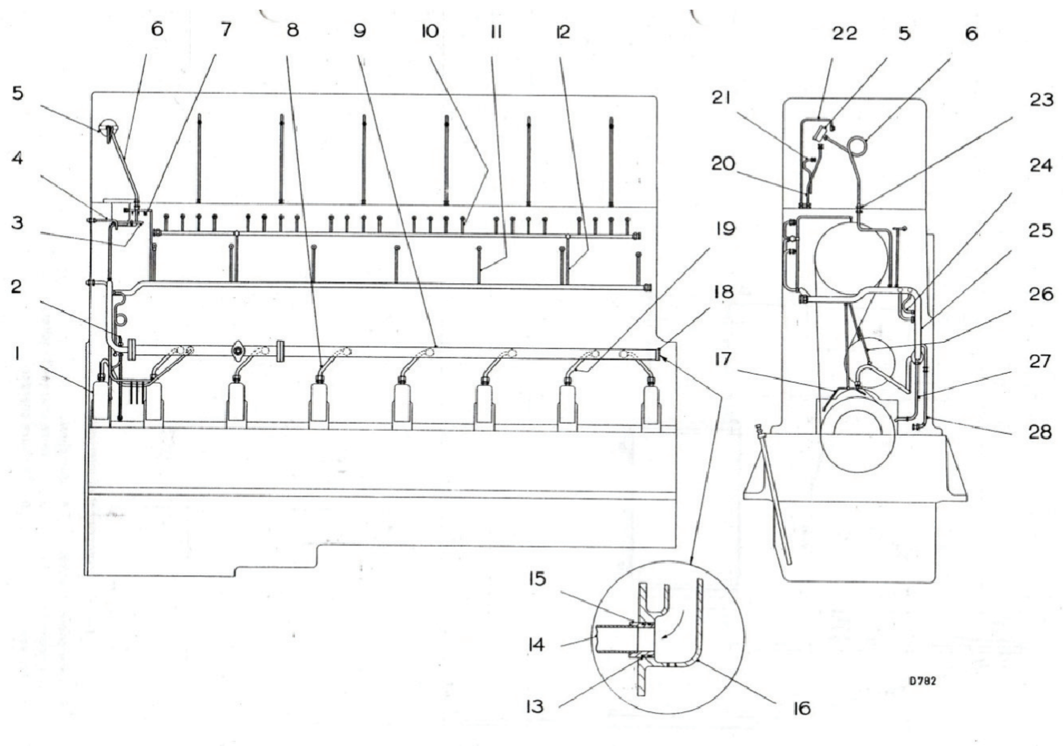

Figure 8.1 Ruston 6AR lubricating system

8.2.3 Results

Data collected during the trials are given in Table 8.2. The table is accompanied by two graphs showing changes in oil viscosity (Figure 8.2) and iron concentration (Figure 8.3). Increasing viscosity can indicate fuel contamination, high iron content may be caused by excessive engine wear.

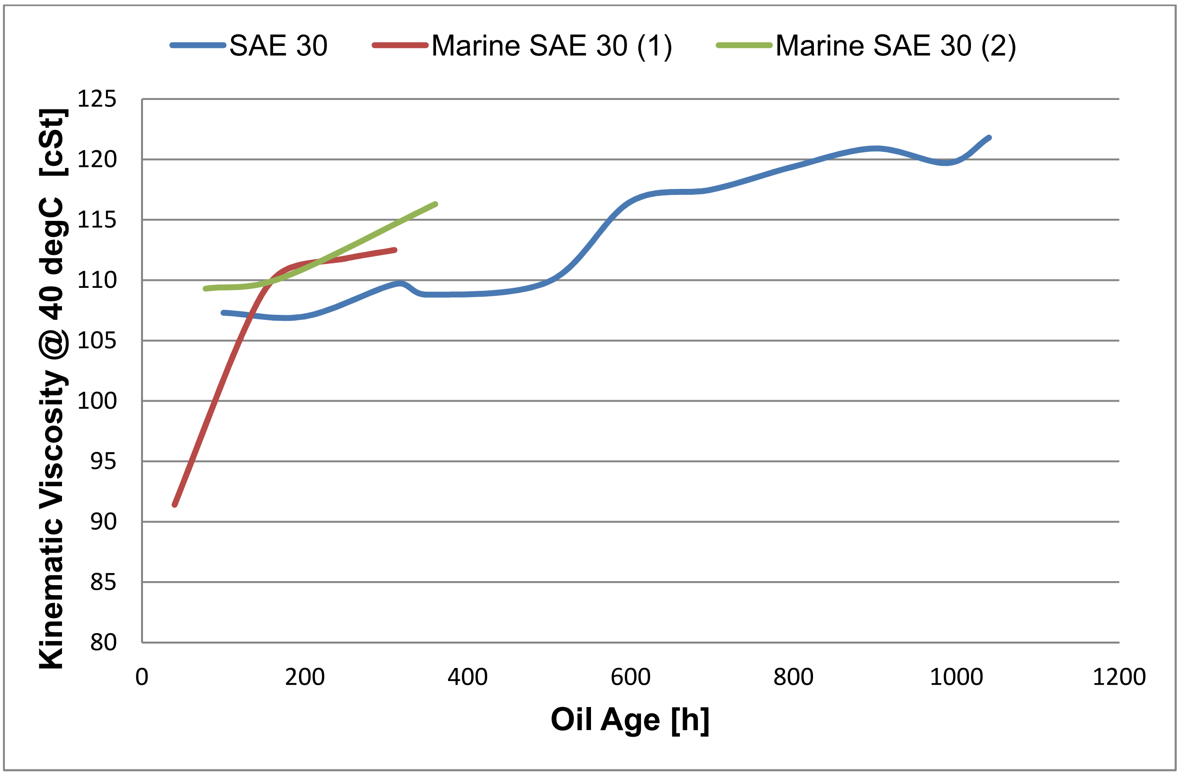

Figure 8.2 Long term effect of animal fat usage on lubricating oil viscosity

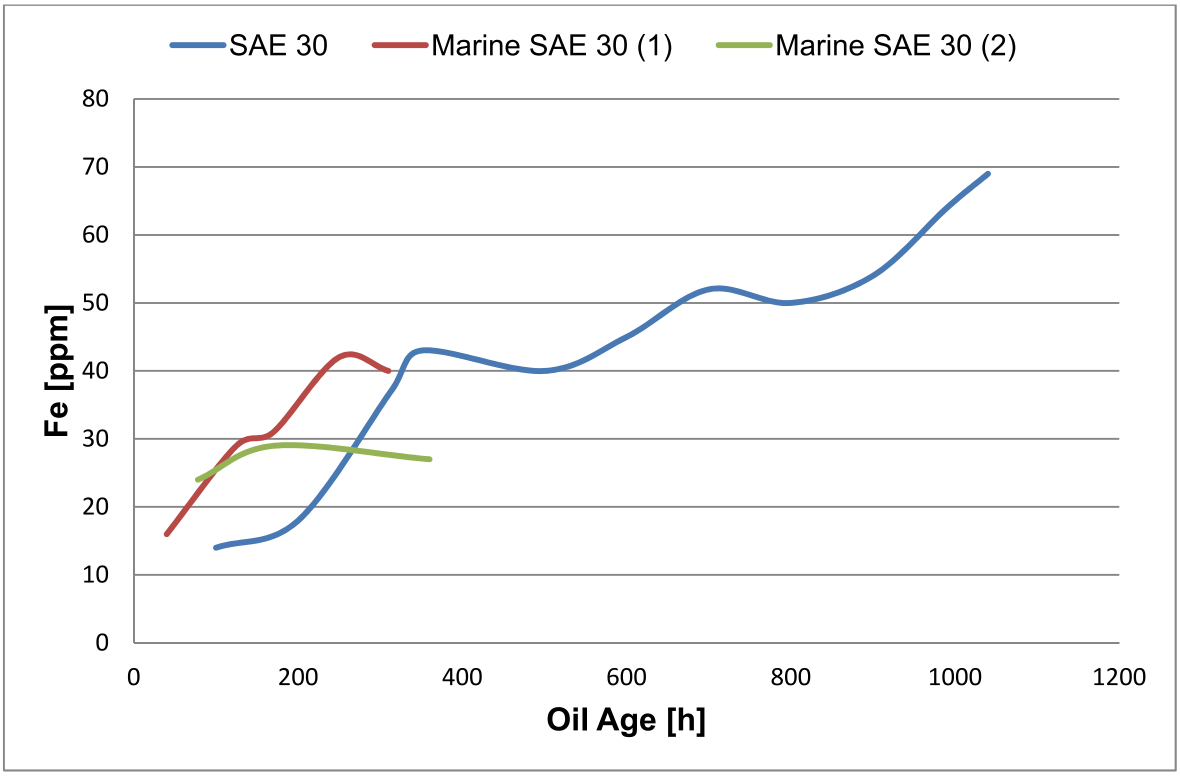

Figure 8.3 Long term effect of animal fat usage on engine wear - iron concentration

Table 8.2 Effect of ageing during operation on animal fat on various types of lubricating oil

Oil Type	**SAE 30**											**Marine SAE 30 (1)**					**Marine SAE 30 (2)**		
Hours	100	200	313	350	500	600	700	800	900	990	1040	40	125	170	250	310	78	172	360
KV [mm^2/s]	107.3	107	109.7	108.8	109.9	116.5	117.5	119.4	120.9	119.7	121.8	91.4	105.8	110.6	111.8	112.5	109.3	110.2	116.3
Soot	0.4	0.5	1.3	1.4	1.7	1.9	2.2	2.2	2.2	2.5	2.5	0.2	0	0.5	0	0.6	0.3	0.3	0.6
Concentration [ppm]																			
Iron (Fe)	14	18	37	43	40	45	52	50	54	64	69	16	29	31	42	40	24	29	27
Copper (Cu)	1	1	4	5	4	5	4	3	3	3	4	1	1	1	2	5	1	1	1
Silicon (Si)	2	6	6	7	5	8	7	6	7	5	9	3	7	10	6	10	17	15	10
Aluminium (Al)	2	2	2	2	1	1	1	1	2	2	2	0	1	2	1	4	0	2	1
Chromium (Cr)	0	0	1	1	1	2	2	2	2	2	2	0	1	1	1	1	0	1	1
Nickel (Ni)	0	0	0	1	1	0	1	0	0	0	1	0	0	0	0	1	0	2	0
Molybdenum (Mo)	47	48	50	50	49	52	59	54	58	62	67	37	21	16	8	7	2	1	1
Manganese (Mn)	0	0	1	1	0	1	0	1	1	1	2	1	2	2	2	2	1	1	1
Lead (Pb)	2	1	2	3	3	4	5	3	5	6	7	6	3	3	1	7	1	8	11
Tin (Sn)	0	0	0	1	0	0	0	0	0	1	2	0	0	2	2	1	0	0	0
Lithium (Li)	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0
Titanium (Ti)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Vanadium (V)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Silver (Ag)	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Boron (B)	6	3	4	5	4	3	2	2	2	4	7	12	9	9	7	6	1	8	4
Sodium (Na)	7	9	16	18	17	26	36	31	32	45	50	10	24	34	61	63	63	119	83
Barium (Ba)	0	1	1	1	0	1	0	0	0	1	1	1	1	1	1	1	0	2	0
Calcium (Ca)	1682	1740	1931	1861	1651	1887	1993	1794	1869	1862	2114	2884	4214	5027	5244	5113	4764	5610	5677
Magnesium (Mg)	9	9	12	15	9	12	12	10	10	11	12	13	19	18	19	18	14	17	16
Phosphorus (P)	689	740	803	790	718	799	858	774	824	860	888	715	665	641	595	549	502	566	567
Zinc (Zn)	74	810	865	887	768	883	988	842	893	946	950	825	771	764	726	695	593	657	643

Where: KV – Kinematic Viscosity

It can be seen that oil viscosity increased for both types of tested oils. During the trials the oil centrifuge had to be cleaned more frequently than for standard fuel operation due to fast deposit formation. The maintenance schedule was altered. Oil contamination with fuel can be caused by increased spray penetration due to different physical properties of fuel; hence droplets may hit liner walls and penetrate to the sump. Excessive wear has not been detected for both types of lubricating oil as concentrations of bearing materials (Cu, Pb, Sn) remained below warning limits. Conclusions are presented in paragraph 8.4.

8.3 Impact on Injectors and Fuel Pumps

Two sets of Ruston FAR 20000 fuel pumps (shown in Figure 8.4) were installed on the Ruston 6AR engine. Technical data are given in Table 8.3. The fuel pumps were inspected daily for leaks. Each set was used for approximately 1000 h.

Table 8.3 Fuel pump specification

Pump type	FAR – 20000
Camshaft speed	300 rpm
Pump stroke	15 mm
Plunger diameter	22 mm
Fuel delivery at full load	200 cm^3/100 strokes
Injector nozzle configuration	10 x 0.014’’
Injector release pressure	200 bar

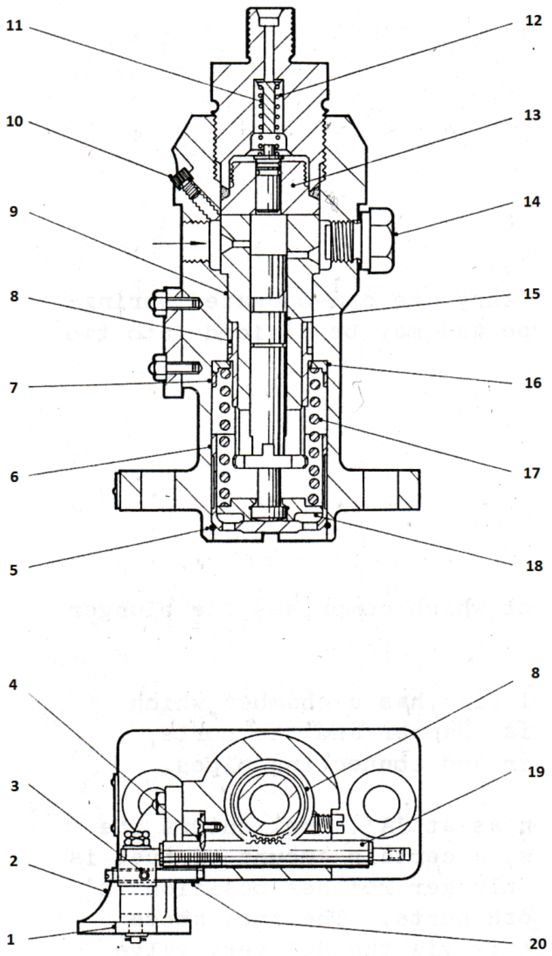

Figure 8.4 Assembly of fuel pump (119)

1 – control rack slipper, 2 – rack support bracket, 3 – lead sealed grub screw for 20, 4 – setting pointer, 5 – tappet retaining ring, 6 – plunger tappet, 7 – spring ring, 8 – operating pinion, 9 – plunger guide, 10 – air vent plug, 11 – delivery valve stop, 12 – delivery valve spring, 13 – delivery valve assembly, 14 – spill plug, 15 – plunger, 16 – upper spring collar, 17 – plunger spring, 18 – lower spring collar, 19 – operating rack, 20 – overload stop screw.

The engine usually operated at high loads, above 75% of nominal power. Throughout the duration of the trials no issues with fuel pumps were recorded. This confirms laboratory test results (paragraph 6.1.2) and the excellent lubricating properties of animal fat. The filtration process used for fuel pre-treatment is efficient enough to provide fuel with a set of properties enabling trouble-free usage in the reciprocating engine fuel supply system. It has to be noted that implementation of these fuels for new common rail systems may require further investigation and specification alteration.

Fuel not complying with internal specifications has also been tested. Contamination with polyethylene, ash and insoluble impurities was noticeably higher. As a result, fuel pumps were damaged in less than 100 hours. The seal between the plunger and the guide was lost and fuel was leaking to the orifice below the fuel pumps, shown in Figure 8.5 (the picture has been taken through the inspection window below the fuel pump assembly; fuel droplets reflect flash light and are visible as a group of white points surrounding the plunger). Fuel injection pressure could not be maintained at the required level, therefore it was impossible to operate the engine at high load. Low injection pressure had an impact on the fuel spray resulting in an increase of emissions of unburned hydrocarbons and carbon monoxide by approximately 300%. The pumps were later dismantled and a visual inspection of the plunger surface confirmed wear signs caused by a higher level of impurities present in the fuel. It has to be highlighted that damage occurred despite having a standard fuel filter in place (5 micron cartridge).

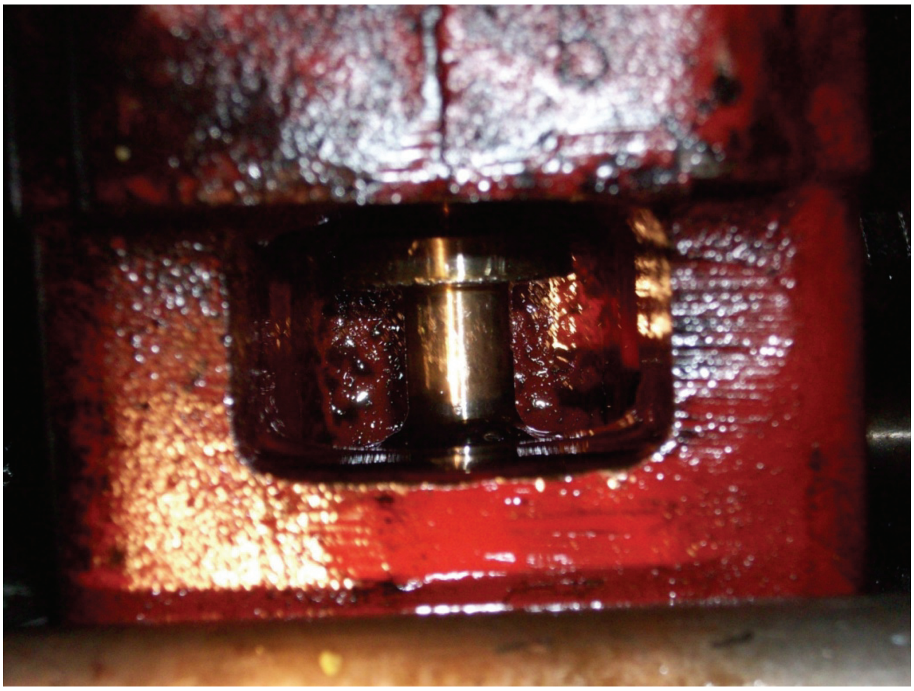

Figure 8.5 Fuel leaking from fuel pumps damaged by fat containing polyethylene

Standard injectors without nozzles' cooling were used. Release pressure was set to 200 bar. Deposit formation on the injector nozzles was detected. Figure 8.6 shows a blocked nozzle (bad case). The tests proved that nozzles can be used for up to 130 hours of continuous operation. After that period the nozzles require cleaning. Usually the nozzles required replacement after two cleaning cycles. As described in paragraph 7.2, emissions of carbon monoxide and unburned hydrocarbons are lower due to the oxygen content in animal fat. Therefore any increase in monitored carbon monoxide emissions or visible smoke can indicate deposit build-up requiring intervention. One of the possible methods of extending cleaning intervals is periodic operation on fossil fuel. Application of this method must be carefully considered, as there is a 10% limit for fossil fuel content in fuel mix used for subsidised renewable electricity generation in the UK (95). The combustion of fat resulted in a higher temperature inside the combustion chamber and in the exhaust system. It led to the nozzle’s tip breaking, as shown in Figure 8.7. Part of the trial run was performed with fuel heated up to 65^{o}C. It resulted in valve damage (please refer to Figure 8.8 and Figure 8.9) and an increased tendency to deposit build-up on the injector nozzles. It can be explained by fat’s higher density, viscosity and surface tension leading to poor atomisation and increased spray penetration (66).

Figure 8.6 Deposit build-up

Figure 8.7 Injector nozzle damage caused by high temperature

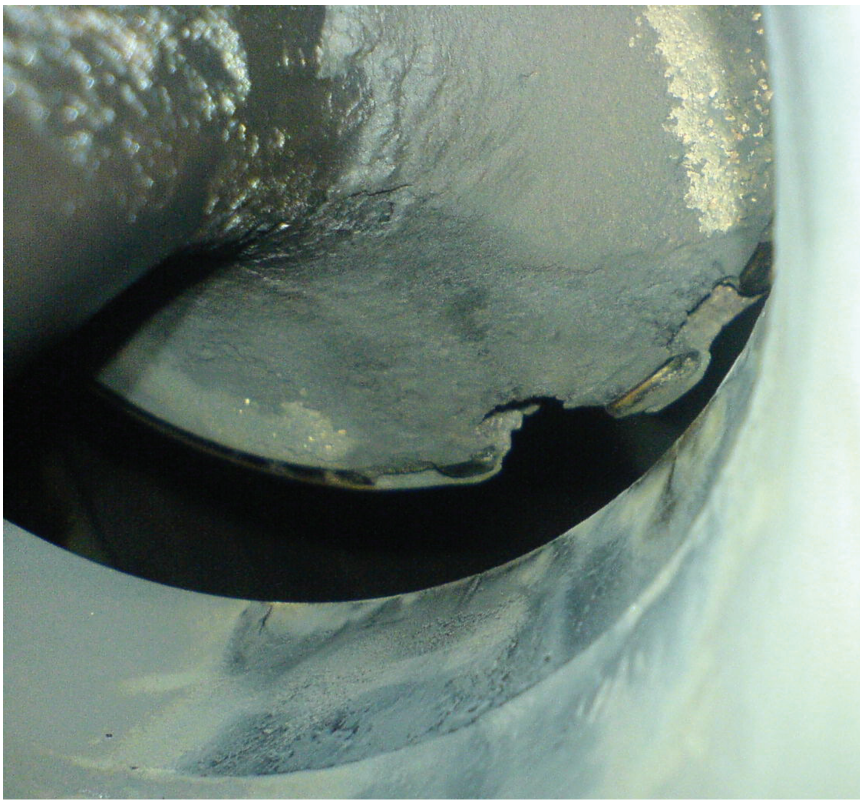

Figure 8.8 Burned exhaust valve

Figure 8.9 Ruston 6AR cylinder head - valve damage visible

8.4 Conclusions

Engine tests lasted for 2000 hours. More than 1 GWh of electricity has been generated and approximately 285 tonnes of animal fat have been utilised. This research has shown that appropriately filtered animal fat can be used as fuel for large, stationary engines.

Usage of animal fat as fuel for an internal combustion engine requires modification of its maintenance schedule and may lead to injection system failures. The conducted tests proved that it is possible to operate a compressed ignition engine fuelled with tallow without major alteration of the lubricating system. Standard lubricating oil (SAE 30 grade) withstood a 1000 hours' change interval. Application of marine oil did not result in a significant difference in oil contamination with various wear products. It has to be noted that due to piston failure, the engine oil (Marine) had to be replaced before reaching the planned 1000 hours. The capacity of the oil centrifuge should be increased to improve removal of fat from the lubricating oil. Another modification that improved operation on animal fat was increased diameter of the pipe feeding the centrifuge and introduction of trace heating. It resulted in improved flow of oil to the centrifuge and ensured that contaminated oil will not solidify in the narrow parts of the lubricating system.

Animal fat has a tendency to build up deposits on the injector nozzles' tips. The relationship between fuel temperature and longevity was observed. Fuel pre heating above 85^{o}C improved the atomisation and emissions (CO, HC). Operation on partial loads or low temperature fuel (below 70^{o}C) resulted in increased deposit build up. Another consequence was poor atomisation and increased spray penetration. The following remedies can be suggested to extend intervals between injector nozzle cleaning and/or replacement: firstly, nozzle cooling can be implemented, the fuel can be fed at a higher temperature so atomisation is improved and cooling should prevent the nozzle from the damage described earlier in this chapter. Another strategy is periodical operation on fossil fuel when deposits are removed.

Chapter 9 CONCLUSIONS AND FURTHER WORK

9.1 Summary of Presented Findings

This thesis contains numerous findings on the use of animal fat in internal combustion engines. The research programme focused on large compressed ignition engines used in marine and stationary power generation applications. The most important and significant findings and observations are presented in the following sections in the order of the original chapters. A summary of the KTP Project – extracted from the KTP Final Report (147) forms Appendix 4.

9.1.1 Consistency of Tallow Properties

The conducted tests identified a high variability of animal fat properties. It was also proven that constant monitoring of the fat properties is required in order to utilise it in the engine, as the quality can vary significantly even from batch to batch. Acidity was identified as a crucial property that has to be improved in order to comply with the bio fuel specification of any available generating set. The impact of ambient temperature on fat acidity has been detected, as high temperature during summer months speeds up the feedstock decomposition process. The most important outcome of research presented in Chapter 5 is the understanding of what is a typical set of properties of animal fat – thus in the further stages of the research process the appropriate fuel sample was used.

The possibility of free fatty acid removal by evaporation has been investigated. The trial runs have shown a promising removal efficiency reaching more than 50%.

9.1.2 Determination of Appropriate Storage and Supply Temperatures

As animal fat is solid at room temperature, pre heating is required to reduce the viscosity and feed the fuel through a standard fuel supply system. Investigation focused on analysis of the effect of elevated temperature on physical properties of the animal fat. The viscosity test showed that animal fat needs to be preheated above 80°C to reduce its viscosity to a level complying with requirements given by 2-stroke large engine fuelled with HFO (Heavy Fuel Oil). The impact of temperature on the viscosity of animal fat is significant; raising the temperature from 40°C up to 60°C results in viscosity reduction from approximately 40 cP down to 20 cP. Further heating up to 90°C reduces viscosity to 9 cP (for low shear rate) and 8 cP (for high shear rate).

The lubricity of animal fat has been analysed – as the HFRR (High Frequency Reciprocating Rig) method has been applied. Tallow lubricating properties are excellent as WSD (Wear Scar Diameter) is less than 110 µm, compared with 320 µm for diesel. It can be explained by the presence of unsaturated fatty acids in the animal fat. Tallow contains 10% oxygen that improves lubricity. No significant impact of elevated temperature on lubricating properties has been detected. Wear scar diameter increased for the highest test point (90°C) only by 7 µm

Pre heating of animal fat reduces its surface tension. Raising the temperature to 90°C lowers the value down to 25.8 [mN/m] from 31.0 [mN/m] recorded at 40°C. Surface tension is still considerably higher than that of mineral fuel – 23.4 [mN/m] recorded at 40°C.

The obtained density test results present a linear trend where density decreases as temperature rises. The measured density at standard conditions (temperature 15°C) – 915 kg/m^3 – is higher than the maximum density for diesel fuels (800 – 845 kg/m^3) specified in a standard (37).

It can be concluded that pre heating of fuel to a temperature of at least 85°C is required to modify its properties to suit the requirements given by HFO fuelled engines and also the Ruston 6AR engine available at the research power plant.

The impact of high fat storage temperature on its properties (acidity) has been studied. Storage at a temperature of 90°C for a prolonged period of time (1 month) did not result in increased acidity. Fat polymerisation did not occur.

9.1.3 Combustion Process Analysis

Recorded cylinder pressure patterns varied from those obtained for diesel for all tested loads. A lower heat release rate for the premixed combustion phase is characteristic for tallow across the tested load range. Due to fat's properties, its atomisation is worse resulting in prolonged combustion. Difficult atomisation is more significant at low and medium loads causing an increase of CO and HC emissions. At high loads, however, the benefit of oxygen presence in tallow leads to more complete oxidation, as a result, emissions of soot, CO and HC are significantly lower. Emissions of NO_x were higher for animal fat at high load. One of the biggest advantages of using the animal fat as fuel for reciprocating engines is its low sulphur content, which eliminates the requirement for a SO_x abatement system.

The research programme was focused on design and implementation of an appropriate nitrogen oxides abatement system. An exhaust gas recirculation system with gases cooling and humidification was designed and installed. The method achieved desired a NO_x reduction of 75% by recirculating approximately 23% of the exhaust at high load. The impact of the reported higher fuel consumption on station feasibility has to be considered. Combining the effect of lowering oxygen concentration by exhaust gas recirculation with the presence of water vapour, can be considered as a feasible method of NO_x abatement, even for stationary engines designed to operate at high loads for prolonged periods of time.

9.1.4 Long Term Effects of Using Tallow on Engine Components

Findings presented in this thesis are supported with experience gained during nearly 2000 hours of extensive tests in the research power plant. One of the outcomes of the KTP project was the establishing of procedures for generating set operation and maintenance and also internal fuel specification. Fuel quality is crucial for problem free operation of the engine on animal fat. It has been proven that engines can run on alternative fuel without significant problems; however, the injectors' maintenance schedule has to be modified to incorporate more frequent cleaning and nozzle replacement due to deposit formation. Fuel pre heating is a simple way to alter properties of viscous fuels like animal fat. The fuel internal specification and operational parameters defined in Chapters 5 and 6 were proven satisfactory for prolonged usage.

9.1.5 Economics of Electricity Generation

An open market for animal fat trade does not exist in the UK, therefore it is difficult to assess the feasibility of electricity generation using it. The collaborative project described in this thesis was a unique opportunity to access data regarding fat pricing. The relationship linking animal fat prices and fossil fuels was presented – based on information collected throughout a period of 12 months. In both analysed cases, a small research power plant and a proposed large generating station, generation was not feasible without additional subsidies in form of a ROC or RHI. The renewable electricity support system in the UK has been described – currently animal fat can be used as a subsidy eligible source of renewable electricity in power plants using internal combustion engines where installed power exceeds 5 MW.

9.2 Suggestions for Future Work

9.2.1 Engine Modifications

It has been proven that fuel temperature has a critical impact on fat atomisation. However, high temperatures may have a negative impact on the injector nozzles – therefore injectors with nozzle cooling should be tested on the engine or the test rig to investigate the long term effect of animal fat usage. An alternative spray system should be tested to investigate spray penetration, cone angle etc. Ideally research should be conducted at facilities using modern optical equipment – such as PDA.

The lubricating oil filtration system capacity should be increased to accommodate any volume of fuel that passes to the sump. It may be interesting to investigate usage of bio based lubricating oils for engines fuelled with animal fat or CPO.

9.2.2 Emissions Abatement

Additional research focusing on the nature of particulates formed during animal fat combustion is required for better assessment of the benefits. The test engine should be equipped with an SCR system – hence the effect of the composition of animal fat on the catalyst longevity may be assessed. The high content of phosphorus may be challenging here.

9.2.3 Animal Fat Quality

Acidity seems to be one of the parameters that should be targeted first if tallow is considered as alternative fuel. A larger scale evaporator should be tested to investigate the possible effect of high temperature exposure on other fat properties.

This thesis focused on pre heating as a way of viscosity reduction. Depending on local circumstances – blending with light hydrocarbons may be a viable solution.

Due to variable and complex chemical composition, cetane number is not an appropriate criterion for ignition quality assessment. A new index, possibly similar to CCAI, should be developed.

The lubricity test presented in this thesis was based on conditions in line with the ISO standard developed for automotive fuels and light marine fuels. The only parameter altered was the fuel temperature. Further investigation should be conducted to verify whether other test conditions such as stroke or load have an impact on the wear scar diameter.

Attempts to source syngas from animal fat were made within the Future Power Systems Group. Up to 10% and 5% vol. of H_2 and CO, respectively, were detected when 60ml/h of tallow fuel was injected. As it has been reported in other studies, adding reformed hydrogen syn-gas as a closed loop to a diesel engine would improve combustion efficiency and therefore specific emissions (148). This reformed syn-gas has also been reported as beneficial to other diesel after-treatment devices (149). Results of tests look promising therefore investigation should be continued.

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