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(54) Title: COMBUSTION OF RENEWABLE OILS AND FATS

(57) Abstract: A method of combusting a renewable oil or fat comprises injecting the oil or fat into a combustion cylinder of a heterogeneous-charge compression-ignition engine and supplying to the cylinder inlet port combustion air or working fluid at a temperature substantially above ambient for substantially the entire time that the engine is running. Other aspects of the invention provide a compression ignition engine for use in the method, and a method of using the engine to combust renewable oils or fats.

## COMBUSTION OF RENEWABLE OILS AND FATS

## BACKGROUND

## 5 a. Field of the Invention

The present invention relates to the combustion of renewable oils and fats, and to a combined heat and power system using the combustion method.

## 10 b. Related Art

There is evidence that anthropogenic CO<sub>2</sub> emissions are affecting the global climate. One method to reduce these emissions is through power generation using renewable fuels. In this case, the CO<sub>2</sub> emitted was previously fixed biologically  
15 from the atmosphere and is essentially being recycled over a short period. Liquid biomass, for example animal fats (tallow etc) and vegetable oils and fats can be considered for use as renewable fuels.

Naturally occurring renewable oils and fats are extracted from plants or rendered  
20 from animals, in distinction from fossil fuels which are non-renewable. Renewable oils and fats typically are predominantly comprised of triglycerides formed by the combination of fatty acid molecules with a glycerine molecule. The term is used herein to include acid oils. Examples of renewable oils or fats include crude plant-extract oils such as crude palm oil, crude coconut oil, crude flax oil, and also  
25 animal-derived fats such as tallow.

There are over forty different fatty acids that can combine with glycerine to form a variety of naturally occurring oils and fats, including oils and fats derived from seeds, such as rape, sunflower and ground nut, or fruit, such as palm or coconut,  
30 as well as oils and fats derived from fish or animals. Oils are usually in a liquid state at ambient temperatures, whereas fats tend to be solid or semi-solid at room temperatures. The term "renewable oil" will be used herein to include renewable fats.

Naturally-occurring renewable oils and oil residues that contain free fatty acids are commonly known as acid oils or fatty acid oils. The term "acid oil" could refer to various oils and fats and for clarity includes: crude oil derived from seeds, fruit, fish  
5 or animals. Such oil will normally contain significant amounts of free fatty acids as well as other contaminants. The crude oil could be oil that has been simply pressed from seeds or fruit, or the crude oil could be a blend of pressed oil and solvent extracted oil. Acid fat is acid oil that is in a solid or semi-solid state at normal ambient temperatures and crude acid fat is also derived from seeds, fruit,  
10 fish or animals. The term "acid oil" will be used herein to include acid fats unless the context otherwise dictates.

Fatty acids and fatty acid residues derived from refining or distillation of naturally occurring oils and fats, or residues left from the distillation of fatty acids, or  
15 residues from any other fatty acid production process.

The term 'acid oil' includes blends comprising or including these materials. Blends may contain a variety of other materials, eg, water.

20 It is well established that oils and fats derived from seeds, fruit, fish or animals tend to burn poorly in normal compression ignition engines, even when the oil is in a refined or partially refined state. Under normal combustion conditions. For example, the exhaust gas from the engine is usually black, and gummy or sticky carbonaceous deposits tend to gradually build up inside the cylinders of the engine  
25 and around valves and fuel injectors.

Free fatty acids in the oil can also produce acidic sump oil, which can then cause serious damage to critical engine components; for example, there have been reports of major problems occurring with the pumps and bearings of engines, as  
30 well as with valves and fuel injectors. In fact some engine manufacturers have refused to allow their engines to be used with acid oils, whilst other manufacturers have refused to guarantee their engines if acid oil is used as fuel. Acid oils also burn more poorly than refined oils because acid oil contains more of the

contaminants that can affect the properties and the combustion performance of the oil. For example, acid oil contains more incombustible material than refined oil. The incombustible material present in the acid oil, including metallic compounds, will be responsible for at least some of the combustion deposits that can occur on valves and fuel injectors of an engine burning acid oil.

Because naturally occurring oils and fats burn poorly, carbon particles are formed inside the engine cylinder during each combustion cycle, and any incombustible material, including metals, released during combustion can adhere to the carbon particles. Any unburned triglycerides and unburned free fatty acids left in the engine cylinder after combustion will also tend to stick to the carbon particles.

One method for utilization of naturally occurring oils and acid oils is as fuels for power generation, and for combined heat and power generation. High efficiency, reliability, stable combustion and low emissions are essential to successful power generation. Power generation plants may typically be in service for 8000 hours per year. Naturally occurring oils typically have poor emissions profiles compared to liquid hydrocarbon fuels, with high production of carbonaceous particulates. Combustion is incomplete, and products of incomplete combustion form deposits on burners and fuel injectors, fouling of valves and contamination of engine lubrication oil, all of which mean reliable operational conditions required for power generation cannot be reached.

A proposed solution to these problems is the use of oxygen enriched combustion, for example as described in GB 2 339 842 or US2002/189243. However, the applicant has discovered that while combustion of oils and fats and emissions may be improved by this method, it does not meet the requirements listed above for power generation. Naturally occurring oils and fats contain acidic species which degrade components in the fuel delivery systems of power generating equipment, an effect which is increased by the higher temperature required for injection of these fuels compared to hydrocarbon distillates. Degradation in performance of fuel pumps and injection equipment means unstable combustion and loss of power which are detrimental to power generation. These problems cannot be addressed

by application of oxygen enrichment as described in the prior art. A system for power generation which meets the criteria of high efficiency, with improved reliability, combustion stability and lower emissions for naturally occurring oils is highly desirable.

5

The overall thermal efficiency of an engine driven combined heat and power system depends upon the total recoverable fraction of waste heat produced by conversion of fuel within the prime move to electrical power.

10 The waste heat thermal balance can be split between:

- Radiant heat
- Coolant and lubricant waste heat
- Combustion air-cooling
- Exhaust gas heat

15

Coolant and lubricant waste heat can be recovered by means of a heat exchanger coupled to a secondary fluid system. As the normal operating temperatures of the engine coolant and lubricant will not exceed 100°C the recoverable fraction will be in the form of 'low grade' heat.

20

Combustion-air cooling is employed on pressure-charged engines to cool the combustion air post-compression to increase charge density. The thermal energy added to the combustion air during compression will be proportional to the thermal efficiency of the compressor. Normal engine operating modes such as the standard diesel cycle attempt to achieve a combustion air temperature as low as possible and normally in the range of 30 – 60°C. To enable such a combustion air temperature to be maintained the charge air cooling circuit is usually kept separate from the main engine coolant circuit and therefore the recoverable fraction of heat from the charge air circuit is very 'low grade'.

25  
30

The major source of waste heat from any engine will be contained in the exhaust gas mass flow. The exhaust gas mass flow is an available source of high grade heat, i.e. over 100°C, and can be used for generating steam independent of or in

conjunction with the low grade system by the well known means of an economise circuit. The recoverable fraction of the exhaust gas thermal energy is limited by the difference in temperature between the exhaust gas mass flow and the minimum temperature allowed at the exit of the heat exchanger. The lower limit is  
5 determined by the dew point of the exhaust gas and as acidic compounds are contained therein the exit temperature will rarely be allowed to fall below 120°C.

It can be seen therefore that the high-grade thermal energy recovery fraction is critically temperature dependant and therefore the overall thermal efficiency of any  
10 combined heat and power system will also be critically dependant on exhaust gas temperature.

As engine primary electrical conversion efficiency increases the temperature of the exhaust gas is reduced; therefore the overall balance between recoverable heat  
15 energy and electrical energy changes.

## SUMMARY OF THE INVENTION

Aspects of the invention are specified in the independent claims. Preferred  
20 features are specified in the dependent claims.

We have found that a heated combustion air cycle can be employed to increase the efficiency of combustion of renewable oils and fats, allowing more useful heat to be extracted. This cycle enables low-grade heat in the inlet air to be transferred  
25 to high-grade heat in the exhaust gases. Heating the combustion air of an engine will reduce power and efficiency by reducing the mass airflow through the engine at any given power. Correcting the mass airflow by adjusting the pressure charging will bring the efficiency and power output back to normal levels while providing greater temperature, and hence more usable heat energy, in the exhaust  
30 gases.

To enable increased combustion-air temperature the charge air after-coolers can be disconnected and additional heat from the radiant losses for example can be

added to the combustion air circuit. The removal of the charge-air after-coolers enables the heat generated by the compressor losses to be passed into the engine cylinder and recycled back into the exhaust gases for recovery; this not only allows access to the energy from the compressor losses but also upgrades  
5 the temperature of these losses into the recoverable zone in the exhaust gas.

A typical high-speed compression ignition engine operating at full power with an electrical output of ~ 1 MWe would have an exhaust temperature of ~ 420°C.

10 The heat balance from the input fuel would be:

- Electricity ~ 38.4%
- Coolant ~ 16.1%
- Exhaust gases ~ 34.4%
- After cooler ~ 7.4%
- 15 • Radiant ~ 3.6%

Using an exhaust gas heat exchanger exit temperature of 120°C would allow the recovery of ~ 71.4% of the exhaust gas thermal energy. Recovery of all the coolant thermal energy and 71.4% of the exhaust gas thermal energy would allow  
20 a total thermal efficiency of ~ 78%.

Increasing the combustion air temperature by, for example, 50°C and correcting for mass flow would enable an exhaust gas temperature rise of at least 50°C taking the exhaust gas to ~ 470°C. The increased exhaust gas temperature would  
25 enable a thermal energy recovery of ~ 74.4% of the exhaust gas thermal energy and a total thermal efficiency of ~ +80%. The increased recoverable component having a temperature of over 100°C would also increase steam pressure yield if steam were a required medium.

30 The minimum temperature necessary for ignition and the minimum temperature necessary for stable operation will vary according to the nature of the material and the construction of the engine. A multiple applies which is dependent on the adiabatic efficiency, the gamma factor (the ratio between the specific heat of the

gas at constant volume and the specific heat at constant pressure) and the compression ratio. The compression ratio is a particularly important factor as regards the overall thermodynamic efficiency of the engine; however practical limits exist as to the maximum compression ratio that can be employed due to structural constraints, material packaging and frictional losses. Non pressure charged diesel cycle engines tend to be limited at ~ 22:1 and pressure charged engines ~ 16:1. Otto cycle engines, due to charge detonation, will normally use a range of compression ratios much lower than for diesel cycle engines in the range of ~ 8:1 – 10:1 Higher compression ratios will indeed produce higher temperature increases after adiabatic compression of the combustion air. However the final gas temperature achieved per unit compression ratio increase is relatively low; for example the compression ratio of a given test engine would have to be raised from 22:1 to ~ 36:1 to attain the same end gas temperature as produced by raising the inlet charge temperature by ~ 65°C. Calculations suggest that a 1°C increase in combustion air inlet temperature can produce about a 3°C or higher temperature increase after compression. Unlike with cold startup systems, the combustion air is maintained at an elevated temperature and preferably pressure-corrected for substantially the entire time that the engine is running, ie for substantially the entire engine operation range.

20

Although some high viscosity materials require to be heated in order to achieve an appropriate viscosity for injection into the engine cylinders, this may be done immediately prior to injection so that the material does not remain at an elevated temperature for long before being combusted.

25

The combustion air is preferably compressed prior to its supply to the engine cylinders. This increases mass flow and improves efficiency. Increasing the mass flow also has the effect of reducing peak temperatures and pressures, which tends to reduce production of NOx gases. Of course, the combustion air is further compressed in the cylinder, where compression-ignition combustion takes place. Any desired level of compression may be applied to the combustion air or working fluid, but in a preferred embodiment the combustion air or working fluid is supplied to the cylinder inlet port at a pressure such that mass flow entering the cylinder via

30

the inlet port is corrected to substantially equal that that would enter the cylinder under standard operating conditions.

5 The compression may readily provided by a turbocharger powered by exhaust gases. The waste heat from the exhaust gas, heat generated by the inherent inefficiency of the turbo compressor or any other method of air heating or combination of heat sources may be used to heat up the combustion air. This approach, with heated compressed combustion air, is the opposite to conventional turbocharged systems, wherein the turbo-pressurised air is cooled down, (inter-/  
10 after-cooled), to increase mass flow.

In broad terms, the invention involves heating combustion air or working fluid to a temperature which enables and/or optimises combustion of fuels outside the balance of properties and conditions of fuel and combustion conventionally known  
15 in the art.

The term "working fluid" is used herein to denote a fluid (gas or liquid) used as the medium for the transfer of energy from one part of a system to another part. The working fluid could comprise air mixed with a gas or vapour which is combustible  
20 or supports combustion.

EXPERIMENTAL RESULTS

Table 1 gives an example of the effect of combustion air temperature change on a 4 cylinder direct injection turbocharged compression ignition engine running on a renewable oil, in this example Palm Fatty Acid Distillate, and coupled to a DC dynamometer. The increase in exhaust temperature of ~56°C can be seen as a product of increasing the combustion air temperature by ~ 42°C whilst electrical efficiency is maintained.

Exhaust Temp.	RPM	Power kWe	NOx ppm	CO ppm	Exhaust O <sub>2</sub> %	Inlet Temp.	Pressure Barg	
			Fuel = 11.457 kg					
339	2333	16.18	680	145	13.3	139.2	1.66	
340	2344	16.22	710	139	13.7	141.1	1.68	
342	2354	16.12	705	142	13.6	142.8	1.67	
344	2320	16.11	690	141	13.6	141.6	1.66	
344	2332	16.01	695	146	13.7	141.7	1.67	
		16.13	Fuel = 9.076 kg			Electrical efficiency: 28.4%		
			Fuel = 11.954 kg					
284	2286	15.87	551	131	13.01	95.3	1.64	
286	2309	16.20	546	135	13.86	97.4	1.66	
289	2292	15.82	557	148	13.81	97.2	1.68	
288	2312	16.01	548	147	13.88	99.2	1.68	
288	2319	15.98	517	133	14.12	99.5	1.68	
		15.98	Fuel = 9.575 kg			Electrical efficiency: 28.5%		

10

TABLE 1

In one embodiment, the oxygen content of the combustion air may be enriched to aid combustion. Oxygen enrichment may optionally be employed in combination with compression of the combustion air.

15

## CLAIMS

1. A method of combusting a renewable oil or fat, the method comprising injecting the oil or fat into a combustion cylinder of a heterogeneous-charge  
5 compression-ignition engine, and supplying to the cylinder inlet port combustion air or working fluid at a temperature substantially above ambient for substantially the entire time that the engine is running.
2. A method according to claim 1, wherein the combustion air or working fluid  
10 is supplied to the cylinder inlet port at a temperature of at least 60°C, preferably 90-250°C.
3. A method according to claim 1 or claim 2, wherein the renewable oil or fat is  
15 an acid oil.
4. A method according to any preceding claim, wherein the combustion air or  
working fluid is supplied to the cylinder inlet port at a pressure such that mass flow  
entering the cylinder via the inlet port is corrected to substantially equal that that  
would enter the cylinder under standard operating conditions.  
20
5. A method according to any preceding claim, further comprising heating the  
oil or fat prior to injecting it into the combustion cylinder.
6. A method according to any preceding claim, wherein at least some of the  
25 combustion air or working fluid is heated using waste heat from the engine.
7. A method according to any preceding claim, wherein the combustion air or  
working fluid is pressurised by means of a turbo-charger driven by the flow of  
exhaust gas from the engine.  
30
8. A method according to claim 7, wherein at least part of the combustion air  
or working fluid is heated by the inherent inefficiency of the turbo charger driven by  
the flow of the exhaust gas from the engine.

9. A method according to any preceding claim, wherein the combustion air or working fluid has an enriched oxygen content.
- 5 10. A method of generating combined heat and power (CHP), including combusting a renewable oil or fat as specified in any preceding claim and using heat recycled from the inlet air to maintain or increase the usable exhaust gas waste heat energy for recovery.
- 10 11. A method according to any preceding claim, wherein the renewable oil or fat is Palm Fatty Acid Distillate.
12. Apparatus for the combustion of renewable oils or fats, comprising a heterogeneous-charge compression-ignition engine having a cylinder, heating  
15 means for heating combustion air to be supplied to the cylinder to a temperature substantially above ambient, and pressurising means for compressing the combustion air to a pressure substantially above atmospheric.
13. Apparatus according to claim 12, wherein the heating means includes a  
20 heat exchanger to transfer heat from the engine exhaust and/or cooling system to the combustion air or working fluid.
14. Apparatus according to claim 12 or claim 13, wherein the heating means is adapted to heat combustion air or working fluid to a temperature of at least 60°C,  
25 preferably to a temperature in the range 90-250°C.
15. Apparatus according to any of claims 12-14, wherein the means for compressing the combustion air or working fluid to be supplied to the cylinder is a turbo-charger arranged and adapted to be driven by flow of exhaust gas from the  
30 engine.

## INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2009/053275

A. CLASSIFICATION OF SUBJECT MATTER  
 INV. F02M31/02 F02M31/04

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

F02M F02D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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Further documents are listed in the continuation of Box C.



See patent family annex.

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# INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No PCT/EP2009/053275
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