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Glycerine from biodiesel: The perfect diesel fuel

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ABSTRACT

Glycerine supply currently exceeds its demand by a significant margin as it is formed as by-product in biodiesel production. Different routes for its utilisation are currently being looked into, especially ones that would allow its use as a fuel addition. However these routes are not as energy efficient as its direct combustion.

Previously glycerine and other very low cetane number calorific liquids were thought impossible to be used as fuels in compression ignition engines. We have developed a combustion cycle that permits the utilisation of glycerine as a fuel in a compression ignition engine without the need for pilot fuels or cetane improving additives. The paper discusses the results of glycerine combustion in standard unmodified Lister-Petter and Deutz compression ignition engines.

Keywords: Glycerine; Combustion; Compression ignition engine; Emissions

1. Introduction

Biodiesel production from vegetable or animal feedstock inevitably results in the glycerine side-product. As much as 100 kg of glycerine is produced for every tonne of manufactured biodiesel. The ability of pharmaceutical and cosmetics industry to absorb the huge amount of glycerine produced is limited. It inspired the search for new and efficient methods of glycerine utilisation.

The comprehensive paper of Pagliaro et al. (2007) and the following book of Pagliaro et al. (2010) list all the viable options of glycerine utilisation, however they lack the most important one: the use of glycerine as fuel for compression ignition engine. Moreover, they state just the opposite that it is not possible to combust glycerine in a diesel engine because the engine would become clogged with polymerisation products and toxic acrolein would be emitted.

Stenhede (2008) at the International Seminar on Gasification stated that glycerine does not ignite in a diesel engine and that Wärtsilä currently is attempting glycerine combustion using pilot fuels.

Other researchers have also stated that ‘glycerol is a poor fuel which does not burn in either petrol or diesel engines’ (Scharmer et al., 2006).

A diesel engine relies upon compression ignition (CI) to burn its fuel, instead of the spark plug used in a gasoline engine. If air is compressed to a high degree, its temperature will increase to a point where fuel will burn upon contact with the air. The air charge is highly compressed to heat the charge to the temperature required for ignition. A diesel engine’s compression ratio is usually between 16:1 and 25:1. This extremely high level of compression causes the air temperature to increase up to 700–900 °C. As the piston approaches top-dead-centre (TDC), diesel-fuel oil is injected into the cylinder at high pressure, causing the fuel charge to be atomised. As a result of the high air temperature in the cylinder, ignition occurs, causing a rapid and considerable increase in cylinder temperature and pressure (generating the characteristic diesel “knock”). The piston is driven downward with great force, pushing on the connecting rod and turning the crankshaft. When the piston approach bottom-dead-centre (BDC) the spent combustion gases are expelled from the cylinder to prepare for the next cycle.

In engine terms the important characteristics of diesel fuel appear to be ignition quality, density, heat of combustion, volatility, cleanliness and corrosion properties. The term ignition quality, loosely covers the ignition-temperature-versus-delay characteristics of a fuel when used in an engine. At a given speed, compression ratio, air inlet and jacket temperature, a good ignition quality means a short delay angle.

In direct injection diesel engines, estimation of ignition delay is quite important. Numerous models for correlating ignition delay were proposed starting from Wolfer (1938).

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The modelling of glycerine behaviour as a fuel in a diesel engine using CFD was presented at Colloquium on Fluid Dynamics (Lábaj et al., 2008). According to simulation results the combustion of pure glycerine in a diesel engine is not viable as it would not produce sufficient power. However, this simulation was constrained by existing preconceptions and it is curious to note that the paper was published after our successful experiments on glycerine combustion took place.

The theoretical study of Teh et al. (2008a,b) considered the requirements for the efficient internal combustion engine from the exergy viewpoint without getting into particulars of fuel atomisation and combustion. The authors came to the conclusions that minimisation of entropy generation due to fuel combustion is the key to the efficient engine. It appeared that this is reached by (a) rapid compression of the reactant mixture to the minimum allowable volume set by the engine compression ratio (while chemical reactions proceed); (b) maintenance of the clearance volume until the cylinder pressure rises to its corresponding constant-UV equilibrium value (due to combustion); (c) rapid expansion of the products. At any given compression ratio, piston engine efficiency is maximised when combustion occurs at the minimum allowable volume (Teh et al., 2008a,b).

The conventional diesel fuel is a complex blend of various saturated and unsaturated hydrocarbons and combustion additives. The number of reactions running during combustions and participating species is numbered by hundreds. Early work by Yu et al. (1956) was able to show the separate effects of physical and chemical ignition delay. For all but very heavy fuels, the physical delay is short compared to the chemical delay.

Glycerine is a single compound and the chemistry of its combustion should be much less complicated, albeit not studied so far. That makes approaching the conditions for an ideal engine stipulated by Teh et al. (2008a,b) less cumbersome.

To increase the compression end gas temperatures three methods can be employed, singularly or in combination:

- Increasing the compression ratio.
- Increasing the mass flow.
- Increasing the inlet air temperature.

Increasing the compression ratio will increase the end gas temperature and pressure but has operational and mechanical limits. The relative end gas temperature increase (per unit of compression ratio) is quite low; this limits the temperatures that can practically be achieved.

Increasing the mass flow through the engine at any given compression ratio and engine speed will increase the end gas temperature due to an increased rate of molecular collision with the piston during the compression stroke leading to increased momentum transfer to the gas.

Increasing the inlet air temperature allows a 'tuneable' end gas temperature. This is due to a normal multiple increase of approximately 3:1 when employing standard compression ratios of 14–16:1.

Increasing the inlet air temperature during engine operation to between 60 and 200 °C enables the rapid ignition of liquids or gases of any cetane number as long as they have a calorific value.

The analysis of engine performance in terms of kinetic theory of gases allows us to formulate the following.

1. Mass flow (the number of molecules) determines engine efficiency.
2. The greater the total number of molecules present within the combustion chamber during the process of combustion for a given calorific input the lower the resultant peak temperature, the greater the momentum transfer between the molecules and the piston and the lower heat loss to the surrounding cylinder surfaces. This mechanism also helps to reduce the production of nitrogen oxides.
3. Increasing the inlet air temperature reduces mass flow and therefore efficiency.
4. Correcting the mass flow by increasing the inlet air mass at any given temperature or increasing the number of molecules of fuel injected into the cylinder, or a combination of both will retain or increase the efficiency.
5. The higher the mass to calorific value ratio of a given fuel the greater the potential for increased efficiency.
6. The lower the number of molecular degrees of freedom of a given fuel the greater the potential for increased efficiency.
7. Once ignited, fuels with a high flame speed, i.e. highly oxygenated fuels, will increase engine efficiency by enabling higher rate momentum transfer to the piston. Fuels of this type normally have very low cetane numbers and are usually employed within Otto cycle engines.
8. Large bore, slow speed engines will by design have increased efficiency due to higher rate momentum transfer to the piston.
9. Increasing the compression ratio is a less effective mechanism for increasing efficiency than increasing mass flow. The compression ratio is purely geometric and will limit maximum allowable mass flow due to peak pressure constructional limits. These limits are well understood by engine manufacturers and a typical turbocharged high efficiency engine compression ratio ranges approximately 12–16:1. Variable compression ratio mechanisms are extremely complex, variable mass flow mechanisms are far simpler.

In order to maintain high efficiency while using alternative and future fuels within compression ignition engines, and to expand the potential for useable renewable fuels, all fuel types need to be considered rather than limiting selection to those fuels that closely match the parameters of diesel fuels or heavy fuel oils.

Therefore the ideal candidate fuel would have a high mass to calorific value ratio, a relatively low number of molecular degrees of freedom, a high molecular input per unit of fuel delivered, a high oxygen content (also extremely beneficial as regards particulate emission but tending towards very low cetane number), have a very high flash point, be non toxic, clean, totally bio-degradable, renewable, have high lubricity and be able to be used in any type of already manufactured compression ignition prime mover. The fuel would also have to be available in large volumes with the potential for growth and at a reasonable cost.

Such a fuel is glycerine (McNeil, 2010, 2011). It is also non-toxic, non-hazardous and does not require any special handling mechanisms. Glycerine oxygen content is 52% and because it is a highly oxygenated compound no particulates could be expected from its combustion. Also, because it is a single compound and not a blend its combustion chemistry should be simpler and chemical delay should be shorter than that for the conventional diesel fuels.