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Measurement of consumption rates of viscous biofuels

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HIGHLIGHTS

- Engine fuel consumption of viscous biofuels difficult to measure online.
- Measuring fuel tank mass not feasible online but accurate and repeatable for longer test runs.
- Inference from CO_2 emissions subject to error but offers good dynamic response.
- Concurrent use of both low-cost methods presented here may be beneficial.

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ABSTRACT

This work investigates the measurement of the consumption rates of viscous biofuels used in internal combustion engines. Most commercial instruments are suitable for traditional petroleum-based fuels, and may exhibit material incompatibility with alternative fuels. Further, some experimental low-grade straight vegetable oils are viscous and relatively quickly degrading fuels, which often need to be heated to assure adequate flow through the fuel system as some are solid at room temperatures. In this study, fuel consumption of straight vegetable oils was measured using an electrically heated fuel tank placed on a scale, and determined as the first derivative of the instantaneous tank mass. While the data were noisy and subject to oscillations and experimental error, repeatable values of the total consumption over various cycles were obtained on diesel fuel, biodiesel and heated rapeseed oil. The measured values were compared with the fuel consumption derived from the exhaust emissions of carbon dioxide and carbon content of the respective fuels. As the advantages of each method are complementary, their parallel use might be beneficial.

1. Introduction

This work is concerned with the measurement of fuel consumption rates of engines operating on biofuels which impose practical constraints due to their viscosity, material incompatibility or other issues.

Biofuels of various origins are being increasingly introduced as a replacement of petroleum-based fuels which are subject to energy security, petroleum price instability, resource depletion, and climate change concerns. Of these, straight vegetable oils, chemically triacylglycerols of fatty acids, are not only used for the production of biodiesel (also FAME – fatty acid methylesters), but also used directly as a fuel. Biodiesel neat or blended with diesel fuel is a popular alternative fuel for compression ignition (diesel) engines [1–3]. Straight oils have historically also been used directly as fuel [4–6], but such use has often been problematic, primarily due to high viscosity of vegetable oils. The majority of the engines powered by vegetable oil use an additional heated fueling system for vegetable oils, with diesel fuel being used to start and warm up the engine, and again to flush the fuel system prior to the engine shutdown.

The need to heat vegetable oils, the higher viscosity of vegetable oils, and the relatively higher propensity of vegetable oil to degrade make it difficult to use many standard online instruments. Additionally, the temperature of heated vegetable oil can vary, by tens of degrees C, with engine operating conditions [7]. Based on densities of 14 oils at 20–100 °C [8], the density of vegetable oils decreases by approximately 0.65 g/m^3 with every 1 °C of temperature increase. At a density of vegetable oils of around 900 g/m^3, a change of 30 °C therefore causes addition or expulsion of about 22 g of fuel for each kg of fuel subject to temperature change.

A review of recent studies on engines powered by straight vegetable oils suggests that most studies use a graded burette and a chronometer [9–14]. Such measurement is simple and practical,

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but it is generally applicable only to steady state operation which lasts until the metered volume of fuel is expended. Metering fuel over arbitrary cycle is possible with a balance, which can be read continuously, or at least at the beginning and end of each segment of interest. Yilmaz and Morton [15] used balance and stopwatch, Fontaras and Samaras [16] an unspecified high-precision balance, and Soltic et al. [17] a commercial dynamic fuel balance (AVL). Real-time readings can also, at least in theory, be obtained by a Coriolis-type flow meter. Many other studies do not present fuel consumption results or do not give detail as to how fuel consumption was measured (i.e., [18–20]). With the exception of dynamic fuel balance used by Ref. [17], there is no account of automated online fuel consumption measurement procedure. Dynamic balance was found by this group not to be suitable, due to a concern of possible damage of this relatively expensive equipment by questionable quality experimental fuels, and a concern of its ability to cope with fuels normally solid or semi-solid at room temperature.

Also, sophisticated balances are typically a feature of well-equipped laboratories. It is apparent from the reviewed studies that many of them were conducted in low-budget laboratories, and the results of many more studies conducted with simplistic equipment never get published in peer-reviewed literature, but are shared online [21]. This is consistent with the observations by the first author that the use of vegetable oils is more favored in lower income rural regions and other places where the financial and other benefits of using vegetable oils outweigh the additional effort, such as switching to diesel fuel prior to engine shutdown.

This study investigates two relatively simple, relatively low-cost methods of determining fuel consumption of heated vegetable oils, which are very tolerable to fuel properties: dynamic measurements of the mass of the entire fuel tank, and inference from CO_2 emissions. As many published studies are based on small "garage-grade" exhaust analyzers, the data presented here was measured with a low-cost garage-grade analyzer.

This work was done as a part of the assessment of instrumentation needs for a newly constructed engine testing laboratory. It was additionally motivated by the desire to offer others a relatively simple, relatively low-budget method of determining fuel consumption of viscous biofuels.

2. Experimental

Tests were carried on Zetor 1505 (tractor engine, mechanically controlled inline fuel injection pump, 250 bar injector opening pressure, 300–1100 bar injection pressure) and Cummins ISBe4 (light truck engine, Common Rail, 400–1500 bar injection pressure) diesel engines operated on diesel fuel, neat fuel-grade biodiesel (methylesters of rapeseed oil, FAME), and heated fuel-grade rapeseed oil (RO). On the Zetor engine, the rapeseed oil was heated to maximum attainable temperature by passage through a heat exchanger with engine coolant. On the Cummins engine, the rapeseed oil was heated to a pre-set temperature in an electrically heated, thermostatically controlled stainless steel household pickling pot. RO was introduced into the engine via a thermally insulated dual-fuel system allowing online switching among fuels. Details of the engine, fuels, cycles, and performed tests and their results have been reported previously [7,22].

The Cummins engine was tested using World Harmonized Steady Cycle (WHSC) and using several version of Engine Stationary Cycle (ESC): ESC cycle as prescribed, ESC cycle with the duration of each mode prolonged to 4 min, and ESC cycle with variable duration of each mode with 1000 s and 2000 s total cycle duration. The duration of each mode was determined by the prescribed mode weight in order to allow for continuous sampling of particulate matter. The Zetor engine used arbitrary points including points specified by the Non-Road Steady Cycle (NRSC, also ISO-8178 schedule C-1).

2.1. Fuel consumption inference from instantaneous tank mass

The fuel tank was placed on a scale (65 kg range, 1 g resolution, Sartorius), the state of which was read at a period of 1 Hz via RS-485 interface. The scale calibration was periodically verified in 0–60 kg range with calibrated 10 kg weights, with departures within 2 g. The temporal and spatial variations in the earth gravitational field and fuel loss due to evaporation were assumed to be negligible. To minimize the effects of the fuel line weight, the fuel lines were suspended through an opening in the fuel tank, without having a physical contact with the tank itself. The buoyancy of the metal fitting at the end of the fuel line was constant as the metal fitting was submerged in fuel at all times. The change in the volume of the submerged part of the fuel line (approximately 14 mm outer diameter, 8 mm inner diameter) was estimated to be 1.0–1.5 cm^3 per 1 dm^3 change in tank fuel volume and was neglected, resulting in a 0.1–0.15% error consistent among all fuels.

2.2. Fuel consumption inference from CO_2 emissions in raw exhaust

The inference of fuel consumption from CO_2 emissions is based on measured mass emissions of CO_2, known carbon content of fuel, and several assumptions and simplifications. The mass emissions of CO_2 were determined as a product of instantaneous molar (volumetric) concentration of CO_2 in the raw exhaust gas, and instantaneous molar exhaust flow. As exhaust flow is difficult to measure directly at a reasonable accuracy, the exhaust flow was inferred from the measured intake air flow and known composition of the exhaust gas.

The intake air mass flow was measured by a thermal mass flow meter (model 620, Sierra Instruments). It was converted to molar flow using molecular weight of air of 28.9 g/mol. The concentration of CO_2 in the exhaust gas was measured by garage-grade (VMK Ltd.) and laboratory (Uras, Hartmann & Braun) non-dispersive infra-red (NDIR) analyzers. In both analyzers, the sample was cooled, the condensate was removed, and the sample was subsequently reheated and passed through the analyzer. In the laboratory analyzer, the sample was cooled to 4 °C, while in the garage-grade analyzer, the sample was cooled to ambient room temperature, for which 20 °C was taken as a representative value. It was therefore assumed that the CO_2 concentrations were measured in sample containing 0.81% (laboratory analyzer) and 2.31% (garage-grade analyzer) water vapor. All data presented here were taken from the garage-grade analyzer.

The inference of exhaust flow from the intake flow and known exhaust gas composition was based on the following assumptions and simplifications about molar flow of exhaust relative to the molar flow of intake air:

1. Dry exhaust flow is lower than intake air flow by concentration of water vapor in intake air; wet exhaust flow is unchanged.
2. Exhaust flow is unchanged by oxidation of fuel and lubricating oil to CO_2 and by losses of fuel to engine lubricating oil.
3. Exhaust flow is higher by one half of the molar flow of carbon monoxide and by the molar flow of gaseous hydrocarbons originating from combustion of fuel and lubricating oil.
4. Exhaust flow is lower by blow-by losses if such are not recirculated into the intake.
5. Effects of formation of PM and of storage of volatiles in the engine and their reentrainment are negligible.
6. Dry exhaust flow is lower by one half of the flow of combustion generated water; wet exhaust flow is higher by one half of the flow of combustion generated water.