Availability Analysis of Alternative Fuels for Compression Ignition Engine Combustion

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Abstract. Modeling of engine heat release from in-cylinder pressure is a common practice for characterizing engine combustion. Fuel property variation induces changes in engine performance, which can be categorized through heat release modeling. One under-utilized form includes an availability analysis that links changes in fuel properties to the amount of availability extracted as work or lost through inefficiencies. Here, a diagnostic heat release model is used to catalogue both the 1st and 2nd Law behavior of numerous alternative fuels. Conventional engine combustion using diesel, biodiesel, renewable jet fuel, and waste-plastic derived diesel are studied, alongside dual-fuel operation of compressed natural gas (with diesel) and synthesis gas (with biodiesel), allowing for the exploration of combustion with respect to changing fuel properties. In particular, more ideal fuel mixing is generally reflected directly in the 2nd Law efficiency. However, high viscosities largely result in a later availability addition that is not extracted as work. While this availability would be wasted at exhaust blowdown, deliberately increasing later temperatures may be useful if paired with exhaust heat recovery systems. Overall, the 2nd Law model presents these tradeoffs more clearly than a traditional 1st Law analysis; thus, its further use may be warranted in concert with advanced engine combustion modes.

Keywords: Availability · Heat release · Alternative fuels · Dual-fuel

1 Introduction

The effects of fuel properties on combustion are a central aspect of engine testing and a common tool for this exercise is to utilize the 1st Law of Thermodynamics to create an engine-out rate of heat release (RHR) model [1]. In particular, the 1st Law analysis is useful for identifying the relative amounts of premixed- and diffusion-dominated combustion. A lesser-utilized alternative is to employ the 2nd Law of Thermodynamics often known as an availability analysis. This model is similar to the 1st Law analogue, but with the important addition of entropy generation [2]:

$$\frac{dA_g}{d\theta} = \frac{dA_c}{d\theta} - \left(\frac{dA_w}{d\theta} + \frac{dA_{ht}}{d\theta} + \frac{dA_{ir}}{d\theta} \right) \tag{1}$$

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where $dA/d\theta$ refers to the rate of change of availability with respect to engine crank angle, and the subscripts correspond to the availability retained by the exhaust gas ($_g$), added by combustion ($_c$), extracted as work ($_w$), lost by heat transfer through the cylinder walls ($_{ht}$), or destroyed by internal irreversibilities ($_{ir}$) by entropy generation [2].

Generally, the 2nd Law analysis is often passed over in favor of the relatively simpler 1st Law RHR analysis. For compression ignition (CI) engines, this is at least partly due to the relative consistency of engine combustion, and the degree to which conventional CI combustion is understood. However, different fuels will often result in changing performance due to dissimilar fuel properties [3]. The most common example of this is in exchanging biodiesel for ultra-low sulfur diesel (ULSD), where the increased viscosity of biodiesel generally inhibits fuel vaporization and atomization, while its higher Cetane Number (CN) and greater oxygen content results in a shortened ignition delay [1, 4]. In turn, this requires re-optimization of the engine's injection strategy to maintain peak efficiency [5]. While this recalibration was relatively difficult to achieve with older mechanical injection systems, the advent of electronic injection systems has made CI fuel-flexibility significantly more feasible [6]. Moreover, this opens up an exploration of fuels with more divergent properties. Included in this are recycled or alternative renewable fuels. For instance, the pyrolysis of waste plastic products can be used to create a liquid hydrocarbon fuel similar to petroleum diesel [7]. Furthermore, while biodiesel itself cannot generally be used in aircraft turbines, the feedstocks used to create biodiesel can alternatively be run through a hydrotreating process to generate an analogue to jet fuel [3].

Finally, electronic injection has enabled control over CI engine combustion to allow for advanced usage of gaseous fuels [8]. Normally, methane-rich fuels (e.g., compressed natural gas aka CNG) cannot be utilized as-is in a CI engine without modifications or new hazards [8]. As an alternative, gaseous fuels can be used in a relatively unmodified CI engine through dual-fuel combustion, whereby fuel is added to the intake and ignited by a direct-injected liquid fuel, reducing efficiency but lowering fueling costs [8]. Dual-fuel combustion also presents the ability to reutilize waste products and unique feedstocks, namely synthesis gas (syngas) derived from the glycerin co-product of biodiesel production [9, 10].

Regrettably, the properties of these alternative fuels can vary widely preventing direct integration into existing systems. Specifically, fuels derived from vegetable oils generally see high amounts of variation depending on the feedstock utilized [3, 4]. Similarly, waste plastic derived diesel is prone to vary based on the methods and mixture of plastics employed in the pyrolysis process [7]. Furthermore, syngas is subject to feedstock and production differences [10], and even established products (e.g., CNG) will often deviate between regions [8]. Overall, this leads to difficulties in fuel studies, as engine researchers must utilize a model that is receptive to these changes.

As a result, this paper explores the use of a diagnostic 2nd Law model to demonstrate the diverse effects of fuel properties on engine combustion while highlighting how it is able to identify the phenomena associated with these properties. In particular, variations in fuel density, viscosity, CN, and energy content and their relation to engine performance are observable through the lens of the 2nd Law model going beyond what is achievable with the 1st Law analysis alone.

2 Experimental Setup and Procedure

The investigation of these various fueling modes was accomplished on a modified naturally-aspirated Yanmar L100v air-cooled single-cylinder CI engine, with a compression ratio of 21.2 and a displacement of 435 cubic centimeters. For brevity, the information included herein is that which is most relevant to generalized operation and testing, and a thorough description (including part numbers) can be found in prior work [6]. The mechanical fuel injection system has been replaced with an electronic system, including a Bosch MS15.1 Diesel ECU, allowing injection variation at a resolution of 0.02° of crank angle (DCA), and pressurized by an externally-powered Bosch CP3.2 fuel pump. The engine's built-in Exhaust Gas Recirculation system has been blocked. Speed and load control of the engine is accomplished via a DyneSystems, Inc. Dymond Series 12 hp alternating current dynamometer, and engine torque is logged with a FUTEK torque transducer. The flowrate of intake air is measured via a Merriam laminar flow element and an Omega differential pressure transducer. Liquid fuel consumption is established by a Micro-Motion Coriolis flow meter. In-cylinder pressure is measured using a pressure transducer and crank-angle encoder at a resolution of 0.2 DCA for 60 consecutive thermodynamic cycles. The liquid fuels utilized herein are soybean biodiesel, renewable hydroprocessed jet fuel, and a fuel derived from waste plastic, along with standard ULSD. These fuels present a wide variety in fuel characteristics as illustrated in Table 1 [3, 7, 10, 11].

Table 1. Liquid fuel thermodynamic properties [3, 7, 10, 11].

Fuel Characteristic	Ultra-Low Sulfur Diesel	Soybean Biodiesel	Renewable Jet Fuel	Waste Plastic Synthetic Diesel
Density [kg/m^3]	837.58	875.58	758.54	800.70
Kinematic Viscosity [cSt]	2.740	4.218	1.542	2.970
Cetane Number [-]	48.61	48.10	68.80	71.88
Lower Heating Value [MJ/kg]	45.60	39.88	46.25	46.29

For dual-fuel testing, two gaseous fuels were chosen (see Table 2): a methane-rich CNG mixture relying on ULSD for a pilot ignition [8, 11] and a hydrogen-rich mixture mimicking syngas derived from glycerin with a soybean biodiesel pilot [10]. Gaseous fuel is fed into the system through a Brooks thermal mass flow controller at 50 psi$_g$ from compressed gas cylinders [6], and is then added to the intake via a mixing box upstream of the intake to produce a relatively homogeneous fuel-air mixture [12]. Fuel flow is categorized through the relative flowrates of gaseous and liquid fuels on an energy-rate-basis, known as the Energy Substitution Rate (*ESR*) [8, 11]:

$$ESR = \frac{\dot{m}_G Q_{LHV_G}}{\dot{m}_G Q_{LHV_G} + \dot{m}_L Q_{LHV_L}} \times 100\% \qquad (2)$$

where the term $\dot{m}$ refers to the mass flow rate, Q_{LHV} indicates the lower heating value, and $_G$ and $_L$ pertain to the gaseous and liquid fuels, respectively. For brevity, this paper focuses on maximal gaseous fuel usage achievable in the flow controller; i.e., 85% *ESR* for CNG-ULSD operation and 30-35% *ESR* for Syngas-Biodiesel operation [8, 11, 13].

Table 2. Gaseous fuel thermodynamic properties [8, 10].

Constituent/Property	Compressed Natural Gas	Hydrogen Rich Syngas
Hydrogen [%]	–	28.70
Methane/Ethylene/Ethane/ Propane/Isobutane [%]	92.00/–/3.50/0.80/0.15	5.10/4.30/2.30/–/–
Nitrogen [%]	2.85	25.90
Carbon Monoxide [%]	–	16.00
Carbon Dioxide [%]	0.70	17.70
Heating Value [MJ/kg]	51.62	10.75

In all testing, combustion timing was normalized by shifting the liquid fuel injection timing to align the peak pressure with that of operation with ULSD [5]. All testing was accomplished under steady-state conditions at 1800 RPM. Engine performance data were logged over the course of 120 s at a sampling rate of 20 Hz. The engine data presented herein correspond to test results at increments of 25% of engine load, ranging from 0% (idle) to 100% of rated engine load (18.0 N-m). However, pressure and 1st Law behavior is limited to 50% and 100% of rated load, as these loads demonstrate both premixed- and diffusion-dominated combustion, respectively [1]. Furthermore, the performance data were used to calculate time-averaged testing results, error analysis, and to generate 1st and 2nd Law Heat Release information [1, 2].

3 Results and Discussion

The pressure traces at 50% and 100% of rated load can be seen in Fig. 1. At both loads, ULSD and biodiesel produced analogous pressure behavior, thanks to their respectively similar fuel characteristics. Increasing the CN, as seen with the waste plastic and renewable jet fuels, lessened premixed combustion; hence, lower peak pressure. Finally, the dual-fueling regimes displayed similar or worsened pressure behavior at lower loads, and universally better performance at higher loads. This was due to two competing effects of the gaseous fuels; a difficulty in igniting, even in the high-temperature environment, and a preference for large degrees of premixed combustion once ignited thanks to the more homogeneous conditions in the cylinder.

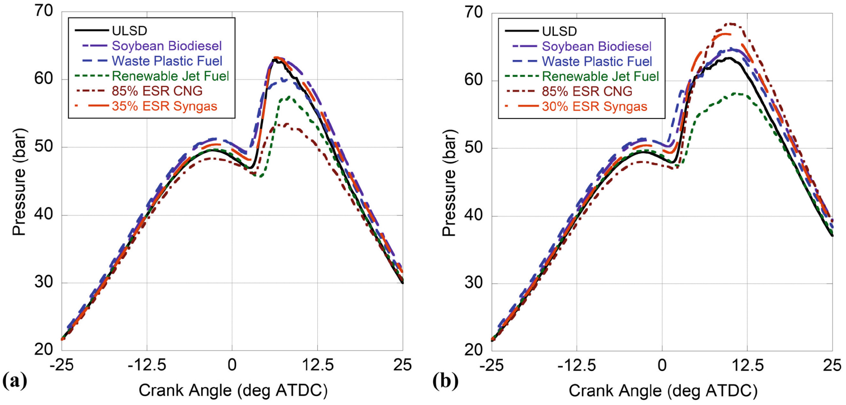

Fig. 1. In-cylinder pressure traces for operation at (a) 50% and (b) 100% of rated load.

The computed RHR for operation at 50% and 100% engine load are shown in Fig. 2, and largely match the behavior seen in the pressure results. Specifically, soybean biodiesel performs most similarly to ULSD, with only a slightly earlier and lower premixed spike, and somewhat worsened diffusion burn (owing to its higher viscosity inhibiting fuel breakup). Comparatively, the renewable jet and waste plastic fuels experienced lower premixed spikes. Here, the high CNs of these fuels may result in them igniting too quickly, prior to there being enough fuel in the cylinder to burn with a significant premixed spike. In the case of the renewable jet fuel, this is worsened by its respectively low viscosity that shortens the ignition delay. Finally, both dual-fuel tests produced higher premixed spikes, owing to the increased fuel-air homogeneity in-cylinder; however, the CNG-ULSD testing illustrates a growth in diffusion burn at high load as the engine struggles to combust large amounts of methane.

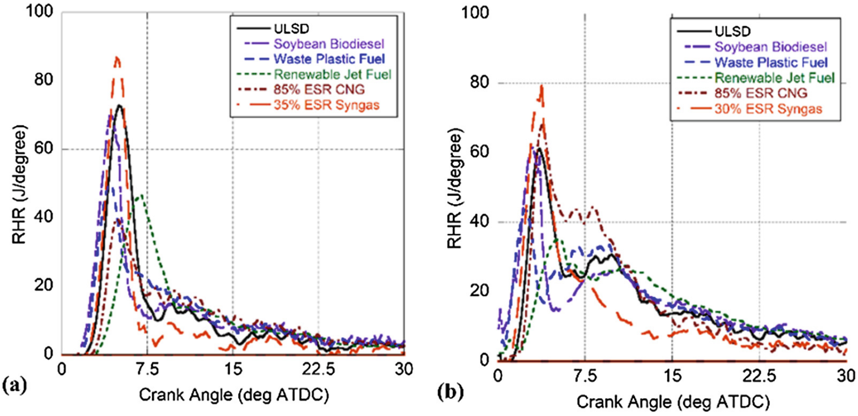

Fig. 2. 1st Law RHR for operation at (a) 50% and (b) 100% of rated load.

With respect to the 2nd Law analysis, the efficiency (Fig. 3a) primarily reflects the ease of fuel/air mixing, with the least viscous liquid fuel (renewable jet) and most homogeneous fueling mode (CNG-ULSD) providing the best operation; whereas, the reduced energy content and higher viscosity of biodiesel results in (largely) the lowest efficiency. In regards to heat transfer losses, cooler combustion leads to fewer losses as less thermal availability leeches out of the cylinder (Fig. 3b). For conventional or near-conventional (i.e., low-*ESR* dual-fuel) combustion, the reduced temperatures principally result in more availability destruction within the cylinder (Fig. 3c). Generally, the authors have found it is advisable to have hotter in-cylinder temperatures to retain availability, which will offset losses from heat transfer [2, 13, 14]. The final pathway for losses is the availability retained by the working fluid in Fig. 3d. Here, higher combustion temperatures while increasing the energy produced during the expansion phase (i.e., diffusion burn) results in a greater amount of availability retention by the exhaust that is subsequently lost to the atmosphere without being utilized. However, if the engine were to be paired with an exhaust heat recovery system [15], this enhanced exhaust availability could promote a secondary work extraction.

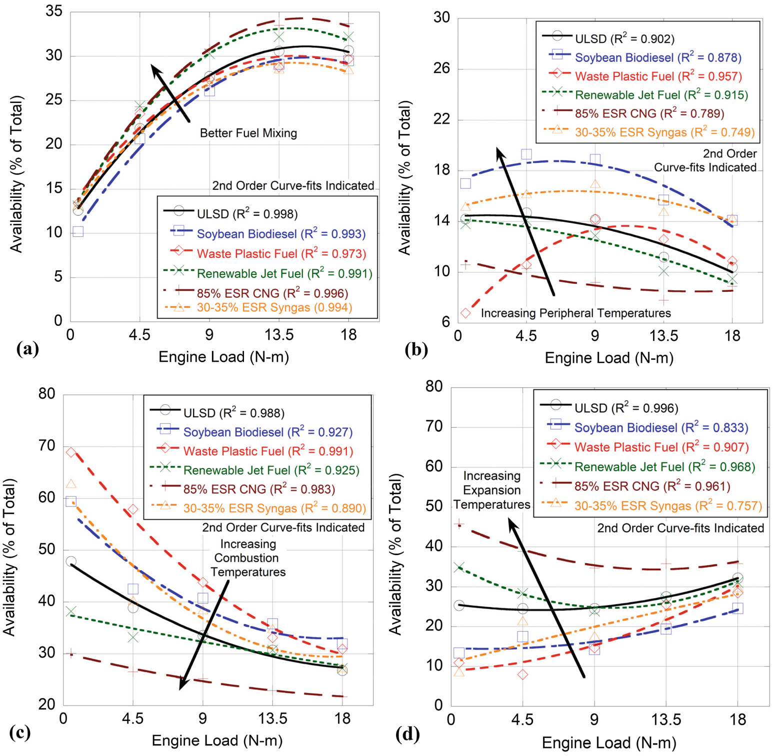

Fig. 3. Percentages of total availability (a) extracted as work (2nd Law Efficiency), (b) lost to heat transfer, (c) lost to entropy generation, or (d) retained by the exhaust gas.

Of note, high-*ESR* dual-fuel operation sees a trend that seems to contradict the prior discussion; i.e., lower entropy generation *and* reduced heat transfer losses. This type of operation may result in flame propagation; thus, flame quenching in the periphery of the cylinder [11, 16, 17]. This could result in relatively high local temperatures (reducing entropy generation) and low global temperatures (mitigating heat transfer losses). Furthermore, decreases in heat transfer losses have been observed in RCCI combustion as opposed to other low-temperature combustion modes, thanks to the relative inhomogeneity of RCCI operation (particularly in comparison to HCCI) [18, 19]. This highlights the benefits of a 2nd Law analysis that is not immediately seen in a 1st Law examination. Specifically, not only do dual-fuel modes promote higher degrees of premixed combustion (1st Law), but they also may be more adept at retaining unused availability in the working fluid (2nd Law) in some cases, making them more attractive than liquid fuels if exhaust heat recovery is considered.

4 Conclusions

The variety of fueling modes for CI engines necessitates a broader understanding of the links between fuel properties and combustion phenomena. In particular, fuel viscosity, energy content, CN, and fuel density all impact the degree of premixed- and diffusion-dominated combustion. Furthermore, advanced operational modes (e.g., RCCI) have pushed CI engines far from their designed combustion regimes. While traditional 1st Law heat release modeling remains a vital tool, more diagnostic options are required. Hence, availability modeling provides a means to measure engine efficiency in a manner not present in the 1st Law model. Overall, 2nd Law efficiency is tied to the ability of the engine to produce a homogeneous fuel-air mixture, and this homogeneity can be increased either through lowered fuel viscosity to promote fuel breakup, or by using gaseous fuels to encourage earlier mixing. Furthermore, combustion temperature is generally reflected in two competing segments of the 2nd Law model. Specifically, higher temperatures promote heat transfer losses while also maintaining a greater temperature difference between the cylinder and the ambient; hence, limiting losses due to internal irreversibilities. Moreover, raised temperatures during expansion (from diffusion burn) can lead to higher amounts of exhaust gas availability. Finally, dual-fuel operation at high ESRs presents unique opportunities by enhancing premixed combustion. However, this may lead to flame propagation and quenching subsequently creating locally high temperatures (limiting entropy production and retaining availability) while also having globally low temperatures (minimizing losses to heat transfer). As a result, dual-fuel usage may promote a greater overall efficiency, particularly if paired with exhaust heat recovery. Here, this effect is only observed using 2nd Law modeling.

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