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Statistical Analysis of Engine System-Level Factors for Palm Biodiesel Fuelled Diesel Engine Responses

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Abstract

In this study, a 0D/1D gas dynamics numerical model of a single-cylinder, 4-stroke diesel engine is used to simulate entire engine cycle from air intake to exhaust product. The engine model is successfully validated against experimental data of both palm biodiesel and fossil diesel for pertinent combustion parameters such as pressure trace, rate of heat release and ignition delay period. This allows rapid system-level thermodynamics simulation of the entire engine. From it, 2000 cases generated from a combination of 13 engine parameters from within the combustion chamber, fuel injector and engine gas flow path, each with four levels were simulated and statistically analysed. Statistically significant independent main effects for outputs such as NO_x, soot, brake specific fuel consumption and indicated power were identified using analysis of variance. Eight predictor equations to correlate the engine parameters to the outputs for both palm biodiesel and diesel were also formulated. In all, this study demonstrated the use of a validated simulation model for large parametric studies of engine parameters through the use of statistical analysis. The outcomes of this study can help in the design and optimisation of biodiesel fuelled diesel engines.

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Keywords: Biodiesel; Diesel; Palm oil; 0D/1D simulation; ANOVA; Predictor equations

1. Introduction

The growing environmental deterioration and petroleum depletion concerns have led to the search for an alternative fuel. The requirements for the alternative fuel sources include being renewable, economically feasible and environmentally friendly, while being compatible with present-day diesel

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engine infrastructure [1]. In the context of diesel engines, biodiesel emerged as the front runner for mainstream adoption. This has led to various experimental studies of to improve biodiesel usage in diesel engines, such as preheating [2], additives [3] and improving cold-flow properties [4]. Additionally, there are also attempts to predict and optimise the combustion performances and emissions characteristics of biodiesel-fuelled diesel engine through artificial neural networks [5], thermodynamic model studies using Taguchi method [6] and 1D fluid dynamics model [7]. However, research work combining the validated 0D/1D gas dynamics models with large set of operating conditions for engine system-level optimisation and prediction is lacking.

In this paper, an experimentally validated 0D/1D numerical model is used to simulate a single-cylinder 4-stroke diesel engine fuelled with biodiesel and diesel. Regression analysis is employed to identify statistically significant independent factors for the formulation of predictor equations for pertinent diesel engine outputs such as emissions concentration, fuel consumption and indicated power.

2. Experimental setup

2.1 Engine setup

A single-cylinder, 4-stroke, direct injection *Yanmar L70* diesel engine with a maximum rated output of 4.5 kW at 3,000 rpm was utilised to obtain the set of experimental data required for the validation of the 0D/1D numerical simulation. The engine has a compression ratio of 20.0. The has a swept volume of the engine of 0.32 L, bore of 78 mm and stroke of 67 mm. A 30 kW eddy current dynamometer was coupled to the diesel engine for load generation and measurement. A high-speed *Dewe-5000* data acquisition system was used for data storing and monitor. It was linked to the *Kistler 6061B* piezo-electric pressure transducer to sample the in-cylinder pressure with respect to the engine crank angle. Fuel consumption was measured via the duration required for the engine to consume 15 mL of fuel gauged with a burette. A K-type thermocouple located at the downstream location of 200 mm from the exhaust muffler with no dilution was used to determine the exhaust gas temperature. Exhaust gas emissions were sampled using an *EMS 5002* gas analyser. The resolutions of the gas analyser for the various gases are 0.01% vol., 0.1% vol., 1 ppm vol., 0.01% vol. and 1 ppm vol., for CO, CO_2, NO, O_2 and UHC, respectively.

2.2. Experimental fuel

The fuels used in the experiment are refined normal grade palm methyl ester (PME), sourced from *Carotino Sdn. Bhd*. Palm based biodiesel is selected as PME has near equal saturated-unsaturated fatty acid methyl ester ratios, allowing for the characteristics of both chemical compound classes to be equally represented. This makes PME a suitable choice to represent biodiesel in general. Commercial grade low sulphur fossil diesel obtained from a local *Petronas* petrol station is used as baseline.

3. Numerical model

Commercial 0D/1D gas dynamics software, *AVL Boost* was used to numerically simulate diesel engine cycles. The simulation model was built based on the *Yanmar* L70 engine, from the air intake pipe to the exhaust pipe as shown in Figure 1. The AVL MCC combustion model, which quantitatively predicts the rate of heat release (ROHR) based on the fuel in the cylinder and the turbulent kinetic energy generated during fuel injection, is used with the classical fuel model. Properties pertinent to the fuel models such as molar mass, lower heating value, stoichiometric air-fuel ratio, elementary ratio, enthalpy and entropy polynomial coefficients for PME and diesel were used as input. For engine friction, the SLM friction model is selected due to its suitability for the relatively low operational temperature and speed of the engine. The friction model factors in friction in the crankshaft, piston group, valve train and auxiliary losses. The AVL 2000 is selected as the heat transfer model due to its good approximation of the volumetric efficiencies for relatively low engine speed operations [8].

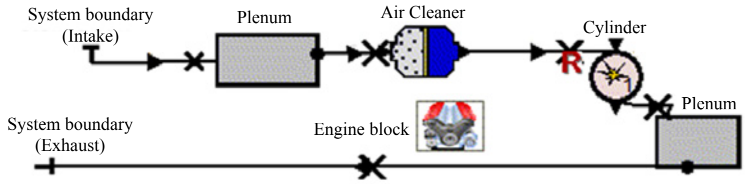

Fig. 1. Engine model schematics.

The model was validated using the experimental data obtained as shown in Fig. 2. Key combustion parameters such as the heat release rate and pressure trace were compared for both biodiesel and the baseline diesel. The simulated engine has a maximum percentage error below 2%, with the timing of the peak pressure being accurate to within 2° CA. The ignition delay periods are also well predicted. This meant that the engine-level gas dynamics and in-cylinder combustion phases are well replicated.

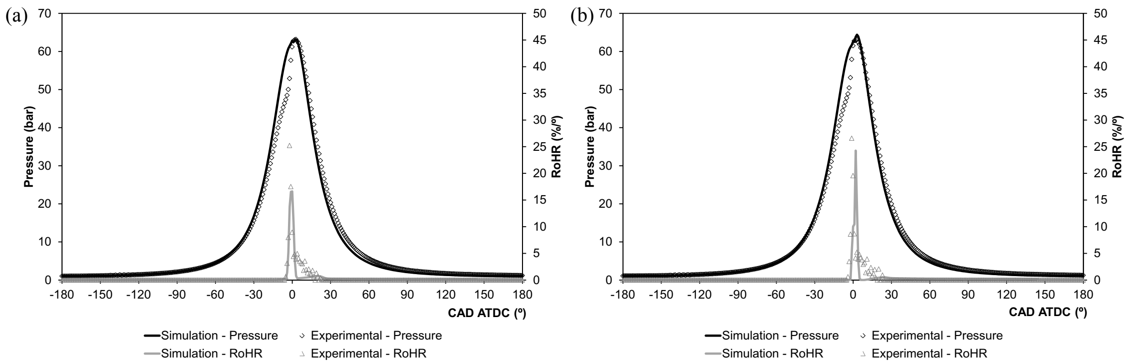

Fig. 2. Validation cases for (a) PME (b) diesel at 2000 rpm

4. Methodology

The validated 0D/1D engine model was used to simulate 1000 cases randomly selected from the combination of 13 independent factors and four levels as specified in Table 1. The output of the simulation cases such as NO_x, soot, brake specific fuel consumption (BSFC) and indicated power, are statistically evaluated to determine the significant independent factors. The 1000 data points for each fuel type were tested for normality to ensure its approximation into a linear pattern consistent with a normal distribution. Residuals were also compared against order to satisfy the independence assumption. Statistical outliers are removed to improve the coefficient of determination to better fit the regression model. From there, the independent factors are considered statistically significant through an analysis of variance (ANOVA) if the P-value is below 0.05, signifying a confidence level of above 95%. From it, linear predictor equations are formed using regression analysis.

Table 1. Factors and levels for the simulation test matrix.

Factors	Abbreviation	Levels
Engine speed (rpm)	ES	2000, 2300, 2600, 2900
Air-to-fuel ratio	AF	11, 17, 23, 29
Filter element length (mm)	FE	25, 29, 34, 39
Compression ratio	CR	16, 18, 20, 22
Injector holes	IH	4, 5, 6, 7
Hole diameter (mm)	HD	0.2, 0.4, 0.6, 0.8
Rail pressure (bar)	RP	1500, 1800, 2100, 2400
Injection timing (CA degree ATDC)	IT	-18, -14, -10, -6
In-cylinder swirl ratio	SR	1.5, 1.8, 2.1, 2.4
Exhaust inner valve seat (mm)	EI	21.5, 27.0, 32.5, 38.0
Exhust valve clearance (mm)	EC	0.35, 0.39, 0.43, 0.47
Intake inner valve seat (mm)	II	22.0, 27.5, 33.0, 38.5
Intake valve clearance (mm)	IC	0.17, 0.21, 0.25, 0.29

5. Results and discussion

Table 2. Main effects and their significance and relative magnitudes.

Factors	NO_x		Soot		BSFC		Indicated power	
	PME	Diesel	PME	Diesel	PME	Diesel	PME	Diesel
ES	+ +	+	+ + +	+ + +	+ + +	+ + +	+ + + +	+ + + +
AF	+ + + +	+ + +	+ + + +	+ + + +	+ + +	+ +	+ + + +	+ + + +
FE	-	-	-	-	-	-	-	-
CR	+ +	+	-	+	+ +	+ +	+ +	+
IH	+ + +	+ +	-	-	+ + +	+ +	+ +	+ +
HD	+ + + +	+ + + +	+ + +	+ +	+ + +	+ + + +	+ + +	+ + + +
RP	+	-	+ + +	+ +	+ +	+ +	+ +	+ +
IT	+ +	+	+ + + +	+ + +	+ + +	+ + +	+ + +	+ + +
SR	-	-	-	+	-	-	-	+ +
EI	-	-	-	-	-	-	-	-
EC	+	-	-	-	-	-	-	-
II	-	-	+	-	-	-	-	-
IC	-	-	-	-	-	-	-	-

The statistically significant main effects were first determined for all of the fuel-output combinations as shown in Table 2. The '+' sign denotes that the main effect is significant, while '-' denotes otherwise. Every additional '+' sign an additional order of magnitude higher, as calculated from the ANOVA's F-value.

5.1. Predictor equations

As the main NO_x formation pathway is through thermal NO formation, the peak in-cylinder temperature and availability of air at the high temperature regions would be the main determinant of NO_x concentration. The peak in-cylinder temperature is determined by the ignition delay period, which in turn is affected by fuel type and degree of fuel atomisation, leading to postulations that NO_x is heavily influenced by the fuel injector parameters. Thus, hole diameter, AFR and injector holes are the major factors affecting the engine-out NO_x concentration. The predicted engine-out NOx emissions are formulated as Eq. (1) and Eq. (2) for PME and diesel, respectively. The accuracy of the predictor equations is statistically expected to be 79.37% and 78.87% for Eq. (1) and Eq. (2), respectively.

$$NO_x\,[g/kWh] = -38.17 - 0.005821\,ES + 1.5755\,AF + 0.34\,CR + 2.686\,IH + 41.51\,HD + 0.001996\,RP - 0.2852\,IT + 12.34\,EC \quad (1)$$

$$NO_x\,[g/kWh] = -13.8 - 0.0018\,ES + 0.763\,AF + 0.1749\,CR + 1.261\,IH + 40.447\,HD - 0.4674\,IT \quad (2)$$

Soot is formed and oxidised during the combustion process. For oxidation of soot to occur, there must be sufficient oxygen molecules and in-cylinder residence time for the mixing between soot and oxygen to occur. Based on the regression analysis, AFR, injection timing and engine speed are the major factors affecting engine-out soot emissions. These factors all influence the overall fuel and oxidiser composition, and also the duration for in-cylinder soot oxidation to occur. The predicted engine-out soot emissions are formulated as Eq. (3) and Eq. (4) for PME and diesel, respectively. The accuracy of the predictor equations is statistically expected to be 88.53% and 65.54% for Eq. (3) and Eq. (4), respectively.

$$Soot\,[g/kWh] = -0.187 + 0.001767\,ES - 0.2727\,AF + 3.488\,HD - 0.001035\,RP - 0.29902\,IT - 0.01199\,II \quad (3)$$

$$Soot\,[g/kWh] = 5.551 + 0.001683\,ES - 0.30494\,AF - 0.0567\,CR + 1.355\,HD - 0.001018\,RP - 0.2878\,IT - 0.463\,II \quad (4)$$

The BSFC of an engine is a good indication of the engine efficiency. It is primarily a function of the engine operating conditions. From the regression analysis, the injector hole diameter, engine speed and injection timing are the major factors influencing BSFC. While engine speed and injection timing determine the engine operating conditions, the injector hole diameter would precede these factors by influencing the combustion quality, as atomisation of fuel which determines the fuel-air mixing and controlling all the phases of combustion is affected. The predicted BSFC is formulated as Eq. (5) and Eq. (6) for PME and diesel, respectively. The accuracy of the predictor equations is statistically expected to be 72.38% and 65.21% for Eq. (5) and Eq. (6), respectively.

$$BSFC\,[g/kWh] = 287 - 0.822\,ES + 46.06\,AF + 36.39\,CR + 110.91\,IH + 1117.1\,HD + 0.2903\,RP + 40.12\,IT \quad (5)$$

$$BSFC\,[g/kWh] = 683 - 0.5538\,ES + 10.11\,AF + 24.57\,CR + 59.17\,IH + 1288.9\,HD + 0.1787\,RP + 30.26\,IT \quad (6)$$

Similar to BSFC, indicated power is mainly a function of operating conditions. As such, the major effects for indicated power are similar to that of BSFC, including engine speed, AFR, injector hole diameter and injection timing. They are all the main determinant of the combustion quality throughout the combustion phases and engine operating conditions. The predicted indicated power is formulated as Eq. (7) and Eq. (8) for PME and diesel, respectively. The accuracy of the predictor equations is statistically expected to be 86.42% and 78.65% for Eq. (7) and Eq. (8), respectively.

$$Power\ [kW] = 1.319 + 0.002356\ ES - 0.15679\ AF - 0.04249\ CR - 0.1046\ IH - 1.8394\ HD - 0.000281\ RP - 0.07753\ IT \quad (7)$$

$$Power\ [kW] = 2.533 + 0.002536\ ES - 0.14677\ AF - 0.0338\ CR - 0.1319\ IH - 3.772\ HD - 0.000342\ RP - 0.07389\ IT + 0.242\ SR \quad (8)$$

6. Conclusions

In this study, an experimentally validated 0D/1D numerical model was developed for a single-cylinder diesel engine fuelled with biodiesel and diesel fuels. Using the model, 2000 cases generated from the combination of 13 system-level and in-cylinder parameters at four levels each were statistically analysed using regression analysis. The independent main effects which are statistically significant were identified for each of the output parameters. NO_x is found to be influenced by injector-related parameters, while soot is affected by oxygen availability and in-cylinder residence time. Engine performance outputs such as BSFC and indicated power are influenced by operating conditions, although they depend on the combustion quality. Eight linear predictor equations were obtained for the outputs with statistically predicted accuracy range of 65-88%. It was found that the statistically significant factors are generally the same for both fuels, leading to the conclusion that the system-level engine parameters are equally important as fuel type in the optimisation of diesel engine emissions and performance.

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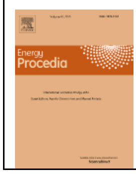

Biography

Cheng Tung Chong is currently a senior lecturer at Universiti Teknologi Malaysia, Malaysia. His research interests include biofuels, gas turbine, diesel engine and spray flame studies.