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Research article

Modeling of specific fuel consumption and emission parameters of compression ignition engine using nanofluid combustion experimental data

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ABSTRACT

This paper investigated the use of mathematical models in predicting the brake specific fuel consumption, and exhaust emissions of a diesel engine in terms of parameters such as load and volume fractions of Fe_3O_4 magnetic nanoparticles. Regression analysis was performed using the experimental data. The experiments were carried out by dispersing the Fe_3O_4 nanoparticles in the diesel fuel with the nanoparticle concentrations of 0.4 and 0.8 vol.%. Moreover, the experiments were performed under variable load conditions, for which a direct-injection diesel engine was employed. The predicted values obtained by the regression equations were compared with the values obtained from the experimental measurements. Analysis of variance (ANOVA) of the results at 95% confidence level showed significance in the developed mathematical models. Furthermore, the regression fitted models were able to predict the brake specific fuel consumption and emission characteristics with a correlation coefficient (R^2) in the range of 94%–98% within the domain of experimental variables. In addition, the nanofluid fuel with the nanoparticle concentration of 0.4 vol.% had an optimal value. The results also revealed a dramatic decrease in NO_x and SO_2 emissions, while a significant increase was observed in the CO emission and smoke opacity by adding magnetic nanoparticles in diesel fuel.

1. Introduction

Nowadays, design and improvement of diesel engines, fuel modification, exhaust gas treatment and alternative fuels are gaining much attention for better fuel economy, better performance and good toxic emissions control. Among these methods, the fuel modification is widely accepted by many researchers. The aim of the fuel modification is to improve the fuel consumption and emissions without requiring modifications to the engine, fuel injection or exhaust systems. The use of metal based additives for fuels was studied by majority of the researchers [1–11]. Hansen et al. [12] studied the combustion of ethanol-diesel fuel blend for engine performance, durability and emissions. They declared that ethanol-diesel blends were technically acceptable for diesel engines. Gürü et al. [13] reported a decline in the freezing point and the exhaust emission of the fuel by adding manganese to the diesel fuel. Metal based additives have many attractive features, however, they tend to easily sediment which is considered a restriction to the extensive application of these materials. The latest advances in nanoscience and nanotechnology have attempted to minimize such limitations by suspending nanometer-sized particles in fluids. There are a number of advantages in using nanoparticles as additives for fuels including less settling velocity of particles, low ignition delay time, as well as mechanical, thermophysical, optical, magnetic, and electrical properties. Tyagi et al. [14] reviewed the role of the Al and Al_2O_3 nanoparticle additives for the diesel fuel. The results obtained in their study indicated that the ignition possibility for the diesel nanoparticle mixture was higher than that of the pure diesel. Sadhik Basha and Anand worked at different dosing levels of alumina nano-additives 25, 50 and 100 ppm [15,16] and also they investigated CNT in the mass fractions of 25 and 50 ppm [17,18]. They found a significant improvement in the combustion efficiency with the reduction in the hazardous emissions. Fangsuwannarak and Triratanasirichai [19] investigated the combustion behavior of TiO_2 nanoparticles dispersed into palm biodiesel. They concluded that the most effective performance was obtained when the nano TiO_2 additive (0.1 by volume) was used. Moreover, the results indicated that the addition of the TiO_2 nanoparticle improved properties of the fuel such as increased cetane number, lower heating value, increased flash point and reduced kinematic viscosity. The use of cerium oxide nanoparticle with sizes of 10–20 nm at different dosing levels (20, 40, 60 and 80 ppm) to biodiesel [20] and with the size of 32 nm and dosing level of 25 ppm in neat diesel and diesel-biodiesel-ethanol blends [21] were reported. The performance and emission patterns of a four-stroke diesel engine were investigated by using the composition of ferrofluid and diesel fuel. The used ferrofluid contained the Fe_3O_4

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magnetic nanoparticles with the particle size of 10 nm and volume concentrations of 0, 0.4% and 0.8%. The results of this investigation showed that the combustion efficiency as well as the CO emissions were enhanced by adding nanoparticles to the fuel however, it decreased the NO_x emissions [22]. Kao et al. [23] investigated the performance of aqueous aluminum nanofluid in a diesel single-cylinder engine. The results showed that nanoparticles significantly increased the total combustion heat. Moreover, a significant reduction was also observed in the fuel consumption and emission concentration of NO_x and smoke. To present a comprehensive analysis on the performance characteristics of the engine, experimental studies must be conducted to determine the influence of input parameters on both the performance and exhaust emissions. In this regard, experimental measurements enhance money and time expenditure therefore, the application of simulations based on limited experimental data is very useful to predict performance characteristics of the engine in a wide range of conditions. Bamgboye and Hansen [24] used the linear regression analysis to create a regression relationship between the cetane number (CN) and fatty acid methyl ester (FAME) composition. In another study, a regression analysis was used to investigate the effect of biodiesel fuel on the brake power [25,26]. The response surface methodology was used successfully by Mumtaz et al. [27] to optimize biodiesel production using chemical and enzymatic transesterification of rice bran and sunflower oils. Mathematical modeling of performance and emission parameters of dual fuel diesel engine [28] and transesterification of *Jatropha curcas* seed oil was reported [29]. According to the literature, there is a few research on the application of the multi regression analysis in modeling the performance and emission parameters of the diesel engine with nanofluid fuels. Therefore, the aims of this research are: (1) regression modeling of performance and emission parameters in relation to volume fraction of nanoparticles and load. (2) Determining significant effect and contribution of each parameter of the model in the brake specific fuel consumption and exhaust emissions.

2. Materials and methods

2.1. Ferrofluid preparation

In the present study, two types of ferrofluid blends are prepared and their performances are then compared with the neat diesel. The ferrofluid presented by the Institute for Colorants, Paint and Coating which is composed of Fe_3O_4 nanoparticles with a mean diameter of 10 nm in diesel fuel base fluid in the original particle volume fraction of 5%, was used in this study. The synthesis approach of the aforesaid ferrofluid and its rheological properties have been found by Ghasemi et al. [30]. The viscosity and density of the nanofluid fuels were calculated based on an expression proposed by Aberoumand et al. [31–32]. Table 1 shows the properties of the employed fuels. In this study the treatments were: diesel fuel and nanofluid fuels (Fe_3O_4 magnetic nanoparticle in diesel fuel with concentration of 0.4 and 0.8% by volume, depicted as 0.4 vol.%NF and 0.8 vol.%NF).

2.2. Experimental measurements

The volume fractions of 0.4% and 0.8% of nanoparticles are prepared by mixing an original ferrofluid with the diesel fuel in a mechanical homogenizer. A single cylinder, naturally aspirated, four stroke, water-cooled, direct-injection diesel engine was employed for the experiment. The detailed specifications of this engine are given in Table 2. The engine was coupled to an electrical generator to apply the load. The fuel specific consumption and the exhaust emissions were measured at various engine loads at a constant engine speed of 2200 rpm. The engine was operated at four load levels as 0.8 kW, 1.6 kW, 3.2 kW and 4.2 kW load. The fuel consumption is measured using a burette and a stop watch. The brake specific fuel consumption was calculated by using the Eq. (1) and Eq. (2).

Table 1
Properties of the tested fuels.

Fuels	Viscosity ($mm^2\ s^{-1}$ at 40 °C)	Density (g/cm^3 at 15 °C)
Diesel	2.52	0.820
0.4 vol.%NF	2.90	0.835
0.8 vol.%NF	2.91	0. 851

Table 2
The specification of the engine.

Type of engine	ZS1125, single-cylinder, naturally aspirated, direct injection
Cycle	Four-stroke
Compression ratio	17.6:1
Cylinder bore	125 mm
Stroke	120 mm
Swept volume	1.473 L
Injection pressure	20 ± 0.49 MPa
Rated output	9 hp/2200 rpm
Cooling	Water cooled
Loading system	Electrical generator

$$M_f = Q_f \cdot p_f \quad (1)$$

$$SFC = M_f / p \quad (2)$$

where M_f is mass flow rate of fuel consumption (kg/h), Q_f is rate of fuel consumption (L/h), p_f is fuel density (kg/L), p is power (kW), and *SFC* is brake specific fuel consumption (kg/kW·h).

A K-type thermocouple is mounted on the exhaust pipe to measure the exhaust gas temperature. The exhaust emissions and smoke opacity were determined using a Testo 350 XL analyzer and a MDO2-LON smoke meter, respectively. A schematic of diesel engine test setup is shown in Fig. 1.

2.3. Multiple linear regressions

The regression models were used to predict the brake specific fuel consumption or emissions of ferofluied fuels given in Eqs. (3) to (6):

$$\text{Quadratic}: \quad y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \varepsilon \quad (3)$$

$$\text{Reduce Quadratic}: \quad y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \varepsilon \quad (4)$$

$$\text{Two Factor Interaction (2FI)}: \quad y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \varepsilon \quad (5)$$

$$\text{Linear}: \quad y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \varepsilon \quad (6)$$

where y is the brake specific fuel consumption or emissions of ferofluied fuels, x_1 is the nanoparticle concentration in vol.%, x_2 is the load, β_0 is the

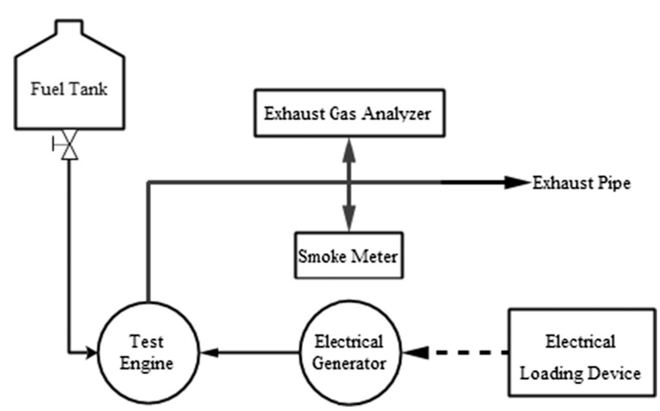

Fig. 1. Schematic layout of experimental set-up.