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Single zone combustion modeling of biodiesel from wastes in diesel engine

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HIGHLIGHTS

- ▶ Derive the biodiesel from restaurant waste.
- ▶ Predict a general model of combustion for diesel fuel and biodiesel from waste cooking oil.
- ▶ Apply the model on biodiesel produced from animal fat residues.

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ABSTRACT

Increasing interest in diesel engine technology and the continuous demand of finding alternate fuels and reducing emissions has motivated over the years for the development of numerical models, to provide qualitatively predictive tools for the designers. Among the alternative fuels, biodiesel is considered suitable and the most promising fuel for diesel engine. The properties of biodiesel from waste oils are found similar to that of diesel. In this present work, a unique single zone combustion model for diesel fuel and biodiesel was implemented to predict the cylinder pressure for the better understanding of combustion characteristics of different fuels tested in a diesel engine and also to predict the combustion and performance characteristics of the same engine running on different fuels. The single zone model coupled with a triple-Wiebe function was performed to simulate heat release between the period of IVC (inlet valve close) and EVO (exhaust valve open). This model also includes the submodels of intake and exhaust gases through the valves, ignition delay, burned fuel during the cycle and heat losses through walls to simulate all phases of combustion. The model calibration was performed using data from experiments on diesel fuel and biodiesel from waste cooking oil. Later the same model was used to simulate the combustion and the cylinder pressure of engine running on biodiesel derived from animal fat residues. Finally, cylinder pressure traces predicted by using single-zone model are compared to experimental pressure traces obtained from a diesel engine fuelled with diesel fuel and biodiesel.

1. Introduction

Diesel engine has gained the name and fame in serving the society in many ways. Its main attractions are ruggedness in construction, simplicity in operation and ease of maintenance. It has become quite popular in transportation and agriculture sector, because of higher brake thermal efficiency. Petroleum products derived from crude oil continue to be the major sources of energy for fuelling internal combustion engines all over the world. However, rapid depletion, rising prices, uncertain supplies and ever increasing requirement of petroleum and most importantly stricter emission norms have triggered an intensive research for fuel alternatives [1,2]. It is therefore important to explore the feasibility of substitution of diesel with an alternative fuel, which can be produced locally on a massive scale for commercial utilization. Hence, efforts are being made all over the world, to find out a suitable alternative fuel for the diesel engines [3–5]. Of the alternate fuels available, biodiesel from vegetable oils, waste vegetable oils and waste animal fat is attractive source of alternative fuel for diesel engines as they are renewable [6–8].

In general, the compression ignition engines are designed for diesel fuel. Using the same engine for biodiesel operation needs minor modifications on the engine operating conditions [9,10]. To avoid a corresponding increase in development time and money, engine manufacturers are continuously looking for ways to improve this development process. It is expected that, in the future, detailed multi-dimensional numerical simulations of the engine combustion process will play an increasingly important role in engine development. Modeling the operation of internal combustion engines gives the basic understanding of the physical and chemical phenomena that occur during different phases of the engine cycle [11–13]. The improvement of mathematical

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Nomenclature

Abbreviations

AFRs	animal fat residues
BD	biodiesel
DF	diesel fuel
EVO	exhaust valve opening
HRR	heat release rate
ID	ignition delay

Variables

A	flow area of exhaust/intake valves (m^2)
a	constant of Wiebe's law concerning the combustion efficiency
A_r	Arrhenius law constant
B	bore diameter (m)
BP	engine break power (kW)
C_1	constant of the Woschni's model
C_2	constant of the Woschni's model
C_d	discharge coefficient
C_v	specific heat at const. volume ($J\ g^{-1}\ K^{-1}$)
E_a	apparent energy of activation ($J\ mol^{-1}$)
h	enthalpy (J)
h_c	convection heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
k	constant of the ignition delay model
m	mass of gas mixture inside the cylinder (g)
M_w	constant of Wiebe's law concerning the combustion velocity

Greek

λ	ratio of the crank radius over the connecting rod length (m)
β_i	fuel fraction burned on the ith phase of combustion
$\Delta\theta$	the duration of combustion (°CA)
θ	crank position (°CA)
θ_0	the start of combustion (°CA)
τ_{id}	ignition delay (m s)
φ	equivalence ratio of the in-cylinder gas mixture
IVC	inlet valve closing
MIP	mean indicated pressure
SE	standard error
SOI	start of injection
SOC	start of combustion
WCO	waste cooking oil
n	constant of the ignition delay model
P	in cylinder pressure (Pa)
Q	heat (J)
R	universal constant of perfect gas ($J\ mol^{-1}\ K^{-1}$)
r	the gas mixture constant ($J\ g^{-1}\ K^{-1}$)
R^2	correlation coefficient
R_{cr}	critical pressure ratio
S	cylinders walls surface (m^2)
T	gas temperature (K)
u	internal energy (J)
V	volume of the combustion chamber (m^3)
W	mean gas velocity in the cylinder ($m\ s^{-1}$)
X_b	burned fuel fraction
S_p	mean piston speed ($m\ s^{-1}$)

Subscripts

a	intake air
comb	combustion
e	exhaust gas
i	ith phase of combustion
wall	walls of the cylinder

computing software increases their ability to solve more complicated equations.

Models of diesel engine combustion are divided into two groups: thermodynamic or zero-dimensional models and multidimensional models. Thermodynamic models are classified into two subgroups: single and multizone models. A single-zone model is often used if there is a need for a fast and preliminary analysis of the engine performance. In single-zone models the cylinder charge is assumed to be uniform in both composition and temperature, and first law of thermodynamics is used to calculate the mixture energy accounting for the enthalpy flux due to fuel injection. The fuel injected into the cylinder is assumed to mix instantaneously with the cylinder charge, which is assumed to behave as an ideal gas [14]. To use a single-zone model in the diesel case the model must be based on empirical heat-release laws. This approach needs a wide identification analysis. Thermodynamic models are used in several studies to compare the new diesel fuel and give a quick analysis of performance [15–20].

2. Preparation of biodiesel from waste cooking oil (WCO)

WCO used in this study is a current feedstock used in restaurants and it has the following composition: 45% of palm oil, 45% of sunflower oil and 10% of rapeseed oil. WCO was used to prepare French fries, meat and fishes. The biodiesel was prepared from WCO by an alkali-catalyzed process using caustic soda (NaOH) as a catalyst and methanol as an alcohol.

The reaction was carried out at 40 °C using 1% of sodium hydroxide and 6:1 methanol to oil molar ratio for 1 h as described in [21]. 1-l of WCO was involved in the reaction and the yield of biodiesel was 97%.

Animal fat residues (AFRs) used in this study were collected from fat traps. The biodiesel was prepared by a two-step acid catalyzed process. The reaction involved 3.6% and 1.8% w of 17 M sulfuric acid and 30% (w) and 10% (w) of methanol at 60 °C for 5 h and 1 h for the first and the second steps, respectively [22]. The reaction yield was 98%.

After a separation of the biodiesel and glycerol, biodiesel was washed by water in order to eliminate excess alcohol and residual catalyst and then dried by calcium chloride ($CaCl_2$). The important characteristics of biodiesel from WCO and AFR are given in Table 1.

3. Materials and methods

A single cylinder, four-stroke, air cooled, direct injection, constant speed, diesel engine developing power output of 7.5 kW at 2500 rpm was used for this work. Test engine specifications are

Table 1
Properties of waste cooking oil biodiesel (WCOBD) and diesel.

Properties	WCOBD	AFR	Diesel fuel
Kinematic viscosity (mm^2/s)	3.5–4.0	4.7–5.6	2.1
Density (kg/m^3)	0.87	0.87	0.84
Lower heating value (kJ/kg)	37,000	37,000	43,000
Chemical composition	$C_{18}H_{36}O_2$	$C_{18}H_{36}O_2$	$C_{21}H_{44}$
Stoichiometric air/fuel ratio	12.5	12.5	15.0
Cetane number	54	53	50