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Full Length Article

Predictive model of the diesel engine operating in dual-fuel mode fuelled with different gaseous fuels

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ABSTRACT

In this work, a predictive model has been developed in order to investigate the dual-fuel diesel engine operating on different gaseous fuels. A thermodynamic single zone modeling of the engine in dual-fuel (DF) mode was carried out to understand the characteristics of combustion and to predict the cylinder pressure. Tow primary fuels were tested, natural gas (NG) and biogas. The biogas fuel is composed of 60% methane (CH_4) and 40% carbon dioxide (CO_2). They are introduced into the intake manifold in order to be mixed with the air. Diesel fuel is the pilot fuel. A single zone model was coupled with a double–Wiebe function and was adopted to simulate the heat release rate. The double-Wiebe function includes six parameters, determined by using the least squares method, based on the experimental values obtained on a single cylinder test bench engine. Also, this predictive model is based on sub-models such as the ignition delay, the heat losses through walls and the flow rate through the intake and exhaust valves. The simulated results were compared with experimental results under different engine loads. The present model reproduces the cylinder pressure with high precision. Moreover, the calculation of other engine parameters such as indicated thermal efficiency and indicated power shows a satisfying and good agreement between both experimental and simulated results with a relative error lower than 5%.

1. Introduction

Diesel engines are widely used in the automotive field, due to their high thermal efficiency, reliability, adaptability and profitability [1]. However, these engines are among the main causes of environmental pollution [2–3]. The main harmful pollutants from these engines are nitrogen oxides (NOx) and particulates. Those pollutants emissions are made up of various types of chemical compounds such as elemental carbon, organic carbon, inorganic ions, etc. [4]. This has motivated automobile manufacturers to continue their research in developing clean and efficient engine designs. Moreover, difficulty lies in improving engine performance, while minimizing pollutant emissions and fuel consumption due to the depletion of fossil fuels. As a result, several studies have been carried out in order to propose techniques optimizing the combustion process. Among these techniques: multiple injections [5], common rail injection [6–7], exhaust gas recirculation (EGR) [8], advance injection [9–10] and alternative fuels from biomass [11].

In order to analyze the efficiency and the power of internal combustion engines, numerical models have been developed. Among them, the theoretical models which represent the first numerical approach. In addition, despite the improvements made in theoretical models, it seems that they cannot take into account some simplifying hypotheses [12]. Therefore, a further improvement of combustion models has been performed using thermodynamic approaches, also called zero-dimensional models, because only time intervenes as independent variable. The basis of zero-dimensional modeling is to write mass and energy conservation equations for which intake and exhaust flow rates, thermodynamic properties and heat transfers must be provided. According to Lounici et al. [13], these models are among the simplest models and the fastest methods to model the combustion process of internal combustion engines.

0D models do not have spatial resolution, but can account one or more zones in the combustion chamber. Temperature and pressure in the cylinder are assumed to be uniform in single-zone models. The injected fuel into the combustion chamber is instantly mixed with the cylinder charge, and the mixture is considered as a perfect gas [14]. Awad et al. [15] developed a single-zone thermodynamic model to study the performance of a diesel engine using biodiesel from waste feedstock. In their work, the combustion of biodiesel was modeled with a triple Wiebe function.

Lounici et al. [13] optimized the heat transfer correlation choice for a spark ignition engine fuelled by natural gas by developing a two-zone

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thermodynamic model. In another study, they reported that dual-fuel (DF) mode is a very effective technique for reducing soot emissions as well as carbon dioxide (CO_2) emissions, particularly at high loads, where soot emissions are highly produced [13]. Abd Alla et al. [16] studied the effect of the amount of pilot fuel and of injection timing on NOx emission in a DF engine (NG/diesel). They noted that NOx emissions increased and those of carbon monoxide (CO) and unburned hydrocarbon (HC) decreased as the amount of pilot fuel is increased at low and high loads. The same observation was reported by Singh et al. [17].

The purpose of the present work is to predict and analyze the performance of a single cylinder, compression ignition (CI) engine, operating in DF mode fueled with different gaseous fuels (biogas and natural gas). A thermodynamic single zone model was developed where the rate of heat release was modeled by a double Wiebe function. This 0D model predicts the pressure as well as the temperature in the cylinder as a function of the crank angle. The simulated results were compared with the experimental ones in order to validate the proposed model.

2. Materials and procedure

2.1. Primary and pilot fuels used in engine test

In this study, two primary gaseous fuels were employed to operate a CI engine running in DF mode. The biogas fuel was synthesized using a computer-controlled mixer. Biogas components were stored in pressurized bottles. However, the natural gas (NG) comes from the gas network. The properties of gaseous and diesel fuels are summarized in Table 1.

2.2. Engine test bench

The engine tests were carried out on a single-cylinder engine (LISTER-PETTER type TS1), air-cooled, 4-stroke, direct injection (Fig. 1). It is designed to operate at variable speed from 0 to 2500 rpm. It generates a power output of 4.5 kW at 1500 rpm. The injection advance of pilot fuel is fixed by the manufacturer at 13°CA before TDC. The main characteristics and more details about the acquisition system could be found in authors previous works [13,15]. The conversion of the diesel engine to operate in dual-fuel mode was suitably carried out by connecting a gas blender to its intake manifold. The primary fuel is mixed with air and introduced into the combustion chamber through the intake manifold. Close to the end of the compression process, the amount of injected pilot fuel was fixed to 5 g/min resulting in a power output of 0.45 kW corresponding to 10% of the maximum power output of 4.5 kW at 1500 rpm. After that, the increase of engine load is achieved by increasing the gaseous fuel flow rate. The experiments were carried out at different loads namely (20%, 40%, 60%, 80%, 90% and 100%) at 1500 rpm.

Table 1
Diesel fuel, natural gas and biogas properties.

Component	Primary fuel 1 (Biogas)	Primary fuel 2 (NG)	Pilot fuel (diesel)
Chemical Composition	60% CH_4, 40% CO_2 (V/V (%))	91% CH_4, 4.78% C_2H_6 0.49% C_3H_8, 0.16% C_4H_{10} (V/V (%))	$C_{12}H_{26}$
Cetane number	–	–	49
Density (kg/m^3)	1.33	0.77	840
Stoichiometric air fuel ratio	6.04	16.31	14.60
LHV (MJ/kg)	17.65	47.95	42

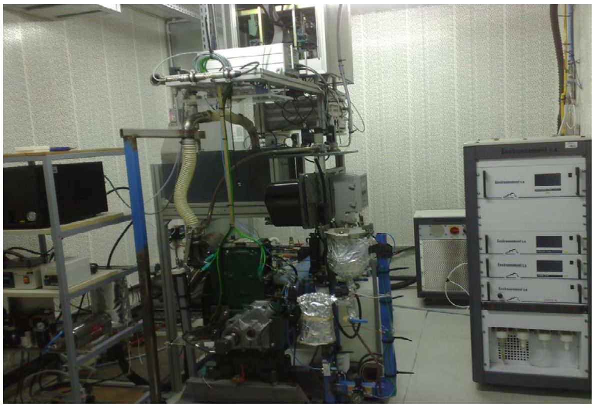

Fig. 1. Experimental setup scheme.

3. Predictive model

Thermodynamic modeling, also known as 0D modeling, is a combination of several models that are in most cases designed from empirical or semi-empirical approaches. They aim to analyze, control and evaluate complex systems with a simulation time close to reality which is very difficult to achieve with other types of modeling [18]. This explains the great interest of the researchers for these 0D models. In order to carry out this type of modeling, it is important to decompose the macro system considered in several sub-systems firstly. The purpose of this decomposition is to represent each element of this system as accurately and faithfully as possible. Thereafter, the sub-systems are grouped together to build the presumed model. Then it must go through the phases of identification, calibration and parameterization. The structure of the model is presented in Fig. 2.

3.1. Model equations

In order to obtain the parameters characterizing this model, namely the pressure, the temperature and the mass of cylinder charge, it is necessary to use the general governing equations such as, energy conservation (Eq. (1)), mass conservation (Eq. (2)), as well as state equation.

$$mC_v dT = -PdV - \sum dQ_{Walls} + dQ_{comb} - udm + h_i dm_i - h_e dm_e \tag{1}$$

where, T [K] and P [bar] are respectively the temperature and the pressure of gas in cylinder. u and h are respectively the internal energy and enthalpy of the gas.

$$dm = dm_i - dm_e \tag{2}$$

The Eq. (2) presents the mass conservation. Indexes i and e correspond to intake and exhaust, respectively.

The volume of the cylinder varies with respect to crank shaft position. It is expressed as a function of the geometrical characteristics of the engine and of the crank angle according to the following relation:

$$V(\theta) = V_{cyl}\frac{\tau_c}{\tau_c - 1} - \frac{1-\cos\theta}{2} + \frac{1}{2}\sqrt{\left(2\frac{L}{C}\right)^2 - \sin^2\theta} \tag{3}$$

where L [m] and C [m] are respectively the connecting rod length and the stroke.

3.2. Sub-models

The present developed predictive model is based on mathematical sub-models in order to reproduce the cycle of a CI engine operating in dual-fuel mode with different gaseous fuels.