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Prediction by mathematical modeling of the behavior of an internal combustion engine to be fed with gas from biomass, in comparison to the same engine fueled with gasoline or methane

Felipe O. Centeno González [a,*], Khamid Mahkamov [b], Electo E. Silva Lora [a], Rubenildo V. Andrade [a], René Lesme Jaen [c]

[a] The Centre for Excellency in Thermoelectric and Distributed Generation (NEST), The Federal University of Itajuba, Av. BPS 1303 Pinheirinho, Itajuba, MG, Brazil

[b] School of Computing, Engineering and Information Sciences, Northumbria University, Ellison Building, Newcastle upon Tyne NE1 8ST, UK

[c] University of Oriente, Sede J.A. Mella. Ave. de las Américas s/n y calle I. C.P. 90900 Santiago de Cuba, Cuba

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ABSTRACT

The performance of a spark ignition internal combustion engine (SI ICE) fueled with biomass gas (woodgas) is evaluated using an analytical mathematical model. For the evaluation, the model was based on the fuel-air thermodynamic cycle for spark ignition engines, taking into account the composition of woodgas used as fuel, the thermodynamic properties of the fuel supplied, the cylinder geometric characteristics, the engine operational conditions, the effects of heat losses in the cycle through the walls of the cylinders and due to the loss as gas "blow-by", the influence of dissociation processes during the combustion and the residual gases remaining in the cylinders at the beginning of the compression stroke. The model can predict of the internal temperatures profiles, heat flow, as well as the work and pressure in relation to crank angle. It was used also to evaluate the influence of the rotation speed, the air ratio and the ignition timing on the engine indicated power. It was found that when feeding the engine with woodgas, a power output between 59 and 65% can be obtained, in comparison it's powered by gasoline.

Additionally, the analysis shown the engine performance when feeding it with pure methane (100%), to give an idea about what would happen if the same engine is fueled with natural gas under the same conditions (the main component of natural gas is methane and the presence of this in composition generally varies between 70 and 95%).

1. Introduction

The combustion of synthesis gas is an important issue in advanced power systems based on the gasification of fuel feedstocks and combined cycles (Boehman and Corre [1], Silva et al. [2]). Several works has evaluated the possibilities to use syngas as fuel in gas turbine engines (Kim et al. [3], Walton et al. [4], Wright and Gibbons [5]), but another possibility is to burn the syngas in stationary reciprocating engines. Whether in spark ignited or compression ignited engines (CI ICE), syngas could serve to power large bore stationary engines, such as those presently operated with natural gas (Boehman and Corre [1]). Boloy et al. [6] stated that burning syngas has a better environmental sustainability than burning fuels such as diesel and B20 biodiesel. This is due that burning of diesel and biodiesel B20 in the ICE that increases the emission of carbon dioxide and particulate matter, in comparison with burning syngas in ICE. From the technical, economical and ecological point of view Gasifier/ICE is an attractive technology in comparison with other combustion technologies. Coronado et al. [7] analyze a tri-generation system (electricity, cold water and hot water), using an internal combustion engine fed with gas from biomass and [7] stated that it is an energetic alternative to adapt a fixed bed gasifier to a compact cogeneration system, in order to cover electrical and thermal demands in a rural area, showing an energy solution for small social communities, using renewable fuels.

The use of biomass gasification gas as fuel for internal combustion engines is a technology that has been used for over a century.

* Corresponding author. Tel.: +55 3588068685.
E-mail addresses: felipecingmec@gmail.com, fcenteno@ingenieros.com (F.O. Centeno González).

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The spark-ignition engines, usually fueled with gasoline are capable of operating using only gas from biomass. Diesel engines can be adapted to run with producer gas by reducing the rate of compression (when necessary to prevent uncontrolled self-ignition of the gas) and installing a spark ignition system (FAO [8]).

Since the efficiency of internal combustion engine depends on various parameters, including the quality of supplied fuel, the geometry and some other engine operating conditions, it is desirable to use mathematical models to evaluate the behavior of an internal combustion engine fueled specifically with woodgas, especially because this gas has a complex composition as a mixture of many components, whose proportions are different, depending on several variables of the gasification process. Internal combustion engine (ICE) modeling is a multidisciplinary task encompassing various areas, including thermodynamics, chemical kinetics, fluids mechanics, heat transference, combustion, and also numerical methods. Despite the complexity, and mainly because engines are traditional machines, there is possible to find in the literature many models of combustion of conventional fuels (e.g., natural gas, propane, gasoline and, diesel) in SI ICEs (Heywood [9], Gong et al. [10], Yamin [11], Cho et al. [12], Yanju et al. [13], Hakan [14], Hu et al. [15], Heywood [16]). However there have been only a few published models that explain the simulation of the synthesis gas combustion in an SI ICE (Rakopoulos et al. [17], Moriyoshi [18], Tan and Reitz [19], Şahin and Durgun [20], Gamiño and Aguillón [21]). This is due to the fact that the synthesis gas is an unusual multicomponent gas fuel (hydrogen, carbon monoxide, and methane), of limited commercial value and variable chemical compositions, because different types of biomass feedstockes and gasifiers could be used to produce the syngas (Boehman and Corre [1], Gamiño and Aguillón [21]).

Rakopoulos et al. [17], Rakopoulos and Michos [22,23] developed and validated a zero-dimensional, multi-zone, thermodynamic combustion model for the prediction of SI ICE performance. Tinaut et al. [24] developed a so-called Engine Fuel Quality (EFQ) parameter to predict the engine performance fueled with syngas. This parameter considers the combined effect of stoichiometric air–fuel ratio and the stoichiometric mixture heating value, both depending on the producer gas composition. Those authors [24] successfully used a two-zone thermodynamic model to predict engine performance, the results of the modeling include the fraction of mass burned, the pressure and temperature evolution and the pollutant emissions. The detailed results of the power evaluation confirm the first order prediction based on the EFQ parameter. The estimation of engine power made by using the EFQ parameter indicates that power at full load is reduced at about two-thirds of the maximum value obtained when a conventional liquid fuel is burned.

To describe the overall operation of the biomass power generation system a mathematical model of an SI ICE is used, which is based on the fuel–air thermodynamic cycle. Such cycle takes into account the composition of syngas as fuel, the heat losses in the cycle due to heat transfer to the walls of the engine cylinders, the dissociation processes which occur during combustion of fuel and also the "blow-by" (the leakage of gases between piston sealing rings and the cylinder wall). Additionally, the engine's model accounts for the influence of residual gases in the cylinder at the beginning of the compression stroke and for variations in thermophysical properties of the fuel–air and residual gases mixture and of combustion products.

The main contribution of this work is that the model presented is able to provide more detailed information on the behavior of an engine fueled with woodgas. The temperature profile, heat flow, work and pressure are predicted and analyzed; the mathematical model is also able to determine the optimal ignition timing. Among other results, it is found that the power output by woodgas is about 59–65% of that of gasoline.

In previously published works, Heywood [9,16], Centeno [25], Centeno et al. [26], Ferguson and Kirkpatrick [27] presented details of the used models and its validation, this work is focused on providing other details of the model's predictions about behavior of the engine fueled with biomass gas, and provides a comparison of feeding pure methane to give an idea about what would happen if the same engine in the same conditions is fueled with natural gas.

2. About the mathematical model used

An analytical mathematical model was used, whose details were presented in a previously published work by the authors [25,26] and based on the original model presented by Ferguson [27]; some changes were made to allow the model to accept biomass gasification gas as fuel. The modification is to introduce mathematical functions to calculate the thermodynamic properties of the gas (specific heat capacity, enthalpy and entropy) as a function of temperature and the distribution of species (CO, CO_2, H_2, CH_4 and N_2). The species present in the biomass gasification gas are usually not fixed and vary according to operating conditions of the gasifier, then the model should be able to predict the thermodynamic properties of woodgas for each temperature within the range of engine operation. It is not the aim of this paper to present the details of the mathematical formulation and due to the large amount of details and the limited space, we recommend the interested reader to refer to Ferguson and Kirkpatrick [27], that provides details of the original model and also refer to previously published work by the authors [25,26] which show the details of the changes made to the original model (Fig. 1).

3. Experimental

The YANMAR BTD22 engine shown in Fig. 2 was used; originally designed to work with Diesel, but modified to work with natural gas. Table 1 shows some engine parameters used in the simulations.

The engine modifications include the installation of spark plugs in the head of cylinders (one per cylinder) and the implementation of a set of double regulating valves in the engine's syngas and air induction system. The double valve system provides a finer adjustment of syngas and air mass flow rates. The engine has the cylinder bore and piston stroke equal to 90 mm with the

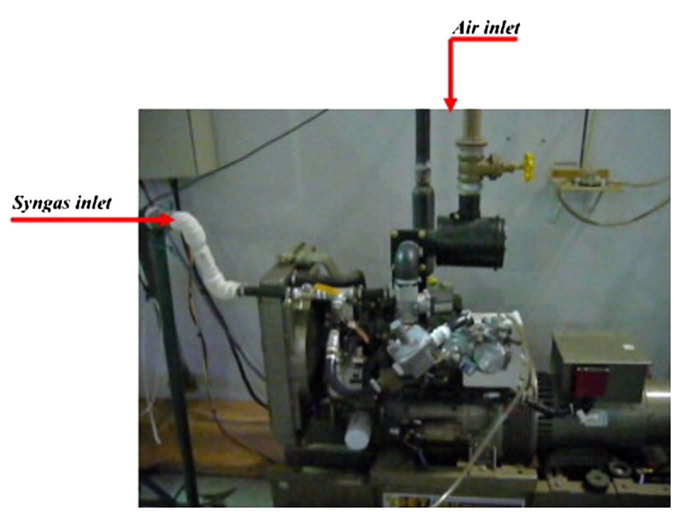

Fig. 1. A spark ignition internal combustion engine YANMAR BTD22.