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Exergy efficiency applied for the performance optimization of a direct injection compression ignition (CI) engine using biofuels

Y. Azoumah [a,*], J. Blin [a,c], T. Daho [b]

[a] Laboratoire Biomasse Energie Biocarburant (LBEB), Institut International d'Ingénierie de l'Eau et de l'Environnement (2iE), Rue de la Science, 01BP 594, Ouagadougou 01, Burkina Faso

[b] Laboratoire de Physique et de Chimie de l'Environnement (LPCE), Département de Physique, UFR-SEA, Université de Ouagadougou, 03 BP 7021, Ouagadougou 03, Burkina Faso

[c] Unité Propre de Recherche Biomasse Energie, CIRAD–PERSYST, TA B-42/16t, 73 Avenue J.-F. Breton, 34398 Montpellier Cedex 5, France

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ABSTRACT

The need to decrease the consumption of materials and energy and to promote the use of renewable resources, such as biofuels, stress the importance of evaluating the performance of engines based on the second law of thermodynamics. This paper suggests the use of exergy analysis (as an environmental assessment tool to account wastes and determine the exergy efficiency) combined with gas emissions analysis to optimize the performance of a compression ignition (CI) engine using biofuels such as cottonseed and palm oils, pure or blended with diesel for different engine loads. The results show that the combination of exergy and gas emissions analyses is a very effective tool for evaluating the optimal loads that can be supplied by CI engines. Taking into account technical constraints of engines, a tradeoff zone of engine loads (60% and 70% of the maximum load) was established between the gas emissions (NO and CO_2) and the exergy efficiency for optimal performance of the CI engine.

1. Introduction

New and renewable alternative fuels as a substitute for petroleum-based fuels have become increasingly important, due to environmental concerns, exhausting of crude oil reserves, unstable costs and transportation problems. One of the renewable alternative fuels is biofuels, which is domestically produced from edible crops (cotton seed, palm nut, ground nut, sugar cane, etc.) and non-edible crops (jatropha curcas, algae, etc.). Furthermore, liquid biofuels such as oleaginous oils can be used not only as pure substances but also in mixtures with petroleum diesel fuel in some unmodified diesel engine [1,2]. Diesel fuel is very important for the economy because it has wide range of usage such as long haul truck transportation, road vehicles, agriculture, construction equipment and electricity power generation [3]. Almost all African countries import petroleum based fuels [4]. Therefore, the substitution of these fuels is of great interest because it will reduce their dependence on petroleum based energy and will create jobs for rural areas where agriculture is the main activity. Conferences [5] are being held now in Africa in order to understand all the issues of producing and using biofuels in engines.

The concern of this paper is to analyze the performance of a compression ignition (CI) engine using local biofuels such as cotton seed oil and palm oil. This type of engine will be used to produce rural electrification and water pumping through rural regions of Burkina Faso. Chosen as a rural area pilot is Solenzo, which is a village of 500 of inhabitants in Burkina Faso. In this village cottonseed oil is produced by the farmers, and the proposal is to use their own oil for their electrification and water pumping purposes.

So far, most of the studies involving engines using biofuels have evaluated their performance based on their brake power, brake thermal efficiency, brake specific fuel consumption (BSFC) and gas emissions analysis [6–8]. By doing so, thermal pollution, for example, is ignored and the real performance of the engines regarding the second law of thermodynamics is overlooked.

This paper is a proposal to use the exergy concept to evaluate the performance of a CI engine using biofuels.

The exergy of an isolated system is a property that is not conserved. It can be generated, destroyed, and stored. Exergy is destroyed mostly as low temperature heat transfer, as well as during chemical reactions [9]. This unutilized exergy normally interacts with its surroundings and can lead to undesirable environmental processes in non- equilibrium situations that can cause environmental harm. Therefore exergy can be thought of as a potential measure of a material for causing harm. The exergy content of a natural material input can be interpreted as a measure of its quality or potential usefulness, or its ability to perform "useful work" [10]. Consequently, exergy can measure resource quality as

* Corresponding author. Tel.: +226 50 49 28 64/96; fax: +226 50 49 28 01/07.
E-mail address: yao.azoumah@2ie-edu.org (Y. Azoumah).

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Nomenclature

BSFC	brake specific fuel consumption; g kW^{-1} h^{-1}
CO_2	carbon dioxide
E_x	exergy consumption, W
LCV	low calorific value; kJ kg^{-1}
$\dot{m}$	mass flow rate, m s^{-1}
NO	nitrogen oxide
$\dot{Q}$	power, W
$\dot{S}_{gen}$	entropy generation rate; W K^{-1}
T	temperature, K
$\dot{W}_e$	converted electric power, W

Greek symbols

δE_x	exergy destruction, W
η_{ex}	exergy efficiency, ratio of the power $\dot{W}_e$ and the exergy consumption E_x
η_{eff}	thermal efficiency, ratio of the converted electric power $\dot{W}_e$ and the power $\dot{Q}_{in}$

Subscripts

H	high temperature (used for the combustion chamber)
L	low temperature (used for the ambient)
in	input
out	output

well as quantity and is applicable for both materials and energy flow.

2. Experimental setup

The pilot equipment selected for present experimental investigations consists of an 8 KVA power generator, modified to operate on diesel fuel or vegetable oils.

This engine system is widely used in rural area for agricultural purposes [11]. A double cylinder, four stroke, constant speed, air cooled, direct injection diesel engine was procured for the experiments. The technical specifications of the engine are given in Table 1. The engine operated at a constant speed of 1500 rpm. The engine is coupled with a three-phase, 220–230 V AC alternator. The alternator is used for loading the engine through two resistive load banks of 4 kW each.

The layout of the experimental setup is shown in Fig. 1. The main components of the experimental setup are two fuel tanks (diesel and vegetable oils), fuel lines, fuel consumption and emissions measurement equipment (flow counter, gas analyzer, etc,). Two fuel filters are provided next to the vegetable oil tank for severe filtration [12].

Two kinds of vegetable oil were used: cotton seed oil and palm oil, which are locally produced. Their characteristics are summarized in Table 3. Because of the high viscosity and low volatility of vegetable oils, which favors their incomplete combustion [13], the engine is started with diesel fuel and, once it warms up to 500 °C, it is switched over to vegetable oils. After concluding the tests with vegetable oils, the engine is again switched to diesel fuel. The engine is stopped when the vegetable oil is purged from the fuel line, injection pump and injectors in order to prevent cold starting problems, corrosion, polymerization and deposits [7,14]. This purging typically takes about 15 min at idling. A thermocouple was installed in the exhaust line to measure the temperature of the exhaust gases.

The composition of these gases was measured using an exhaust gas analyzer (TESTO 350; see specifications in Table 2).

Table 1
Diesel electric generator specifications

	Characteristics	Specification
Engine	Type	Lombardini 9LD 561-2/L, four strokes, air cooled, direct injection, two cylinders, compression ignition engine, constant speed
	Stroke/Bore	90 mm/88 mm
	Displacement volume	1120 cm^3
	Rated power	12 kW at 2200 tr/min
	Compression ratio	17.5:1
Generator	Type	Genelec
	Power	8 kVA
	Cos φ	0.8
	RPM	1500

3. Experimental test matrix

Experiments were conducted for optimizing the performance of the engine through the various loads supplied to the engine. Performance and emissions tests were conducted for diesel fuel, pure cotton seed oil, palm oil and blends of diesel and cotton seed oil.

In any such test, the engine is started with diesel and idling for 15 min. Then, with the two resistive load banks, a maximum engine load of 6 kW is supplied to the engine for a period, about 5 min, until a steady state is reached. This step is necessary to warm the combustion chamber up to 500 °C and to improve the combustion of pure vegetable oils. All the experiments were carried out at an ambient temperature of about 36 °C. The tests were conducted in three phases:

a. First, tests were conducted with diesel fuel to generate baseline data. The measurement of exhaust gas temperature, the gas emissions concentration and the fuel consumption are carried out after the steady state is reached with the maximum engine load. Then, these measurements are also carried out for engine loads in the range of 30–90% of the maximum load.
b. Second, tests were conducted using pure vegetable oils. The measurement of exhaust gas temperature, the gas emissions concentration and the fuel consumption are carried out after the steady state is reached for engine loads ranging from 30% to 100% of the maximum engine load.
c. Third, tests were conducted using blends of cottonseed oil with mineral diesel. Several blends of varying concentrations are prepared ranging from 0% to 50% (cotton seed oil) through 20%, 30% and 40%. The measurement of exhaust gas temperature, gas emissions concentration and fuel consumption are carried

Table 2
Technical characteristics of the gas analyzer TESTO 350

Gas	Detector	Resolution	Scale	Accuracy
CO_2	Evaluated from O_2	0.1%	0–CO_{2max}	–
O_2	Electrochemical cell	0.1%	0–21%	0.2%
NO	Electrochemical cell	1 ppm	0–3000 ppm	±5 ppm (<100 ppm) ±5% v.m (<2000 ppm) ±10% v.m (<3000 ppm)
NO_2	Electrochemical cell	1 ppm	0–500 ppm	±10 ppm (<100 ppm) ±5% v.m (<200 ppm)