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Neat diesel beats waste-oriented biodiesel from the exergoeconomic and exergoenvironmental point of views

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ABSTRACT

In the present study, a DI diesel engine operating on various diesel/biodiesel blends containing different amounts of polymer waste was thermodynamically scrutinized using two exergy-based methods, i.e., exergoeconomic and exergoenvironmental analyses for the first time. Exergoeconomic and exergoenvironmental parameters were calculated for five fuel blends utilized throughout this study at different engine loads and speeds. These approaches were used to make decisions on fuel composition and engine operational conditions by taking into account the financial and environmental issues. The results showed that the exergoeconomic and exergoenvironmental parameters varied profoundly with engine load and speed. In general, increasing engine load remarkably decreased the unit cost and the unit environmental impact of the shaft work exergy, while enhancing engine speed acted oppositely. More specifically, the lowest unit cost and unit environmental impact of full load work exergy were found to be 36.08 USD/MJ and 32.03 mPts/GJ for neat diesel and B_5 containing 75 g EPS/L biodiesel, respectively, both at engine speed of 1600 min^{-1}. Moreover, the exergoeconomic and exergoenvironmental factors of the diesel engine were very poor due to the higher thermodynamic losses occurring during the combustion process. Although the maximum exergetic efficiency of the diesel engine was obtained for B_5 including 50 g EPS/L biodiesel, the exergoeconomic and exergoenvironmental analyses could not detect any spectacular differences among the fuel blends applied. Overall, using biodiesel in neat or blended form appeared to be less attractive strategy from the exergoeconomic and exergoenvironmental perspectives considering the current biodiesel prices and production technologies.

1. Introduction

Today, over 80% of the global energy consumption is met by fossil fuels, i.e., coal, petroleum, and natural gas [1]. However, the widespread utilization of conventional fuels especially in the transportation sector has led to serious environmental and health concerns [2]. Hence, growing attentions are paid to the development of eco-benign renewable energy carriers such as biodiesel, bioethanol, and biohydrogen with an aim to partially replace their fossil-oriented counterparts. Amongst these renewable transportation fuels, biodiesel has found relatively widespread commercial applications due to its similar physiochemical attributes to those of mineral diesel [3–5]. However, biodiesel suffers from several drawbacks like poor cold properties and lower calorific value [6]. In an attempt to address these shortcomings, Mohammadi et al. [7] and Pourvosoughi et al. [8] dissolved polymer wastes (expanded polystyrene) into biodiesel and stabilized the fuel blend using acetone. These led to improved energy content and cold flow properties of the fuel blends developed. Although the polymer waste incorporation into biodiesel showed great promises, new fuel blends only have a chance to survive if they are thermodynamically, economically, and environmentally sound. Therefore, the cost-effectiveness and eco-friendliness of the biodiesel blend containing waste polymers should still be investigated using advanced engineering approaches.

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Nomenclature

b	specific environmental impact (mPts/kJ or mPts/MJ)
$\dot{B}$	environmental impact rate of exergy flow (mPts/h)
c	specific cost ($/kJ or $/MJ)
C	carbon number of fuel (–)
C_p	specific heat capacity (kJ/kg °C)
$\dot{C}$	cost rate of exergy flow ($/h)
ex	specific exergy (kJ/kg)
$\dot{Ex}$	exergy rate (kW)
f_b	exergoenvironmental factor
f_c	exergoeconomic factor
H	hydrogen number of fuel (–)
$\dot{m}$	mass flow rate (kg/s)
$\dot{n}$	molar flow rate (mol/kg)
O	oxygen number of fuel (–)
P	pressure (kPa)
q_{LHV}	lower heating value (kJ/kg)
$\dot{Q}$	heat transfer rate (kW)
R	gas constant (kJ/kg K)
$\bar{R}$	universal gas constant (8.314 J mol/K)
S	sulfur number of fuel (–)
t	cumulative working hours (h)
T	temperature (K)
r_b	relative environmental impact difference
r_c	relative cost difference
x	mass fraction (–)
y	mole fraction (–)
$\dot{Y}$	engine environmental impact rate (mPts/h)
$\dot{W}$	work (kW)
$\dot{Z}$	engine investment cost rate ($/h)

Greeks

ε	specific chemical exergy (kJ/mol)
ω	angular velocity (rad/s)
τ	torque (N m or kN mm)
φ	quality factor (–)

Subscripts

a	air
c	coolant
ch	chemical
CI	capital investment
CO	construction
des	destruction
DI	dismantling
f	fuel
g	exhaust gas
i	numerator
in	inlet
l	loss
$LOSS$	loss
OM	operating & maintenance
out	outlet
ph	physical
ref	reference
s	source
TOT	total
w	work

Abbreviations

B	biodiesel
BTE	brake thermal efficiency
CO	carbone monoxide
CO_2	carbone dioxide
DI	direct injection
EPS	expanded polystyrene
KOH	potassium hydroxide
LCA	life cycle assessment
NOx	nitrogen oxide
O_2	oxygen
O&M	operation and maintenance
P	polystyrene

Traditionally, energy analysis is performed using the first law of thermodynamics to assess diesel engine performance, i.e., brake thermal efficiency (BTE). In this context, a significant deal of literature is available on using thermal efficiency for evaluating and comparing diesel engine performance operating on various fossil and renewable fuels and their blends. For example, Buyukkaya [9] evaluated the BTE of a diesel engine working with rapeseed oil biodiesel and its blends. Zhu et al. [10] tested the BTE of Euro V diesel fuel, biodiesel, and ethanol–biodiesel blends on a 4-cylinder DI diesel engine. Chauhan et al. [11] compared the BTE of biodiesel obtained from *Jatropha* oil with neat diesel fuel a basal fuel. Wang et al. [12] carried out a comparative study to assess the BTE of a heavy-duty diesel engine operating on diesel and biodiesel at high altitudes. Can [13] studied the BTE of waste-oriented biodiesel/No. 2 diesel fuel blends and compared them with neat diesel fuel. Sanli et al. [14] examined the BTE of pure and blended waste cooking oil biodiesel in a DI diesel engine. Gnanasekaran et al. [15] assessed the effect of injection timing on the BTE of a DI diesel engine fueled with fish oil biodiesel. Prabu et al. [16] studied the effects of waste cooking oil biodiesel content and the presence of butylated hydroxytoluene and n-butanol as additive on the BTE of a diesel engine.

However, this energetic indicator cannot provide adequate information regarding the productivity and sustainability of internal combustion engines. This could be ascribed to the obvious weakness of energy analysis in providing sufficient information into the irreversibility aspects of energy conversion systems. During the past decades, intensive worldwide efforts have been made to develop various approaches such as emergy, life cycle assessment (LCA), and exergy for decision-making on productivity and sustainability aspects of energy production/consumption systems in response to both energy crisis and environmental concerns. Amongst the developed approaches up to date, thermodynamically-rooted exergy-based methods have been found capable of successfully paving the way for addressing these issues.

Simply speaking, the maximum capacity of a given kind of energy or material in generating useful work when it is brought to a complete equilibrium with its surroundings through reversible processes can be regarded as exergy. This powerful indicator can precisely quantify resources destruction occurring when producing a given amount of energy or material. Due to the unique conceptual features of exergy analysis in revealing the irreversibility aspects of thermodynamic systems, it has received an increasing attention in recent years to develop, analyze, and optimize energy conversion processes.

In parallel with other energy research projects, various research attempts have been conducted using the exergy concept for analyzing and optimizing diesel engines working with various renewable and non-renewable and their blends. For instance, Tat [17] exergetically analyzed a DI diesel engine working with yellow grease methyl ester, soybean oil methyl ester, and soybean oil methyl ester containing 2-ethylhexyl nitrate. da Costa et al. [18] aimed at investigating the performance characteristics of a diesel engine operating on natural gas and diesel mixture using the exergy concept. Gümüş and Atmaca [19] determined the exergetic