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Availability analysis of using iso-octane/n-butanol blends in spark-ignition engines

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ABSTRACT

The current work presents a detailed energy and exergy analysis of an iso-octane/n-butanol blend-fueled spark-ignition (SI) engine to investigate exergy loss mechanisms and understand how the exergy destruction changes with different iso-octane/n-butanol blend fuels. Energy and exergy analysis was applied to a quasi-dimensional two-zone SI engine model, including Wiebe function to model the actual combustion process based on fuel types and operating conditions. Results were obtained for an SI engine at 3000 rpm by changing spark timing, volume fraction of n-butanol, and load. When sweeping spark timing, it was found that the location of maximum first and second-law efficiency appear at around −31 °CA ATDC for iso-octane, BU10, BU20 and BU30, and approximately −28 °CA ATDC for n-butanol. Increasing butanol fraction in the blends increases the percentage of total irreversibility in total availability at either MBT or constant spark timing, while has slight influence on availability transferred by heat transfer. At the MBT spark timing and WOT condition, the first-law efficiency increases slightly with increase of n-butanol, while the second-law efficiency for blended fuel decreases slightly. However, with decreasing engine load, the percentages of total irreversibility and availability transferred by heat transfer increase, the first and second-law efficiencies both decrease.

1. Introduction

Automobile is thought to be a major contributor to fossil fuel resource's depletion as well as global air pollution. Additionally, the previous uncertainties related to oil price, increasingly stringent emission regulations, and the needs for increased energy security and diversity have drawn a growing public and scientific attention on developing clean and renewable energy resources, like biofuels [1,2]. When compared to fossil fuels, biofuels include a wide range of fuels and are easy to obtain, environment friendly and economical [3]. Among all kinds of alternative fuels, bio-alcohols are considered to be promising alternative fuels as they can be produced by alcoholic fermentation from renewable resources, for instance, various grown crops and even waste products, via established and new processes [4].

Bio-alcohols are commonly used as engine fuels or fuel additives due to their fuel properties. A comparison between the physical and chemical properties of gasoline, methanol, ethanol and n-butanol [1] is shown in Table 1. It can be observed that the lower heating value of alcohol rises with increasing carbon atom number, which indicates that n-butanol will reduce the fuel mass consumption compared to methanol and ethanol. The saturation pressure (volatility) of alcohols decreases as carbon atom number increase, which means that n-butanol will have fewer cavitation and vapor lock problems. The heat of vaporization of butanol is less than half of that of methanol. In addition, n-butanol tolerates water contamination better and is less corrosive than ethanol, which makes it more suitable for distribution through existing pipelines. These properties indicate that n-butanol has the potential to overcome most of the drawbacks brought by the low-carbon alcohols. For these reasons, numerous experimental and theoretical studies have been performed on the use of gasoline-bio-butanol blended fuels in internal combustion engines [5–15].

Engine cycle simulation along with experimental validation can significantly reduce the expense of time and cost when parametric and comparative analysis of different fuels is performed. Although

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Nomenclature

A	availability, J
a	Wiebe efficiency parameter or mass specific availability, J/kg
$a_{f,ch}$	mass specific fuel chemical availability, kJ/kg
c_p	mass specific heat at constant pressure, J/(kg K)
c_v	mass specific heat at constant volume, J/(kg K)
D	cylinder bore, m
E	total energy, J
F	heat transfer area, m^2
G	Gibbs free enthalpy, J
h	mas specific enthalpy, J/kg
h_c	convective heat transfer coefficient, W/(m^2 K)
I	irreversibility, J
L_{cr}	connecting rod length, m
L_s	stroke length, m
m	mass, kg
N	engine speed, rpm; number of mole, mole
p	pressure, bar
Q	heat, J
R_c	compression ratio, dimensionless
R_g	specific gas constant, J/(kg K)
S	entropy, J
s	mass specific entropy, J/kg
T	absolute temperature, K
U	internal energy, J
S_L	laminar flame velocity, m/s
V	volume, m^3
W	work, J
x_b	burned gas mass fraction, dimensionless
y	mole fractions of species in the air-fuel mixture, dimensionless
w	mean gas velocity, m/s
ΔHc	heat of combustion, kJ/mol

Greek Letters

α	energy fraction, dimensionless
ρ_E	energy density, kJ/mL
η_I	the first-law efficiency, %
η_{II}	the second-law efficiency, %
θ	crank angle, °CA
λ	ratio of crankshaft to connecting rod, dimensionless
ε	compression ratio, dimensionless
μ	chemical potential
φ	fuel-air equivalence ratio, dimensionless
ψ	form factor

Abbreviations

ATDC	after top dead center
CA	crank angle
CA50	crank angle at 50% mass fraction burnt
EVO	exhaust valve opening
LHV	lower heat value
MBT	maximum brake torque
MFB	mass fraction burnt
IVC	intake valve closing
SI	spark ignition
TDC	top dead center
WOT	wide open throttle

Subscripts

b	burned
comb	combustion
dest	destruction
e	exhaust
f	fuel
g	gas
i	inlet
L	laminar
m	maximum
pot	potential
Q	heat
r	residual
ref	reference
s	start of combustion
tot	total
u	unburned
W	work
w	wall
0	true dead-state or standard conditions

Superscripts

ch	chemical
tm	thermomechanical
0	restricted dead-state

the first-law of thermodynamics has been widely used as a primary tool to evaluate the performance of such energy conversion devices, it is unable to afford an intrinsic comprehension into engine operations. However, the second law of thermodynamics, which affirms that 'energy' has quality as well as quantity, can yield a true measure of the extent of conversion of fuel energy into useful work, and clearly identify the causes and sources of thermodynamic losses and consequent impacts on the environment. As a result, the second law of thermodynamics analysis can provide reference for improving and optimizing future engine's design.

In recent years, increasing recognition and application of the availability analysis has been carried out. Some reviews about exergy and energy analysis have been published [16–18]. The detailed parametric studies [19–21] revealed that fuel type, equivalence ratio, exhaust gas recirculation (EGR), inlet oxygen concentration, etc. are the primary reasons for variations in availability destruction.

In the past decades, several investigations have been performed to study the exergy loss of SI engine fueled with alcohol fuels. Gallo et al. [22] carried out an exergetic analysis for ethanol- and gasoline-fueled SI engines using a simulation model. They found that ethanol gives less irreversible combustion and higher exergetic efficiency than gasoline even at the same compression ratio. Alasfour [23] performed an availability analysis on an SI engine through an experimental investigation, which fueled with a 30% volume butanol-gasoline blend over a wide range of fuel/air equivalence ratios ($\varphi = 0.8$–1.2). The availability analysis shows that, at$\varphi = 0.9$, when a butanol-gasoline blend is used, the engine second-law efficiency shows a reduction of 7% compared to pure gasoline fuel.

Rakopoulos et al. [24] developed a zero-dimensional, multi-zone, thermodynamic combustion model for the prediction of SI engine performance and NO_x emissions, in which the second-law analysis was included. The results revealed that the degree of reversibility of the combustion process in each of the multiple