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Effects of charge properties on exergy balance in spark ignition engines

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ABSTRACT

This study investigates the effects of the air–fuel mixture (charge) properties on the exergy balance in spark ignition engines. A thermodynamic cycle model including compression, combustion and expansion processes is used. The principles of the second law are applied to the cycle model to perform an exergy analysis. Variation of the exergetic variables during the investigated portion of the cycle are examined as a function of the charge properties, i.e., fuel–air equivalence ratio, residual gas fraction and initial charge temperature. The results show that increasing fuel–air equivalence ratio causes an increase in irreversibilities and also exergy losses with heat transfer and exhaust gases, but enriching the air–fuel mixture beyond the stoichiometric ratio makes no significant contribution to the exergy transfer with work transfer. A slightly lean mixture also gives the best first and second law efficiencies. It is observed that there is a linear relation between the residual gas fraction and the exergetic variables. An increase in the residual gas fraction decreases the irreversibilities and exergy losses aside from the exergy transfer with work transfer. However, increasing the residual gas fraction positively affects the first and second law efficiencies because of the diluting of the charge. Increase of initial charge temperature creates a reduction in the irreversibilities and the exergy losses and, it also results in a lower exergy output by work transfer. Further, increase of initial charge temperature negatively influences the first and second law efficiencies.

1. Introduction

The four stroke spark ignition (SI) engine cycles contain four sequential processes: intake, compression, expansion (including combustion which lasts from the end of compression to the beginning of expansion), and exhaust. Intake is the first stroke; in which a fuel–air mixture (charge) is inducted into a cylinder by the movement of a piston from the top dead center (TDC) to the bottom dead center (BDC) [1,2]. A desired amount of fuel is added into the inducted air via a carburetor or a fuel injection system. The temperature of the charge increases because of the heat energy transferred from the hot intake system and the cylinder walls. The mixing of the charge in the cylinder by hot residual gases remaining from the previous cycle causes an additional increase in the temperature and a variation in its composition. The properties such as fuel–air equivalence ratio, residual gas fraction and initial charge temperature determine the quality of the fuel–air mixture. The quality of charge plays an important role in the rest of the cycle; it influences the power, efficiency and emissions of SI engines. In recent decades, engine cycle simulations have been increasingly used because of the increasing performances of computers, which have allowed the researchers to perform numerical experiments [3]. However, most of earlier studies on engine simulations were based on the mass conservation and energy balance equations. Such an analysis of an engine system makes it possible to analyze engine performance and predict emissions, but it is not possible to evaluate the energy degradation that causes reductions in work output. The second law of thermodynamics, however, makes a distinction between the quantity and the quality of energy by considering the irreversibilities [4,5]. Therefore, using the second law of thermodynamics together with the conservation principles makes it possible to distinguish the exergy (availability) that is consumed in a real process from the energy that is conserved [6,7]. The application of exergy analysis to engineering systems is very useful because it can provide quantitative information on irreversibilities and various exergy losses. Therefore, there has been a growing interest in recent decades in exergy analysis as applied to internal combustion engines (ICEs). A review study that contains a general listing with descriptions, significant findings and comparisons of previous studies was published by Caton [8]. More recently, Rakopoulos and Giakoumis published another review paper with a different philosophy, and a new perspective developed for second law applications to ICEs operation [7]. Of these studies, there are only a limited number of studies on the second law analysis of ICEs, and few of them address SI engines. However, some fuel–air mixture properties have been examined by a few authors as a part of their studies. Lior and Rudy performed an exergy analysis for an air–fuel mixture based ideal Otto cycle to improve the understanding of exergy utilization [9].

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Nomenclature

A	total availability or exergy (J)
a	specific availability or exergy (J/kg)
b	cylinder bore (m)
E	total energy (J)
I	irreversibility (J)
i	specific irreversibility (J/kg)
imep	indicated mean effective pressure (bar)
L_{cr}	length of connection rod (m)
L_s	stroke length (m)
m	mass (kg)
n	engine speed (rpm)
p	pressure (bar)
Q	heat transfer (J)
Q_{LVH}	lower heating value of fuel (J/kg)
r_c	compression ratio (–)
S	total entropy (J/K)
s	specific entropy (J/kg K)
T	absolute temperature (K)
U	total internal energy (J)
v	specific volume (m^3/kg)
V	volume (m^3)
W	work transfer (J)
x_b	burned mass fraction (–)
x_r	residual gas fraction (–)

Greek symbols

$\Delta\theta_b$	burn duration (deg.)
ε	error value (–)
ϕ	fuel–air equivalence ratio (–)
θ	crank angle (deg.)
θ_s	spark timing angle (deg.)
η_I	first law efficiency (%)
η_{II}	second law efficiency (%)
μ	chemical potential (J/kg)
μ_1^0	chemical potential of environmental species at dead state (J/kg)

Subscripts

0	reference, ambient or dead state conditions
b	burned
ch	chemical
char	charge
comb	combustion
dest	destroyed
exh	exhaust
f	fuel
gen	generation
kin	kinetic
pot	potential
Q	heat transfer
tm	thermomechanical
tot	total
u	unburned
W	work transfer
w	wall

The effects of the compression ratio and the equivalence ratio were investigated to identify possible ways to improve cycle efficiency. They stated that the efficiency decreases by increasing fuel–air equivalence ratio. Shapiro and Van Gerpen performed exergy analysis for both SI and diesel engines by using a two-zone combustion model [10]. The effects of the equivalence ratio, the mixing of fuel and air, the residual gas fraction and the burn duration on irreversibilities and chemical and thermomechanical exergies were investigated. They stated that both the equivalence ratio and the residual gas fraction have a large influence on chemical and thermomechanical exergies. Rakopoulos performed another exergy analysis study to assess of cycle performance over a range of design and operation conditions [11]. Similar variations were obtained for the effectiveness of air–fuel mixture based ideal Otto and real engine cycles. The effectiveness was decreased by increasing the fuel–air equivalence ratio, and the values of the real cycle stayed below that of an ideal cycle. Caton examined the effects of combustion on exergy destruction by selecting representative operating conditions for ICEs [12]. He declared that the absolute value of destroyed exergy for per unit mass of mixture is increased by increasing fuel–air equivalence ratio. He also stated that the total reactant exergy destroyed by combustion decreases as the reactant temperature is increased. This study focuses on charge properties in particular, with the goal of making an additional contribution by investigating the effects of the equivalence ratio, the residual gas fraction, and the charge temperature on the exergy balance of SI engines. To meet this goal, a thermodynamic model for SI engines developed originally by Ferguson [1] is modified and used throughout the study.

2. Thermodynamic Cycle model

Only the closed part of the cycle is taken into account in this study. It is assumed that the intake valve closes and the compression period starts at −180 crank angle degrees (CAD) at BDC, where the cylinder contains a homogenous unburned gas mixture of air, fuel, and residual gases. The mixture is compressed until the start of combustion at a specified crank angle before TDC. It is assumed that combustion creates a second zone (burned gas zone) that contains combustion products in an equilibrium state. The mass burning rate during combustion can be determined by using the cosine burn rate formula [1,2]:

$$x_b = m_b/m_{tot} = 0.5\{1 - \cos[\pi(\theta - \theta_s)/\Delta\theta_b]\}. \quad (1)$$

Burn duration is an input variable in some heat release models, but here, it is determined from the empirical correlations according to certain design and operating parameters [13]. After completion of combustion, the expansion process ends at +180 CAD at BDC. Through the simulation, the instantaneous cylinder volume and pressure, the temperatures of burned and unburned zones, the work output and heat energy loss can be calculated by numerically integrating the ordinary differential equations derived from the mass and energy conservation equations. The composition and thermodynamic properties of the burned and unburned zones are obtained from generally accepted algorithms [1,2]. The full details of the cycle model can be found in the literature [1,3].

3. Exergy analysis

The second law is analogous to the statement of entropy balance [4,5]. Considering the combination of the first and second law of thermodynamics, the availability equation can be written for a closed system as

$$A = E + p_0V - T_0S, \quad (2)$$

where E is the total energy which is a sum of internal, kinetic and potential energies as follow $E = U + E_{kin} + E_{pot}$.

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