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Multidimensional modeling of the effect of exhaust gas recirculation on exergy terms in a homogenous charge compression ignition engine fueled by diesel/biodiesel

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ABSTRACT

Increased environmental pollution and finitude of fossil fuels have raised the concern for the main energy resources consumers in the world. Biodiesel fuel, as a renewable and degradable fuel, has received increasing attention globally. Although, the increased NO_x emission owing to the inclusion of oxygen in the biodiesel fuel structure is a considerable environmental penalty. Use of hot exhaust gas recirculation (EGR) is recommended to reduce NO_x emission. With respect to the fact that the hot EGR does not adversely affect the other emissions, exergy analysis can evaluate the performance of the engine supplied with biodiesel fuel using the hot EGR. In the current study, the effect of the hot EGR on a biodiesel-fueled homogeneous charge compression ignition(HCCI) engine in terms of the second law of thermodynamics is studied. The quantity of biodiesels equals 0%, 20%, and 50% of total injected pure diesel fuel mass (i.e., B0, B20, and B50) and the introduced EGR mass fraction equals 0%, 10%, 20%, and 30%. Based on a FORTRAN code, various accumulative exergy terms are calculated for different employed biodiesels and EGRs. The results revealed 66.7% increase in the accumulative heat loss exergy (AH.E), 2.9% decrease in the accumulative work exergy (AW.E), and 14.6% decrease in the accumulative irreversibility (AI), from B50-EGR = 0% to B50-EGR = 30%.Moreover, the exhaust thermomechanical exergy increased by 39.3% from B0-EGR = 0% to B0-EGR = 30%. Finally, the exhaust chemical exergy increased by 46.7% from B20-EGR = 0% to B20-EGR = 30%. It can be concluded from the results that the hot EGR could relatively decrease the work exergy. The irreversibility, on the other hand, significantly decreased while the heat transferred through the cylinder wall and exhaust increased.

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1. Introduction

Economizing fuel consumption in internal combustion engines concurrent with enhanced exhaust emissions is of worldwide importance. HCCI combustion has been proposed as an effective method with less NO_x emission and fuel consumption, as well as with high efficiency. With respect to the fact that the maximum efficiency in internal combustion engines could reach 45%, researchers have identified the energy loss sources through conducting exergy analysis (Taghavifar et al., 2015). As a matter of fact, to achieve a detailed conception for construction of engines and in order to specify energy loss sources, the parameters participated in exergy destruction were explored (Abusoglu and Kanoglu, 2008; Flynn et al., 1984). The exergy analysis was conducted in internal combustion engines as the first law of thermodynamic was inadequate in picturizing the complete energy transfer (Fathi et al., 2011; Gümüş and Atmaca, 2013; Saxena et al., 2013; Taghavifar et al., 2014; Chintala and Subramanian, 2014; Jafarmadar and Nemati, 2017). Several research studies have been conducted and reported in the literature on performance of HCCI engines based on the exergy analysis. Recently published studies are summarized as follows:

Jung and Iida (2015) experimentally studied the effect of EGR and rebreathed EGR on pressure rise rate (PRR) in an HCCI engine fueled with dimethyl ether. They concluded that the retard in the combustion phasing resulted in the maximum PRR. Moreover, the chemical effects of the residuals retained from the previous cycle recovered the indicated mean effective pressure (IMEP). In Ref. Hegner and Atakan (2016), an HCCI engine fueled with the preheated methane gas and EGR was used in a polygeneration

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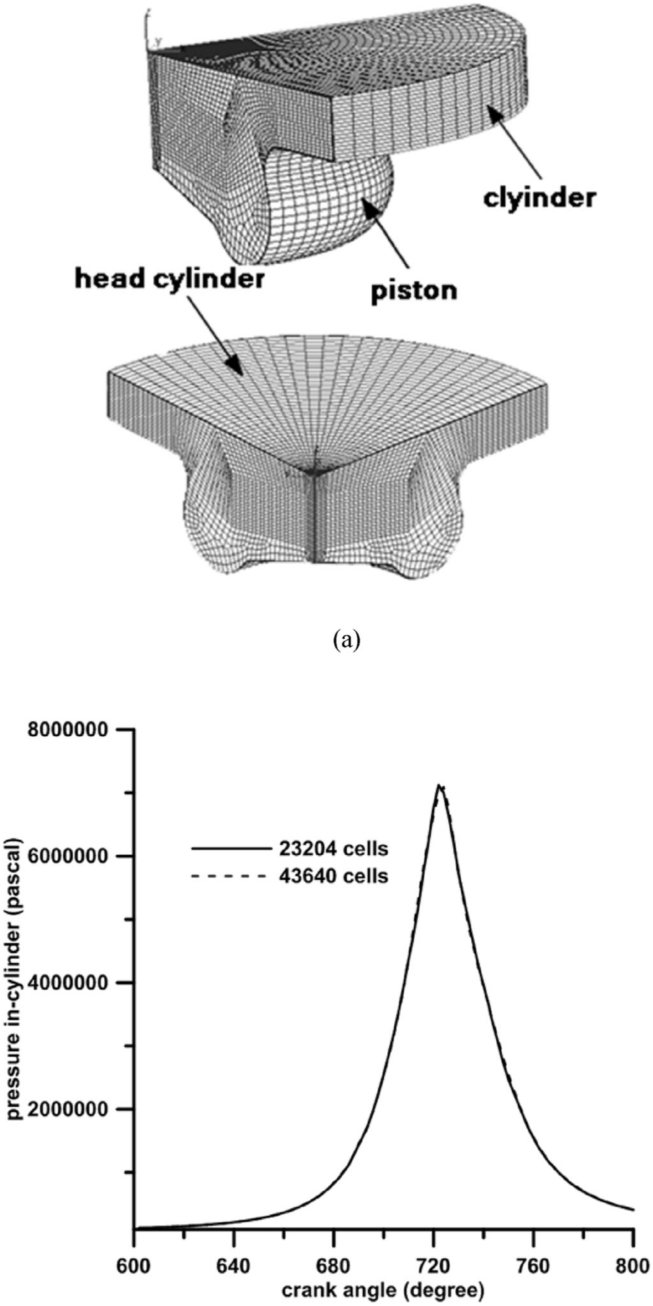
process to contribute to hydrogen-, heat- and power-output. They revealed the increased exergetic efficiency up to 80% with the reduction of fuel consumption up to 40% in comparison with the separately produced hydrogen, heat and power. From the perspective of exergy analysis, the effect of EGR introduction on an HCCI engine fueled with natural gas/n-heptane was studied by Amjad et al. (2011). Results revealed that, with the increase in EGR percentage, the AW.E, thermomechanical exergy (T.E), and AI decreased while chemical exergy (C.E) increased. Introduction of EGR up to an optimum value resulted in enhancement of the second-law efficiency. Finally, the variation in exergetic performance coefficient (EPC) (Ust et al., 2007) showed that EGR = 35% yielded the optimum engine performance. In another study, the effect of adding a reformer gas (i.e., a mixture of carbon monoxide and hydrogen) to an HCCI engine fueled with iso-octane and n-heptane as blended fuels based on the exergy analysis was studied by Neshat et al. (2016). The result showed that, when 5% or 10% of the total fuel was appropriated for the reformer gas, the first and second law efficiencies obtained the optimal values. The effect of EGR on exergy terms in an HCCI engine fueled with diesel/natural gas was studied by Jafarmadar et al. (2015). The fuel-air ratio was set constant at 0.3. The results showed that the EGR increase led to reduced peak pressure and temperature, as the EGR = 30% significantly deteriorated the combustion process. Moreover, the EGR increase resulted in reduced accumulative burned fuel, heat loss, and work exergies, while it caused increased exhaust exergy loss. Finally, the EGR introduction increased irreversibility and thus, the second law efficiency was reduced. The efficiency of gasoline reformed molecule HCCI combustion based on exergy analysis was studied by Yu and Su (2017). Results of their study revealed that the highest value of exergy efficiency at the compression ratio of 17–21 in the gasoline HCCI engine operation was higher than that in the reformed molecule HCCI engine. This trend was due to comparatively reduced exergy destruction, less exhaust dilution, and increased work efficiency. In another study, Yan and Su (2015) analyzed the exergy losses of a reformed molecule HCCI. They concluded that the second law efficiency was enhanced when the compression ratio was heightened. Moreover, they stressed that the reformed molecule HCCI shortened but controlled combustion durations, reduced exergy losses, and increased engine efficiency. The EGR influence on exergy terms in diesel/hydrogen fueled HCCI engine was investigated by Jafarmadar and Nemati (2017). The ratio of gas fuel/air was kept constant at 0.3 and EGR increased from 0% to 30% in 10% increments. According to their study, by increasing the EGR, the exergy efficiency, work exergy, and irreversibility decreased while the exhaust exergy increased. A thorough investigation of the literature on the performance of HCCI engines yielded no study on exergy analysis in diesel/biodiesel fueled HCCI engines with EGR implementation. In the current study, the combustion chamber and the combustion model are simulated with the aid of computational fluid dynamics (CFD) code and extend coherent flame model-three zone (ECFM-3Z) model, respectively. By utilizing an in-house FORTARN code, exergy analysis was conducted on the energy degradation locations. Briefly, via employing various biodiesel/diesel fuel blends and hot EGR rates, the current study calculates different accumulative exergy terms in order to evaluate the success of the biodiesel and EGR employment.

Table 1
Initial and boundary condition.

Mean inner piston wall temperature	575 K
Mean inner liner wall temperature	475 K
Mean inner head wall temperature	550 K
Initial pressure	1 bar
Initial temperature at EGR = 0%	380 K
Initial temperature at EGR = 10%	422 K
Initial temperature at EGR = 20%	484 K
Initial temperature at EGR = 30%	563 K
Turbulent kinetic energy	9.6 m^2/s^2
Turbulent dissipation rate	4236.13 m^2/s^3
Turbulent time scale	0.0055 s

2. Energy analysis

The dispersed, continuous, compressible, and multi-component flow field is modeled using a three-dimensional CFD model. Mass, momentum, and energy conservation laws as a set of governing



(a)

(b)

Fig. 1. (a) Geometry of the combustion chamber at TDC from two views. (b) Grid dependency based on the in-cylinder pressure.

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