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Thermodynamic energy and exergy analysis of three different engine combustion regimes

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HIGHLIGHTS

- Energy and exergy distributions of three different combustion regimes are studied.
- CDC demonstrates the highest utilization efficiency of heat transfer and exhaust.
- HCCI achieves the highest energy and exergy efficiencies over CDC and RCCI.
- HCCI and RCCI demonstrate lower exergy destruction than CDC.
- Combustion temperature, rate, duration and regime affect exergy destruction.

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ABSTRACT

Multi-dimensional models were coupled with a detailed chemical mechanism to investigate the energy and exergy distributions of three different combustion regimes in internal combustion engines. The results indicate that the 50% heat release point (CA50) considerably affects fuel efficiency and ringing intensity (RI), in which RI is used to quantify the knock level. Moreover, the burn duration from the 10% heat release point (CA10) to CA50 dominates RI, and the position of 90% heat release point (CA90) affects fuel efficiency. The heat transfer losses of conventional diesel combustion (CDC) strongly depend on the local temperature gradient, while it is closely related to the heat transfer area for homogeneous charge compression ignition (HCCI) and reactivity controlled compression ignition (RCCI). Among the three combustion regimes, CDC has the largest utilization efficiency for heat transfer and exhaust energy due to its higher temperature in the heat transfer layer and higher exhaust pressure and temperature. The utilization efficiency of heat transfer and exhaust in RCCI is less affected by the variation of CA50 compared to those in CDC and HCCI. Exergy destruction is closely related to the homogeneity of in-cylinder temperature and equivalence ratio during combustion process, the combustion temperature, the chemical reaction rate, and the combustion duration. Under the combined effect, HCCI and RCCI demonstrate lower exergy destruction than CDC at the same load. Overall, the variations of the exergy distribution for the three combustion regimes obtained from the second law of thermodynamics are consistent with those from the first law of thermodynamics. HCCI demonstrates the highest energy and exergy efficiency, and CDC performs the worst.

1. Introduction

Reduction of harmful emissions from internal combustion engines is an urgent task for vehicle manufactories, and it is attracting increasing attention all around the world. Meanwhile, more stringent restrictions on carbon dioxide (CO_2) raises a great challenge for engine combustion systems. The target of CO_2 emissions in the European Union is required to be below 130 g/km by 2015 for all new cars and below 95 g/km is expected to be demanded by 2021 [1]. Therefore, improvement of the in-cylinder combustion process to simultaneously obtain high fuel efficiency and low exhaust emissions is imperative.

The first law of thermodynamics has been widely used to quantify the fuel efficiency of internal combustion engines [2]. However, besides the quantity of energy, the quality of energy is

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another important indicator for energy utilization, which cannot be obtained from the first law (energy) of thermodynamics. Thus, the second law (exergy) of thermodynamics is usually introduced to provide more thorough insight into the thermodynamic process during engine cycles [3,4]. Consequently, the sources and magnitudes of the energy wasted in the system can be evaluated, and a guide to take full advantage of the system energy can be provided.

The exergy of a system under a given state, also known as availability, is the maximum output power that can be potentially extracted from the system when the system reaches thermal, mechanical, and chemical equilibrium with its surroundings while experiencing a reversible process. Thermal equilibrium is the state that the temperature of a system is equal to that of its surroundings. The state in which no pressure gradient exists between the system and its surroundings is defined as mechanical equilibrium. When all the components in a system cannot interact with its surroundings to produce work, it is called chemical equilibrium [5]. If a system is only in thermal and mechanical equilibriums, the state of the system is defined as the restricted dead state. When all the three equilibria are obeyed, the state of the system is defined as the reference dead state. The selection of the reference dead state is very important since it determines the amount of system exergy. For the reference dead state, the pressure and temperature are usually taken as $p_0 = 1.01325$ bar and $T_0 = 298.15$ K, and the molar compositions of the environment are 20.35% O_2, 75.67% N_2, 0.03% CO_2, 3.03% H_2O, and 0.92% various other substances [6].

For internal combustion engines, the input energy can be mainly divided in four parts according to the first law of thermodynamics, including incomplete combustion, heat transfer losses, exhaust losses, and indicated output power [7,8]. However, in the view of exergy analysis, energy degradation happens along the whole cycle due to irreversibility. Accordingly, exergy analysis should be performed to evaluate the maximum achievable engine efficiency. In conventional diesel combustion (CDC) engines, the major exergy destruction is produced from combustion, fuel-air mixing, friction, and throttling [9]. Under typical operating conditions, the combustion process accounts for more than 90% of the total exergy destruction [10], and the other exergy destructions from pumping and fuel/air mixing processes are usually one or two orders of magnitude smaller [11].

A large amount of effort has been devoted to investigate the effects of operating parameters on exergy distributions in spark ignition (SI) and compression ignition (CI) engines. In a direct-injection SI engine fueled with hydrogen, Nemati et al. [3] examined the terms in the second law of thermodynamics by adjusting the injection timing and equivalence ratio of the hydrogen fuel. It was found that exergy destruction and exergy transfer through the exhaust gases were significantly affected by equivalence ratio and exergy destruction could be reduced by retarding the injection timing of the hydrogen and by decreasing the overall equivalence ratio. Djermouni and Ouadha [12] investigated the impact of a turbo charger on the thermodynamic performance of a HCCI engine fueled with natural gas. They indicated that both energy and exergy efficiency were enhanced with an increase of compressor and turbine efficiency. Furthermore, a parametric study was conducted by Zheng and Caton [13] to explore the influence of exhaust gas recirculation (EGR) on exergy efficiency in a low-temperature combustion (LTC) engine with late injection. It was concluded that the reduction of exergy destruction with the introduction of EGR was primarily attributed to the heating effect of EGR on the intake charge, which correspondingly led to an increase in combustion temperature. The similar conclusion that elevating the initial charge temperature contributed to the reduction of exergy destruction was drawn by Fathi et al. [14].

As indicated in previous studies, exergy destruction is inevitable in engines, and occupies 5–25% of the total input fuel exergy [15,16]. Caton [17] found that exergy destruction in engines can be reduced with an increase of reactant temperature and equivalence ratio, whereas the effect of reactant pressure was less pronounced. According to the work of Rakopoulos and Giakoumis [18], it was indicated that the premixed combustion fraction, combustion duration, and injection timing only marginally affected the exergy destruction during the combustion process, while the chemical reaction rate of the fuel was the dominant factor. Overall, it can be concluded from the previous studies that exergy destruction is closely related to the combustion process.

Advanced combustion strategies with premixed LTC, including homogeneous charge compression ignition (HCCI), premixed charge compression ignition (PCCI), and reactivity controlled compression ignition (RCCI), which manifest different combustion characteristics from CDC [7,19], are attracting more and more attention due to their advantages in fuel economy and exhaust emissions. However, the fundamental reasons for their superiority in fuel efficiency have not been comprehensively revealed, and the potential of maximum work extraction from LTC engines still remains ambiguous. By coupling multi-dimensional models and a detailed chemical mechanism, the energy and exergy distributions of different combustion regimes are systematically analyzed and compared in this study. The important factors that affect exergy destruction are revealed, and the potential for energy utilizations for the different combustion regimes are identified.

2. Numerical models

The simulations conducted in this study were based on the updated KIVA-3V code [20], in which several improvements to the physical and chemical sub-models have been made to enhance prediction accuracy. A new generalized re-normalization group (gRNG) κ-ε turbulence model proposed by Wang et al. [21,22] was adopted, which avoids the over-predicted turbulent energy in the RNG turbulence model by considering the flow strain rate. The hybrid Kelvin Helmholtz (KH)-Rayleigh Taylor (RT) model [23] was utilized to reproduce the spray droplet breakup process. Grid independence was improved by employing the spray collision model developed by Nordin [24]. A new spray/wall interaction model proposed by Zhang et al. [25] was employed which is specifically improved for the conditions relevant to LTC engines. The wall heat transfer model developed by Han and Reitz [26] was employed because it is capable of characterizing the effect of variations of gas density and turbulent Prandtl number in wall boundary layers. The CHEMKIN solver [27] was integrated into the KIVA-3V code to describe the complex chemical kinetic combustion process. A skeletal oxidation mechanism of n-heptane and iso-octane (primary reference fuel, PRF) [28] consisting of 49 species and 163 reactions was built through a decoupling methodology. It was demonstrated that the ignition and combustion characteristics of diesel and gasoline can be satisfactorily captured by the mechanism with n-heptane and iso-octane as the respective surrogates [29,30]. In addition, the extended Zeldovich nitrogen oxide (NO_x) sub-mechanism and an improved phenomenological soot model [31] were coupled with the chemical mechanism. Note that soot emissions were very low for all cases and are not discussed here.

3. Exergy analysis methodology

The thermal and mechanical exergy of the working fluid are usually combined as thermomechanical exergy. The thermomechanical exergy $\left(Ex^{th}_{exhaust}\right)$ and chemical exergy $\left(Ex^{ch}_{exhaust}\right)$ of exhaust gases can be respectively predicted as follows: