두 상이한 압력조건에서의 RCCI연소에 관한 직접수치모사 연구

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A DNS Study of Reactivity Controlled Compression Ignition (RCCI) Combustion under Two Different Pressure Conditions

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ABSTRACT

The ignition characteristics of PRF/air mixtures under RCCI conditions at naturally-aspirated and boosted intake pressure are investigated numerically using a 116-species reduced PRF mechanism. The effects of compression heating and expansion cooing by the motion of piston in an engine cylinder are also accounted for by adopting a compression heating/cooling model. *iso*-Octane and *n*-heptane are selected as two different fuels of low and high reactivity, respectively. The average mixture is PRF50. The effects of thermal and reactivity stratifications are investigated using 1-D direct numerical simulations (DNSs). It is found that (i) *n*-heptane stratification plays a predominant role in reducing the peak heat release rate (HRR) and advancing the overall combustion for the low- and high-intake pressures in time. However, its effect is significantly reduced by the cooling effect of temperature, while *iso*-octane stratification is not much affected by this cooling effect; (ii) *iso*-octane stratification has no effect on the overall combustion for the intake pressure of 1 atm. However, it produces a positive effect on advancing the overall combustion at the intake pressure of 1.88 atm and reducing the peak HRR significantly. Dual-fuel stratification of two different-reactivity fuels can be used to extend the operating range of RCCI combustion to a higher load by smoothly prolonging sequential ignition process under a highly-boosted condition.

Key Words: DNS, HCCI, RCCI, dual fuel stratification, PRF reduced mechanism

A dual-fuel reactivity controlled compression ignition (RCCI) concept as a variant of homogeneous charge compression ignition (HCCI) is now believed to address the issues relevant to HCCI combustion. In the RCCI concept, two fuels with different ignition characteristics are blended inside the combustion chamber. Combustion timing is manipulated by the ratio of the relative mass of the two fuels and the combustion duration is controlled by spatial reactivity stratification induced by the direct injection of the high reactivity fuel. By appropriately choosing the reactivities of two fuels, their relative amounts, and the injection timing, RCCI combustion can effectively control the combustion process and hence, has a potential to dramatically reduce fuel usage and pollutant emissions by a controlled-low temperatures and controlled-lean equivalence ratios [1].

John E. Dec et al. [2] found that gasoline has no equivalence-sensitivity under an ambient intake pressure while it is highly sensitive to boosted condition such that partial-fuel stratification strategy can be used under highly boosted conditions. Recently, Wissink et al. [3] demonstrated that direct dual fuel stratification (DDFS) is beneficial for distributing heat release rate (HRR) and reducing pressure rise rate (PRR) at high load. The advantages of RCCI and partially premixed combustion (PCC) were effectively combined with DDFS by controlling the start of the heat release event with the diesel injection and the peak and duration of the heat release event with near-TDC gasoline injection, DDFS achieved comparable efficiency to RCCI, while simultaneously decreasing HRR. However, the effects of stratification of both gasoline and diesel on the overall combustion characteristics are not well understood, especially at different intake-pressures.

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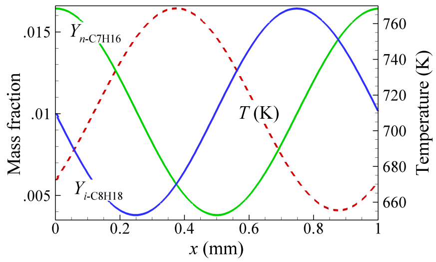

Fig. 1 Representative initial Y_k–T relations for dual fuel stratification

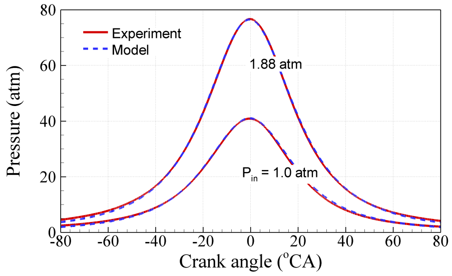

Fig. 2 Experimental and modeled motored-pressure history as a function of crank angle degrees. Experimental motored-pressure trace taken from experiment by Wissink et al. [3] operating at 1300 RPM under low- and high-load conditions of p_{in} of 1 atm & 1.88 atm respectively.

In our previous studies [4 - 11], the ignition characteristics of HCCI, SCCI, and RCCI combustion in constant volume have been investigated. In a real RCCI engine, however, the overall combustion process including the first-stage ignition is highly affected by both the compression heating before the top dead center (TDC) and the expansion cooling after the TDC by the piston motion.

The objective of the present study is, therefore, to investigate the effects of various reactivity stratification strategies on the ignition process of the reactivity stratified PRF/air mixture under RCCI conditions with natural and boosted intake pressures. 1-D DNSs of RCCI combustion are performed with the 116-species reduced PRF mechanism and the effects of the compression heating and expansion cooling by a piston motion are also accounted for by including mass source term in the governing equations.

The Sandia DNS code, S3D, was used to simulate RCCI combustion process. For all DNSs, the mean temperature, T_0, is 712 K and the mean fuel is PRF50 (50% *iso*-octane + 50% *n*-heptane by volume). For a typical RCCI combustion concept, *iso*-octane and oxidizer are homogeneously premixed; while, *n*-heptane is directly introduced in the cylinder to generate some degrees of mixture stratification. Similar concepts are applied in the present study for the cases denoted with *n*-heptane stratification. However, for dual fuel stratification, both *iso*-octane and *n*-heptane are inhomogeneously initialized.

A negative fuel-temperature correlation due to the cooling effect by a late direct injection is considered. Figure 1 shows the negative correlation of the total fuel mass fraction and temperature, and the uncorrelation of *iso*-octane and *n*-heptane mass fractions. For

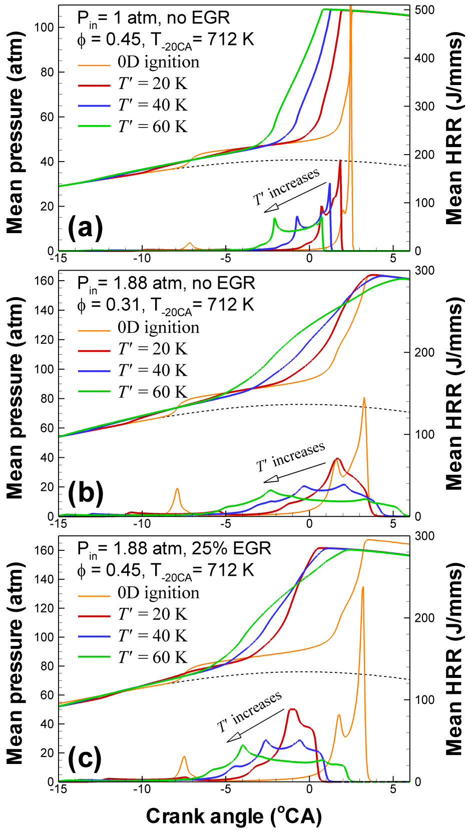

Fig. 3 Temporal evolutions of mean pressure and mean HRR for three different levels of thermal stratificaion of 20 K, 40 K, and 60 K with (a) Pin = 1 atm, (b) Pin = 1.88 atm with no EGR, and (c) Pin = 1.88 atm with 25% EGR addition.

a perfectly-negative correlation, the temperature is normalized based on the *iso*-octane/*n*-heptane mass fraction profiles.

The effects of the compression heating and expansion cooling are mimicked using an inert mass source term added to the governing equations as in [12] with a modification such that the inert mass source term is adjusted to each local grid point to maintain a uniform pressure throughout the computational domain. The motored pressure history was modeled with a perfect agreement with an experimental one taken from [3] as shown in Fig. 2. Two motored pressure traces, p_{in} of 1 atm and 1.88 atm, are chosen as two representative pressures for natural aspirated and boosted pressures, respectively.

To show the relative effect of temperature and reactivity stratification on the overall combustion, their effect is separatedly investigated. The effect of thermal stratification on the temporal evolutions of mean pressure and mean HRR under two different intake pressures is shown in Fig. 3. As readily shown, even under different intake pressures, the trend of the overall temporal combustion is nearly the same with increasing T'. In particular, the mean pressure and mean HRR are more distributed in time, and the ignition delay timing is more reduced with increasing T'.

Figure 4a-c and 4d-e respectively show the effect of reactivity stratification onlt, and reactivity-temperature stratification on the temporal evolutions of mean pressure and mean HRR under two different intake pressures. As expected, for p_{in} = 1 atm, the effect of *iso*-octane stratification has no effect on the overall combustion behavior (see Fig. 4a); while for p_{in} = 1.88 atm, *iso*-octane inhomogeneities have the positive effect on advancing the ignition delay (see Fig. 5b-c),

Fig. 4 Temporal evolutions of mean pressure and HRR for different reactivity stratification strategies at (a) & (d) p_{in} = 1 atm, (b) & (e) p_{in} = 1.88 atm with no EGR, and (c) & (f) p_{in}= 1.88 atm with 25% EGR addition. Note that Cases in Fig. 5a-c were initialized with only reactivity stratification (T' = 0 K) whereas Cases in Fig. 5d-f were initialized with negative reactivity-T correlations (T' = 40 K).

especially for the case with 25% EGR addition. *n*-Heptane stratification plays a predominant role in reducing the peak HRR and advancing the overall combustion (Fig. 4a-c), compared to that of *iso*-octane stratification.

For a negative reactivity-temperature correlation caused by the cooling effect of late direct injection, the cooling effect of temperature significantly eliminates the effect of reactivity stratification induced by *n*-heptane inhomogeneities on reducing the peak HRR, while it has a small cancelling effect on *iso*-octane stratification as shown in Figs. 4d-f, especially with Cases involving boosted conditions. As such, inhomogeneities in both *iso*-octane and *n*-heptane inhomogeneities have a positive effect on reducing the peak HRR and distributing the HRR over time by a prolonged sequential ignition process (see Cases with dual-fuel stratification in Fig. 4d-f).

The ignition behaviors can further be understood by investigating the 0-D ignitions of PRF100/air mixtures under different pressures as shown in Fig. 5. Figure 5 reveals that the ignition delay of *iso*-octane is significantly reduced and its ignition delay is approximately order of 1 ms with increasing pressure. Therefore, the low-temperature chemistry can be involved in the combustion process under boosted conditions such that *iso*-octane stratification can play a significant role in enhancing the overall combustion of RCCI combustion with dual fuel stratification, resulting in a considerable reduction in the peak HRR by a prolonged sequential ignition process.

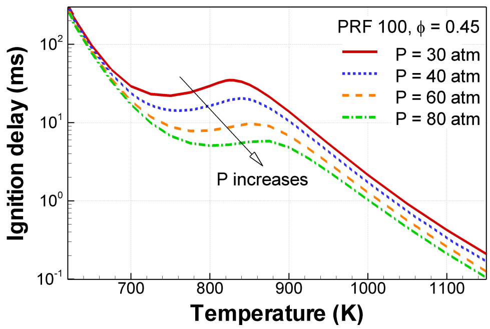

Fig. 5 0-D ignition delays of PRF/air mixture as a function of initial temperature under initial pressures of 30, 40, 60, and 80 atm for PRF100 (*iso*-octane).

In summary, the RCCI combustion concept with dual fuel stratification can have a great potential in manipulating its combustion process and hence, it can accomplish boosted combustion under higher operating load condition.

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