DDFS조건에서의 희박 PRF/공기 혼합물의 점화에 대한 분할 분사의 효과에 관한 직접수치모사

김종학[*]. 유광현[*]. 정석호[**].유춘상[*†]

A DNS study of the effect of split injection on the ignition of a lean PRF/air mixtures under DDFS conditions

Jong Hak Kim[*], Gwang Hyeon Yu[*], Suk Ho Chung[**], Chun Sang Yoo[*†]

ABSTRACT

The effects of injection strategy for the control of ignition of PRF/air mixture in dual fuel engines has been investigated by direct numerical simulations (DNSs) with a 121-species pseudo reduced kinetic mechanism. The 2-D DNSs of direct dual fuel stratification (DDFS) combustion are performed by splitting the amount of the injection of *iso*-octane (i-C_8H_{18}) with a pseudo-*iso*-octane (PC_8H_{18}) model. It is found that the main ignition of split injection occurs at earlier timing than single injection and its overall combustion phase is also advanced in time.

Key Words : DNS, DDFS, Split injection, PRF

Homogeneous charge compression-ignition (HCCI) combustion engines are being developed as an alternative to conventional engines. High efficiency with low emissions in HCCI combustion engines can be achieved under lean, dilute, high pressure and low temperature conditions [1-4]. Despite of its promising advantages over conventional internal combustion (IC) engines, several challenges should be solved such as mitigating excessive pressure rise rate (PRR) and controlling ignition timing under high-load operation conditions due to instantaneous ignition of the homogeneous charge [1-7]. To overcome these challenges, many alterations to HCCI engines have been made in the engine community [1-10].

Recently, direct dual fuel stratification (DDFS) combustion has been suggested as one of the most competitive alternatives to HCCI combustion because it has more controllable parameters of the combustion process with the benefits of HCCI combustion [6-10]. In the DDFS combustion, an early injection of gasoline produces premixed background charge. And followed direct injection of diesel generates reactivity stratification. The ignition timing is controlled by the direction injection of diesel.

To control the overall combustion process, certain direct injection strategies can be carried out. Dividing a single injection into many smaller injections helps to further decrease the noise while suppressing the increase of fuel consumption and emissions [11-13]. For these reasons, many researchers have studied the effects of injection parameters such as injection timing, dwell, and the use of exhaust gas recirculation (EGR) [11-16]. Split injection approach can be implemented by dividing the single injection into two or four successive equal injections with certain dwell between successive injections.

In the investigated split injection approach, *n*-heptane and oxidizer are first supplied through port fuel injection (PFI) to produce well-premixed charge, followed by split direct injections of *iso*-octane to generate spatial inhomogeneities in reactivity. By adjusting the number of divided injections of *iso*-octane, we can control the start of combustion and reduce the required intake pressure and temperature.

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[*] 유니스트 기계공학과
[**] Clean Combustion Research Center, KAUST
[†] 연락저자, csyoo@unist.ac.kr
TEL : (052)217-2322 FAX : (052)-217-2309

Table 1 Injection timing and duration, and fuel mole fraction of single and split injection strategies

	Split 1	Split 2	Split 4
t_{inj} (ms)	0	0, 0.5	0, 0.25, 0.5, 0.75
t_{dur} (ms)	0.8	0.4	0.2
n-C_7H_{16}	0.324	0.324	0.324
i-C_8H_{18}	0.676	0.338×2	0.169×4
PC_8H_{18}	0.676	0.338×2	0.169×4

Direct numerical simulations (DNSs) were performed to investigate the effect of the split injection schemes on the DDFS combustion using S3D, which was linked with CHEMKIN and TRANSPORT software libraries. S3D solves the compressible Navier-Stokes, species continuity, and total energy equations. An eighth-order central differencing scheme and a fourth-order explicit Runge-Kutta method were applied for spatial discretization and time integration, respectively. The computational domain is a 2-D square box with each size, L, of 3.2 mm. The number of grids considered is 1280^2 attributing to high grid resolution of 2.5 μm. The boundary conditions are set as periodic in both directions. Initially, the turbulent velocity fluctuations are superimposed on the zero mean velocity field according the the Passot-Pouquet turbulent kinetic energy spectrum function. For all 2-D DNSs, the most energetic length scale, $l_e =$ 1.737 mm, is selected. Turbulence intensity, $\mathbf{u}'$, of 0.5 is deliberately selected to ensure that the turbulence time scale, $\tau_t = l_e/u' =$ 3.474 ms $\sim \tau_{ig}$ in a real engine. The compression heating and pseudo-species models [7] are used in present DNSs.

In this study, the combined effect of the number of injections and amounts of *iso*-octane on the ignition of a lean primary reference fuel (PRF)/air mixture is investigated (see Table 1). Single, two and four split injections of *iso*-octane are added to the fuel/air mixture, while keeping the equivalence ratio the same as $\phi_0 =$ 0.45. For all DNSs, mean temperature, pressure and are 760 K and 18.2 atm at -25 °CA ATDC, respectively. In a recent experimental study [17], the RMS of temperature fluctuation in an engine was found to be 13.3 K at TDC which is corresponding to 15 K in numerical simulations. For 2D DNSs, initial value of temperature fluctuation, $\boldsymbol{T'}$ of 30 K, is selected to match $\boldsymbol{T'}$ at TDC with experimental results. This is because turbulent mixing reduces the temperature fluctuation in half at TDC. To save computational cost, all the simulations start at -25 °CA ATDC, at which the injection of n-heptane is assumed to be already finished.

The objective of the present study, therefore, is to provide a better understanding of the effects of the split injection strategies on PRF/air mixture under DDFS conditions using DNSs by varying three key parameters: (1) injection timing, (2) duration, (3) amount of *iso*-octane under same initial conditions can be examined

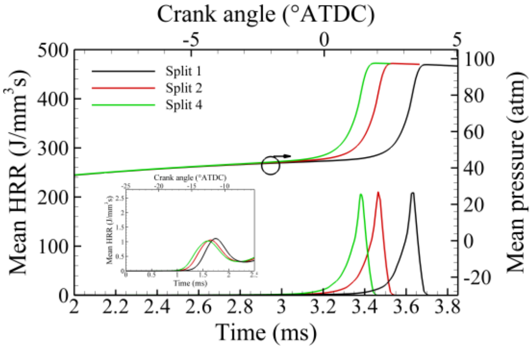

Fig. 1 Temporal evolutions of mean HRR and mean pressure for split injection strategies

Figure 1 shows the temporal evolution of the mean pressure, $\bar{\boldsymbol{p}}$, and HRR, $\bar{\dot{\boldsymbol{q}}}$, for single and two and four split injections. First, the main ignition timing is monotonically enhanced with increasing the number of splitting by increasing the homogeneity of fuel/air mixture. Second, the same tendency of first-stage ignition timings is also featured. In other words, the gap of second-stage ignition timings is consequently affected by the short gap of first-stage ignition. The split injection strategies decrease ignition delay, which means the required intake pressure and temperature can be reduced by the injection strategies. It can improve thermal efficiency of the DDFS combustion engines.

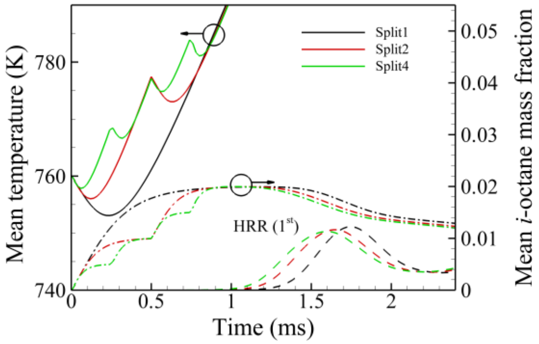

Fig. 2 Temporal evolutions of mean temperature, first-stage HRR and *iso*-octane mass fraction for split injection strategies

Figure 2 shows the temporal evolution of the mean temperature, $\overline{\boldsymbol{T}}$, and first-stage HRR, $\bar{\boldsymbol{q}}_{\boldsymbol{1^{st}}}$, and *iso*-octane mass fraction for single and two and four split injections. The ignition delay of the DDFS combustion features a monotonic behavior with increasing the number of split injections due to the different effect of fuel evaporation on low-, intermediate-, and high-temperature chemistry of the PRF oxidation. The pseudo-species model [7] is used for simulating the effects of the split direct injection. The chemical species, PC_8H_{18}, which forms stratified mixture field is non-reactive during the initial phase of the simulation. While the enthalpy of formation of PC_8H_{18} is chosen to be lower than i-C_8H_{18} to mimic the evaporation cooling of fuel, all the thermochemical and transport properties of the PC_8H_{18} are identically same with those of i-C_8H_{18}. The temperature drop (i.e. $\boldsymbol{\Delta T} \approx$ 8 K) is caused by the latent heat of evaporation of direct fuel injection. The sum of the temperature drop of split injection cases is same with single injection. On the other hand, the main ignition timing is enhanced by the injection strategies. This is because split injection induces rapid recovery of temperature, which consequently reaches the critical start points of low-temperature chemistry.

Figure 3 shows instantaneous isocontours of cumulative (25%, 50%) and the maximum normalized HRR for different additives injection types. The local HRR, $\dot{\boldsymbol{q}}$, is normalized by the maximum HRR of 0-D ignition, $\dot{\boldsymbol{q}}^{\boldsymbol{0}}_{\boldsymbol{m}}$ = 1426, 1436, 1435 J/mm^3 for single, two and four split injections.

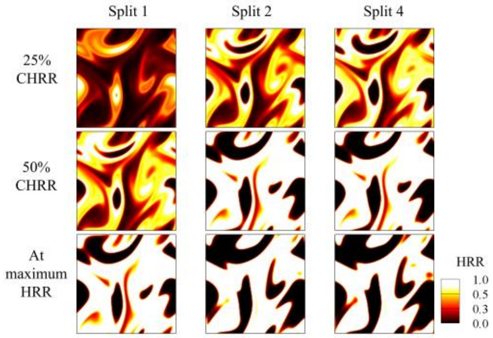

Fig. 3 Isocontours of normalized HRR for no additive, single, two and four split injection strategies (from left to right) at times of 25% (first row), and 50% (second row) cumulative mean HRR and at the maximum HRR (third row).

It is readily observed that overall combustion phase is advanced in split injection cases. It may induce the spontaneous auto-ignition dominantly during short ignition delay. This is because the combustion occurs simultaneously in the domain with high HRR, implying that split injection strategies lead to homogenize the fuel/air mixture. It thus can be employed to improve the quality of combustion and efficiency of engines.

The effects of split injection strategies on the ignition of PRF70/air DDFS combustion were investigated computationally by varying injection timing, duration and amount of *iso*-octane. It was found that under same initial mean temperature, pressure and equivalence ratio, the injection strategies enhance first- and main ignition timing. It is concluded that split injection advances low-temperature chemistry process related with the formation of cool flame. Spontaneous auto-ignition mode is predominant for split injection cases. It is elucidated that split injection strategies can improve the quality of combustion.

후 기

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