Effects of Fuel Stratification on Ignition Kernel Development and Minimum Ignition Energy

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1 Introduction

Fuel-stratified combustion has several advantages compared to homogeneous premixed combustion. Therefore, it has broad application especially in internal combustion engines. For examples, fuel stratification in direct-injection spark-ignition (DISI) engines helps to extend the lean limit of engine operation [1,2]; and it can be used to control combustion phasing in homogeneous charge compression ignition (HCCI) engines [3] and to prevent knocking in DISI engines [4]. In the literature, there are many studies on the fundaments of stratified combustion ([5] and references therein). It was found that stratified flame has a memory of previous flame history and different fuel stratification conditions can either enhance or reduce the flame propagation speed compared to homogeneous mixtures [6]. Therefore, flame propagation in fuel-stratified mixture has different characteristics compared to that in homogeneous mixture.

However, most of previous studies on fuel-stratified combustion focused on flame propagation, while there is little attention on ignition. Besides, the characteristics of ignition kernel propagation in fuel-stratified mixtures are not well understood. This motivates the present work, which investigates the ignition and flame kernel propagation in fuel-stratified mixtures. To the authors' knowledge, the only work on ignition and spherical flame propagation in fuel-stratified mixture was conducted by Ra [7] and Balusamy et al. [5] as mentioned above. However, these two studies [5,7] did not investigate the influence of fuel stratification on the critical ignition condition and small ignition kernel evolution, which shall be assessed in the present work. Besides, for fuel-lean mixture, fuel stratification with higher equivalence ratio around the ignition kernel than that in the surroundings is expected to enhance ignition kernel propagation and thereby promote ignition. In fact, as shall be shown in this study, fuel stratification does promote ignition and reduce the minimum ignition energy (MIE).

In this study, one-dimensional numerical simulation is conducted to investigate ignition and spherical flame kernel propagation in n-decane/air mixtures. The one-dimensional numerical simulation cannot simulate the practical three-dimensional problems, and it does not consider multi-dimensional effect. However, the one-dimensional numerical simulation can simplify the problem and obtain some reasonable results and

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conclusions. Therefore, the objective is to assess the effects of fuel stratification on the ignition kernel propagation and on the MIE.

2 Computational Methods

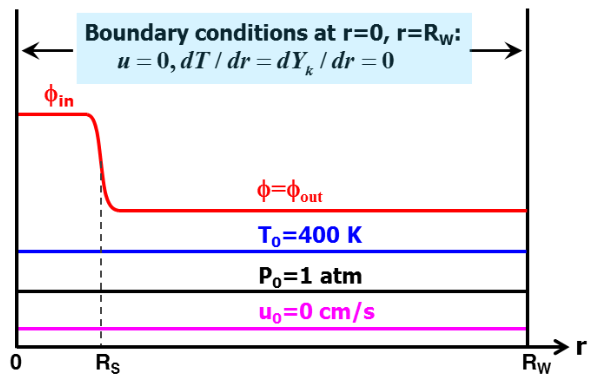

Fig. 1. Schematic of the initial and boundary conditions used in the simulation of ignition and spherical flame kernel propagation in fuel-stratified n-decane/air mixture.

We consider ignition and spherical flame propagation processes in fuel-stratified n-decane/air mixture. Stratified mixture inside a closed spherical chamber with the inner radius of R_W is ignited in the center and the resulting spherical flame kernel propagates outwardly. Spherical symmetry is assumed and thereby one-dimensional simulation is conducted. The initial and boundary conditions are sketched in Fig. 1. Fuel stratification is introduced by specifying a gradual change along radial direction of the spherical symmetrical calculation domain in the initial equivalence ratio profile using the hyperbolic tangent function:

$$\phi(r,t=0)=\frac{\phi_{in}+\phi_{out}}{2}-\frac{\phi_{in}-\phi_{out}}{2}\tanh\left(\frac{r-R_S}{\delta}\right) \tag{1}$$

where ϕ_{in} and ϕ_{out} are respectively the inner and outer equivalence ratio; R_S is the stratification radius; and δ is the thickness parameter. The initial mixture is homogeneous if $\phi_{in}=\phi_{out}$. In this study, the thickness parameter is fixed as δ=0.04 mm. Therefore, fuel stratification is characterized only by three parameters, ϕ_{in}, ϕ_{out} and R_S. As shown in Fig. 1, the initial temperature of T_0=400 K, pressure of P_0=1 atm, and flow velocity of u_0=0 cm/s are uniformly distributed in the whole computational domain of $0\leq r\leq R_W$. The chamber radius is fixed to be R_W=20 cm and only flames with radii below 2 cm are considered. The ignition and spherical flame propagation processes are simulated using the in-house code A-SURF (Adaptive Simulation of Unsteady Reacting Flow) [8-10]. Details on governing equations, numerical schemes and code validation of A-SURF can be found in Refs. [8-10] and are not presented here. To mimic the practical spark ignition process in which energy is deposited around the center during a short period, a source term is included in the energy equation [11]. The minimum ignition energy (MIE) is calculated by trial-and-error with relative error below 2%.

3 Results and Discussion

As mentioned before, fuel stratification is characterized by three parameters, ϕ_{in}, ϕ_{out} and R_S. In the following, we fix two of these three parameters and assess the influence of third parameter on ignition and flame kernel propagation.

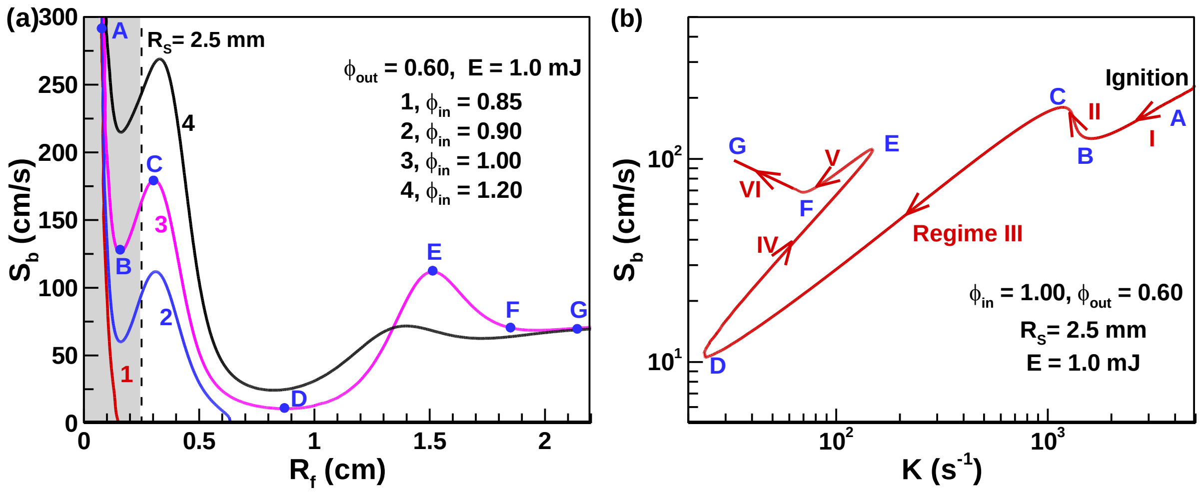

Fig. 2. Change of the flame propagation speed with (a) flame radius with different values of ϕ_{in}, (b) stretch rate with value of ϕ_{in}=1.0 for fuel-stratified $nC_{10}H_{22}$/air with fixed values of ϕ_{out}=0.6, E=1.0 mJ and R_S=2.5 mm.

Figure 2(a) demonstrates the influence of inner equivalence ratio on ignition in fuel-stratified $nC_{10}H_{22}$/air mixture. The results for different values of ϕ_{in} and fixed values of ϕ_{out}=0.6, E=1.0 mJ and R_S=2.5 mm are presented. For ϕ_{in}=0.85 (line #1 in Fig. 2(a)), flame propagation speed decreases quickly to zero and thereby ignition fails. This is expected since the ignition energy of E=1.0 mJ is smaller than the MIE of E_{min}=1.08 mJ for homogeneous mixture with ϕ=0.85. For ϕ_{in}=0.9 (line #2 in Fig. 2(a)), the ignition kernel can propagate beyond the stratification radius R_S since the ignition energy of E=1.0 mJ is larger than the MIE of E_{min}=0.81 mJ for homogeneous mixture with ϕ=0.9. However, after the flame reaches the outer zone with ϕ_{out}=0.6, its propagation speed eventually decreases to zero and ignition failure happens. When the inner equivalence ratio is further increased to ϕ_{in}=1.0 and 1.2 (lines #3 and #4 in Fig. 2(a)), a self-sustained propagating spherical flame can be successfully initiated. It is noted that the ignition energy of E=1.0 mJ is more than one-order smaller than the MIE for homogeneous mixture with ϕ=0.6. Therefore, Fig. 2(a) indicates that fuel stratification can greatly promote ignition for fuel-lean n-decane/air mixture.

Figure 2(a) indicates that there exist six distinct flame regimes for successful ignition with ϕ_{in}=1.0 (i.e., line #3 in Fig. 2(a)): the ignition energy induced flame kernel propagation regime (I), the first unsteady flame transition regime (II), the fuel stratification induced flame kernel propagation regime (III), the second unsteady flame transition regime (IV), the overdriven flame propagation regime (V), and the normal flame propagation regime (VI). Regimes I to VI corresponds to AB, BC, CD, DE, EF and FG in Fig. 2(a), respectively. These six regimes are more clearly demonstrated in Fig. 2(b), which plots the flame propagation speed as a function of stretch rate. Regimes I, IV, V and VI are similar to the four regimes of the homogeneous mixture. In regime I, the ignition kernel propagation is mainly driven by ignition energy deposited around the center. Therefore, the ignition kernel propagation speed decreases quickly along AB; In regime II, flame propagation is mainly driven by chemical reaction and transport rather than ignition energy deposited at the center. Therefore, the S_b increases drastically. The regime III has same in trend in both S_b-R_f and S_b-K profiles with regime I. However, unlike regime I induced by ignition energy deposition, the ignition kernel propagation in Regime III is caused by fuel-stratification.

Figure 2 shows that successful ignition can be achieved by increasing the inner equivalence ratio. Similarly, the ignition kernel propagation can also be enhanced by increasing the outer equivalence ratio once it can propagate beyond the stratification radius. This is demonstrated by Fig. 3. For low values of ϕ_{out}, (lines #1 and #2 in Fig. 3(a)), the propagation speed decreases to zero and ignition fails though the ignition kernel can propagate beyond the stratification radius. Successful ignition is observed only when the outer equivalence ratio is high enough (lines #3, #4 and #5 in Fig. 3(a)). Stratified ignition depends on not only the equivalence ratios, ϕ_{in} and ϕ_{out}, but also the stratification radius, R_S. Figure 2(b) plots the flame propagation speed as a function of flame radius for different values of R_S and fixed values of ϕ_{in}=1.0, ϕ_{out}=0.7 and E=1.0 mJ. As expected, ignition failure happens to small stratification radius (R_S=0 mm and R_S=1 mm) while successful ignition occurs for large stratification radius (R_S=2 mm and R_S=∞). Therefore, for given values of ϕ_{in}, ϕ_{out}, and E, there is a critical stratification radius, beyond which successful ignition occurs.

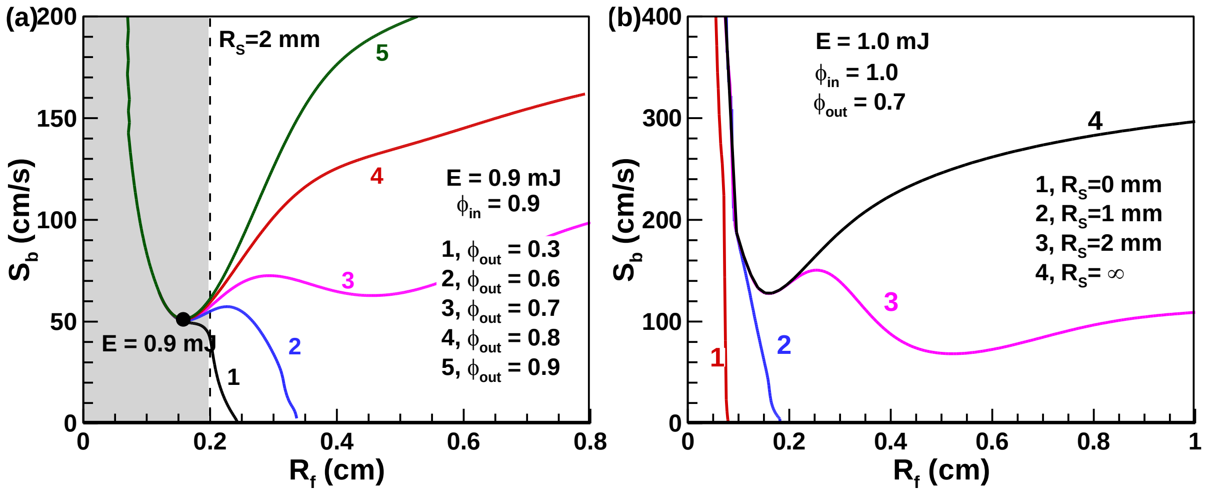

Fig. 3. Change of the flame propagation speed with flame radius for fuel-stratified $nC_{10}H_{22}$/air with (a) different values of ϕ_{out} and fixed values of ϕ_{in}=0.9, E=0.9 mJ and R_S=2 mm; (b) different values of R_S and fixed values of ϕ_{in}=0.9, ϕ_{out}=0.7 and E=0.9 mJ.

The above results indicate that fuel-stratification promotes ignition of lean $nC_{10}H_{22}$/air mixture and that successful ignition can be achieved by increasing the inner equivalence ratio and/or stratification radius. To quantify the ignition promotion by fuel-stratification, we investigate the influence of inner equivalence ratio and stratification radius on the MIE. The results are summarized in Figs. 4. Figure 4(a) depicts the change of the MIE, E_{min}, with inner equivalence ratio, ϕ_{in}. The results for different values of stratification radius are plotted together for comparison. The case of R_S=∞ corresponds to the homogeneous mixture with ϕ=ϕ_{in}. The case of R_S=0 mm corresponds to the homogeneous mixture with ϕ=ϕ_{out}=0.7. Therefore, the MIE has fixed value of E_{min}=7.9 mJ for ϕ=0.7 and it is independent of ϕ_{in}. The results in Fig. 4(a) indicate how fuel-stratification affects the MIE of fuel-lean (ϕ=0.7) $nC_{10}H_{22}$/air mixture. For small value of stratification radius, R_S=0.5 mm, the ignition promotion due to fuel-stratification is not substantial: the largest reduction in MIE occurs to ϕ_{in}=1.4 and the MIE is 6.95 mJ (only 12% lower than 7.9 mJ). When the stratification radius is increased to R_S=1.0 mm, the MIE is shown to be greatly reduced, especially at large values of ϕ_{in}. When the stratification radius is further increased to R_S=2 mm, the MIE is shown to decrease rapidly with the increase of ϕ_{in} and it approaches to a nearly constant value for ϕ_{in}≥0.9. For R_S=2 mm and ϕ_{in}=0.9, the MIE is E_{min}=0.82 mJ, which is about one-order smaller than E_{min}=7.9 mJ for the case without fuel-stratification (i.e., R_S=0 mm and ϕ=ϕ_{out}=0.7). Therefore, fuel-stratification with R_S=2 mm can greatly enhance the ignition and reduce the MIE for fuel-lean (ϕ=0.7) $nC_{10}H_{22}$/air mixture.

Figure 4(b) shows the change of the MIE with the stratification radius for fuel-stratified $nC_{10}H_{22}$/air with (ϕ_{in}=0.8, ϕ_{out}=0.7) and (ϕ_{in}=1.0, ϕ_{out}=0.7). Successful ignition is achieved for values of E and R_S above the curves in Fig. 4. With the increase of the stratification radius, the MIE decreases rapidly and it approaches to a nearly constant value at R_S=1.5 mm for ϕ_{in}=1.0 and at R_S=2.5 mm for ϕ_{in}=0.8. Therefore, there exists an optimum stratification radius for a given inner equivalence ratio. Besides, Fig. 4 indicates that the optimal stratification radius decreases as ϕ_{in} increases. Therefore, effective ignition enhancement can be achieved by choosing proper values of stratification radius and inner equivalence ratio.

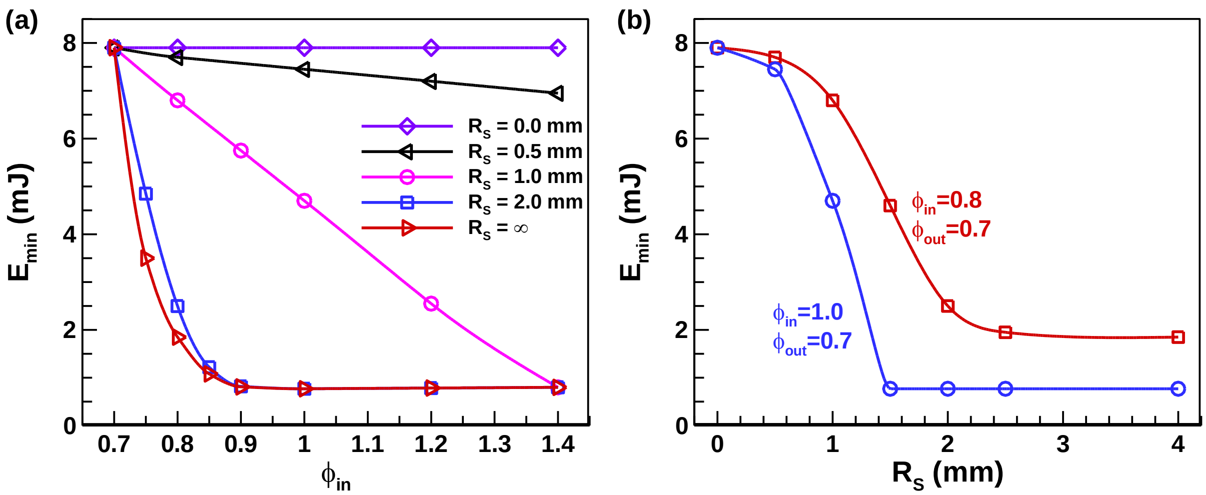

Fig. 4. The MIE as a function of (a) inner equivalence ratio with different values of R_S; (b) stratification radius with two different values of ϕ_{in} for fuel-stratified $nC_{10}H_{22}$/air mixtures with fixed values of ϕ_{out}=0.7.

4 Conclusions

Ignition and spherical flame kernel propagation in fuel-stratified n-decane/air mixtures are studied by 1D simulation. The effects of fuel stratification on critical ignition condition and spherical flame kernel propagation are examined. For fuel-stratified n-decane/air mixture, both the ignition kernel propagation and the MIE are strongly affected by the equivalence ratios, ϕ_{in} and ϕ_{out} as well as the stratification radius, R_S. Six distinct flame regimes are observed for successful ignition in fuel-stratified mixture. It is found that the ignition kernel propagation can be induced by not only the ignition energy deposition but also the fuel-stratification. As shown in Figs. 4, for fuel-lean n-decane/air mixture, fuel-stratification can greatly promote ignition kernel propagation and reduce the MIE. Effective ignition enhancement through fuel stratification can be achieved by choosing proper values of inner equivalence ratio and stratification radius. This indicates that fuel-stratified ignition can be used to prevent ignition failure at ultra-lean conditions in internal combustion energies and to achieve reliable high-altitude relight in jet engines.

Acknowledgements

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