

층류 비예혼합 부상 화염에서의 희석제에 따른 부상 높이 변화

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Variation of Liftoff height with diluents in Laminar Non-premixed Lifted Flame

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ABSTRACT

With diluents (CO₂, N₂, and He) added to fuel or oxidizer stream, stationary lifted flame in non-premixed laminar coflow-jet has been studied. For CO₂ and N₂ diluted in oxidizer stream, liftoff height significantly increased with diluent mole fraction, while in He-diluted case liftoff height slightly increased. In fuel-diluted stream, liftoff height as adding He and N₂ slightly increased, but CO₂-diluted flame oscillated. To investigate change of liftoff height with diluent mole fraction, laminar burning velocity, effects of diluents, and buoyancy were considered.

Key Words : Liftoff height, negative buoyancy, diluent effects, stabilization mechanism

Lifted flames in laminar jets have been extensively studied to identify stabilization and oscillation mechanisms. In particular, the flamebase of the laminar lifted flame has the tribrachial structure with coexistence of lean, premixed and diffusion flames, and is located at the point where the flame propagation speed and the local flow speed are balanced [1-2]. The propagation speed of the tribrachial flame is affected by the mix strength, fuel fraction gradient, Lewis number, and flame curvature, but the local flow speed is dependent on flow redirection and buoyancy [3]. These factors can cause the lifted flame to manipulate the position of the flame base and lead to flame oscillation or U-shaped behavior [3-4]. Especially, Van et al. [4] found that oscillating lifted flames are caused by competition between the positive buoyancy of the flame and the negative buoyancy of the fuel stream, which is heavier than the surrounding air. Therefore, the reduction of

local flow speed due to negative buoyancy may play an important role in adjusting the position of the lifted flame.

Figure 1 is a schematic of the experimental apparatus, which consists of a coflow burner, a flow control system, and a measuring system. A fully developed flow was secured by using a fuel nozzle having a diameter of 4 mm and a length of 40 cm. A quartz cylinder with an inner diameter of 100 mm, a length of 60 cm was used for the coflow jet. The coflow rate V_{co} was fixed at 5 cm/s. Honeycomb was installed on the coflow burner to ensure uniform flow. High purity (99.95%) propane and oxygen were used as fuels and oxidants, respectively. Carbon dioxide, nitrogen and helium were used as diluents. The flow rate was controlled by mass flow controller and flow software. Experiments were performed in the range of $18 \leq U_0 \leq 60$ cm/s to ensure laminar fuel jets, where U_0 represents the initial fuel jet velocity. Lifted height was measured using a digital VCR camera and analyzed using Matlab-based software. Figure 2 shows the change in lift height, H_L , depending on the mole fraction of the diluent injected into the fuel or coflow jet at $U_0 = 18$ cm/s.

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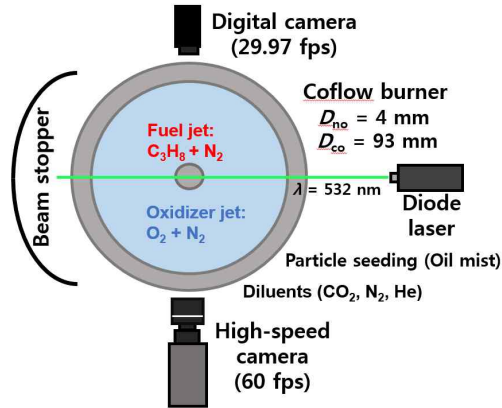


Fig. 1 Schematic of the experimental setup.

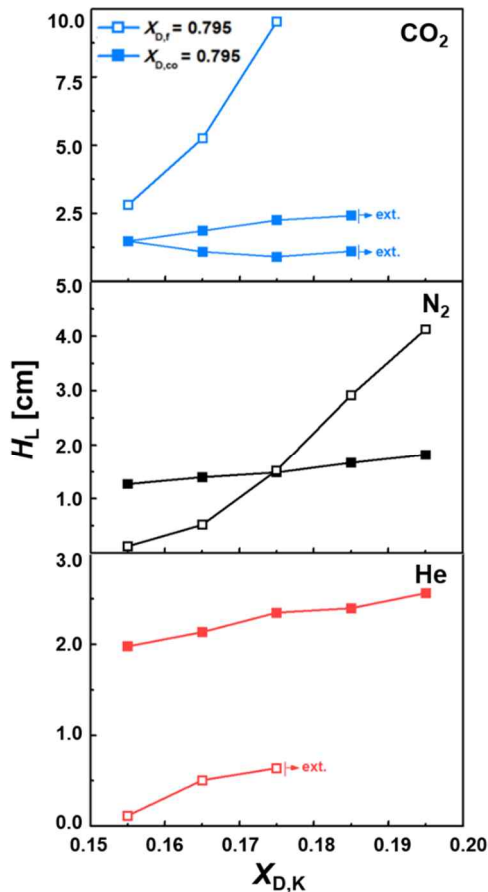


Fig. 2 Lift-off heights versus diluent mole fraction in various diluents added to fuel (block) or oxidizer (hollow) at $U_0 = 18$ and $V_{co} = 5$ cm/s.

At this time, the mole fraction of the diluent is defined as $X_{D,K} = X_i / (X_K + X_{N_2} + X_i)$, K

denotes fuel or oxidant jet, i denotes carbon dioxide, nitrogen and helium, and X_{N_2} is fixed at 0.62. In contrast to the lift-off height when injected into the fuel jet, for CO_2 and N_2 diluted in the oxidant jet, H_L increases significantly with the diluent mole fraction due to the decrease in oxygen concentration. In particular, lifted flames with CO_2 diluted in the fuel jet will oscillates as the diluent mole fraction increases, due to the density of the fuel jet being heavier than the coflow jet. However, helium diluted in the oxidant jet is considered to be nearly constant, increasing slightly with increasing diluent mole fraction. Since the stabilization mechanism of the laminar floting flame must be accounted for by the balance between the propagation speed of the trident flame and the local flow speed, the laminar combustion velocity, S_L , was calculated to reveal the relationship between the H_L and the diluent controlled flame velocity. Although the velocity of tribrachial flames differs from S_L due to flow redirection effects, concentration gradients, and flame curvature, it can be described qualitatively as tribrachial flame velocity in that lifted flames travel along stoichiometric line. Figure 3 shows the laminar flow rate for the coflow with diluent mole fraction calculated using USC 2.0. S_L of the helium-diluted flame is the largest, which indicates that the lifted flame shows an increase in H_L as the flame propagation rate decreases with decreasing molar fraction of coflow diluent. However, these results are comparable in the quantity of H_L with diluent. The S_L difference of Fig. 3 can be explained by three diluent effects: thermal, chemical and dilution effects [5–8]. Thermal diffusion and chemical effects indicate differences in thermal diffusivity or specific heat with diluent and chemical dissipation of carbon dioxide, respectively. Also, the dilution effect only shows a decrease in oxygen concentration. In order to calculate the chemical effects, a false species was used that did not react with the thermal, radioactive and transport properties of the true species. In order to consider the thermal diffusion effect, the specific heat according to the mole

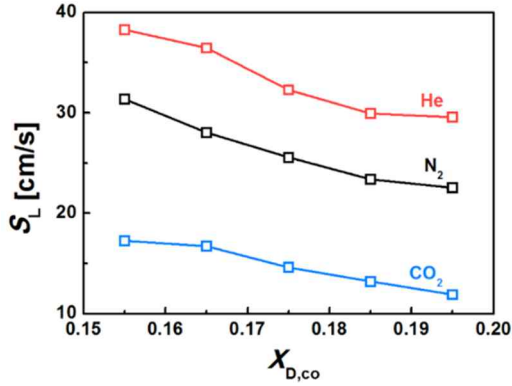


Fig. 3 Predicted laminar burning velocities in diluted with He, N₂, and CO₂

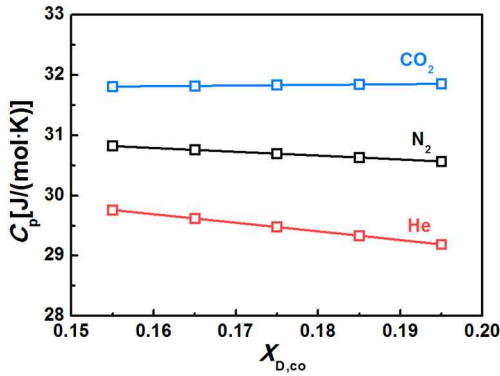


Fig. 4 Heat capacity at constant pressure as a functional dependency of diluent mole fraction.

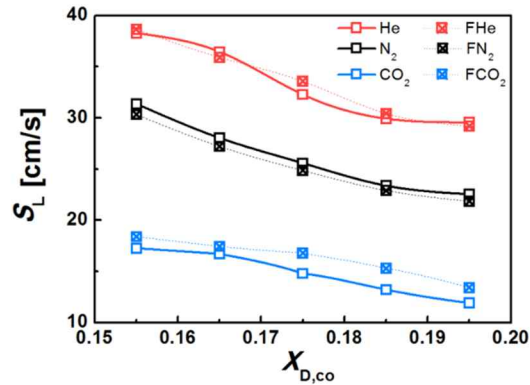


Fig. 5 Computed laminar burning velocities with true (solid) and false (dotted line) species.

fraction of diluent at 298 K, 0.1 MPa is shown in Fig. 4. As the mole fraction of oxygen decreases as the mole fraction of the diluent on the coflow side increases, the specific heat of helium ($C_{p, He} = 20.79$ J/mol·K) less than the specific heat of oxygen ($C_{p, O_2} = 29.38$

J/mol·K). The specific heat of the helium-infused flame decreases as the mole fraction of the diluent increases. On the other hand, the specific heat of carbon dioxide ($C_{p, CO_2} = 36.94$ J/mol·K) is greater than that of oxygen, so the specific heat of the flame injected with carbon dioxide increases. The specific heat of a nitrogen-injected flame is almost constant because the specific heat of nitrogen ($C_{p, N_2} = 29.12$ J/mol·K) is similar to that of oxygen. Figure 5 shows the S_L according to the diluent to show the chemical effects analyzed by comparing the actual species with the fake species. The difference between the S_L of the actual species and the fake species is caused by the chemical effect of the diluent, which means that the distinct S_L difference in carbon dioxide means that the chemical effect plays an important role in changing the height of injury. However, for helium and nitrogen, the chemical effects are minimal. To compare the effects of the three diluents, the results of Fig. 4 and 5 are shown using the contribution factor in Figure 6. The contribution factor for each diluent effect is defined as follows [8]:

$$\text{Dilution effect: } \frac{S_L[0] - S_L[FN_2]}{S_L[0] - S_L[i]}, \quad (1)$$

$$\text{Thermal effect: } \frac{S_L[FN_2] - S_L[Fi]}{S_L[0] - S_L[i]}, \quad (2)$$

$$\text{Chemical effect: } \frac{S_L[Fi] - S_L[i]}{S_L[0] - S_L[i]}, \quad (3)$$

where 0 means no dilution and i means carbon dioxide, nitrogen, and helium. In the case of carbon dioxide, the relatively high contribution factor of the dilution effect shows that the dilution effect plays an important role in reducing the S_L , but the thermal and chemical effects are relatively insignificant. In the case of nitrogen, the contribution factor of thermal and chemical effects is close to zero, but the dilution effect is 1. This means that the reduction of S_L with diluent mole fraction is under the influence of the dilution effect. The contribution factor for the chemical effect of helium is almost equal to zero, and the dilution effect is the dominant factor in the reduction of S_L . On the other hand, the contribution factor of the thermal effect has a negative

value, indicating that the thermal effect increases the S_L . However, as mentioned previously, the question of whether the H_L of the helium dilution flame does not change significantly with increasing mole fraction of the coflow diluent in Fig. 2 is no longer explained by the reduction of the S_L and the diluent effects. In this regard, we must consider the buoyancy forces acting on the laminar flotation flames. The negative buoyancy caused by the difference between the heavy fuel jet and the coflow jet must reduce the local flow velocity affecting the change in H_L . It is future work that to quantitatively compare the effect of buoyancy on the local flow rate with diluent, the flow field will be visualized using the Mie-scattering technique.

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