Experimental study on Extinction behavior in buoyancy-minimized Counterflow Diffusion flame

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1 Introduction

The fire suppression in ISS has been an important issue such that the enormous budget can be wasted meaningless and astronaut's life can be lost. In general, water spray, Halon, and gaseous diluents could be used as an extinguisher. However, the water spray and Halon could be regulated in ISS because it induces the malfunction of electronic device and it is fatal to astronauts. Moreover, flame characteristics in space are different from those on ground because there is no buoyancy. In this situation, gas diluents cannot help being used and have to be optimized in space.

Cup burner and counter-flow burner have been utilized as a standard burner in the fire research. The latter has a merit in that flame extinction can be defined well by physical parameters in one-dimension flame structure and impact of the ventilation flow in ISS on it can be described appropriately. Since the comprehensive review [1], flame structures and extinction behaviors in non-premixed counter-flow configuration have been extensively studied [2-6]. However, most of them have been focused on those in highly strained non-premixed counter-flow flame. Meanwhile those in low strained non-premixed flame have been sparse in the literature.

T'ien's research group showed that the diffusion flame thickness could be 2~3 cm at the global strain rate of 2. It means that the burner diameter should be more than 20 cm to be analyzed in one-dimensional similarity concept.[7] In reality, they conducted experiment with the burner diameter of 23 cm, they also confirmed that both low and high strain rate flames were extinguished through a flame hole.[8] Maruta et al. performed microgravity experiment, and they showed that low strain rate flam extinction is attributed to radiative heat loss whereas high strain rate flame is caused by flame stretch.[9] However, there was a room to argue for whether the results obtained experimentally with a finite burner diameter of 14 mm could be analyzed in one-dimensional similarity concept. Therefore, it

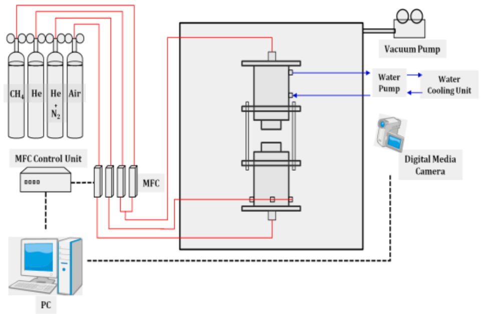

Figure 1. Schematic diagram of counterflow burner and flow systems.

is necessary to study consider of multi-dimensional response for study with finite burner diameter. In reality, Park and his coworkers [10-12] with finite burner diameters of 18, 26, 46 mm demonstrated that low strain rate flame extinction could be mainly attributed to radial conductive heal loss and partly to radiative heat loss.

Meanwhile, the outermost edge of counterflow diffusion has a typical partially premixed configuration. If the edge flame is stationary, the edge flame propagation velocity is has to be balanced to the local flow velocity, thus implying that the propagation velocity of the edge flame is always negative in a coordinate sense. Furthermore note that the edge flame speed has a functional dependency on the mixture strength, fuel concentration gradient, buoyancy, Lewis number, differential diffusion, among other factors.[13] In such cases, when one of them varied, the edge flames were self-excited.[14-16] The studies [10-12, 16] in counterflow configuration also showed that low strain rate flame was not extinguished through a hole but shrinkage of the outermost edge flame forward to the flame center. At some flame conditions, the flames were self-excited prior to flame extinguishment through the shrinkage of the outer edge flame. The self-excitation frequency was almost less than 1.0 Hz and sometimes slightly larger than 1.0 Hz. It was also recognized that the self-excitation was caused by reduction of edge flame speed due to radial conductive heat loss to ambience. However, their results particularly at low strain rate flame could have a defect in that buoyancy effects could not be excluded. In this situation, further research efforts are required to clarify important role of the outermost edge flame in flame extinction without having any impact of buoyancy effects. However, in conducting such experiments, one has to not only pay the huge price for using microgravity facilities but also achieve ones goal within a time limit.

In the present study a method to minimize buoyancy effect is designed to further study important role of the outermost edge flame particularly at low strain rate flames. Using this method, critical diluent mole fractions at flame extinction are presented with a functional dependency on global strain rate. Additionally, buoyancy effect for self-excitation of outer edge flame is discussed.

2 Experimental Method

The schematic diagram for the counter-flow burner and flow system used is shown in Fig. 1. The counter-flow burner with inner nozzle diameter of 26.0 mm was installed in a compartment to prevent external disturbances. The water jacket was used to cool the upper burner surface. Exhaust gases were sucked through two pipes by a vacuum pump. Helium-diluted methane and air were supplied through the upper and lower nozzles, respectively. The experiment was performed in a way that mole fraction of the diluent was increased at a fixed strain rate until the flame was extinguished. The global strain rate varied from 4.7 to 50s^{-1}. The global strain rate was defined as follows:[4]

$$a_g = \frac{2V_a}{L}\left(1 + \frac{V_f\sqrt{\rho_f}}{V_a\sqrt{\rho_a}}\right) = \frac{2V_a}{L}\left(1 + V_r\frac{\sqrt{\rho_f}}{\sqrt{\rho_a}}\right) \tag{1}$$

where V and ρ, denote the nozzle exit velocity and the reactant stream density, respectively, and the

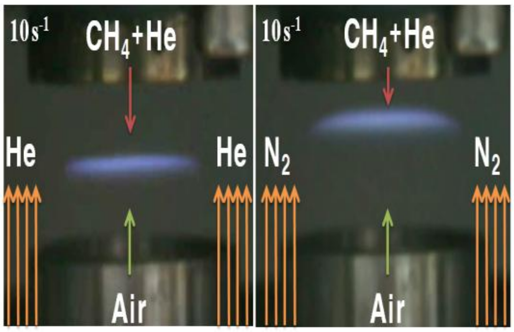

Figure. 2 . Flame locations in cases of helium and nitrogen curtain flows.

subscripts, a and f, represent the air and fuel streams, respectively.

The density in the flame zone was in range of 0.15~0.16 kg/m^3 and the density of helium at 298K and 1 atm was about 0.17 kg/m^3. In such a situation, the buoyancy force can be of 10^{-2} g when helium is used as the curtain flow. Fig. 2 compares flame locations at the same flame condition ($a_g = 10s^{-1}$) when helium and nitrogen are taken as each curtain flow. The flame is positioned almost at the center with helium curtain flow; meanwhile it is closed to the upper nozzle. Using helium curtain flow is a useful way to minimize buoyancy effect.

The fuel and diluents used were methane with a purity of 99.95 %, nitrogen with a purity of 99.999 %, and helium with a purity of 99.99 %. To clarify buoyancy effect in self-excitation of the outermost edge flame, the ambient density was controlled by adding nitrogen into helium curtain flow. The dynamic behavior of flame was captured by a digital media camera and analyzed using a Matlab-based program.

3 Result and Discussion

Fig. 3 shows variations of critical helium mole fractions at flame extinction with global strain rate by varying mole fraction of curtain flow. All flame extinction curves are typically of C-shape. There exists limit strain rate below which even pure methane can be extinguished. The limit strain rate was 5.7 s-1 in He curtain flow, and it was extended to 4.7 s-1 in curtain flow with He mole fraction of 0.7. The results also shows that the critical helium mole fraction is the lowest in case of using pure He curtain flow, and then increases as adding nitrogen gradually. This tendency is much more significant at low strain rate and mild at high strain rate. Meanwhile, the flame configuration around the outermost edge is of a partially premixed flame. If the edge flame is stationary, the edge flame speed is balanced to the local flow speed vectorially. Then, in a coordinate sense, the outermost edge flame speed is always negative, thereby tending to being shrunk forward to the flame center unless heat is added from the flame center to the edge flame. There are various factors to affect edge flame speed: buoyancy, mixture strength, Lewis number, and heat addition (loss) to (from) the edge flame. When we change diluent mole fraction in curtain flow, the mixture strength and fuel Lewis number will not vary. Furthermore, note that flame locations even at low strain rate do not vary so much while the mole fraction in curtain flow changes to 0.7, implying that buoyancy effect is still negligible. In this situation, buoyancy will not affect edge flame speed. Then, such a variation, appeared in Fig. 2, may be attributed to varying thermal conductivity in curtain flow. This also implies that the flame extinction is not free from conductive heat loss around the outermost edge to ambient curtain flow. Once excessive conductive heat is lost from edge flame to ambience (curtain flow), edge flame speed can be decreased, causing shrinkage of the edge flame. In this situation, unless sufficient heat is not supplied from the flame center to the edge flame convectively and/or conductively, the edge flame can shrunk forward to the flame center and finally extinguished. However further convincing explanation can be made through further experiments and numerical simulations in the future.

Meanwhile, the previous study [16] showed numerically and experimentally that low strain rate flame

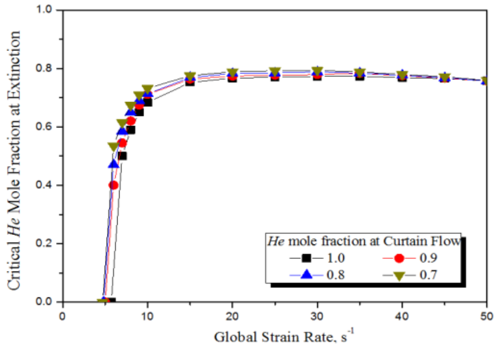

Figure 3. Variations of critical mole fraction at flame extinction with global strain rate.

was extinguished through shrinkage of the outermost edge flame and high strain rate flame was extinguished through a hole from flame center. That is, from the comparison of energy in low strain rate flame, the radial conductive heat loss was overwhelms the other loss terms including radiative loss while the radial convective heat is added to the outermost edge flame and thereby helps sustaining to flame extinction. This repetitive nature caused a self-excitation less than or slightly larger than 1.0 Hz just prior to flame extinction. However such a self-excitation of edge flame could not be addressed in the study. In laminar lifted jet and/or 2D mixing layer flames, several self-excitations were observed: a buoyancy-induced self-excitation with O(10.0 Hz) due to a flame-flicker [15], a buoyancy-driven self-excitation with O(1.0 Hz) [13, 15] due to accumulation of partially premixed, preheated mixture in front of edge flame, Lewis-number-induced one with O(1.0 Hz) [15, 17], and a heat-loss-induced self-excitation with O(< 0.1 Hz). The heat-loss-induced self-excitation was caused by conductive heat loss from premixed wings to trailing diffusion flame. Then, in the present counterflow configuration, such a heat-loss-induced self-excitation, caused by conductive heat loss from premixed wings to trailing diffusion flame, will not appear. Based on the previous observations [16], we also investigated the self-excitation frequency. Figure 4 demonstrates power spectrums at various flame conditions. Note that, in the present counterflow configuration, the buoyancy-driven self-excitation will not appear since a partially premixed, preheated mixture in front of edge flame is not accumulated. The results show that the self-excitation with O(10.0 Hz) due to a flame-flicker does not appear. Then, the possible self-excitation of edge flame in counterflow configuration can be heat-loss-induced self-excitation and/or Lewis-number-induced one. The self-excitation, observed in the previous studies [10-12, 16], was obtained when we use N_2 curtain flow and we added N_2 in the fuel side. Similarly, we reproduced the similar experiments in N_2 curtain flow except that, instead of N_2, we added He in the fuel side as shown in Fig. 4a. The result exhibits that only a self-excitation with 1.35 Hz exists similarly to those in the previous observation. When He curtain flow is used in Fig. 4b, two self-excitation frequencies of 1.26 and 4.83 Hz are observed. The former still has the similar frequency to those in the previous studies. However, the latter cannot be addressed definitely to Lewis number since it can be a modulated form of the former. To eliminate the former frequency, we increased the strain rate in N_2 curtain flow since high strain rate flame was stationary in the previous studies. Fig. 4c shows that the high strain rate flame is not self-excited but stationary in N_2 curtain flow. Again, we conducted the same experiment in HE curtain flow. In Fig. 4d, the self-excitation around 1.0 Hz, at high strain rate flame over the turning point on C-curve, does not appear but that with 4.87 Hz arises again. The self-excitation can be convinced to be related to Lewis-number-induced one. Note that fuel Lewis number in He- or N_2-diluted methane flame is around unity or slightly larger than unity. The previous study [17] showed that edge flame could be self-excited by Lewis numbers less than unity in case that excessive heat is lost from edge flame. Then, in Fig. 4d, using HE curtain flow with high thermal conductivity can cause excessive heat to be lost from the edge flame, thereby producing such a self-excitation. Again, this makes one know that using N_2 curtain flow (thereby buoyancy effect) suppresses Lewis-number-induced self-excitation. To confirm this, we examined the self-excitation due to Lewis number with diluent mole fraction in curtain flow in Fig. 5. The results show that the

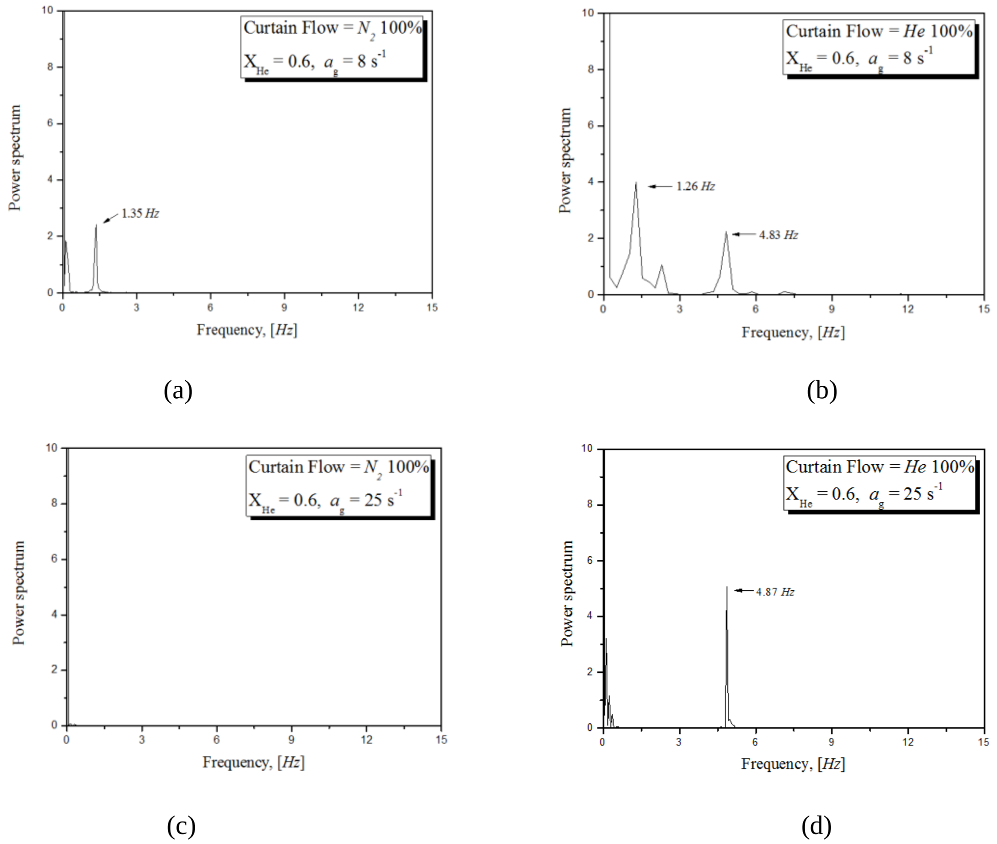

Figure 4. Variations of flame oscillation frequency in terms of both global strain rate and buoyancy.

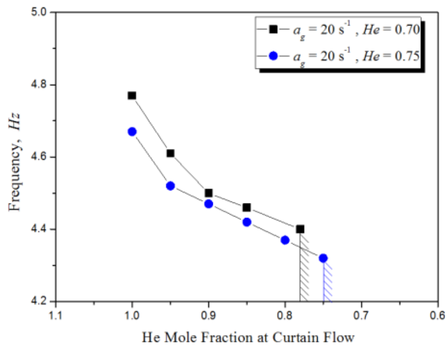

Figure 5. Various of flame oscillation frequency with helium mole fraction at curtain flow.

self-excitation frequency decreases in decrease of He mole fraction (thereby when buoyancy effect is enhanced). However, there remains still to answer what the self-excitation around 1.0 Hz is. Such a self-excitation always appeared just prior to flame extinction through shrinkage of edge flame forward to flame center. This is very similar to the observation, in which the flame was self-excited just prior to flame extinction in microgravity [18]. However, detailed explanation can be made through further experiments and numerical simulations in the future.

4 Conclusion

Experiments on flame extinction in counterflow configuration were conducted by varying diluent mole fraction in curtain flow. Utilizing He as a curtain flow is a useful way to minimize buoyancy effect in a manner that buoyancy force can be of O(10^{-2}g). The critical helium mole fraction is the lowest in case of using pure He curtain flow, and then increases in decrease of He mole fraction in curtain flow. Edge flame was self-excited in range of 4.0-5.5 Hz when excessive amount of conductive heat is lost from edge flame even at fuel Lewis number around unity. The self-excitation around 1.0 Hz appeared just prior to flame extinction, similarly to those conducted previously by T'ien and his coworkers in microgravity conditions.

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