Stabilization of Laminar Hydrocarbon Jet Diffusion Flames in Earth's and Micro-gravity

Logan Smith, Daniel Souza, Fumiaki Takahashi
Department of Mechanical and Aerospace Engineering, Case Western Reserve University
Cleveland, Ohio, USA

Abstract

Liftoff and blowout stability limits of laminar jet diffusion flames have been studied further in Earth's gravity (1*g*) and compared with the data obtained in microgravity (μ*g*) previously within the Microgravity Science Glovebox aboard the International Space Station. The fuels used include C_1 – C_4 gaseous hydrocarbons (methane, ethane, ethene, propane, butane, and 1-butene) and selected fuels diluted with nitrogen (70 % methane and 20 % ethene). The fuel issues from a fuel tube with an inner diameter between 0.4 mm and 3.2 mm into a co-flowing air duct (76 mm × 76 mm square cross-section) with the mean air velocity between 10 cm/s and 70 cm/s. The fuel jet is ignited at low fuel and air velocities to form a stable burner rim-attached flame. The fuel or air velocity is gradually increased until the flame lifts off the burner rim and then blows out. The dynamic flame lifting phenomena are recorded with color video and digital still cameras. The critical liftoff/blowout jet velocities are, in general, larger in μ*g* than in 1*g*. The gravity effect decreases for fuels with high critical fuel and air velocities (e.g., ethene). For the lighter-than-air fuel (methane), there seems to be an additional gravity effect. For small fuel jet diameters, a rapid dilution of the fuel by air seems to reduce the critical jet velocity at the stability limit. For the fuel with nitrogen dilution, the lower reaction rates also result in lower flame stability. On the other hand, higher reaction rate fuels (alkenes > alkanes) have the higher stability limits.

1 Introduction

The structure and stability of laminar jet diffusion flames in both Earth's gravity (1*g*) and microgravity (μ*g*) have been studied [1-17] extensively because of their essential importance in combustion systems and spacecraft fire safety.

In early 2012, NASA's Structure and Liftoff In Combustion Experiment (SLICE) was conducted within the Microgravity Science Glovebox (MSG) aboard the International Space Station. This work is an extension of the SLICE project to study on flame liftoff conditions in 1*g* to compare with the μ*g* data. Previous testing conducted under SLICE provided valuable μ*g* results in understanding the laminar diffusion flame stability

Correspondence to: fxt13@case.edu

selected types of fuels. The present study initiates to characterize the stability of a wider variety of fuels, including C_1 – C_4 alkane, alkene, and alkyne hydrocarbon fuels with or without dilution with an inert gas (nitrogen) and will enhance our understanding of the physical and chemical processes influence on flame liftoff phenomena. The new data can be used for vigorous testing numerical models leading to further understanding of jet diffusion flame stability.

2 Experimental Methods

Figure 1 shows the experimental apparatus (SLICE engineering model), which is used in a vertical orientation in the 1*g* testing. The fuels used are methane, ethane, ethene, propane, butane, and 1-butene, 70 % methane in nitrogen, and 20 % ethene in nitrogen. The fuel tube inner diameters are 0.4 mm, 0.8 mm, 1.6 mm, 2.1 mm, and 3.2 mm. The co-flowing air duct has a 76 mm × 76 mm square cross-section and the mean air velocity can be adjustable between 10 cm/s and 70 cm/s. The fuel jet is ignited at low fuel and air velocities to form a stable burner rim-attached flame. The fuel or air velocity is gradually increased until the flame lifts off the burner rim and then blows out. The dynamic flame lifting phenomena are recorded with color video and digital still cameras. The video images are post-processed to determine the exact liftoff point. At the point of lifting, the set fuel and air flow rates (indicated in the video) are recorded to determine the critical fuel velocity and critical air velocity. This liftoff/blowout limit measurement is then repeated at several other values of the co-flow air velocity.

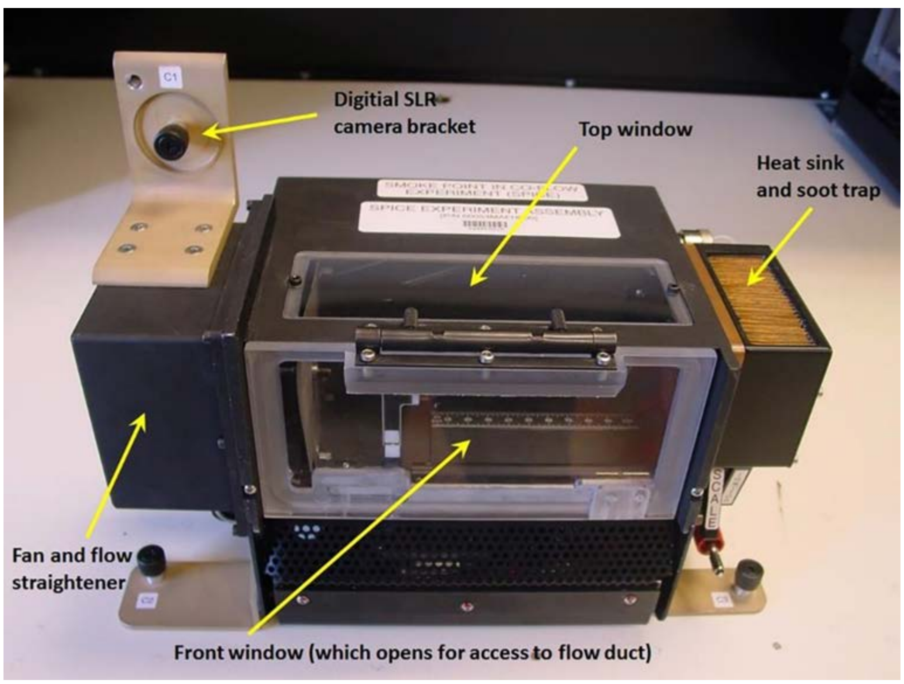

Figure 1. Experimental apparatus

3 Results and Discussion

The results of the flame stability measurements (for methane, ethane, ethane, 70 % methane and 20 % ethane; 0.4 mm, 0.8 mm, 1.6 mm, 2.1 mm fuel tube inner diameter) previously conducted in 1g [18] and compared with the SLICE μ*g* data are summarized as follows.

- The critical liftoff/blowout jet velocities are, in general, larger in μ*g* than in 1*g*.
- The gravity effect decreases for fuels with high critical fuel and air velocities (e.g., ethene).
- For the lighter-than-air fuel (methane), there seems to be an additional gravity effect.
- For small fuel jet diameters, a rapid dilution of the fuel by air seems to reduce the critical jet velocity at the stability limit.
- For the fuel with nitrogen dilution, the lower reaction rates also result in lower flame stability.
- The higher reaction rate fuels (alkenes > alkanes) have the higher stability limits.

In the present study, four fuels (ethane, propane, butane, 1-butene) and two fuel tube inner diameters (0.4 mm and 0.8 mm) are used. Figures 2 and 3 show the stability limits for 0.4 mm i.d. and 0.8 mm i.d., respectively. As is observed previously, the critical fuel jet velocity at lifting decreases as the air velocity is increased for each fuel. The new observations in this study for both 0.4 mm and 0.8 mm are as follows.

- For alkanes, at a fixed air velocity, ethane has the largest critical jet velocity and those of propane and butane are much smaller.
- The alkene (1-butane) has much larger critical jet velocity than the alkane (butane). This trend must be attributable to the higher reactivity (represented, for example, by the laminar flame speed) of alkenes compared to alkanes. This result extends the previous observation for C_2 hydrocarbons (ethane vs. ethane) to C_4 hydrocarbons (butane vs. 1-butene).
- The effect of the tube diameter is the same as previous results, i.e., for each fuel, the critical jet velocity at the stability limits at a fixed air velocity is much smaller for the smaller inner diameter (0.4 mm) due rapid dispersion of the fuel.

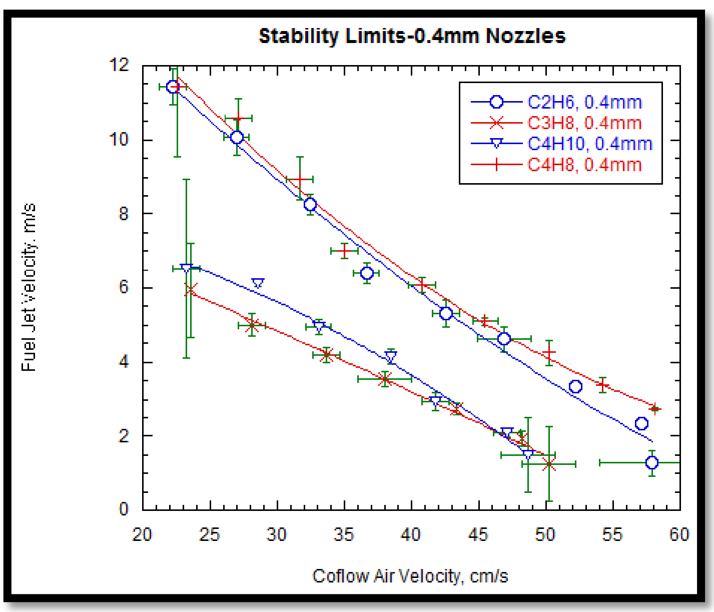

Figure 2. Stability limits of various fuels for a 0.4 mm i.d. tube

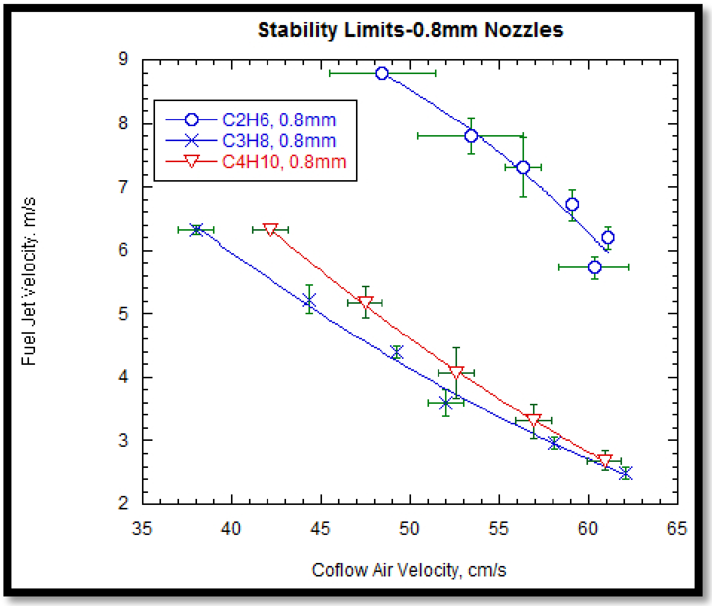

Figure 3. Stability limits of various fuels for 0.8 mm i.d. tube

Figure 4 shows the critical fuel jet velocity at the stability limit for all fuels and tube inner diameters used. Similarly, to burning 1-butene through the 0.8mm burner tube, all the other combinations of fuel type and tube diameter would produce stability limits that exceed the capabilities of the apparatus (the SLICE engineering model): the fuel mass flow controller (500 sccm N2) and the coflow air velocity up to 70 cm/s. In order to complete testing of the other fuel types and burner diameters a new experimental apparatus is needed.

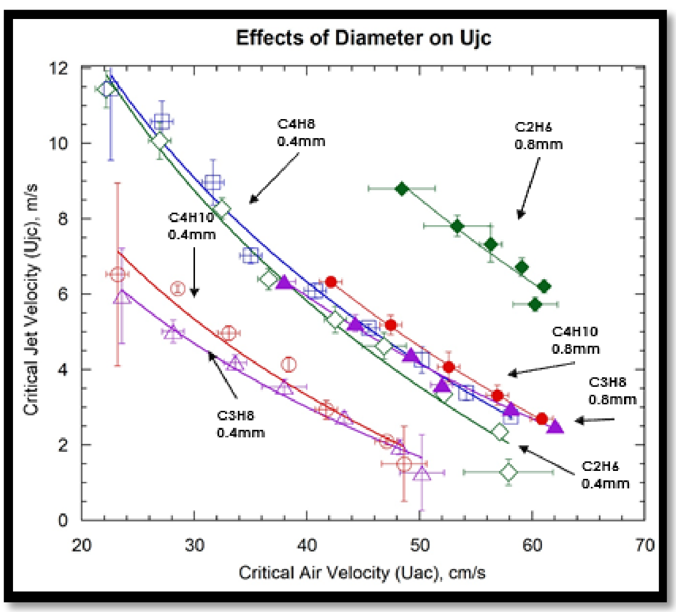

Figure 4. Stability limits of various fuels for 0.4 and 0.8 mm i.d. tubes

4 Conclusion

The critical fuel jet velocity at lifting stability limits of laminar jet diffusion flames have been studied further in 1*g* and compared with the data obtained in μ*g* previously in the International Space Station. The gravity effect on the liftoff phenomena is more evident if the fuel and air velocities at the stability limit are low. Thus, for the fuels with high reactivity (e.g., alkenes > alkanes) and for the larger fuel tube diameters, the critical jet velocity is high and the gravity effects are reduced. For the lighter-than-air fuel (methane), there seems to be an additional buoyancy effect. On the other hand, for the fuel with nitrogen dilution, the lower reaction rates result in lower flame stability and subjected to low gravity effects.

Acknowledgements

Supported by the NASA Space Life and Physical Sciences Research and Application Division (SLPSRA)

References

[1] Cochran TH, Masica WJ. (1970). An investigation of gravity effects on laminar gas jet diffusion flames. Proc. Combust. Inst. 13: 821.

[2] Edelman RB, Fortune OF, Weilerstein G, Cochran TH, Haggard JB. (1972). An analytical and experimental investigation of gravity effects upon laminar gas jet-diffusion flames. Proc. Combust. Inst. 14: 399.

[3] Gollahalli SR, Savas O, Huang RF, Rodriquez Azara JL. (1988). Structure of attached and lifted gas jet flames in hysteresis region. Proc. Combust. Inst. 21: 1463.

[4] Chen L-D, Seaba JP, Roquemore WM, Goss LP. (1989). Buoyant diffusion flames. Proc. Combust. Inst. 22: 677–684.

[5] Chung SH, Lee BJ. (1991). On the characteristics of laminar lifted flames in a non-premixed jet. Combust. Flame 86: 62–72.

[6] Kioni PN, Rogg B, Bray NC, Linãń A. (1993). Flame spread in laminar mixing layers: the triple flame. Combust. Flame 95: 276.

[7] Bahadori MY, Stocker DP, Vaughan DF, Zhou L, Edelman RB. (1993). Effects of buoyancy on laminar, transitional and turbulent gas jet diffusion flames. Modern Developments in Energy, Combustion, and Spectroscopy (F. A. Williams et al., eds.), Pergamon Press, New York, p. 49.

[8] Hegde U, Zhou L, Bahadori MY. (1994). The transition to turbulence of microgravity gas jet diffusion flames. Combust. Sci. Technol. 102: 95.

[9] Buckmaster J, Weber R. (1996). Edge flame holding. Proc. Combust. Inst. 26: 1143.

[10] Wichman I, Ramadan B. (1998). Theory of attached and lifted diffusion flames. Phys. Fluids 10: 3145.

[11] Agrawal AK, Cherry SM, Gollahali SR. (1998). Effects of buoyancy on steady hydrogen gas-jet diffusion flames. Combust. Sci. Technol. 140: 51.

[12] Walsh KT, Fielding J, Smooke MD, Long MB. (2000). Experimental and computational study of temperature, species and soot in buoyant and nonbuoyant coflow laminar diffusion flames. Proc. Combust. Inst. 28: 1973.

[13] Urban DL, Yuan ZG, Sunderland PB, Lin K-C, Dai Z, Faeth GM. (2000). Smoke-point properties of non-buoyant round laminar jet diffusion flames. Proc. Combust. Inst. 28:1965.

[14] Faeth, G. M. (2001). Laminar and turbulent gaseous diffusion flames. Microgravity Combustion: Fire in Free Fall (H. D. Ross, ed.), Academic Press, San Diego, p. 83.

[15] Qin X, Puri IK, Aggarwal SK. (2002). Characteristics of lifted triple flames stabilized in the near field of a partially premixed axisymmetric jet. Proc. Combust. Inst. 29: 1565.

[16] Takahashi F, Katta VR. (2000). A reaction kernel hypothesis for the stability limit of methane jet diffusion flames. Proc. Combust. Inst. 28: 2071.

[16] Takahashi F, Katta VR. (2002). Reaction kernel structure and stabilizing mechanisms of jet diffusion flames in microgravity. Proc. Combust. Inst. 29: 2509.

[17] Takahashi F, Katta VR. (2005). Further studies of the reaction kernel structure and stabilization of jet diffusion flames. Proc. Combust. Inst. 30: 383.

[18] Takahashi F,, Kulakhmetov R, Stocker DP, Ma B, Long MB. (2012). Microgravity enhances the stability of gas-jet diffusion flames. 28th Annual Meeting of the American Society for Gravitational and Space Research.