

PREDICTION OF THE LIFTOFF, BLOWOUT AND BLOWOFF STABILITY LIMITS OF PURE HYDROGEN AND HYDROGEN/HYDROCARBON MIXTURE JET FLAMES

Y. Wu¹, Y. Lu¹, I. S. Al-Rahbi,¹ and G. T. Kalghatgi²

¹Department of Chemical and Process Engineering, University of Sheffield, Sheffield S1 3JD, UK

²Shell Global Solutions (UK), Cheshire Innovation Park, P.O. Box 1, Chester CH1 3SH, UK

ABSTRACT

The paper presented experimental studies of the liftoff and blowout stability of pure hydrogen, hydrogen/propane and hydrogen/methane jet flames using a 2 mm burner. Carbon dioxide and Argon gas were also used in the study for the comparison with hydrocarbon fuel. Comparisons of the stability of H₂/C₃H₈, H₂/CH₄, H₂/Ar and H₂/CO₂ flames showed that H₂/C₃H₈ produced the highest liftoff height and H₂/CH₄ required highest liftoff and blowoff velocities. The non-dimensional analysis of liftoff height approach was used to correlate liftoff data of H₂, H₂-C₃H₈, H₂-CO₂, C₃H₈ and H₂-Ar jet flames tested in the 2 mm burner. The suitability of extending the empirical correlations based on hydrocarbon flames to both hydrogen and hydrogen/hydrocarbon flames was examined.

1.0 INTRODUCTION

The stabilization mechanisms of turbulent jet flames have been the topic of many papers and the most recent review was given by Peters [1]. It has emerged that the most successful theories to explain and predict the liftoff height location are the premixed flame propagation models [2-7] based on proposal by Vanquickenborne and van Tiggelen [2]. The importance of the isothermal mixing process of the jet was emphasised by Pitts [3-5]. The turbulent burning velocity has been one of the focused points for discussion using the premixed flame stabilization approach. Kalghatgi [6] assumed that the ratio of burning velocity to laminar burning velocity was proportional to the square root of the local turbulence Reynolds number based on the integral length scale. He successfully correlated the experimental data for CH₄, C₂H₄, C₃H₈ and H₂ into a single formula. More recent studies focused on the role of intermittence and large scale eddies and associated with premixed combustion by Broadwell et al. [7] and Burgess and Lawn [8]. Experimental studies of the large scale vortical structures in lifted flame were carried out by Schefer et al [9-10] using planar images of CH₄, CH and temperature.

So far most jet flame researchers have used pure hydrocarbon fuels or fuels diluted with air or nitrogen. Empirical correlations were developed to predict flame stability limits for pure and inert gas diluted hydrocarbon fuels. As hydrogen is becoming an important part of energy sector, there is a need to study the stability characteristics of both hydrogen and hydrogen/hydrocarbon flames. Studies on stability of hydrogen/hydrocarbon blended fuels are scarce. Recently, the stability of hydrogen and natural gas blended fuel was discussed by Choudhuri and Gollahalli [11]. The effect of hydrogen addition into methane on the flame stability under fuel lean condition was studied by Schefer [12] using swirl-stabilized flame. However it is not clear if the established premixed flame propagation models can be applied to jet flames of blended fuels. It is also necessary to examine the suitability of extending the empirical correlations based on hydrocarbon flames to both hydrogen and hydrogen/hydrocarbon flames. This work addressed these issues through a study of the stability of hydrogen flame with addition of propane, methane, carbon dioxide and argon.

2.0 THE EXPERIMENTAL STUDY

The experiments were carried out using a burner with a 2 mm inner diameter. The burner was fitted with flow settling chamber and flow straightening device. The gasses were introduced from compressed gas bottles through flow meters and were mixed before channeling into the settling chambers. The visual characteristics of the flames of pure hydrogen were very different from H₂/C₃H₈, H₂/CH₄ and H₂/CO₂

flames. The pure hydrogen jet flames were almost invisible. H_2/CO_2 flames and H_2/CH_4 were in blue. The H_2/C_3H_8 flames resembled characteristics of propane ones and appeared in blue in the base of the flame, but bright yellow in the main combustion zone. To visualize the flames and establish the lift off height of the flames, both schlieren technology and direct digital photography technology were used to capture the flame images of hydrogen, hydrogen/carbon dioxide flames. All flame images were captured using digital camera and processed using computer graphic packages.

3.0 EXPERIMENTAL RESULTS

3.1 Stability of Pure Hydrogen Jet Flames

Lifted hydrogen jet flames were produced in the 2 mm diameter burner. The liftoff velocity measured for pure hydrogen flame was 730 m/s. As shown in Figure 1, the liftoff height increased linearly with jet velocity. Three sets of experimental data from the current study using different image techniques were presented. Set 1 & 2 used the direct photography technique to determine the liftoff height, and set 3 used a Schlieren system to visualize the flame. The measured liftoff heights are in good agreement with the results of Kalghatgi [6] and Cheng and Chiou [14]. Blowout of pure hydrogen jet flame was not achieved in these experiments.

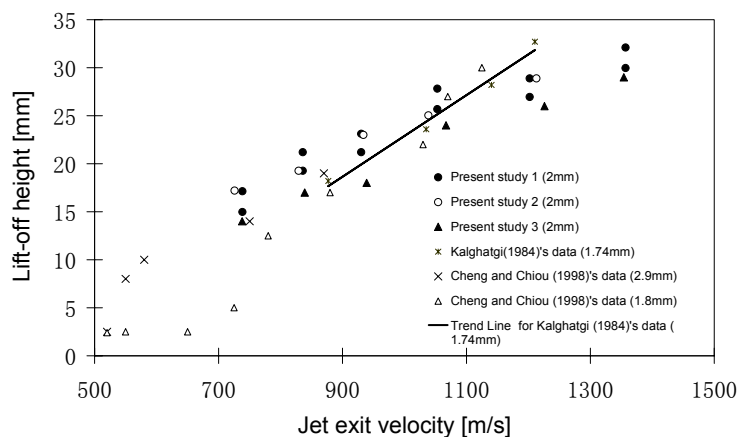


Figure 1. Comparison of experimental measured liftoff height of pure hydrogen jet flames against the jet velocity.

3.2 Stability of $H_2-C_3H_8$ Jet Flames

Experimental test was carried out to study the effect of C_3H_8 addition on an initially attached and an initially lifted H_2 jet flame. C_3H_8 addition to attached H_2 flames always produced lifted flames, which were blown out at high jet velocities. Direct flame blowoff was not observed. Here blowoff refers to an attached jet flame extinguishing and liftoff is never observed. C_3H_8 addition to lifted H_2 flames increased the liftoff height by nearly 2.6 times before blowout was observed. The blowout occurred at C_3H_8 concentration of around 4 to 5 %.

3.3 Effect of CO_2 and Ar Gas Addition on the Stability of H_2 Jet Flames

The effect of CO_2 addition on the stability of an initially attached and also an initially lifted H_2 flame was examined experimentally. The experimental results showed that when CO_2 was added to an attached H_2 flame, two flame stability regimes were identified. There is a critical CO_2 concentration. If CO_2 concentration was greater than 6.4 %, addition of CO_2 produced a stable attached flame leading to direct blow off at high velocities. If CO_2 concentration was less than 6.4 %, CO_2 addition produced a lifted

flame and then the flame was blown out at higher velocities.

Experiments were also carried out to examine the effect of CO₂ addition on lifted H₂ flames. It was showed that the CO₂ addition increased the liftoff height by nearly two times the initial liftoff height of pure H₂ flames.

Tests were also carried out using argon for comparison with CO₂. Argon behaved in a similar way to CO₂ and required a slightly higher blow out velocity.

3.4 Stability of H₂-CH₄ Jet Flames

Test results demonstrated that effects of CH₄ addition were different from C₃H₈ addition. Similar to the effect of CO₂ addition, there were two flame stability regimes when CH₄ was added into initial attached hydrogen jet flames. If the CH₄ concentration is greater than 20%, flame would remain attached until blowoff at high velocity. If the CH₄ concentration is less than 20%, CH₄ addition to an initial attached hydrogen jet flame can produce lifted flame. However the blowout flame conditions were not obtained in present study.

4.0 DISCUSSIONS

4.1 Liftoff Height

Figure 2 shows a comparison of the liftoff height of H₂/C₃H₈, H₂/CH₄ and H₂/CO₂ flames. The addition of the CH₄, CO₂ and C₃H₈ always increased the liftoff height of the initially lifted hydrogen diffusion flames. Addition of C₃H₈ produced the highest liftoff height. For the same jet exit velocity and same concentration of the diluents, the addition of C₃H₈ produced liftoff height around 15 to 30% higher than that of the addition of CO₂. For the similar amount of diluent addition, at the same jet exit velocity, the addition of CH₄ produced liftoff height lower than that of the addition of C₃H₈. At jet exit velocity higher than around 1000 m/s, the liftoff height of flames with CH₄ addition are shown to be higher than that with CO₂ addition. It might be predicted that at the high concentration of diluent (potentially be higher than 10%), the addition of CH₄ would produce higher lifted flames than that of CO₂.

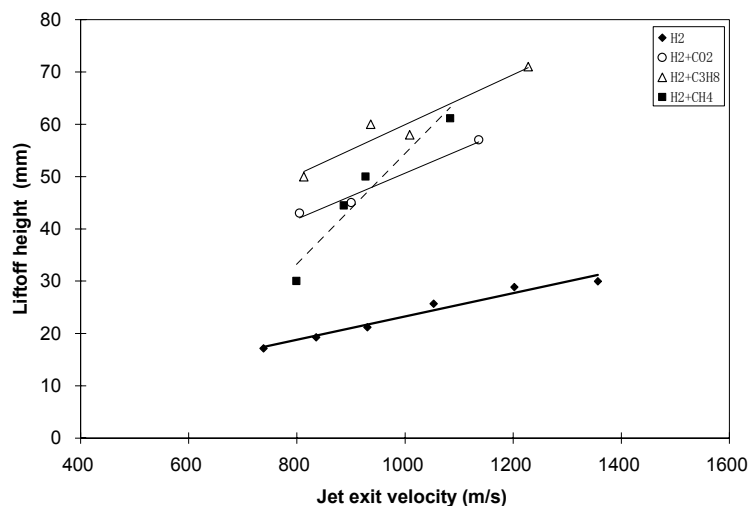


Figure 2. Comparison of the liftoff height of H₂/C₃H₈, H₂/CH₄ and H₂/CO₂ flames.

4.2 Liftoff Velocity

A comparison of effect of propane addition and methane additions on liftoff velocity is shown in Figure 3. The results showed that for the same concentration, methane addition required much higher liftoff velocity than propane addition.

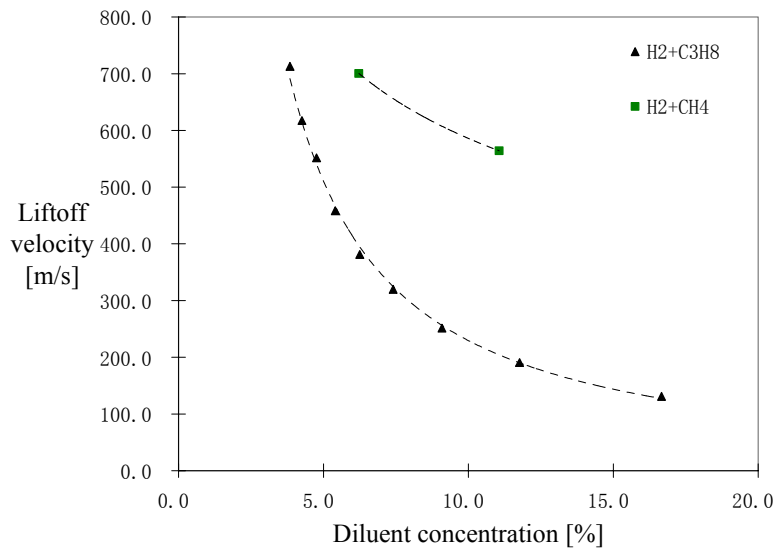


Figure 3. Comparison of liftoff velocity H₂/C₃H₈ and H₂/CH₄ flames.

4.3 Blowout and Blowoff Velocity

Effects of C₃H₈, CH₄ and CO₂ additions on blowout or blowoff velocity were very different. Addition of C₃H₈ produced lifted flame and then blowout of the flame at higher velocity. Addition of C₃H₈ didn't cause direct blowoff. CO₂ additions produced lifted flame in low concentration, but at high concentration, flame would remain attached until blowoff. Therefore for H₂/CO₂ flames both blowout and blowoff velocities were obtained. For H₂/CH₄ flames, only blowoff at high concentration was obtained. In Figure 4, the blowout and blowoff velocities are plotted against the addition concentration. It was shown that for the same jet velocity, CH₄ required much higher concentration to produce blowoff than CO₂. It was also showed that C₃H₈ requires higher velocity to blowout than CO₂.

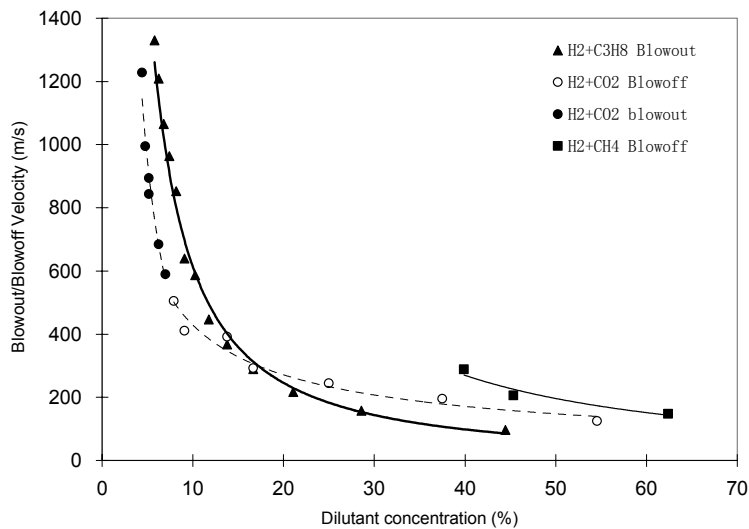


Figure 4. Comparison of blowout and blowoff velocity of H₂/C₃H₈, H₂/CH₄ and H₂/CO₂ flames.

4.4 Laminar Burning Velocity

Experimental studies of the laminar or fundamental flame velocity of hydrogen-air mixtures and diluted hydrogen-air mixtures have been reported in a number of studies [15-20]. The measured laminar burning velocity peaked at a rich mixture of equivalence ratio 1.8. However the reported value of the maximum laminar flame velocity of hydrogen air mixture varied from 250 cm/s to 370 cm/s. The discrepancy was mainly due to whether the effect of stretch rate over the laminar flame velocity for the spherically expanding flames was taken into account. The flame velocity without inclusion of stretch effect was much higher than the unstretched flame velocity. A comparison of experimentally values of unstretched laminar flame velocity as a function of the equivalence ratio is given by Lamoureux, et al [15].

The effect of adding hydrocarbon fuel into the hydrogen-air mixture has been studied recently [16,17,19 and 20]. Leason [19] experimentally studied the effect of various additives, including hydrogen, on the burning velocity of propane-air mixture. Though this work covered a wide range of equivalence ratio, it was limited to hydrogen concentrations in the H_2 - C_3H_8 mixture of between 5 and 30%. In our study, hydrogen was the dominant fuel with a small amount of propane addition. Some experimental data were obtained by Milton and Keck [17] on the burning speed of hydrogen/methane and hydrogen/propane mixtures at stoichiometric ratio. In the present study, the laminar burning velocity for hydrogen/propane was determined by plotting Milton and Keck's data and fitting a suitable equation.

The effect of CO_2 dilution on the spherical flame Markstein number and unstretched laminar velocity was discussed by Lamoureux, et al [15]. However only limited laminar velocity data of lean hydrogen/ CO_2 mixture were reported. In the present study, the laminar flame velocity for the hydrogen/ CO_2 mixture is determined using Yumlu's equation [21].

A comparison of the effect of CO_2 and C_3H_8 addition on the laminar flame velocity of H_2 - CO_2 mixture and H_2 - C_3H_8 mixture is shown in Figure 5. It was clearly shown that the reduction in the burning velocity by adding propane was much more significant and greater than by adding CO_2 . For H_2 - C_3H_8 and H_2 - CH_4 mixture, the laminar flame velocity reduced rapidly with the increasing concentration of propane/methane. The burning velocity of the mixture approached that of pure hydrocarbon fuel, when the hydrocarbon fuel addition was increased above 30%. Hydrocarbon fuel appeared to be the dominant element governing the laminar burning velocity of the mixture. This can be attributed to the chemical kinetic mechanisms of the hydrocarbon-air reaction. Hydrocarbon fuel relies on reaction with H, O and OH free radicals to break down to smaller hydrocarbon molecules and water. H, O and OH free radicals are also of vital importance for the chain propagation of hydrogen. However, the reaction rate for hydrocarbon fuel with H, O and OH free radicals is much faster than the H_2 , H, O and OH chain reactions. Therefore the hydrocarbon fuel acted as sink for H, O and OH free radicals and so dominates the reaction, which then hinders the H_2/O_2 reactions.

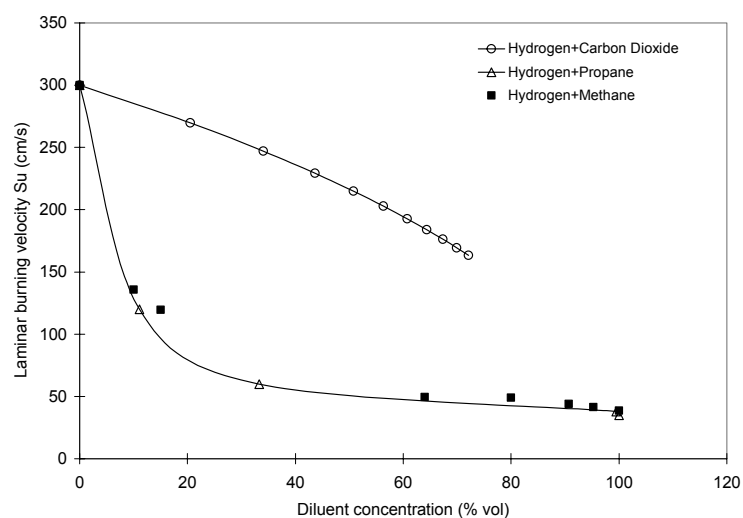


Figure 5. The laminar burning velocity of H_2/C_3H_8 , H_2/CH_4 and H_2/CO_2 flames.

4.5 Stoichiometric mass fraction

The addition of C_3H_8 and CH_4 also changes the mixture's stoichiometric fuel/ air ratio. The effect of hydrocarbon addition on the stoichiometric mass fraction is plotted in Figure 6. C_3H_8 addition increased the mixture's stoichiometric fuel/ air ratio significantly.

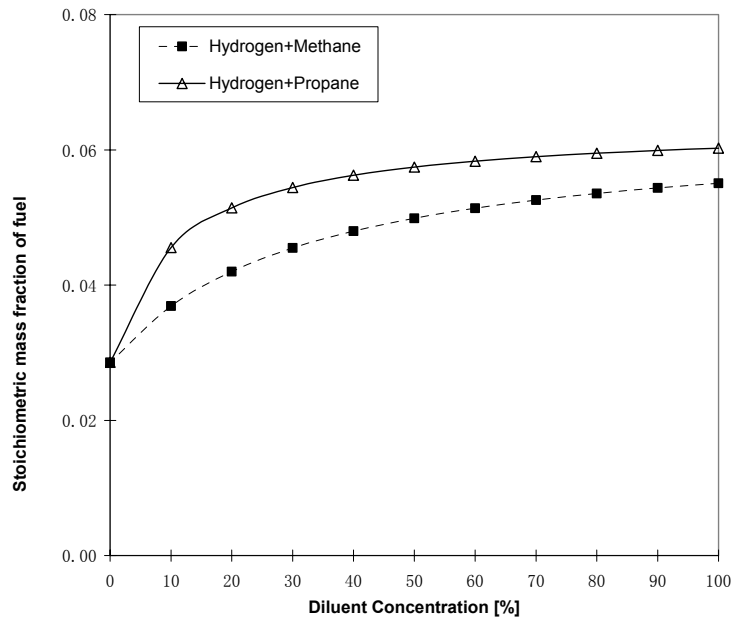


Figure 6 Comparison of stoichiometric mass fraction of fuel of the $H_2-C_3H_8$ mixtures and H_2-CH_4 mixtures as a function of diluent concentration.

4.6 Assessment of Empirical Correlations

The non-dimensional analysis of liftoff height approach used by Kalghatgi [6] was adopted in present study to correlate liftoff data of H_2 , $H_2-C_3H_8$, H_2-CO_2 , C_3H_8 and H_2-Ar jet flames tested in the 2 mm burner. The measured liftoff height was plotted against the jet exit velocity divided by the square of the maximum laminar flame velocity in Figure 7. It was shown that the hydrogen line was separate from the propane line and data from mixtures scattered in between. Considering Kalghatgi's non-dimensional

analysis of liftoff height approach [6], Figure 8 shows the turbulence Reynolds number, $Res_u = \frac{h s_u}{\nu_{jet}}$,

against the jet exit velocity divided by the burning velocity and modified by jet to air density ratio, where h is flame liftoff height, ν_{jet} is the viscosity and s_u is the laminar flame velocity. The experimental data can be fitted into a single line with a slope of 48, which is slightly lower than 50 obtained by Kalghatgi [6] for undiluted CH_4 , C_2H_4 , C_3H_8 and H_2 flames.

The comparison of measured hydrogen liftoff height to predictions from Kalghatgi's correlation[6] and Miake-Ley & Hammer correlation [22] is shown in Figure 16. In the data analysis, the value of the laminar flame velocity for hydrogen was taken from the measurement of unstretched laminar flame velocity by Lamoureux et al [15]. 2.55 m/s was used as the maximum laminar flame velocity for pure hydrogen. The comparison in Figure 9 showed that Kalghatgi's correlation predicted lower liftoff height for H_2 flames and Miake-Ley & Hammer correlation gave higher liftoff height for H_2 flames. It is worth

noting that the reported values of laminar flame velocity of hydrogen flames are scattered in the range 370 cm/s to 250 cm/s. For hydrocarbon fuel, the maximum burning velocity occurred near the stoichiometric, therefore stabilization point of hydrocarbon fuel is stoichiometric. Unlike hydrocarbon fuel, hydrogen's maximum flame velocity occurs at the equivalence ratio 1.8. Recent experimental work of Tacke et al [23] showed that stabilization point of hydrogen flame was on the lean side not rich side. Further work with detailed concentration measurement is needed to clarify stabilization point of hydrogen flame and diluted hydrogen flames, therefore to allow a determination of suitable flame velocity values for the hydrogen or diluted hydrogen fuels in the empirical correlations of flame stability limits.

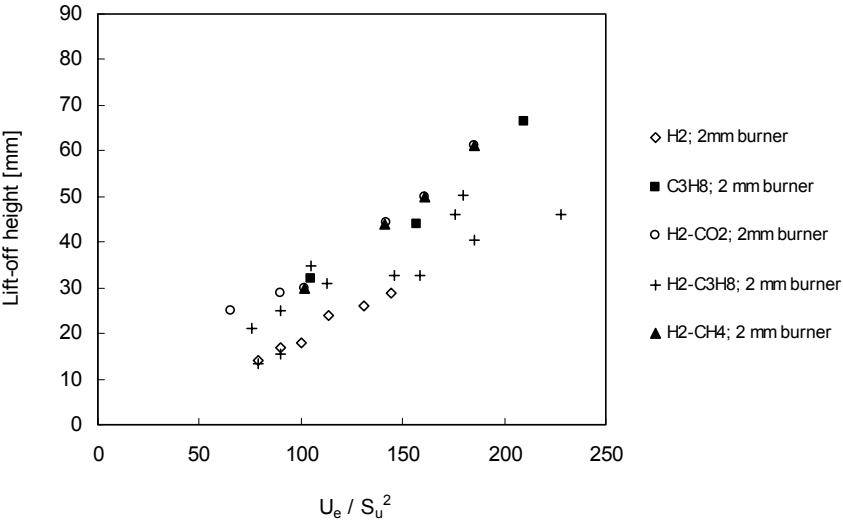


Figure 7: Variation of measured liftoff height with ratio of jet velocity to $U_e / (S_u)^2$.

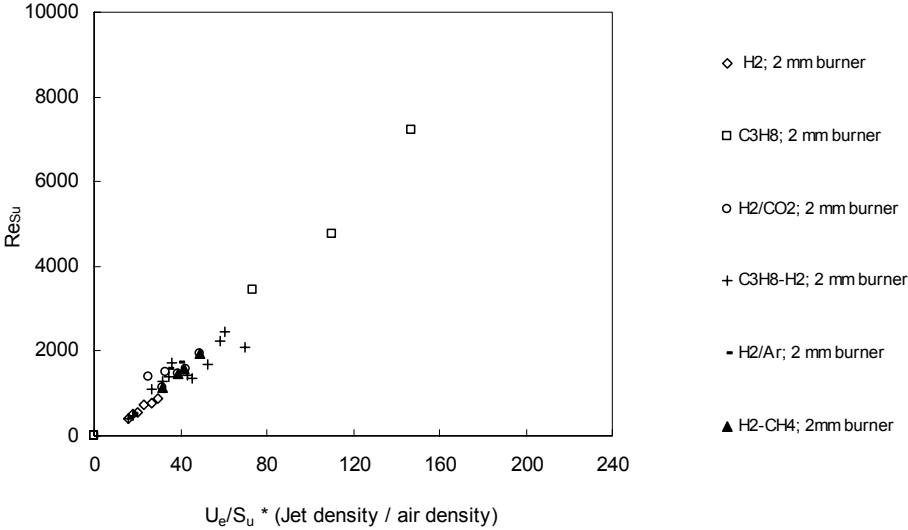


Figure 8: Non-dimensional analysis of liftoff height.

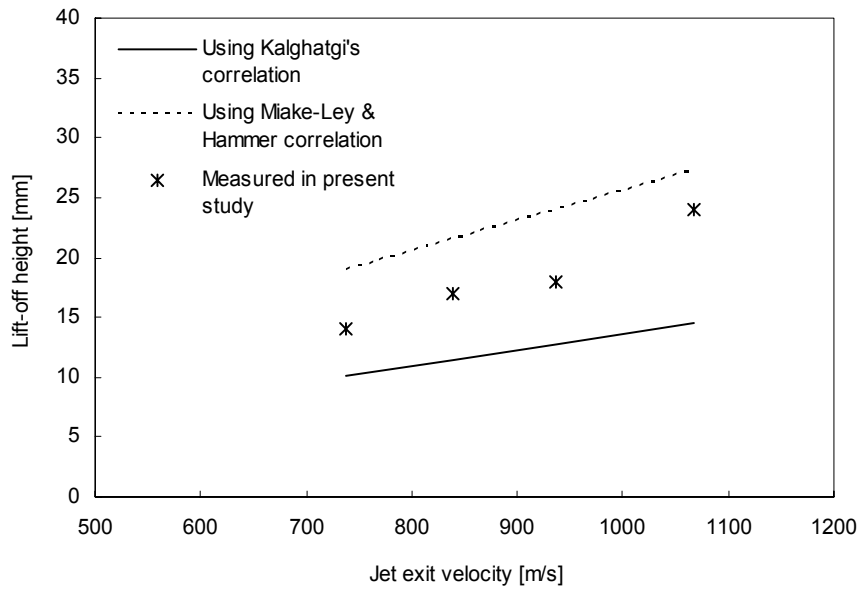


Figure 9: The comparison of measured hydrogen lift-off height to predictions from Kalghatgi's correlation and Miake-Ley & Hammer correlation.

5.0 CONCLUSIONS

- The flame lift-off height of the pure H_2 jet diffusion flame was found to increase with the jet velocity. Measured H_2 lift-off heights agreed well with other published experimental data. Agreement with previously published correlations was found to depend on the value used for the maximum laminar burning velocity of H_2 . The reported values of laminar flame velocity of hydrogen flames are scattered in the range 370 cm/s to 250 cm/s. The discrepancy was mainly due to whether and how the effect of stretch rate over the laminar flame velocity for the spherically expanding flames was taken into account.
- Comparisons of the stability of H_2 - CO_2 , H_2 - C_3H_8 and H_2 - CH_4 flames showed that the addition of C_3H_8 to hydrogen required least lift-off velocity and produced highest lift-off height among three additive gases. C_3H_8 is most effective in producing lifted flames.
- The experimental results also showed that C_3H_8 addition is more effective in blowout of a hydrogen flame than CO_2 addition. CO_2 addition is more effective in blowoff attached hydrogen/additives flames than CH_4 addition.
- The effects of methane on the hydrogen flame were different from the ones of propane and had similarities to the ones of carbon dioxide. At high concentration, direct blowoff of the methane/hydrogen was observed.
- The lift-off process of H_2 - C_3H_8 , H_2 - CH_4 and H_2 - CO_2 jet flames was strongly influenced by the chemical kinetics. Hydrocarbon acted as a sink for the active radicals that are of importance in the combustion chemistry of H_2 . The hydrocarbon is the dominant element in determining the burning velocity of hydrogen hydrocarbon mixtures.
- Using non-dimensional analysis of lift-off height approach, the experimental data can be fitted into a single line with a slope of 48, which is slightly lower than 50 obtained by Kalghatgi [6] for undiluted CH_4 , C_2H_4 , C_3H_8 and H_2 flames. The uncertainty using this approach is the value of the maximum laminar flame velocity of hydrogen flames.

REFERENCES

1. Peters N, *Turbulent Combustion*. Cambridge University Press, U.K., 2000.
2. Vanquickenborne V and Van Tiggelen A, *Combustion and Flame*, 10(1966) 59-69.
3. Pitts WM, *Proc. Combust. Inst.* 22 (1984) 253-360.
4. Pitts WM and Marto PJ, the second ASME-JSME Thermal Engineering Joint Conference, Honolulu, HI, March 22-27, 1987.
5. Pitts WM, *Combustion and Flame*, 76(1989)197-212 .
6. Kalghatgi GT., *Combustion Science and Technology*, 41 (1984)17-29.
7. Boadwell JE, Dahm JA and Mungal MG, *Proc. Combust. Inst.* 20 (1984) 303-310.
8. Burgess CP and Lawn CJ, *Combustion and Flame*, 119(1999)95:108.
9. Schefer RW, Namazian M and Kelly J, *Proc. Combust. Inst.* 22(1988) 833-842.
10. Schefer RW and Goix PJ, *Combustion and Flame*, 112(1998)559-574.
11. Ahan R. Choudhuri and Gollahalli SR, *AIAA Journal of Propulsion and Power* , 19(2003) 220-225.
12. Schefer RW, *International Journal of Hydrogen Energy*, 28(10)(2003)1131-1141.
13. Fu S and Wu Y., *Optical Engineering*, Vol 40 Part 8 (August 2001)1661-1666.
14. Cheng TS and Chiou CR, 1998, *Combustion Science and Technology*, 136(1-6), 81-94.
15. Lamoureux, N, Djebaïli-Chaumeix, N and Paillard, C.-E., *Experimental Thermal and Fluid Science* 27(2003) 385-393.
16. Huang, Z., Zhang, Y., Zengg, K., Liu, Bing, wang, Q. and Jiang, D., *Combustion and Flame* 146 (2006)302-311.
17. Ilbas, M., Crayford, A. P., Yilmaz, İ., Bown, P. J. and Syred, N., *International Journal of Hydrogen Energy* 31 (2006) 1768-1779.
18. Liu, D.D.S. and MacFarlane, R., *Combustion and Flame* 49 (1983) 59-71.
19. Leason BD, *Proc. Combust. Inst.* 4(1952) 396-375.
20. Milton BE and Keck JC, , *Combustion and Flame*, 58 (1984) 13-22.
21. Yumlu VS, , *Combustion and Flame*, 12 (1968) 14-18.
22. Miake-Lye, R. C. and Hammer, J. A., *Proc. of Combust. Inst.*, 22 (1988) 817-824.
23. Tacke MM, Geyer D, Hassel EP and Janicka J, *Proc. Combust. Inst.* 27 (1998) 1157-1165.