Computational Study of The Stability of Turbulent Hydrogen Jet Flames with Methane Addition

Syahirah Khaliesah Jaafar, Mahar Diana Hamid
Department of Chemical Engineering, Faculty of Engineering, Universiti Malaya, 50603 Kuala Lumpur

Mahar.diana@um.edu.my

Abstract. As the world predominately relies on fossil fuels to meet the current energy demands, the increasing consumption of it negatively impacts the environment. Thus, among constant search of a cleaner alternative fuel, hydrogen offers the greatest potential benefits in terms of energy supply and environmental impacts. However, hydrogen combustion is challenged by the difficulties in its production, storage, and end-use. Therefore, another method to enhance hydrogen combustion is to use hydrogen with methane addition as fuel. This study presents the effect of methane addition on the stability of hydrogen-methane flames by performing numerical analysis. In this study, the stability parameters such as lift-off height, lift-off velocity and blow-out velocity of hydrogen-methane jet flames were tested in three different mixing configurations. The first was to inject pure methane and pure hydrogen flames to form a jet flame. The second was to premix hydrogen and methane to form a jet flame. The third was to inject methane as an annular jet with hydrogen as the centre. All three different mixing configurations shows different results in terms of its stability parameters. From the first configuration, the lift-off height of pure methane is higher than pure hydrogen. From the second configuration, as methane concentration increases, the lift-off height increases but the lift-off velocity decreases. From the third configuration, the lift-off height highly depends on the velocity of annular jet flow but weakly depends on the central hydrogen jet flow. Generally, for all the mixing configurations, the lift-off height increases linearly with jet exit velocity.

1. Introduction

1.1. Fossil fuel as Primary Source of Energy
Due to the increasing world population growth, the use of fossil fuel which mainly comprises of coal, oil and natural gas has been exploited to satisfy the world energy demand. Recently, the air pollution has reached limits of considerable dangerousness for the environment, which is a direct repercussion of the constant combustion products provided by energy systems, especially fossil fuel [1]. The combustion products of fossil fuels have proven to negatively impact the environment and are the main source of most global problems such as the greenhouse effect, hole in the ozone layer and acid rains as it releases damaging pollutants such as $\text{SO}_x$, $\text{NO}_x$, particulate, carbon monoxide and carbon dioxide. Therefore, one clear solution to solve the future energy problem and reduce the dependency towards the use of
fossil fuels as a primary source of energy can be obtained through the use of renewable sources and by means of the exploitation of new low-polluting fuel that offers clean combustion [2].

1.2. Fossil fuel as Primary Source of Energy
Among the various alternative fuels that have been proposed among researchers, the use of hydrogen as a new fuel source has proven to offer the highest potential benefits to the future energy supply and the environment as it offers clean combustion and other attractive combustion characteristics. Hydrogen as fuel has been used by NASA since the 1970s to launch rockets and space shuttles into orbit due to its high energy content per unit weight. However, combustion of pure hydrogen increases the risk of explosion due to its wide range of flammability limits that might potentially cause the flame to blast off when burn, thus poses high safety hazards if it were to be used as a fuel in its pure form.

During these past decades, various research has been performed to understand the combustion characteristics of pure hydrogen and to improve its combustion characteristics by the addition of hydrocarbons to produce a mixture of hydrogen-hydrocarbon fuel which is effective in improving the fuel-combustion behaviour, which are proven by various research study on the stability of hydrogen-hydrocarbon fuel done. Some of the research includes Choudhuri and Gollahalli [3] which studied on the combustion characteristics of hydrogen-hydrocarbon hybrid fuels. Schefer [4] has also investigated on the hydrogen enrichment for improved lean flame stability by adding methane. A study by Wu et al. [1] predicts on the stability limits of pure hydrogen and hydrogen/hydrocarbon mixture jet flames. The progress in combustion investigations of hydrogen/hydrocarbon has been summarised by Tang and Zhang [5]. In terms of kinetics, Messaoudani et al. [6] studied the effects of hydrogen addition on the chemical kinetics of hydrogen-hydrocarbon flames. In ensuring that the hydrogen-hydrocarbon mixture is safe to be used, the stability characteristics of the fuel such as the lift-off height, lift-off velocity and blow-out velocity first be studied and understood.

1.3. Research Gaps
Numerous studies were performed to understand the characteristics of hydrogen as a fuel and to improve its combustion characteristics by the addition of hydrocarbons such as methane and propane. However, most of the studies were performed experimentally and by using a different configuration of burners and combustors thus resulting in inaccurate correlations. Although most of the studies apply existing established numerical correlations, the exact flame structure and behaviours are difficult to visualize. Therefore, simulation study should be performed on the hydrogen-hydrocarbon mixture flame to give a better visualization of the flame structure and its stability parameters.

1.4. Research Objectives
The aim of this research is to simulate the stability of turbulent hydrogen jet flames with methane addition of various hydrogen-methane compositions in a single concentric burner configuration. The main objectives are as below:

- To perform numerical simulation on the combustion reaction of hydrogen-methane fuel using ANSYS Fluent with various fuel ratio.
- To determine the influence of methane addition to the stability of hydrogen-methane jet flame in terms of its lift-off height, lift-off velocity and blow-out velocity.
- To validate the flame stabilization parameters result obtained from simulation with previous experimental results.
2. Methodology

2.1. Simulation Method
The simulation study was carried out by using Ansys FLUENT simulation software by using a nozzle geometry as described by Wu et al. [1] in their experimental study on the stability of turbulent hydrogen jet flames with carbon dioxide and propane addition. The geometry includes a straight concentric burner with a 5.3 mm nozzle diameter whereby an insertion was placed in the inner nozzle for a high velocity single jet flame to reduce the inner diameter to 2 mm. The detailed mechanical layout of the burner can be seen in Figure 1 below. As this study focuses on the flame combustion structure, thus only the nozzle of the burner is necessary to include in the geometry and meshing.

![Mechanical layout of the burner](image)

**Figure 1.** Mechanical layout of the burner [1]

2.2. Flow Configurations
Three flow configurations were required for the study of the flame stability parameters of pure H\textsubscript{2}, pure CH\textsubscript{4}, and H\textsubscript{2}-CH\textsubscript{4} flames. In the first configuration, pure H\textsubscript{2} fuel and pure CH\textsubscript{4} fuel were injected directly from the inner burner inlet into the central settling chamber to produce a jet flame by using an insertion in the inner diameter of burner. The second configuration was conducted by premixing H\textsubscript{2} with CH\textsubscript{4} with varying fuel ratio whereby it will be injected from the inner burner into the central settling chamber to produce a jet flame. The final flow configuration was performed by injecting hydrogen into the central settling chamber through inner burner while methane will be injected into the annular flow settling chamber through the co-flow inlet.

2.3. Simulation Setup
In ANSYS Fluent, there are various parameters that needed to be fixed and manipulated throughout the whole simulation process. The manipulated variables throughout this simulation are the inlet velocity magnitude and the mole fraction for each fuel species which is dependent on the mixing configurations. Some of the parameters that was fixed in the simulation are as tabulated in Table 1 below.
### Table 1. Fixed parameters in Ansys FLUENT setup.

| Parameters                      | Data/Value                  | Parameters                      | Data/Value                  |
|---------------------------------|-----------------------------|---------------------------------|-----------------------------|
| Mode                            | Planar                      | Initialization Temperature      | 1000K                       |
| Viscous Model                   | k-epsilon                   | Type of Outlet                  | Pressure Outlet             |
| Species Transport               | Chemkin-Import Mechanism    | Wall Motion                     | Stationary                  |
| Chemkin Mechanism               | San Diego Thermodynamics    | Wall Shear Condition            | No Slip                     |
| Turbulence-chemistry Interaction| Finite Rate                 | Wall Material                   | Steel                       |
| Type of Inlet                   | Velocity Inlet              | Wall Temperature                | 300K                        |
| Inlet Temperature               | 300K                        | Mole Fraction of O$_2$          | 1.0                         |

2.4. Post-processing and Analysis

In analysing the result, the effects of jet exit velocity magnitude and the mole fraction for each species to the stability parameters of the jet flames were studied. From the simulation, it is not possible to obtain the stability parameters directly, but it can be obtained by analysing the corresponding temperature and velocity profile as discussed more below.

2.4.1. Lift-off Height. The lift-off height was obtained from the relationship between height of flame at every point and its corresponding temperature with different velocity and mole fraction of the fuel. For example, the temperature contour which can be seen in Figure 2 below can be translated to a graphical form as shown in Figure 3, whereby the exact height at the initialization temperature of 1000K can be obtained.

![Figure 2. Temperature contour of pure H$_2$ flame at a jet exit velocity of 600 m/s.](image)

![Figure 3. Graph of temperature (K) against position (m) for pure H$_2$ flame](image)
2.4.2. Lift-off Velocity The lift-off velocity is the velocity at which the temperature reaches the initialization temperature which can be obtained from similar method as the lift-off height but utilizing the flame velocity profile.

2.4.3. Blow-out Velocity Blow-out velocity is the velocity which the flame extinguishes when it is in lifted state. Therefore, the blow-out velocity can be obtained when the temperature does not reach the initialization temperature. This method requires trial and error method, whereby some conditions may not experience flame blow-out. Since this simulation assumes complete combustion, therefore flame blow-out may not be experienced at all.

3. Results and discussion

3.1. Pure hydrogen and pure methane jet flames
Lifted hydrogen and methane flames were produced in the geometry of 2 mm diameter burner. From Figure 4, at a jet exit velocity of 600 m/s, \( \text{H}_2 \) flame reaches a lifted state where its lift-off height reaches 13.68 mm from the nozzle exit. At a much higher jet exit velocity of 1600 m/s, the lift-off height approaches 21.40 mm. Therefore, the lift-off height of pure hydrogen jet diffusion flames can be seen to increase linearly with jet velocity. The measured lift-off heights are in good agreement with the results of Kalghatgi [7], Cheng and Chiou [8], and Wu et al. [9].

![Figure 4. Lift-off height against jet exit velocity for pure \( \text{H}_2 \) jet flames.](image)

![Figure 5. Comparison between lift-off height of pure \( \text{H}_2 \) and pure \( \text{CH}_4 \) jet flames.](image)
From Figure 5, at a similar range of jet exit velocity of 600 – 1600 m/s, pure CH₄ flames achieved a much higher lift-off height as compared to pure H₂. However, similar trend was obtained for pure CH₄ whereby the lift-off height increases linearly with the jet exit velocity. Based on study performed by Messaoudani et al. [6], the amount of free radicals especially O, OH and H will determine the physical combustion characteristics and the overall chemical reaction of the flame. Thus, higher lift-off height obtained for pure methane is potentially due to the lower amount of free radicals as compared to pure hydrogen which lowers the combustion reaction rate thus resulting in higher lift-off height required.

### 3.2. Premixed hydrogen and methane as jet flame.

From Figure 6, at various CH₄ concentration, the flame obeys the same trend whereby its lift-off height will increase with increasing jet exit velocity. However, at CH₄ concentration of 10%, the lift-off height achieved are in the range of 55.15 mm to 59.18 mm. Whereas, at 90% methane addition a much higher lift-off heights were obtained which are in the range of 84.98 mm to 95.60 mm. Therefore, the lift-off height of premixed H₂/CH₄ jet diffusion flames increases with the increase in CH₄ concentration. Similar to case 1, the higher lift-off height obtained as methane concentration increases is potentially due to the decrease in amount of free radicals which reduce the combustion rate of the flame.

**Figure 6.** Comparisons of the lift-off heights at various H₂/CH₄ additives concentration.

**Figure 7.** Comparisons of the lift-off velocities at various H₂/CH₄ additives concentration.
As shown Figure 7, at various methane concentration, the flame lift-off velocity decreases with increasing jet exit velocity. At jet exit velocity of 600 m/s, jet diffusion flame with 90% methane addition obtained a high lift-off velocity of 460.67 m/s as compared to jet diffusion flame of 10% methane addition which obtained a lower lift-off velocity of 364.09 m/s. Thus, the lift-off velocity of premixed $\text{H}_2/\text{CH}_4$ jet diffusion flames increases with the decrease in methane concentration. By decreasing the methane concentration, the presence of hydrogen will increase which results in high amount of free radicals. Thus, the free radicals will increase the flame speed resulting in higher lift-off velocity. The overall trend in are similar to the experimental data which has been obtained by Wu et al. [9].

3.3. Methane as annular jet around central hydrogen jet flame.

From Figure 8, by increasing the hydrogen jet exit velocity and keeping the methane annular velocity constant, the lift-off height does not show any huge changes. However, by keeping hydrogen jet exit velocity constant, the methane annular flow velocity will increase. Hence, for a hydrogen-methane co-flow configuration, the lift-off height strongly depends on the methane annular flow velocity but weakly depends on the hydrogen central jet exit velocity. This is due to the mixing process in a co-axial jet can be divided into three flow regions and in one of the region which is the fully merged zone, the flow becomes self-similar.

![Figure 8. Lift-off height of H$_2$/CH$_4$ co-flow at various methane annular flow velocity.](image)

4. Conclusion

From this research study, numerical simulation of the stability parameters of hydrogen enriched methane jet flame at various mixing concentration was managed to be performed by using ANSYS Fluent. In terms of stability behaviour of the flame, the addition of methane does results in changes in the flame kinetics and stability parameters of the jet flame such as the lift-off height, lift-off velocity and blow-out velocity of various mixing configuration. In summary, the lift-off height increases linearly with the jet exit velocity in all three mixing configurations. The lift-off height also were observed to increase as the concentration of methane in the fuel mix increases. When methane were injected as an annular flow, the lift-off height of the flame depends weakly on the velocity of central hydrogen jet flow but strongly depends on the velocity of methane annular jet flow. In terms of the lift-off velocity, at various concentration of methane, the lift-off velocity decreases with increasing jet velocity. As the concentration of methane is reduced, the lift-off velocity will increase. As this study assumes total combustion occurs in the system, whereby the mole fraction of oxygen equals to 1, flame blow-out were not experienced for the flame of jet exit velocity ranging from 600 m/s – 1600 m/s. In this research, the flame stabilization parameters results obtained from the simulation performed has been validated and correlated with previous experimental data performed by previous researchers cited.
5. References

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