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## Stability of Partially Premixed Ammonia/Methane Flames in a Concentric Flow Conical Nozzle Burner

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**Abstract:** Ammonia, as a carbon-free fuel, holds promise as a potential alternative to fossil fuels. However, its practical implementation requires a comprehensive understanding of its combustion properties, particularly concerning flame stability. This study investigates the stability and flame appearance of partially premixed ammonia-methane flames in a concentric flow conical nozzle burner. The research explores the effects of varying the ammonia fraction in the inner stream, the outer stream velocity, and the degree of partial premixing (expressed as  $L/D$ ). The findings indicate that flame stability is enhanced by increasing the outer stream equivalence ratio, while it is reduced by increasing the degree of premixing via higher  $L/D$  values. Notably, the case of  $L/D = 0$  demonstrates a virtual improvement in flame stability, attributed to the absence of reaction between the inner mixture and the stable outer methane flame. This study provides valuable insights into the combustion characteristics of ammonia-methane blends under partially premixed conditions.

**Keywords:** Partially Premixed Combustion; Ammonia; CFCN; Flame Stability

### 1. INTRODUCTION

The world is facing the significant challenge of satisfying the growing energy demand, while also minimizing the environmental consequences of energy generation. Hydrocarbon fuels, due to their excessive usage, serve as primary contributors to greenhouse gas emissions, particularly  $\text{CO}_2$  emissions. Therefore, there is a global trend toward developing and utilizing affordable, low-emission, and sustainable energy systems and fuels. This progression aligns with the objectives of COP21, also referred to as the 2015 Paris Climate Conference, which emphasizes the strong need to decarbonize energy production systems [1].

Ammonia is a promising fuel in low-carbon energy applications due to its abundant hydrogen content, cost-effective storage and transportation, and potential for minimal carbon emissions. However, ammonia combustion faces several challenges, such as high  $\text{NO}_x$  emissions, narrow flammability limits (16%-25% by volume in air), low energy density compared to hydrocarbon fuels, and low burning velocity, which disrupts flame stability [2]. These challenges limit the practical use of ammonia as a fuel. A proposed solution to improve burning velocity and flame stability involves introducing a reactive fuel like natural gas (NG) or hydrogen ( $\text{H}_2$ ) to the ammonia-air blend [3][4]. Methane, which is the main constituent of natural gas, is a fuel that combusts cleanly, emitting mainly water and  $\text{CO}_2$  [5]. Various combustion applications have utilized methane, such as Lean Burn Gas Engines (LBGEs) [6]. However, this may also affect  $\text{NO}_x$  emissions and other combustion characteristics.

Partially premixed combustion is a widely used mode of combustion in numerous applications, including diesel engines and gas turbines. Numerous research studies indicate that partially premixed flames provide greater

stability than both premixed and non-premixed flames [8]. This stability can be attributed to the unique triple-flame structure, characterized by lean and rich pockets, where the combustion reactions occur. These pockets provide sufficient energy and radicals to sustain the reaction and keep the flame stable.

In this study, we investigated the impact of the degree of partial pre-mixing on the stability of ammonia-methane flames using a concentric-tube conical nozzle burner more details regarding the burner geometry can be found elsewhere [7]. Only a brief introduction about the burner is given here, the burner consists of two concentric tubes, where the burner can change the degree of premixing between the outer and inner stream by changing the recess distance between the exits of the two tubes. Moreover, to enhance flame stability, a conical nozzle is attached to the exit of the burner tip. In this work, the inner stream consists of a premixed ammonia-air mixture, while the outer stream consists of a premixed methane-air mixture. The degree of partial premixing is varied by changing the mixing length ( $L$ ) and the outer flame equivalence ratio  $\Phi_{\text{out}}$  at different outer mixture velocities. The co-flow is set at a remarkably low velocity (0.75 m/s) to dilute any residual ammonia, due to its toxic nature. The study incorporates six levels of partial premixing in terms of  $L/D = 0, 1.5, 2.5, 5, 7.5$ , and  $10$ , where  $L/D = 0$  representing no premixing between the inner and outer flow streams. The outer equivalence ratio  $\Phi_{\text{out}}$  is set at  $1.3, 1.1$  and  $0.96$  for different cases. To the best of our knowledge, this is the first study that examines the effect of partial premixing on ammonia-methane flames using this burner configuration. Previous studies have used only air in the inner and fuel in the outer stream [8][7][9][10].

## 2. EXPERIMENTAL SETUP AND METHODS

Figure 1. (a) shows the schematic of the burner design, which consists of two vertical tubes: an inner stainless-steel tube with an inner diameter ( $d$ ) of 4 mm and a wall thickness of 1 mm, and an outer steel tube with an inner diameter of 14 mm and a wall thickness of 2 mm. The inner tube carries a mixture of  $\text{NH}_3$  and air, while the annular passage between the inner and outer tubes carries a mixture of  $\text{CH}_4$  and air to boost flame stability as shown in Fig 1.b. The burner design allows for partial premixing of the fuel and air mixtures, which can be controlled by adjusting the mixing distance ( $L$ ), defined as the distance between the exits of the inner and outer tubes. The mixing distance can be expressed in terms of the  $L/D = 0, 1.5, 2.5, 5, 7.5$ , and  $10$ . A cone with a half-cone angle of  $26^\circ$  is positioned above the burner to act as a stabilizer, which has been discussed its stabilization mechanism previously in [9]. A co-flow air is supplied by an air blower around the flame through a honeycomb (Perforated) plate, as shown in Fig.1b, which provides a uniform and stable air stream with a fixed velocity of  $0.75$  m/s. The velocity of the co-flow air is controlled by a 4 inches gate valve and measured by a hot wire anemometer. The flow rates of the inner air,  $\text{CH}_4$ , and  $\text{NH}_3$  are controlled by using needle valves and measured by using SIARGO digital mass flow meters of models MF5706 and MF5712, respectively, with an accuracy of  $\pm(0.5+2.0\text{FS})\%$ . The flow rate of the outer air is measured by using a calibrated ball rotameter.

The flame is confined in a combustion chamber with dimensions of  $200\text{ mm} \times 200\text{ mm} \times 700\text{ mm}$ , as shown in Fig.1c. The combustion chamber is designed with an extended length to accommodate the anticipated long flames produced by ammonia combustion. The side walls of the chamber are equipped with rectangular windows made of thermal glass. These windows facilitate flame monitoring and optical-based measurements, providing future potential for a laser-based measurement program. The combustion chamber ends with a converging flange into a 60 mm diameter circular exhaust tube as shown in Fig 1.c.

The outer streams of  $\text{CH}_4$  and air are independently supplied from their respective cylinders, passing through controlling valves and flow meters before being combined in a mixing chamber. This mixture is then introduced into the outer annular passage. The same process applies to the inner stream of  $\text{NH}_3$  and air. These two streams mingle within the mixing distance  $L$ , adjustable by altering the  $L/D$  ratio. The stability program in this study involves setting the equivalence ratio and mixture velocity of the outer stream, then introducing a known ammonia blend into the inner stream, which ranges from 0 (no ammonia) to 6 SLPM in increments of 2 SLPM. With each blend, the inner air flow rate gradually increases until the blow-off point is reached, where the blow-off inner mixture velocity ( $V_{mi}$ ) is noted. These steps are then replicated at another outer mixture velocity ( $V_{mo}$ ). This procedure is conducted at  $L/D$  ratios ranging from 0 to 10 in increments of 2.5.

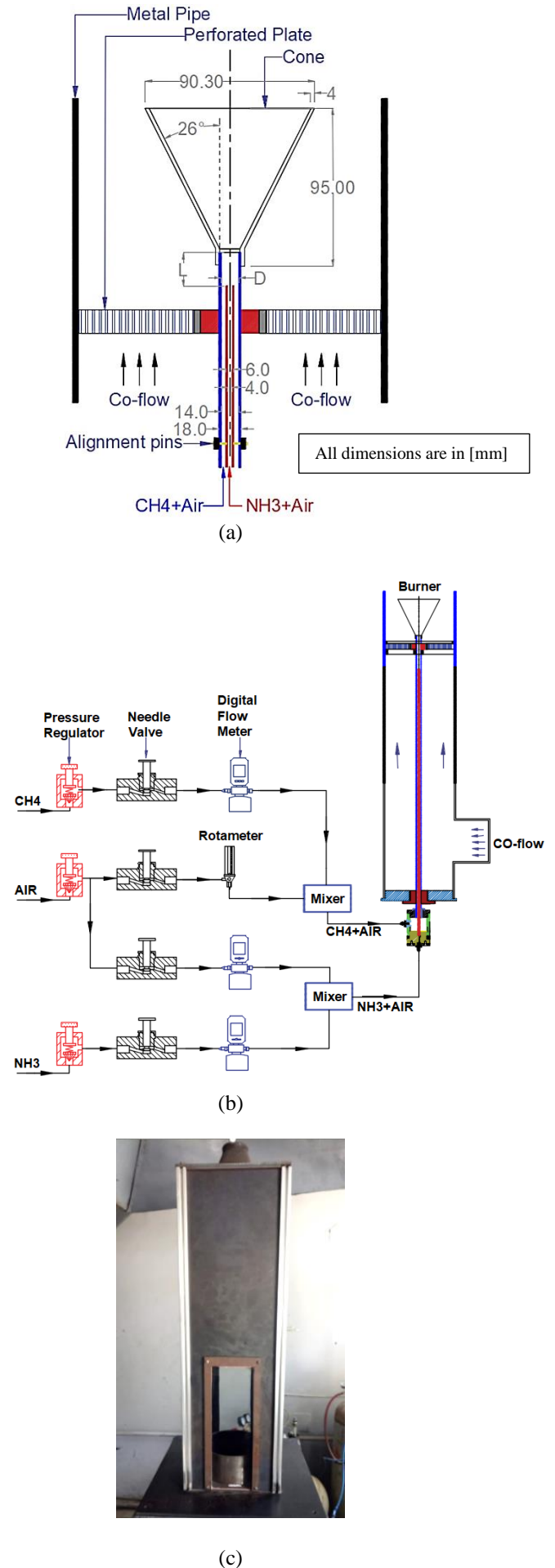


Fig. 1. (a) Burner Schematic, (b) Flow Diagram, and (c) Combustion chamber

### 3. RESULTS AND DISCUSSION.

This section presents the results of the experiments. Discussion and interpretation of the results will be provided alongside the results as well.

#### 3.1 Flame Stability:

This study investigates the stability of partially premixed flames produced by a concentric flow conical nozzle burner (CFCN) with different levels of partial premixing ( $L/D$ ). Previous studies have suggested that partially premixed flames offer greater stability than premixed and non-premixed methane flames and that the ideal  $L/D$  for stability is 5, due to the emergence of a triple-flame structure [8]. Nonetheless, the present study differs from the previous studies in terms of burner dimensions and flow arrangement, as it uses a premixed mixture of  $CH_4$ +Air in the outer stream and  $NH_3$ +Air in the inner stream.

Figure 2 illustrates how the inner blow-off mixture velocity ( $V_{mi}$ ) varies with the outer mixture velocity ( $V_{mo}$ ) at a constant outer equivalence ratio ( $\Phi_{out}$ ) of 0.96, for various  $NH_3$  blends (0, 2, 4, and 6 SLPM) in the inner stream and various  $L/D$  values. The data indicates that at  $L/D = 0$ , maximum stability limits are reached for all  $NH_3$  blends, with  $V_{mi, max}$  reaching 110 m/s in certain cases, which is more than double the blow-off velocity compared to the nearest results. However, this result is deceptive as the inner stream penetrates the flame before arriving at the blow-off point and does not react with the outer stream, as demonstrated in Fig. 3.a. Conversely, Fig. 3.b shows a regular flame before blow-off without inner flow penetration.

The figure also reveals that for  $L/D = 1.5, 2.5$ , and 5, stability steadily improves with increasing  $V_{mo}$ . However, for  $L/D = 7.5$  and 10, stability remains relatively constant or, in some cases, slightly diminishes as  $V_{mo}$  increase. It is noteworthy that the overall flame stability tends to decrease as  $L/D$  values increase. This could potentially be attributed to the dilution of the outer mixture with a less reactive mixture as the  $L/D$  value rises. It is also noted that the flame with  $NH_3 = 4$  and 6 SLPM cannot be sustained for  $L/D = 10$ , and therefore it is not presented in the figures. This might further indicate that a high degree of pre-mixing does not foster stability for these burner configurations and conditions.

The influence of enriching the flame by increasing the outer equivalence ratio  $\Phi_{out}$  from 0.96 to 1.3 on flame stability has also been evaluated. This was also tested at various  $NH_3$  blends. It was seen that increasing  $\Phi_{out}$  enhances flame stability, indicated by increasing the inner velocity blow-out limit. This could be attributed to the rise in overall fuel content and flame-burning velocity as the outer equivalence ratio  $\Phi_{out}$  ascends. This aligns with the results from previous studies [4-5]. Fig. 4 displays the burner's performance at different  $\Phi_{out}$  values at  $L/D = 2.5$  and 5, for an  $NH_3$  blend of zero and 2 SLPM. The trend of stability remains consistent across all the tested conditions.

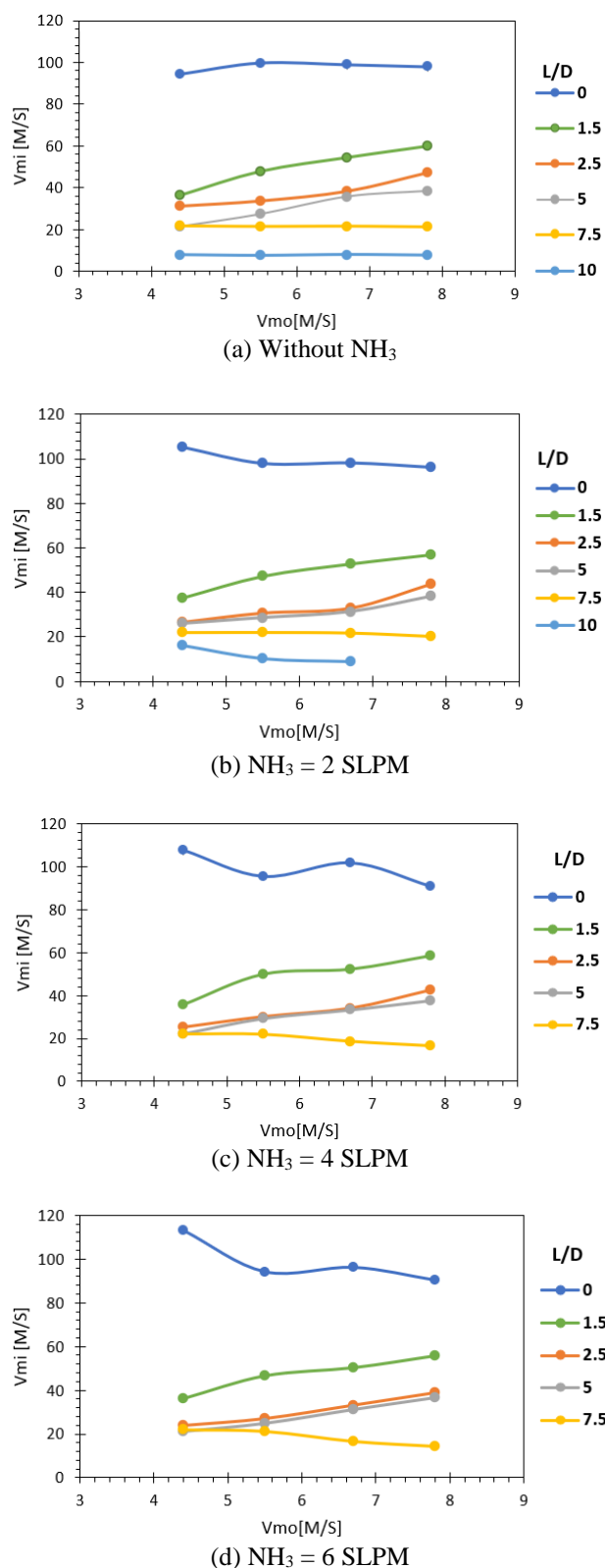


Fig. 2. Stability curve at  $\Phi_{out} = 0.96$  and  $NH_3$  blend, at (a) zero, (b) 2 SLPM, (c) 4 SLPM, (d) 6 SLPM

Figure 5 shows that at  $L/D=5$  flame is more stable than  $L/D=2.5$  and 7.5 in rich condition which can prove that partially premixed flames is more stable than premixed and non-premixed flames in ammonia flames.

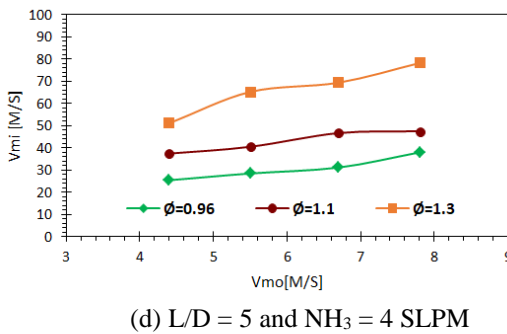
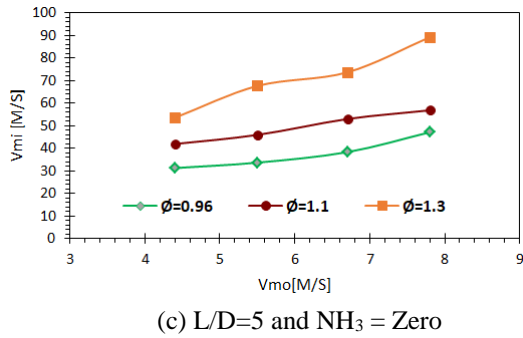
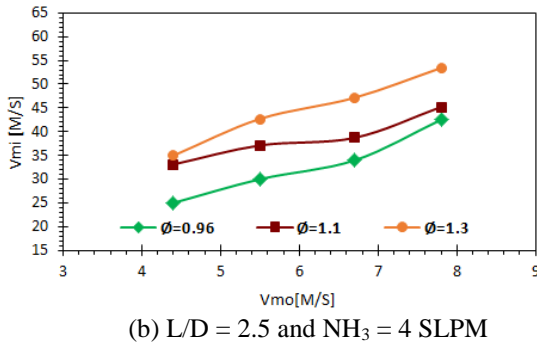
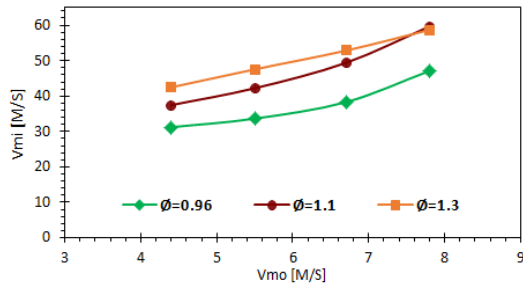
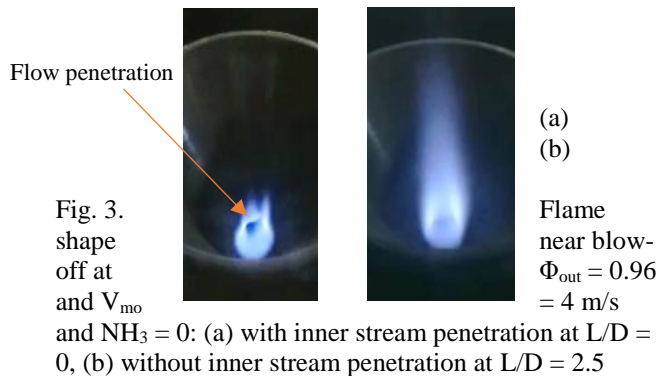


Fig. 4. Outer flame equivalence ratio effect: (a)  $L/D = 2.5$  and  $NH_3 = 0$ , (b)  $L/D = 2.5$  and  $NH_3 = 4$  SLPM, (c)  $L/D = 5$  and  $NH_3 = \text{Zero}$ , and (d)  $L/D = 5$  and  $NH_3 = 4$  SLPM.

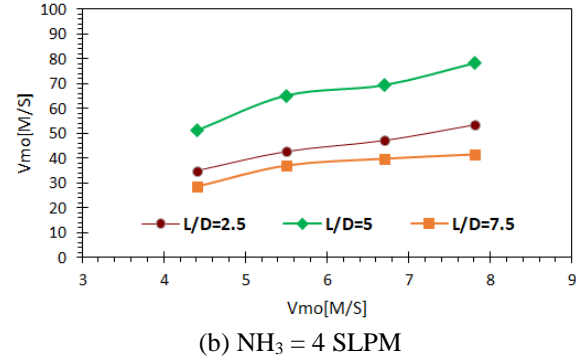
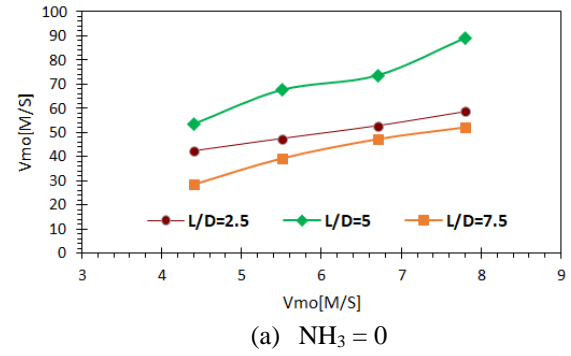


Fig. 5. Stability curve at  $\Phi_{out} = 1.3$  and  $NH_3$  blend: (a) zero, (b) 4 SLPM.

Figure 6 presents the influence of  $L/D$  and  $NH_3$  concentration on  $RE_j$  (jet blow-off Reynolds number) at blow-off, with  $V_{mo} = 5.5$  m/s and  $\Phi_{out} = 0.96$ . Notably,  $RE_j$  remains almost constant for different  $NH_3$  blends, suggesting that the addition of  $NH_3$  does not significantly impact flame stability.

In addition, Figure 7 illustrates the effect of  $L/D$  and outer flame mixture velocity ( $V_{mo}$ ) on  $RE_j$  at  $NH_3 = 4$  SLPM and  $\Phi_{out} = 0.96$ . Unlike the effect of the  $NH_3$  concentration, the results show a gradual increase in  $RE_j$  at the blow-off point with increasing  $V_{mo}$  for all  $L/D$  values.

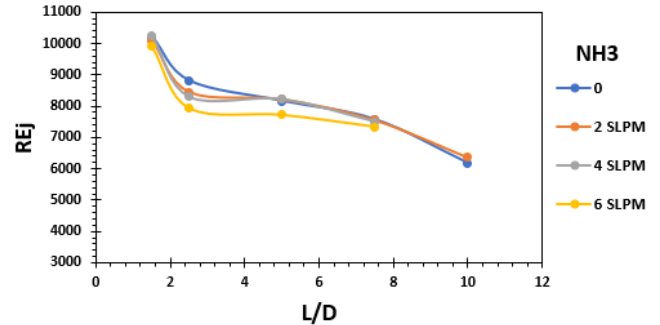


Fig. 6. Effect of  $L/D$  and  $NH_3$  blend on jet Reynolds number at  $V_{mo} = 5.5$  m/s and  $\Phi_{out} = 0.96$ .

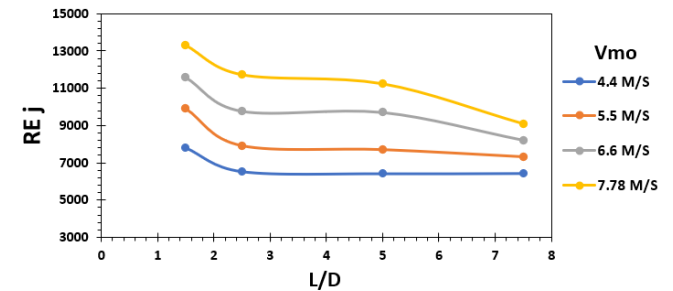


Fig. 7. Effect of  $L/D$  and outer flame mixture velocity on blow-off jet Reynolds number at  $NH_3 = 4$  SLPM and  $\Phi_{out} = 0.96$ .



### 3.2 Flame Appearance:

This section investigates the partially premixed methane and ammonia methane flame appearance changes with many parameters such as inner and outer stream mixture velocity, outer flame equivalence ratio, and changing the ammonia blend in the inner stream.

Figure 8 shows the effect of the inner stream velocity (air only) on the flame appearance at  $L/D = 2.5$ . The plot shows that with an increase in the inner air velocity the flame length decreases. This could be attributed to the fact that by increasing the core air velocity, the combustion process becomes more efficient, leading to a faster and more complete burning of the fuel. This, in turn, results in a shorter flame length.

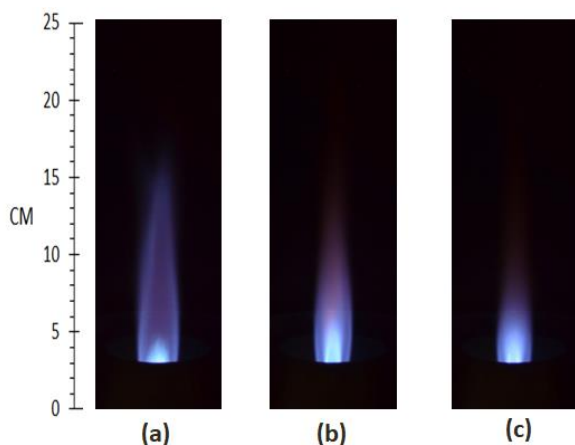


Fig. 8. Effect of inner stream mixture velocity at  $\Phi_{out} = 0.96$  and  $NH_3 = 0$  SLPM,  $V_{mo}=5.5$  m/s and  $L/D = 2.5$ , at (a)  $V_{mi}= 6.75$  m/s, (b)  $V_{mi}= 13.5$  m/s, and (c)  $V_{mi}= 20$  m/s.

Figure 9 illustrates how the flame shape is influenced by the outer mixture velocity. The results demonstrate that increasing the outer flame mixture velocity also impacts the flame length, while keeping the outer flame equivalence ratio and inner stream velocity constant. The flame length increases with the rise in  $V_{mo}$ , which is attributed to the overall increase in equivalence ratio.

Figure 10 demonstrates that increasing the  $NH_3$  percentage in the inner stream leads to an increase in flame length. This effect is attributed to the low reactivity and burning velocity of ammonia. Furthermore, the central region of the flame exhibits an orange-yellow chemiluminescent color, which intensifies with higher  $NH_3$  concentrations. In contrast, the outer perimeter of the flame appears blue, which is a result of the flame being composed of methane and air. The distinct coloration in the central flame region is associated with the presence of  $NH_2$  alpha and  $H_2O$  vapor bands, as reported in previous research [11].

Figure 11 illustrates the influence of the level of partial premixing on the appearance of the flame while keeping all the other parameters intact. The results indicate that as the level of partially premixed condition ( $L/D$ ) increases, the blue ring luminosity around the ammonia inner stream becomes lighter. This observation suggests a direct effect of the increasing  $L/D$  on the outer stream, affecting the overall appearance of the flame.

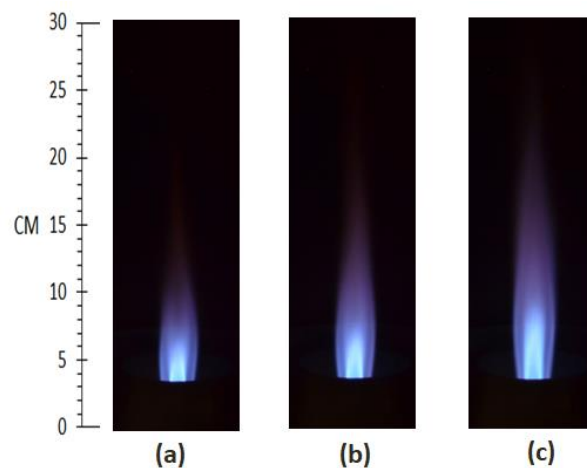


Fig. 9. Effect of outer stream mixture velocity at  $\Phi_{out} = 0.96$ ,  $NH_3 = 0$  SLPM,  $V_{mi}=13.5$  m/s and  $L/D = 2.5$  at (a)  $V_{mo}= 4.4$  m/s, (b)  $V_{mo}= 5.5$  m/s, and (c)  $V_{mo}= 6.6$  m/s.

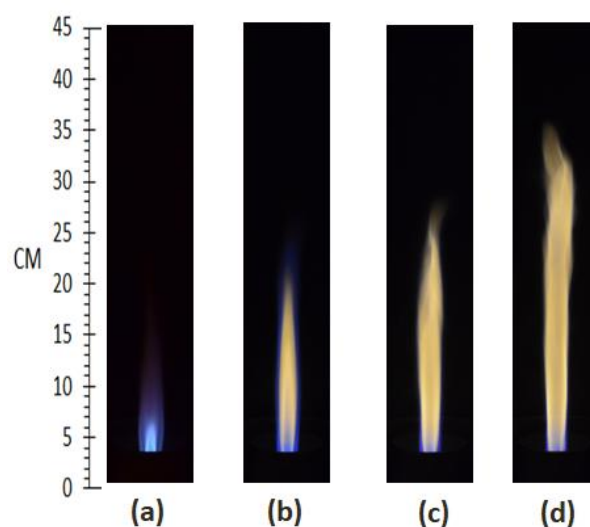


Fig.10. Effect  $NH_3$  in the inner stream on flame appearance at  $\Phi_{out} = 0.96$  and  $V_{mo}=13.5$  m/s ,  $V_{mi}=13.5$  m/s and  $L/D = 2.5$  at (a) 0 SLPM, (b) 2 SLPM, (c) 4 SLPM, and (d) 6 SLPM.

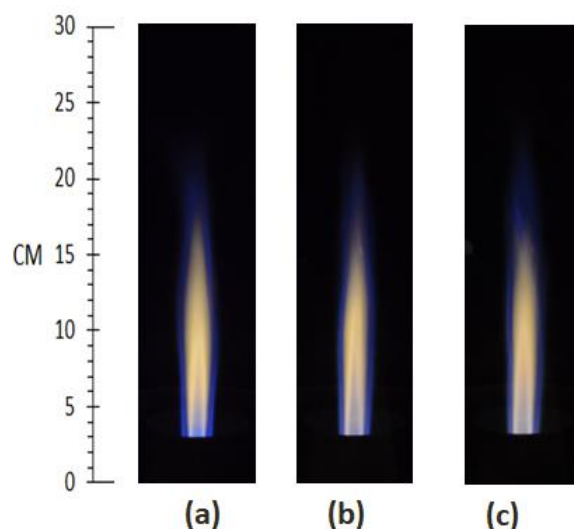


Fig. 11. Effect  $L/D$  on flame appearance at  $\Phi_{out} = 0.96$  and  $V_{mo}=13.5$  m/s ,  $V_{mi}=13.5$  m/s and  $NH_3=2$  SLPM at (a)  $L/D=2.5$ , (b)  $L/D=5$ , and (c)  $L/D=7.5$ .

#### 4. CONCLUSIONS

This study investigated the stability of partially premixed ammonia/methane flames in a concentric flow conical nozzle burner under various conditions, such as the level of partial premixing, the outer flame equivalence ratio, the outer flame mixture velocity, and the ammonia blends in the inner stream. The main findings of this study are:

- At  $L/D = 0$ , the inner stream penetrated the flame without reacting, creating a false impression of improved stability for different ammonia blends and outer stream velocities.
- At  $L/D = 1.5, 2.5$ , and  $5$ , stability slightly improved with increasing the outer mixture velocity at a constant equivalence ratio.
- At  $L/D = 10$  and ammonia blends of  $4$  and  $6$  SLPM, the flame was not stable when the level of partial premixing increased at  $\Phi_{out} = 0.96$ .
- At  $L/D = 7.5$  and  $10$ , the flame was insensitive to the outer mixture velocity at  $\Phi_{out} = 0.96$ .
- At  $L/D = 2.5$  and  $5$  and ammonia blends  $NH_3 = 0$  and  $4$  SLPM, stability improved when the outer flame equivalence ratio increased to  $1.1$ .
- $L/D = 5$  is more stable than  $L/D = 2.5$  and  $7.5$  in rich flames.
- The blow-off jet Reynolds number was independent of ammonia blends for all cases of  $L/D$ .
- The blow-off jet Reynolds number was sensitive to the outer flame mixture velocity.
- Increasing the inner stream mixture velocity decreases the flame size.
- Increasing the outer flame mixture velocity increases the flame size.
- Adding  $NH_3$  to the partially premixed flames increases its size and displays a chemiluminescent orange-yellow color.
- The variation in the level of partial premixing in the ammonia-methane flame directly influences the appearance of the outer stream by reducing its luminosity, without significantly affecting the size of the flame.

These findings contribute to the understanding of the effects of ammonia/methane blends on flame stability and suggest directions for future research on this topic.

#### 5. REFERENCES

- [1] J. Delbeke, A. Runge-Metzger, Y. Slingenberg, and J. Werksman, "The paris agreement," *Toward a Clim. Eur. Curbing Trend*, pp. 24–45, 2019, doi: 10.4324/9789276082569-2.
- [2] A. M. Elbaz, S. Wang, T. F. Guiberti, and W. L. Roberts, "Review on the recent advances on ammonia combustion from the fundamentals to the applications," *Fuel Commun.*, vol. 10, no. February, p. 100053, 2022, doi: 10.1016/j.jfueco.2022.100053.
- [3] A. M. Elbaz, A. M. Albalawi, S. Wang, and W. L. Roberts, "Stability and characteristics of  $NH_3/CH_4$ /air flames in a combustor fired by a double swirl stabilized burner," *Proc. Combust. Inst.*, vol. 000, pp. 1–9, 2022, doi: 10.1016/j.proci.2022.06.004.
- [4] M. Zhang *et al.*, "The regulation effect of methane and hydrogen on the emission characteristics of ammonia/air combustion in a model combustor," *Int. J. Hydrogen Energy*, vol. 46, no. 40, pp. 21013–21025, 2021, doi: 10.1016/j.ijhydene.2021.03.210.
- [5] R. Khudhair and Y. Jung, "Environmental and Economical Evaluation of Liquefied Natural Gas Vehicles Promotion Program in The City of Baghdad," *Proc. Int. Exch. Innov. Conf. Eng. Sci.*, vol. 8, pp. 31–37, 2022, doi: 10.5109/5909059.
- [6] E. Abdelhameed and H. Tashima, "An investigation on the behavior of the torch flame in the LBGE combustion process," *Proc. Int. Exch. Innov. Conf. Eng. Sci.*, vol. 8, pp. 207–214, 2022, doi: 10.5109/5909093.
- [7] A. M. Elbaz, "Early structure of LPG partially premixed conically stabilized flames," *Exp. Therm. Fluid Sci.*, vol. 44, pp. 583–591, 2013, doi: 10.1016/j.expthermflusci.2012.08.021.
- [8] F. El-Mahallawy, A. Abdelhafez, and M. S. Mansour, "Mixing and nozzle geometry effects on flame structure and stability," *Combust. Sci. Technol.*, vol. 179, no. 1–2, pp. 249–263, 2007, doi: 10.1080/00102200600809324.
- [9] M. S. Mansour, A. M. Elbaz, and M. Samy, "The stabilization mechanism of highly stabilized partially premixed flames in a concentric flow conical nozzle burner," *Exp. Therm. Fluid Sci.*, vol. 43, pp. 55–62, 2012, doi: 10.1016/j.expthermflusci.2012.03.017.
- [10] A. M. Elbaz, M. F. Zayed, M. Samy, W. L. Roberts, and M. S. Mansour, "The flow field structure of highly stabilized partially premixed flames in a concentric flow conical nozzle burner with coflow," *Exp. Therm. Fluid Sci.*, vol. 73, pp. 2–9, 2016, doi: 10.1016/j.expthermflusci.2015.08.016.
- [11] A. Hayakawa, T. Goto, R. Mimoto, Y. Arakawa, T. Kudo, H. Kobayashi, *Fuel* 159 (2015) 98–106.