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

Eslam I. Mohamed
Continuous Combustion Laboratory, Mechanical Power Engineering Department, Faculty of Engineering at El-Mataria, Helwan University

Ahmed H. Elkholy
Continuous Combustion Laboratory, Mechanical Power Engineering Department, Faculty of Engineering at El-Mataria, Helwan University

Hany A. Moneib
Continuous Combustion Laboratory, Mechanical Power Engineering Department, Faculty of Engineering at El-Mataria, Helwan University

Ayman M. Elbaz
Clean Combustion Research Center (CCRC), King Abdullah University of Science and Technology (KAUST)

https://doi.org/10.5109/7158034

出版情報：Proceedings of International Exchange and Innovation Conference on Engineering & Sciences (IEICES). 9, pp.423-428, 2023-10-19. 九州大学大学院総合理工学府
バージョン：

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

Eslam I. Mohamed[1*], Ahmed H. Elkholy[1], Hany A. Moneib[1], Ayman M. Elbaz[2]
[1]Continuous Combustion Laboratory, Mechanical Power Engineering Department, Faculty of Engineering at El-Mataria, Helwan University, Cairo 11718, Egypt
[2]Clean Combustion Research Center (CCRC), King Abdullah University of Science and Technology (KAUST), 23955-6900 Thuwal, Kingdom of Saudi Arabia
*Corresponding author email: eslami_brahim@m-eng.helwan.edu.eg

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 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 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 (H2) 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 CO_2[5]. Various combustion applications have utilized methane, such as Lean Burn Gas Engines (LBGEs)[6]. However, this may also affect 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.

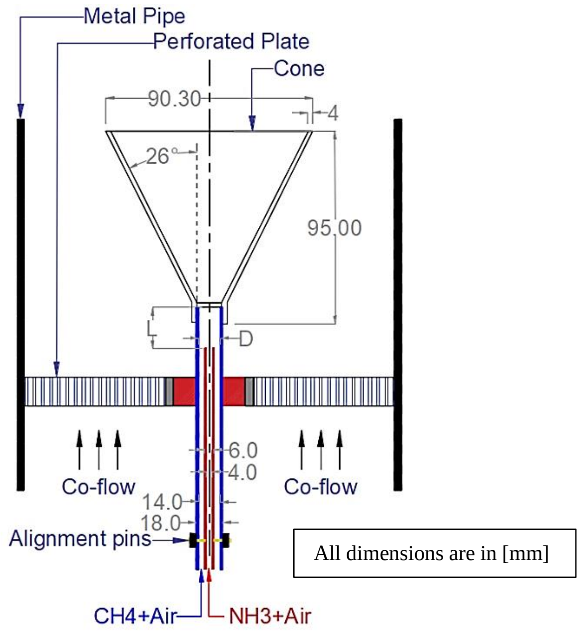
In this study, we investigated the impact of the degree of partial pre-mixing on the stability of ammonia-methane flames using a concentric-tube conical nozzle burner more details regarding the burner geometry can be found elsewhere .[7] Only a brief introduction about the burner is given here, the burner 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 Φ_{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 Φ_{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

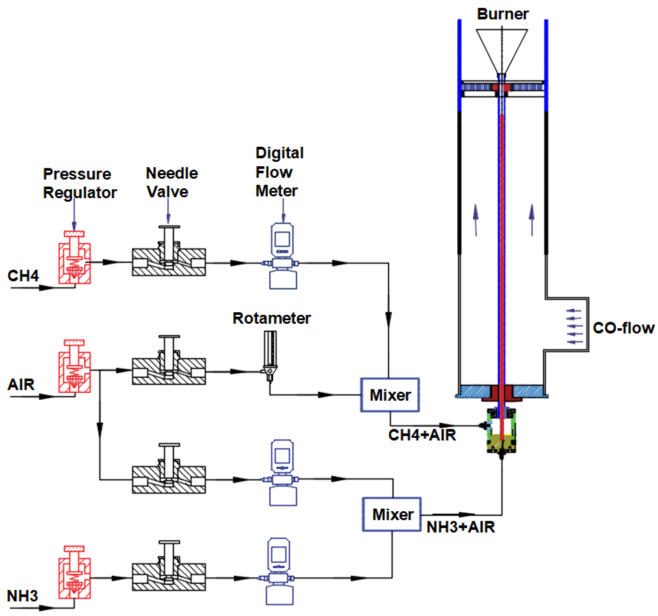
Figure 1. (a) shows the schematic of the burner design, which consists of two vertical tubes: an inner stainless-steel tube with an inner diameter (d) of 4 mm and a wall thickness of 1 mm, and an outer steel tube with an inner diameter of 14 mm and a wall thickness of 2 mm. The inner tube carries a mixture of NH_3 and air, while the annular passage between the inner and outer tubes carries a mixture of 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° 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, CH_4, and 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 ±(0.5+2.0FS) %. 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 mm × 200 mm × 700 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 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 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.



(a)



(b)

(c)

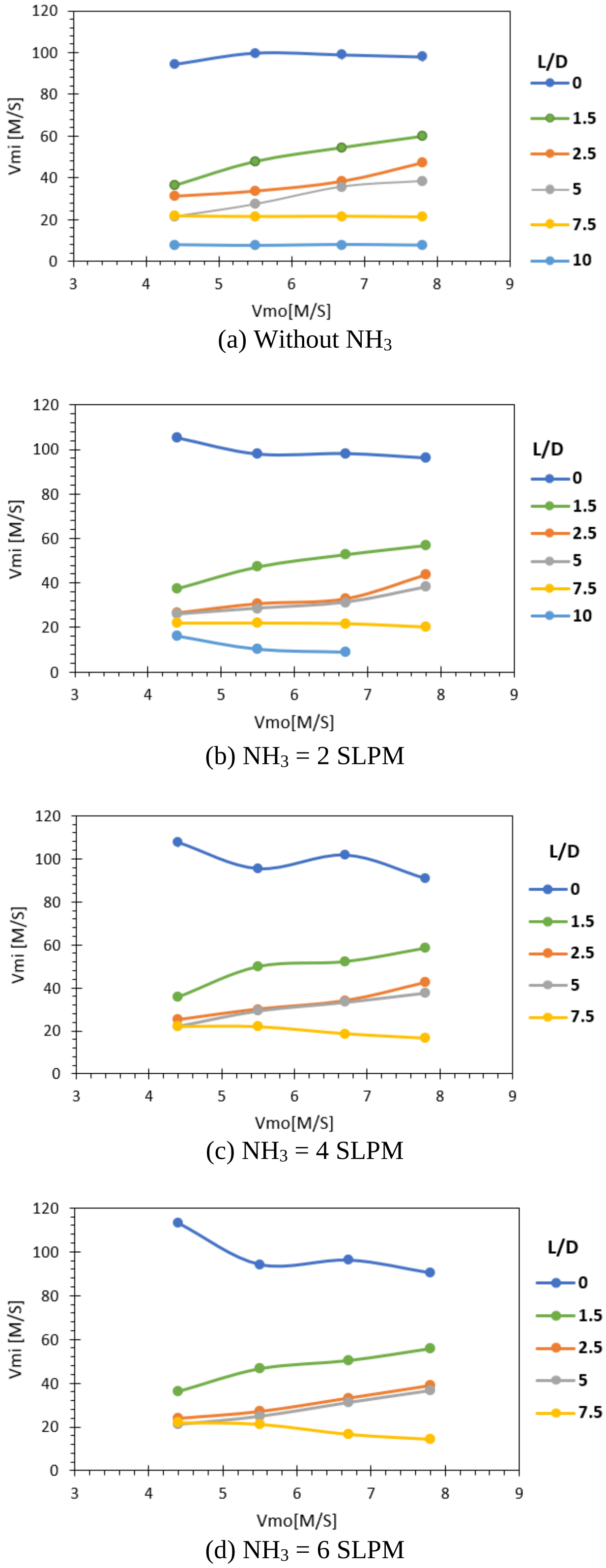
Fig. 1. (a) Burner Schematic, (b) Flow Diagram, and (c) Combustion chamber

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 (Φ_{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 Φ_{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 Φ_{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 Φ_{out} ascends. This aligns with the results from previous studies [4-5]. Fig. 4 displays the burner's performance at different Φ_{out} values at L/D = 2.5 and 5, for an NH3 blend of zero and 2 SLPM. The trend of stability remains consistent across all the tested conditions.



(a) Without NH_3

(b) NH_3 = 2 SLPM

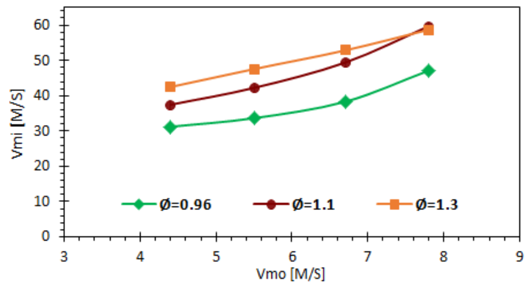
(c) NH_3 = 4 SLPM

(d) NH_3 = 6 SLPM

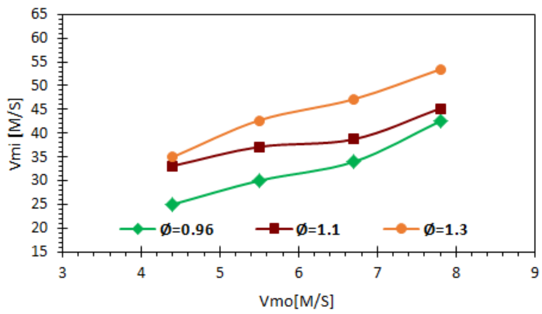
Fig. 2. Stability curve at Φ_{out} = 0.96 and NH_3 blend, at (a) zero, (b) 2 SLPM, (c) 4 SLPM, (d) 6 SLPM

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 .

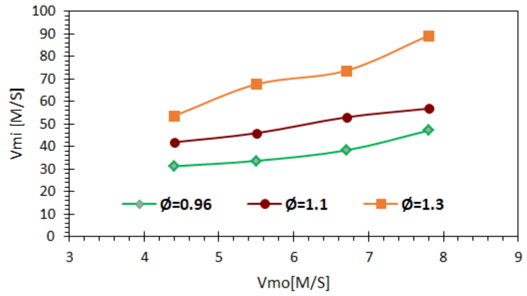
Fig. 3. Flame shape near blow-off at Φ_{out} = 0.96 and V_{mo} = 4 m/s and NH_3 = 0: (a) with inner stream penetration at L/D = 0, (b) without inner stream penetration at L/D = 2.5



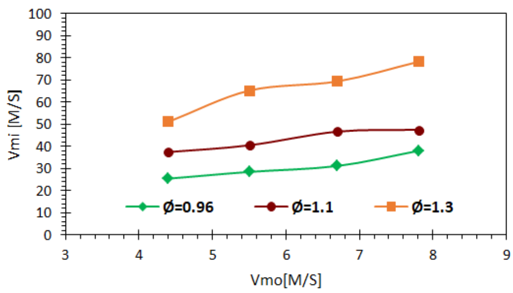
(a) L/D = 2.5 and NH_3 = 0



(b) L/D = 2.5 and NH_3 = 4 SLPM

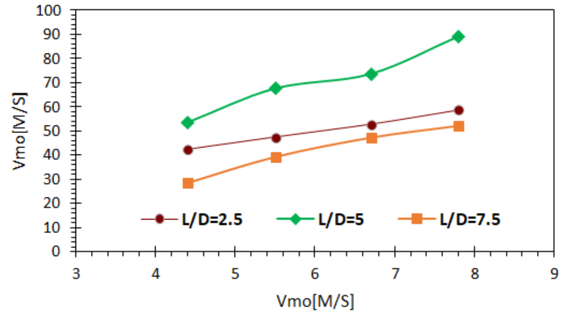


(c) L/D=5 and NH_3 = Zero

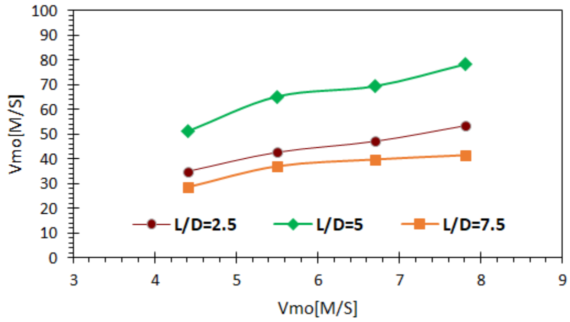


(d) L/D = 5 and NH_3 = 4 SLPM

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 = Zero, and (d) L/D = 5 and NH_3 = 4 SLPM.



(a) NH_3 = 0



(b) NH_3 = 4 SLPM

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

Figure 6 presents the influence of L/D and NH3 concentration on REj (jet blow-off Reynolds number) at blow-off, with V_{mo} = 5.5 m/s and Φ_{out} = 0.96. Notably, REj 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 REj at NH_3 = 4 SLPM and Φ_{out} = 0.96. Unlike the effect of the NH_3 concentration, the results show a gradual increase in REj at the blow-off point with increasing V_{mo} for all L/D values.

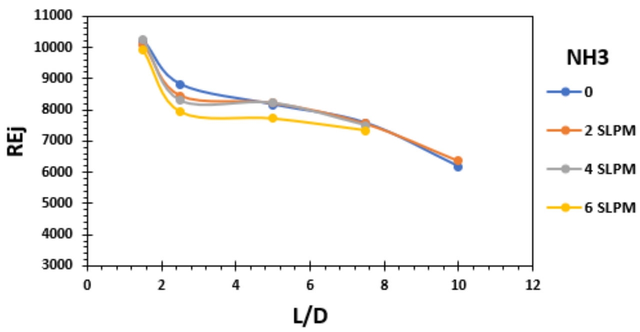


Fig. 6. Effect of L/D and NH_3 blend on jet Reynolds number at V_{mo} = 5.5 m/s and Φ_{out} = 0.96.

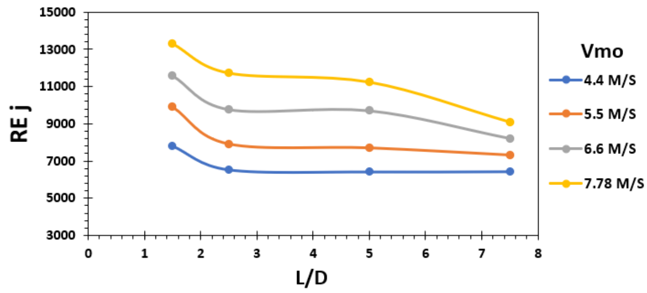


Fig. 7. Effect of L/D and outer flame mixture velocity on blow-off jet Reynolds number at NH_3 = 4 SLPM and Φ_{out} = 0.96.

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 steam 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.

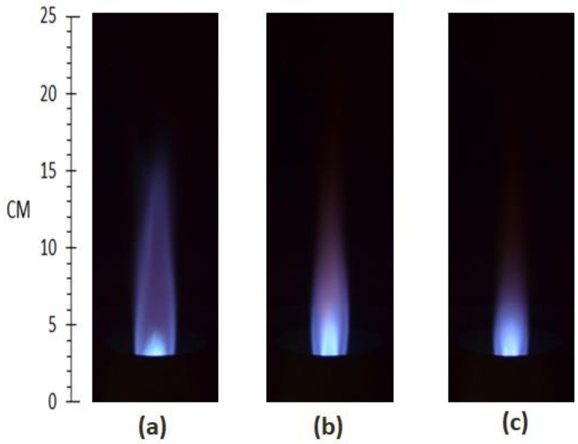


Fig. 8. Effect of inner stream mixture velocity at Φ_{out} = 0.96 and NH_3 = 0 SLPM, V_{mo}=5.5 m/s and L/D = 2.5, at (a) V_{mi}= 6.75 m/s, (b) V_{mi}= 13.5 m/s, and (c) V_{mi}= 20 m/s.

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 NH3 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 NH3 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 NH2 alpha and H2O 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.

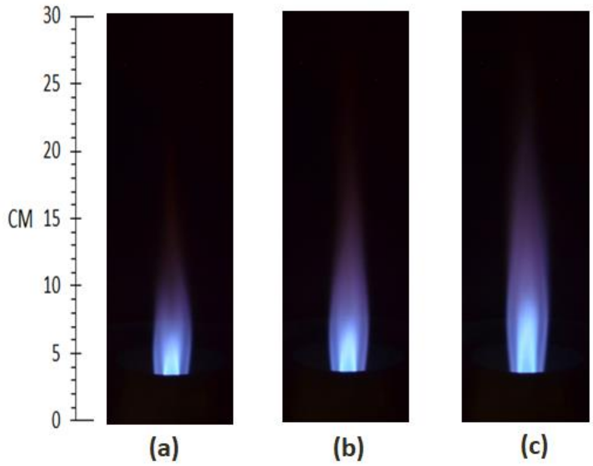


Fig. 9. Effect of outer stream mixture velocity at Φ_{out} = 0.96, NH_3 = 0 SLPM, V_{mi}=13.5 m/s and L/D = 2.5 at (a) V_{mo}= 4.4 m/s, (b) V_{mo}= 5.5 m/s, and (c) V_{mo}= 6.6 m/s.

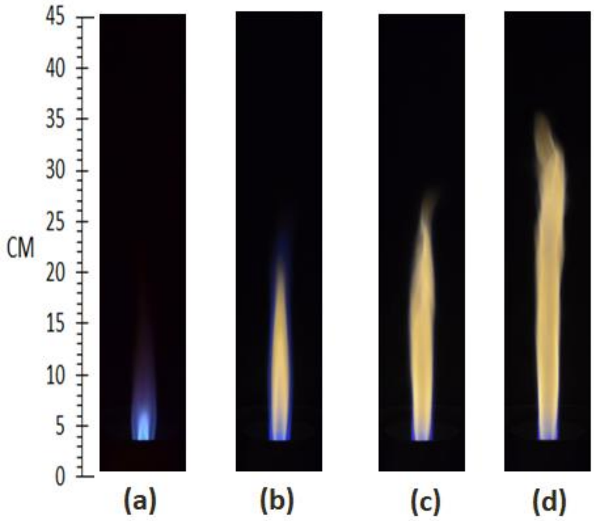


Fig.10. Effect NH_3 in the inner stream on flame appearance at Φ_{out} = 0.96 and V_{mo}=13.5 m/s , V_{mi}=13.5 m/s and L/D = 2.5 at (a) 0 SLPM, (b) 2 SLPM, (c) 4 SLPM, and (d) 6 SLPM.

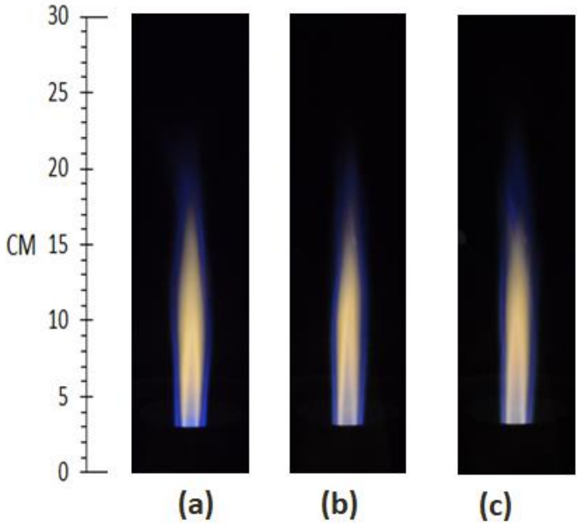


Fig. 11. Effect L/D on flame appearance at Φ_{out} = 0.96 and V_{mo}=13.5 m/s , V_{mi}=13.5 m/s and NH_3=2 SLPM at (a) L/D=2.5, (b) L/D=5, and (c) L/D=7.5.

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 Φout = 0.96.
- At L/D = 7.5 and 10, the flame was insensitive to the outer mixture velocity at Φout = 0.96.
- At L/D = 2.5 and 5 and ammonia blends NH3 = 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 NH3 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," *Towar. 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 NH3/CH4/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 Liquified 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 .