MIXING AND NOZZLE GEOMETRY EFFECTS ON FLAME STRUCTURE AND STABILITY

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Abstract

Flame stability and mean structure of partially premixed flames have been investigated under the effect of the level of partial premixing and nozzle cone angle. The stability curves and maps of the mean flame structure based on temperature and CO and O_2 concentrations measurements in some selected partially premixed flames in the thin reaction zones regime are presented and discussed. More radial and axial mean profiles of temperature and CO and O_2 concentrations are also presented for another set of flames at the same equivalence ratio and several nozzle cone angles.

The data show that partially premixed flames are more stable than non-premixed and premixed flames. An optimum degree of partial premixing was achieved in the present burner, beyond which the flames are less stable. This optimum level was achieved when the dimensionless mixing length normalized by the nozzle diameter is equal to 5. At this level of partial premixing the structure is likely to form three interacting reaction zones of lean, rich and diffusion with expected triple flame structure.

In partially premixed flames a stabilization core has been observed close to the conical nozzle that provides more heat source at the nozzle exit. This is responsible for stabilizing the flames at high Reynolds number.

The data also show that the cone angle has a great influence on the flame stability. Increasing the cone angle leads to more air entrainment, breaking the stabilization core and hence reduces the flame stability. The cone, in all cases, provides protected environment at the early stage of reaction near the nozzle exit where intense turbulence is expected. This leads to highly stable flames as compared to similar burners without cone.

Introduction

Burner stability and reduction of pollution levels are the main concerns of designers of industrial burners and many practical combustion systems. Flame stabilization is affected by several parameters such as mixing and boundary conditions at the nozzle exit. Partially premixed flames are likely to be more stable than premixed flames [1-3] and thus can be more attractive for practical applications. Several techniques have been used at the nozzle exit to stabilize the flames. Examples of those techniques are the swirl [4-7], pilot flame [8-11] and flame holder [12-13]. Recently Mansour [3] has designed and developed a concentric flow conical nozzle burner for highly stable flames. The stabilization mechanism in his burner is

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based on partially premixed combustion and a conical nozzle located at the nozzle exit to produce more uniform turbulence. Detailed measurements of temperature, using Rayleigh scattering, OH-radical, using laser induced fluorescence, and velocity field, using Planar Imaging Velocimetry (PIV) technique, are available for different flames in this burner at half cone angle of 26^o. The effect of the level of partially premixing of the jet and the cone angle on the flame structure and stability have not been yet investigated. Accordingly the aim of this work is to study the effect of both factors on the flame stability and mean flame structure in order to provide better understanding of flame stabilization mechanism. This should also lead to optimum operating conditions of the burner.

Partially premixed flames cover a wide range of applications: e.g. diesel engines, gas turbines, some industrial burners and lifted flames. Unlike non-premixed and premixed flames where modeling is based on one conserved scalar [14-17], partially premixed flames may require two conserved scalars for modeling [15,18,19]. Several research groups [20-25] have addressed the structure of partially premixed flames experimentally and theoretically. The main conclusion describes the structure as a multi-reaction zones structure that likely follows the triple flame theory. Therefore stability depends on this structure that survives better at high turbulence level, as compared to other modes of combustion, due to heat transfer from the triple point.

In the present study the stability limits under wide range of premixing level, nozzle cone angle, turbulence, and jet equivalence ratio are fully characterized. In addition, the mean flame structure of partially premixed flames at the same level of stability and partially premixed flames at the same jet conditions with variable nozzle cone angle are presented and discussed.

Burner Design

As explained above, this work is directed at the study of the effect of degree of mixing and nozzle cone angle on the stability and flame structure. The present burner design is similar to the concentric flow conical nozzle burner design developed by Mansour [3] with two modifications to replace the conical nozzle and to change the degree of partial premixing. Accordingly, the present modified design uses replaceable conical nozzles and variable mixing volume as explained below. The schematic drawing of the burner design is shown in Fig. 1. The burner consists of two concentric stainless-steel tubes with a conical nozzle at the exit of the outer tube. The air flows through the inner tube while fuel flows through the outer tube. Mixing starts at the exit of the inner tube and continues through a premixing distance "L" between the exit of the inner tube and the exit of the outer tube. The inner tube is allowed to move in order to vary the mixing length from 0 to 10 cm. For L = 0 the flames are called non-premixed. The degree of mixing increases by increasing the distance L. For short L the jet is called partially premixed while for quite long L the jet may reach fully premixed conditions.

Seven conical nozzles with half cone angles, _, of 10^o, 15^o, 20^o, 25^o, 30^o, 35^o and 40^o have been used. The cone height is kept constant for all conical nozzles and equals 53 mm. For each conical nozzle the mixing length and jet velocity and equivalence ratio have been varied to study stabilization. Based on the measured stability limits several flames have been selected for more detailed investigation.

Experimental and Measurements

The present measurements are directed at the study of the burner stability limit and then focused on some selected flames for mean temperature and species concentration maps and profiles. The stability was detected at the minimum equivalence ratio for a specific air flow rate at which the flame survives while blow-off occurs below this value.

The air and fuel flow rates were measured using Dwyer Instruments Rota-meters with accuracy of ± 4% of the measured value for both fuel and air flow meters. The temperature was measured using a 100 _m R-type (Platinum-13% Rhodium vs. Platinum) thermocouple. The species concentrations were measured using electrochemical gas sampling instrument (LAND LANCOM model 6500A). Two species were measured: Oxygen and carbon monoxide. The accuracy of O_2 measurements is within ± 0.2% while that for CO is ± 2% of the measured value. The gas analyzer CO range is from 0 % to 10 %. Sampling was achieved using a water-cooled stainless steel probe of 2 mm diameter. The probe was fixed on a three-dimensional traverse mechanism for mapping the flame structure with steps of 1 mm.

In addition flow visualization technique has been used to trace the entrained air into the burner cone, using smoke generator and digital high-shutter-speed CCD camera. A special, aromatic-oil-based material stick was used to generate a reddish-grey smoke, which was located outside the conical nozzle. Being of an oily basis, the generated smoke continued to burn with reddish luminous traces that follows the entrained air and photographed using the CCD camera. To increase the contrast between the reddish color of the smoke and the blue one of the flame, a special red-light incandescent lamp was used. Video films and still photographic images were obtained at several operating conditions. Those images were used for the analysis of entrained air in the present data.

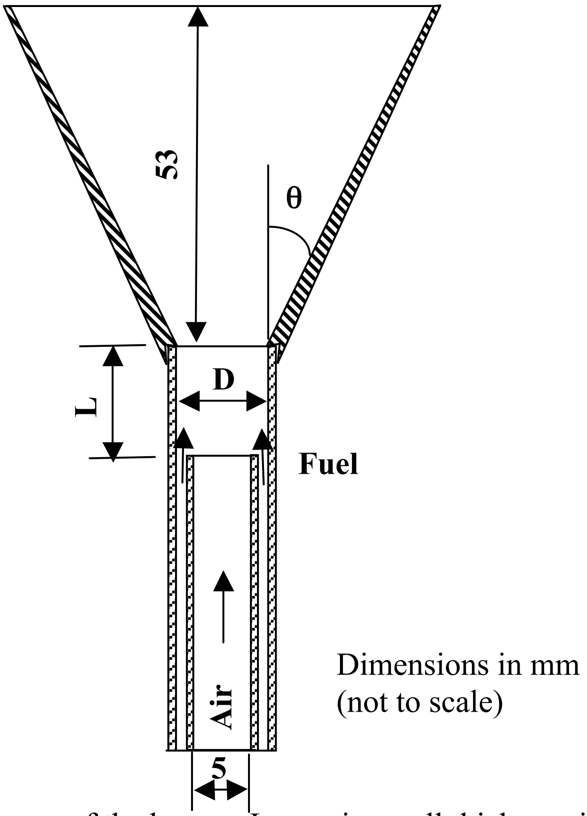


Figure 1 A schematic diagram of the burner. Inner pipe wall thickness is 0.5 mm.

Stability Limit and Selected Flames

The stability characteristic was investigated based on two factors: the degree of premixing and cone angle of the conical nozzle. The degree of partial premixing is controlled by varying the mixing length, L. In the present work L varied from 0 cm to 10 cm. The stability point, above which the flame is stable, was obtained by decreasing the fuel flow rate for a stable flame while the air flow rate was kept constant. The stability limit was recorded at the minimum fuel flow rate that corresponds to extinguished flame. Stability is defined here by an attached flame to the nozzle, while lifted flames are also shown in the present data. Five runs were conducted at air flow rates of 5.98 kg/hr, 6.9 kg/hr, 7.82 kg/hr, 8.73 kg/hr and 9.65 kg/hr. The data are shown in Fig. 2 using commercial LPG fuel (50 % Butane and 50 % propane by volume). The data are presented as the jet equivalence ratio versus the dimensionless L/D, where D is the nozzle diameter (= 8 mm) for all runs at various half cone angle.

In general the stability curves show that there is a point on each curve that shows better stability with minimum jet equivalence ratio. This point occurs almost at the same L/D (=5) in all runs and for all cone angles. Beyond this point the flame is less stable. At smaller L/D towards non-premixed conditions (L/D = 0) the flames are less than those at higher L/D (>5) where more mixing is expected. This indicates that at the minimum point on the curve (L/D = 5) the level of partial premixing is optimum for high stability. Combustion of non-homogeneous mixture is likely to form multi-reaction zones structure, lean rich and diffusion, due to the interaction between lean and rich pockets in the flame [15]. These reaction zones interact and likely to meet forming triple flame structure that survives at higher turbulence level. The triple flame structure has been recently observed in partially premixed lifted flames [23,24,26]. So, in the present flames at L/D = 5 the possibility of creating such structure is high and thus higher stability could be achieved. The multi reaction zones structure has also been observed in the same burner with half cone angle of 26^{o} using combined Rayleigh OH-LIF technique [3]. This supports our hypothesis.

The concave stability curves with steeper gradient at the non-premixed side prove that partially premixed flames survive better than premixed and non-premixed flames and the worst stability occurs at non-premixed conditions.

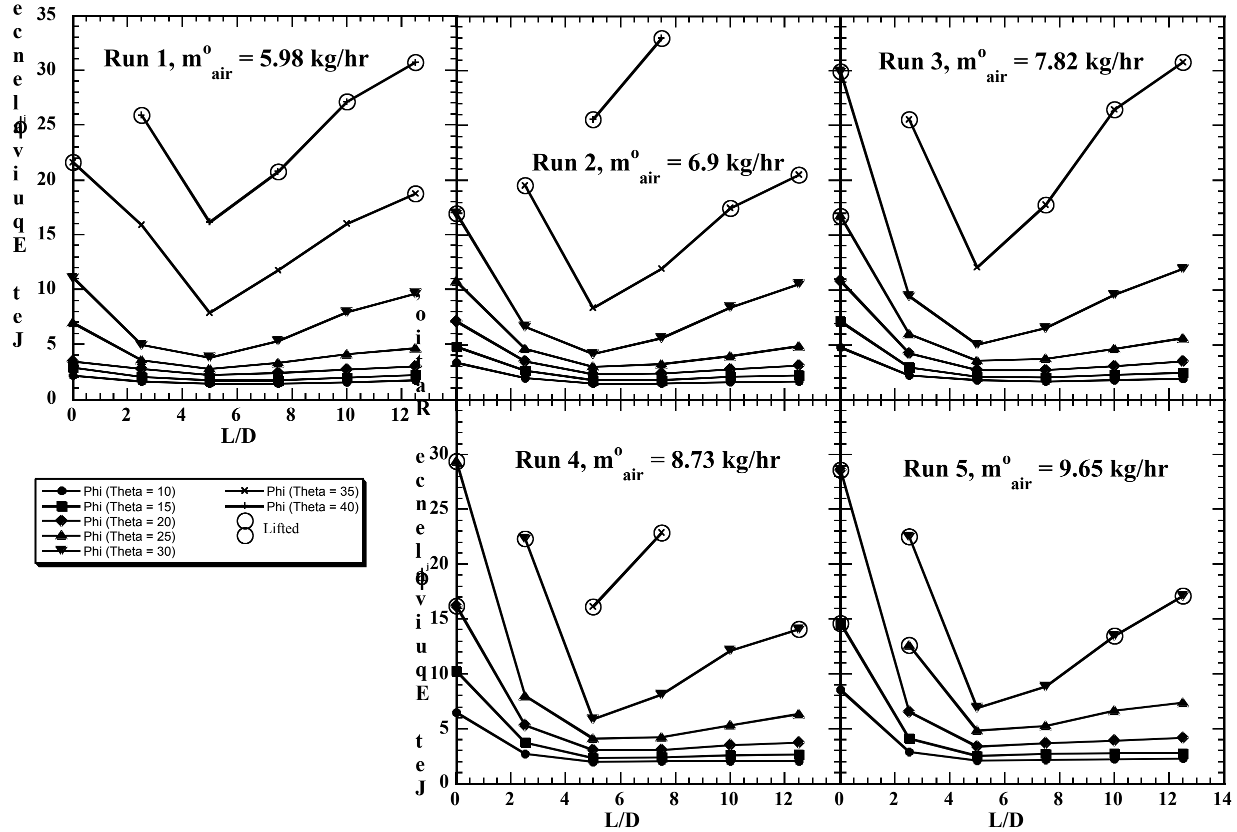


Figure 2 The stability curves of the burner for different nozzle cone half angle at five runs: from Run 1 to Run 5. The air flow rate varies from Run 1 to Run 5 as shown above. The open circles represent lifted flame conditions.

Further analysis of the stability limit can be obtained from the data at L/D = 5 where the relations between the jet velocity and jet equivalence ratio at blow-off for several nozzle cone angles are illustrated in Fig. 3.a. In addition, to study the effect of cone angle on stability at a constant turbulence level several curves are illustrated in Fig. 3.b for the same jet velocity.

Figure 3.a shows that the flame stability improves by reducing the nozzle cone angle. However, at smaller cone angle the flame touches the cone wall and this increases its temperature adding one more stabilization parameter. In some industrial burners it is not recommended to increase the nozzle head temperature. Figure 4 shows photographs of three selected flames in Run 3: PP20I, PP25I and PP30I for the present investigation at the same L/D = 5 with different cone angles of 20 °, 25° and 30 °, from left to right, respectively. The conditions of the selected flames are listed in Table 1 below. The heating rate of each flame, Q^o, is also listed in Table 1. The photographs show that the flame touches the wall at smaller cone angle. Figure 3.b shows that the relation between the jet equivalence ratio at blow-off and nozzle cone angle follows an almost parabolic equation for each jet velocity.

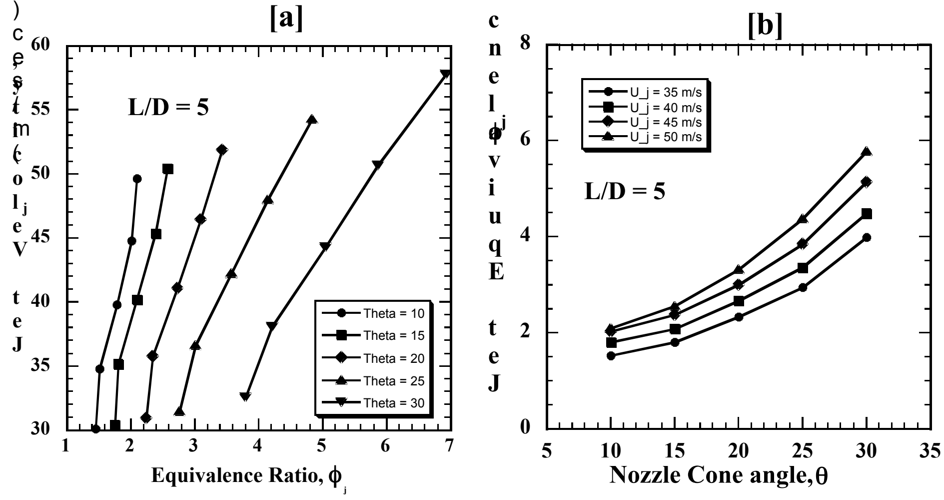
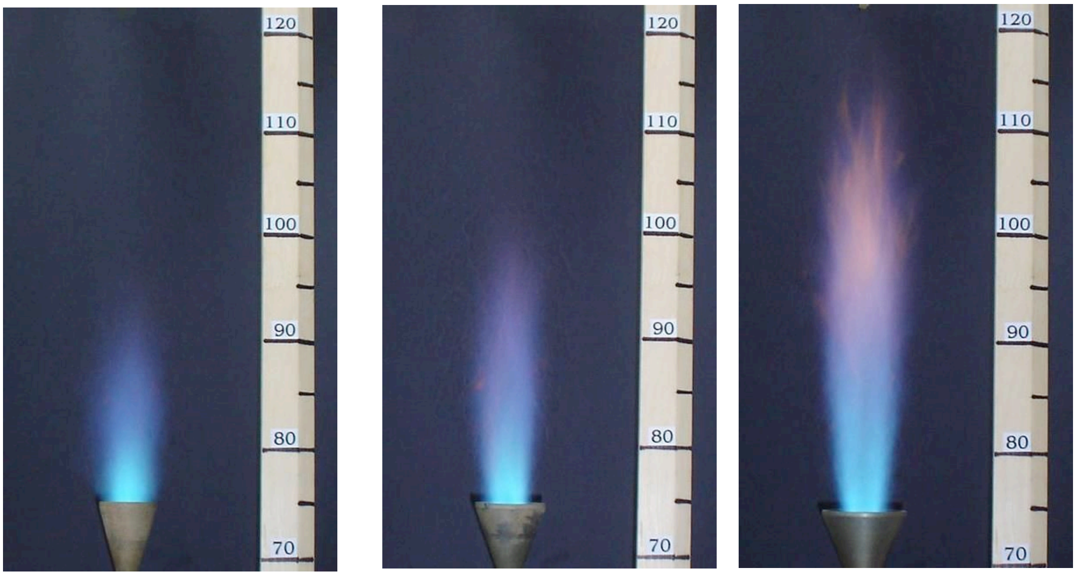


Figure 3 [a] The jet velocity is plotted versus the jet equivalence ratio at blow-off limit. [b] The jet equivalence ratio is plotted versus the nozzle cone angle for constant jet velocities.

U_j = 42.96 m/s
ϕ_j = 4.11 m/s

U_j = 44.68 m/s
ϕ_j = 5.37 m/s

U_j = 47.65 m/s
ϕ_j = 7.54 m/s



PP20I

PP25I

PP30I

Figure 4 Photographic images of three flames: PP20I, PP25I and PP30I, at the same L/D = 5 of run 3 with different cone angles of 20 °, 25° and 30 °, from left to right, respectively

Table 1 Conditions of five selected flames

Flame	U_j m/s	ϕ_j	θ	RD	Q^o kW
PP20I	42.96	4.11	20	0.50	28.8
PP25I	44.68	5.37	25	0.50	37.7
PP30I	47.65	7.54	30	0.50	53.1
PP25II	47.65	7.54	25	1.12	53.1
PP20II	47.65	7.54	20	1.77	53.1

Mean Flame Structure

The measurements were focused on the five selected partially premixed flames listed in Table 1. The five flames were selected to study flames at the same stability level (the first three flames PP20I, PP25I and PP30I), and to study the effect of nozzle cone angle with other parameters kept constant (flames PP30I, PP25II and PP20II).

The flames shown in Fig. 4 are those selected to have the same relative deviation from extinction limit based on the equivalence ratio data illustrated in Fig. 2. The relative deviation is defined as RD = $(\phi_j - \phi_E) / \phi_E$, where ϕ_j is the jet equivalence ratio and ϕ_E is the extinction value at L/D = 5. The relative deviation for the above flames was selected to be 50 %. All flames are from Run 3 where the air flow rate is m^o_{air} = 7.82 kg/hr. The second set is formed from two additional flames PP20II and PP25II with flame PP30I from the first set. All flames in this set have the same equivalence ratio of 7.54 and jet velocity of 47.65 m/s from Run 3.

The measurements in the first set cover maps of temperature and species concentrations, while the measurements in the second set cover axial profiles along the centerline and radial profiles at the conical nozzle rim. The maps were obtained with small steps of 2 mm along the radial and axial directions within the conical nozzle and radial steps of 2-4 mm above the nozzle. The axial steps above the conical nozzle vary between 1 cm near the nozzle and 2 cm further downstream. This provides quite fine resolved maps of the mean flame structure.

The flame structure of the three partially premixed flames at the same relative deviation from the blow-off limit in the first set is illustrated in Figs. 5-6. All flames are selected at the optimum L/D value of 5. Based on some dimensional analysis of length and time scales we may classify the present to be in the thin reaction zones regimes of Peters [15].

The main feature of the three flames is the existence of intense reaction core, with high CO and low O_2 concentrations and high temperature, starts at an early position within or near the conical nozzle tip. The previous measurements of OH and Rayleigh in partially premixed flames in the same burner at $\theta = 26^o$ concluded that the flame is stabilized by the existence of stabilization core at the nozzle exit at the early stage of the flame. The present data, shown in Figs. 5,6 supports this conclusion and adds more that the stabilization core is also affected by the nozzle cone angle where a narrower zone can be observed by increasing the cone angle. In addition, air entrainment increases by increasing the nozzle cone angle and this leads to necking of the stabilization core and expected to cause a break at higher cone angle. This may thus lead to flame blow-off due to expected extinction of the stabilization core. In bluff body flames with flat plate at the nozzle, i.e. corresponding to an angle θ of 90^o, two recirculation zones are observed [13] due to the necking effect described above. The arrows illustrated in Fig. 5 are obtained at almost the same scale from the smoke tracing images showing the entrained air in flames PP25I and PP30I at larger cone angle. One image with tracing smoke is shown in Fig. 6.b for flame PP25I. More images are collected showing similar trends but with different levels of air entrainment depending on nozzle cone angle. At $\theta = 20^o$ no smoke tracer could be detected which may indicate low or no air entrainment and thus the flame is not affected by surrounding air at the early stage (stabilization core). The maps of CO and O_2 concentrations and temperature illustrated in Figs. 5 and 6 show more compact undisturbed stabilization zone.

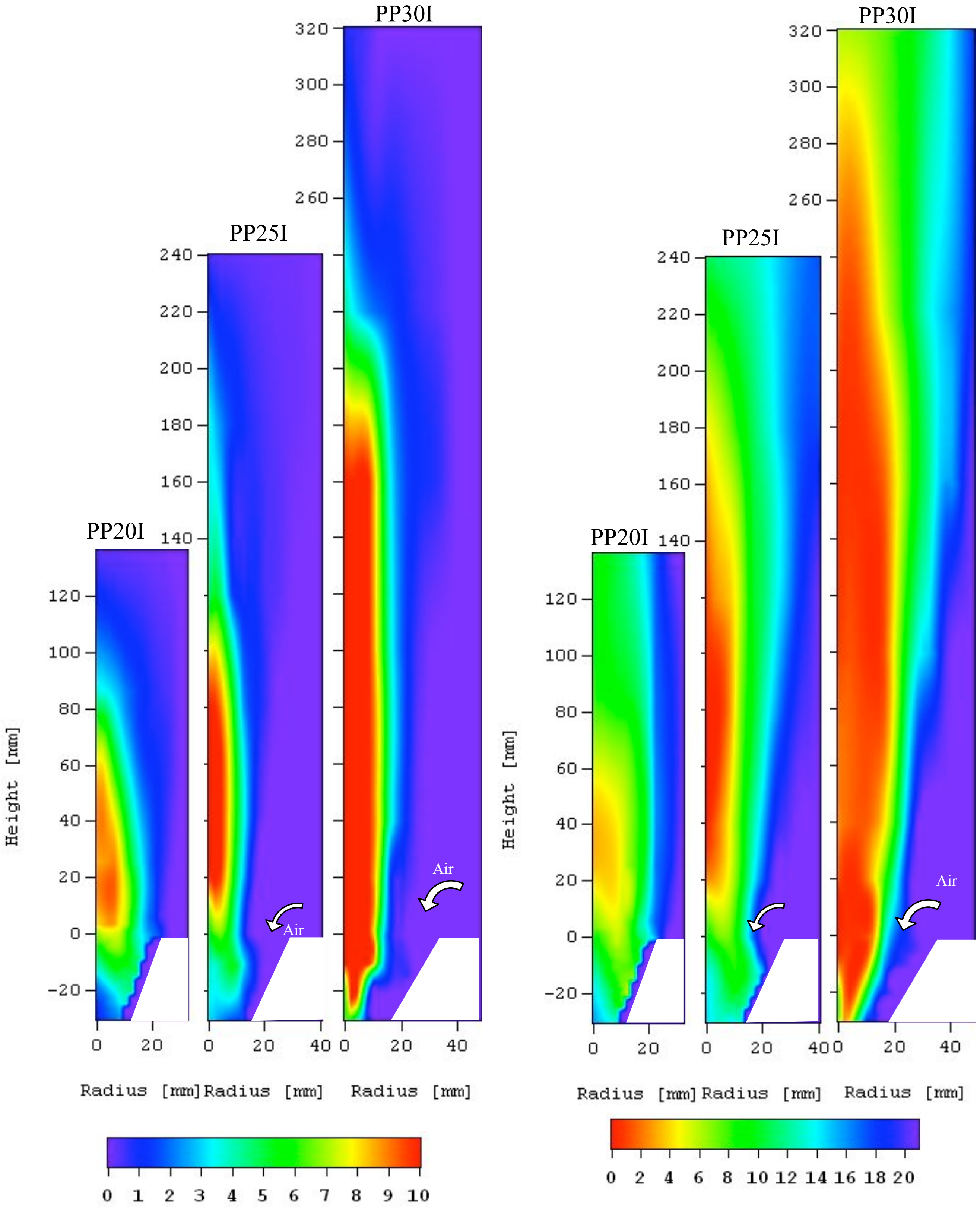


Figure 5 [a] CO and [b] O_2 concentrations maps in flames PP20I, PP25I and PP30I from left to right, respectively. The red CO concentration refers to level ≥ 10 % CO.

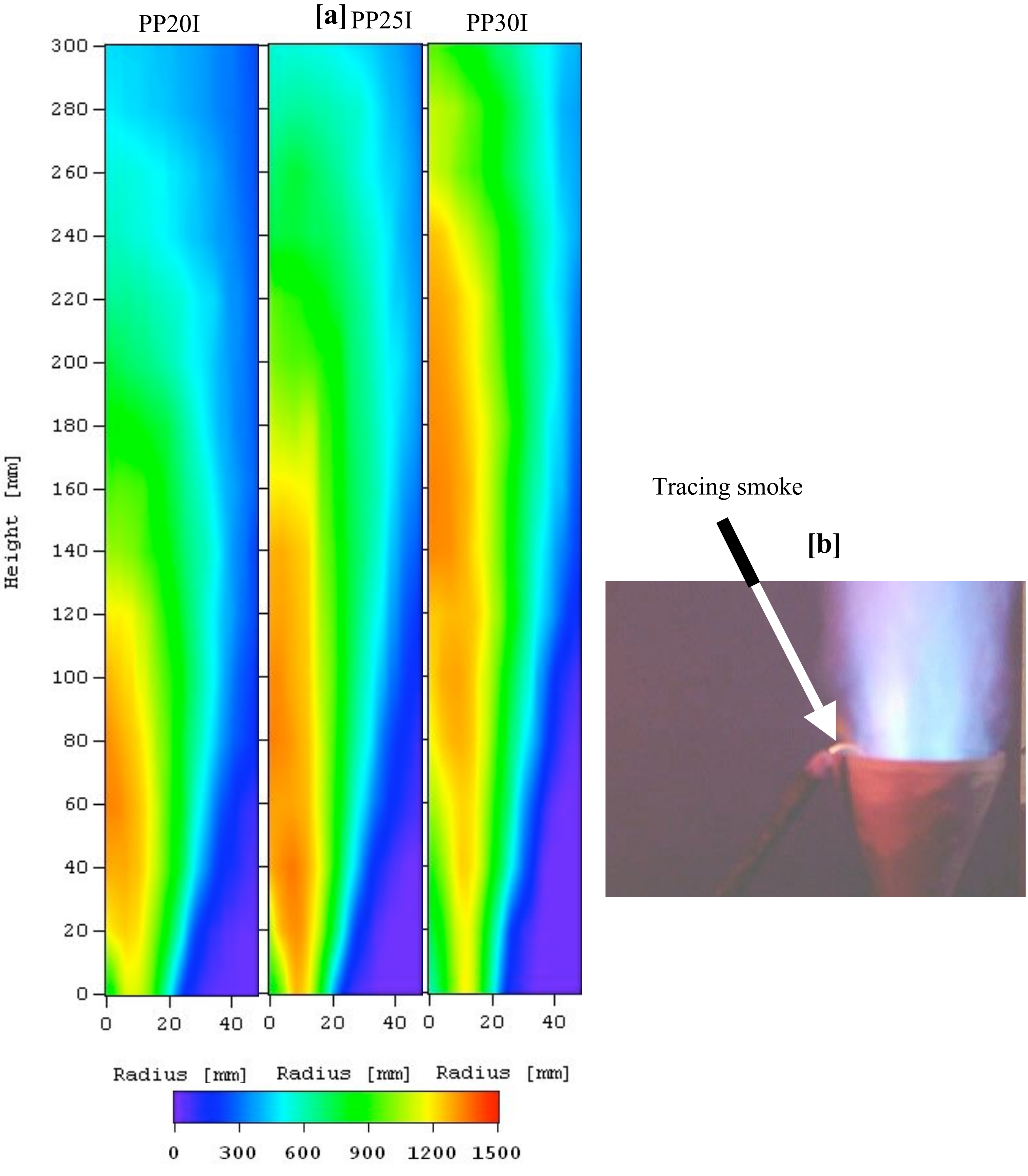


Figure 6 [a] Temperature maps in flames PP20I, PP25I and PP30I from left to right, respectively. [b] Smoke tracing image for air entrainment detection in flame PP25I.

The second set of flames (PP20II, PP25II and PP30I) is focused on studying the effect of nozzle angle at fixed jet velocity of 47.65 m/s and equivalence ratio of 7.54, as explained above. The data are illustrated in Fig. 7 as axial and radial profiles of temperature and O_2 and CO concentrations. Three conical nozzles with half cone angles of 20^o, 25^o and 30^o were used. The data show that increasing the cone angle leads to longer and narrower stabilization core where the CO is high, O_2 is low and temperature is high. This can be, as explained above, due to the effect of air entrainment into the nozzle squeezing the stabilization core and thus elongate it.

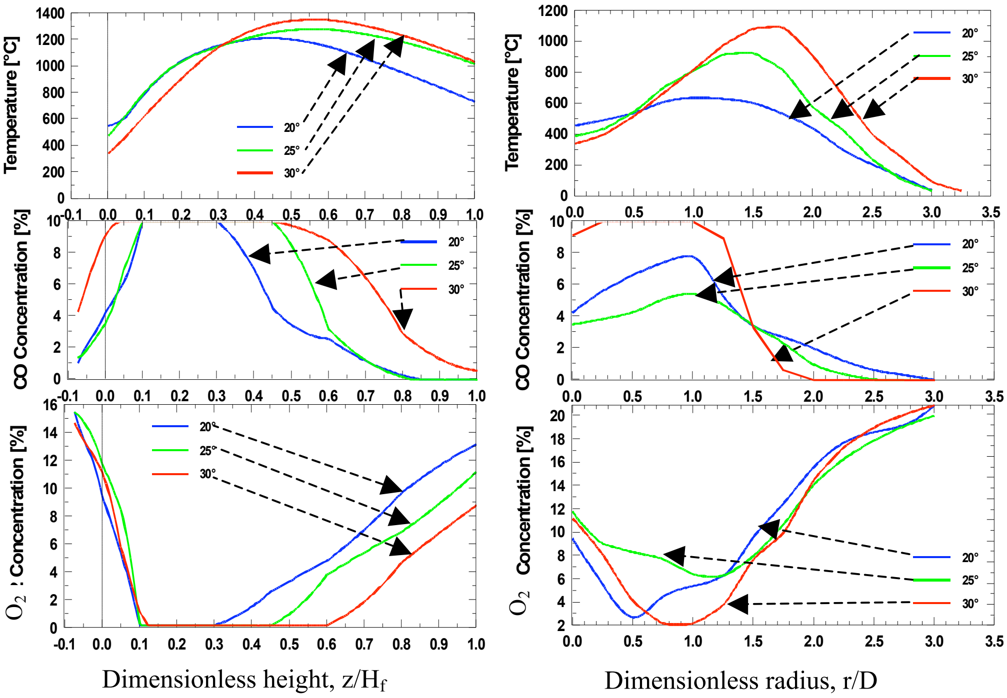


Figure 7 Temperature, Oxygen and CO concentrations axial [a] and radial [b] profiles of flame PP20II, PP25II and PP30I.

Conclusions

The effects of partial premixing level and nozzle cone angle at the nozzle exit of a concentric flow conical nozzle burner on the burner stability and flame structure have been investigated and discussed in the present work. Seven conical nozzles and variable mixing levels have been used with LPG fuel. In addition the mean structure based on maps of temperature, and CO and O_2 concentrations of five flames are presented and discussed.

The data show that partially premixed flames are more stable than premixed and non-premixed flames. An optimum level of partial premixing has been obtained for all conical nozzles at a mixing length of five times the nozzle diameter. The data show also that the stability can be improved by decreasing the nozzle cone angle. The stabilization mechanism of this burner attributes flame stability to the existence of a stabilization core at the early region of the flame near the nozzle exit. This core shows high rate of reaction with the low oxygen concentration, high CO concentration and high temperature.

Air entrainment increases by increasing the nozzle cone angle and this affects the structure of the stabilization core that leads to elongated and narrow structure. This can thus be disturbed easily by the air entrainment.

More detailed flame structure measurements are required based on quantitative Rayleigh, Raman and LIF techniques in order to provide more quantitative data bank for model verification and development.

References

1. Mansour, M. S., "Studies of Turbulent Hydrocarbon Flames in a Reverse Flow Reactor. Ph.D. Diss.," Sydney University, Sydney, Australia, 1990.
2. Mansour, M. S., Bilger, R. W., and Dibble, R. W., "Raman/Rayleigh and mie-scattering Measurements in a Reverse Flow Reactor Close to Extinction," Proc. Combust. Inst., volume 22, pp. 711 – 719 (1989).
3. Mansour, M. S., "A Concentric Flow Conical Nozzle Burner for Highly Stabilized Partially Premixed Flames," Combust. Sci. and Tech., Vol. 152, pp. 115 – 145 (2000).
4. Masri, A. R. and Al-Abdeli, Y. M., "Stability Characteristics and Flow Fields of Turbulent Non-Premixed Swirling Flames," Combustion Theory and Modeling, vol. 7, no. 4, pp. 731 – 766 (2003).
5. Schefer, R. W., Wicksall, D. M., and Agrawal, A. K., "Combustion of Hydrogen-Enriched Methane in a Lean Premixed Swirl-Stabilized Burner," the Proceedings of the Combustion Institute, Volume 29, pp. 843 – 851 (2002).
6. Ji, J., and Gore, J. P., "Flow Structure in Lean Premixed Swirling Combustion," the Proceedings of the Combustion Institute, Volume 29, pp. 861 – 867 (2002).
7. Kalt, P. A. M., Al-Abdeli, Y. M., Masri, A. R., and Barlow, R. S., "Swirling Turbulent Non-Premixed Flames of Methane: Flow Field and Compositional Structure," the Proceedings of the Combustion Institute, Volume 29, pp. 1913 – 1919 (2002).
8. Starner, S. H., and Bilger, R. W., "Characteristics of a Piloted Diffusion Flame Designed for Study of Combustion Turbulence Interactions," Combustion and Flame, Vol. 61, pp. 29 – 38 (1985).
9. Masri, A. R., Dibble, R. W., and Barlow, R. S., "The Structure of Turbulent Non-Premixed Flames Revealed by Raman-Rayleigh-LIF Measurements," Prog. Energy Combust. Sci., Vol. 22, pp. 307 – 362 (1996).
10. Chen, Y-C., Peters, N., Schneemann, G. A., Wruck, N., Renz, U. and Mansour, M. S., "The Detailed Flame Structure of Highly Stretched Turbulent Premixed Methane-Air Flames," Combust. Flame, Vol. 107, pp. 223 – 244 (1996).
11. Balow, R. S. and Frank, J. H., "Effects of Turbulence on Species Mass Fractions in Methane/Air Jet Flames," Twenty-Seventh Symposium International on Combustion, The Combustion Institute, Pittsburgh, 1998.
12. Esquiva–Dano, I., Nguyen, H. T., and Escudie, D., "Influence of a Bluff-Body's Shape on the Stabilization Regime of Non-Premixed Flames," Combustion and Flame, vol. 127, pp. 2167 – 2180 (2001).
13. Masri, A. R., Dally, B. B., Barlow, R. S., and Carter, C. D., Twenty-fifth Symposium (international) on Combustion, The Combustion Institute, Pittsburgh, p. 1301 (1994).
14. Bilger, R. W., (1980) "Turbulent Flows with non-premixed reactants", in P. A. Libby and F. A. Williams, editors, Turbulent Reacting Flows, pp: 65-113, Springer-Verlag, Berlin.
15. Peters, N., Turbulent Combustion, Cambridge Monographs on Mechanics,

Cambridge University Press. Cambridge, UK, 2000.

16. Bray, K. N. C., and Moss, J. B. (1977), “A Unified Statistical Model of the Premixed Turbulent Flame”, Act Astronautica 4, 291-319.
17. Abou-Ellail, M. M. M., Beshay, K. R. and Mansour, M. S., (2000), “A Flamelet Model for Premixed Methane-Air Flames.”, Combustion Science and Technology, Vol. 153, 223-245.
18. Müller, C .M., Breitbach, M., and Peters, N. (1994), “Partially Premixed Turbulent Flame Propagation in Jet Flames”, Twenty-Fifth Symposium (Int.) on Combustion, The Combustion Institute, Pittsburgh, pp. 1099-1106.
19. Mansour, M. S., Chen, Y-C. and Peters, N., (1999b), “Highly Strained Rich Methane Flames Stabilized by Hot Combustion Products.” Combustion and Flame, 116:136-153.
20. Law, C. K., Zhu, D. L., Li, T. X., Chung, S. H., and Kim, J. S., (1989) “On the Structure and Extinction Dynamics of Partially Premixed Flames: Theory and Experiment”, Combust. Sci. and Technol. 64:199-232.
21. Lee, B. J., and Chung, S. H. (1997) “Stabilization of Lifted Tribrachial Flames in a Laminar Non-Premixed Jet” Combust. Flame, 109:163-172.
22. Mansour, M. S., Bilger, R. W. and Dibble, R. W. (1993), “Turbulent Partially Premixed Flames of Propane Near Extinction in a Reverse Flow Reactor.” Eighth (Int.) Conference on Mechanical Power Engineering, Alexandria, Vol. 1, pp. 149-160.
23. Mansour, M. S., “Stability Characteristics of Lifted Turbulent Partially Premixed Jet Flames”, Combustion and Flames, 133:263-274, (2003).
24. Mansour, M. S., “The Flow Field Structure at the Base of Lifted Turbulent Partially Premixed Jet Flames”, Experimental Thermal and Fluid Sciences, Vol 28/7 pp 771-779 (2004)
25. Mansour, M. S., “A Study of Turbulent Partially Premixed Flames Based on Simultaneous Imaging of Velocity Field and OH Radical,” Combust. Sci. and Tech., volume 174, pp. 47 – 78 (2002).
26. Joedicke, A., Mansour, M. and Peters, N. “The Stabilization Mechanism and Structure of Turbulent Hydrocarbon Lifted Flames”, Proc. of the Combustion Institute, 30, pp. 901-909 (2005)