

Structures and Stabilization of Low Calorific Value Gas Turbulent Partially Premixed Flames in a Conical Burner

B.B. Yan^{1,2}, B. Li³, E. Baudoin¹, C.Y. Liu^{1,2}, Z.W. Sun³, Z.S. Li³, X.S. Bai^{*1},
M. Aldén³, G. Chen², M. Mansour⁴

¹Division of Fluid Mechanics, Lund University, 221 00 Lund, Sweden

²Faculty of Environmental Science and Engineering, Tianjin University, 30072, China

³Division of Combustion Physics, Lund University, 221 00 Lund, Sweden

⁴National Institute of Laser Enhanced Sciences, Cairo University, Egypt

Abstract

Experiments were carried out on partially premixed turbulent flames stabilized in a conical burner. The investigated gaseous fuels are a mixture of CH₄, CO, CO₂, H₂ and N₂, simulating typical products from gasification of biomass. The fuel and air were partially mixed in a co-centric tube. Flame stabilization behavior with and without the cone was investigated and significantly different stabilization characteristics were observed. Planar Laser induced fluorescence (LIF) of a tracer species, acetone, and OH radicals was carried out to characterize the flame structures. The data show that the flames with the cone are more stable than those without the cone. Without the cone the burner is a typical jet; the critical jet velocities for blowoff and liftoff of biomass derived gases are found to be much higher than that for methane/nitrogen mixture with the same heating values. With the cone, it was shown the stability of flames is not sensitive to the compositions of the fuels. From the PLIF images it was shown that in the conical burner, the flame is stabilized by the cone at nearly the same position for different fuels. The flame is believed to be controlled by the vorticity structure inside cone which depends on the cone angle and flow speed, and less sensitive to the fuel compositions.

Introduction

Biomass derived fuels are important ingredients for heat and power production owing to the renewable nature and sustainable availability of this energy source. There are considerable interests from industry to utilize biomass gasification and pyrolysis gases in gas turbine applications. This type of gas is often called low calorific value (LCV) gas and is typically composed of H₂, CO, CH₄ and a small amount of higher-order hydrocarbons [1]. Also it contains N₂, CO₂, and these inert gases lead to lower heating value of the mixture gas than pure H₂ or natural gas. Many previous investigations have been carried out to study the combustion characteristics of LCV gas, for example the laminar burning velocity, NO_x formation, flame stability and flame structure.

From a practical point of view, it is important to know the stability behavior of LCV gas flames in different type of burners such as jet flame/Bunsen burners. The stability of lifted jet flame with model LCV fuel has been studied recently [2], where the fuels utilized are CH₄ and C₂H₄ diluted by N₂. The relationships between liftoff velocity and dilution, liftoff height behavior as well as reattachment condition were described. The stabilization mechanism of lifted jet flame of CH₄ diluted with N₂ was investigated in [3], in which it was reported that stationary lifted flames were only observed in the near field of coflow jets. The stability behavior of a LCV gas in a jet flame burner is carried out in this study.

Recently, experimental and numerical studies of a conical burner were carried out for different fuels [4,5]. It was shown that the cone enhances significantly the stability of flames. In this study the stability behavior in the conical burner for LCV gases is examined. A model LCV gas corresponding to the biomass gasification gases co-firing with natural gas with a low heating value of 23 MJ/Nm³ are studied. Another gas is a mixture of methane and nitrogen having the same LHV. It was shown that in the conical burner the flame stability is insensitive to the fuels; however, when the cone is removed, i.e. with jet flame burner, the flame liftoff and blow-off conditions are very sensitive to the fuel compositions. To investigate the mechanisms of flame stabilization in the conical burner, planar laser induced fluorescence (PLIF) technique is used to detect the OH radicals and a fuel tracer species (acetone) inside the cone.

Experimental setup

The burner consists of a vertical tube surrounded by an outer tube. The inner and outer tubes are 6.8mm and 9.7mm inside diameter and with lip-thickness of 1.2mm and 2.3mm, respectively (see Fig.1). During all experiments, these two tubes keep concentric with different mixing distance *L*, which is the distance between the inner tube exit and outer tube exit. Changing this mixing distance can alter the degree of partial premixing. The fuel flow discharges through the outer tube while the air flow through inner one. A quartz-glass conical nozzle, which makes optical access

*Corresponding author: Xue-Song.Bai@energy.lth.se
Proceedings of the European Combustion Meeting 2009

and observation possible, with half cone angle of 26° is installed at the outer tube exit and used to stabilize the flames. Detailed information about the burner can be seen elsewhere [4, 5].

The model low calorific value gases considered in this work are a mixture of typical biomass derived gases (BDG) and methane. Mixing of these gases is necessary to improve the heating value from about 5 MJ/Nm^3 to above 23 MJ/Nm^3 . Their compositions and low heating values of the model gases are shown in Table 1. The compositions of BDGs are taken from reference [6], which are typical compositions of gases produced in a gasification demonstration plant in Sweden. The LCV gas 1 is mixed by 60% CH_4 and 40% BDG by volume, while MN consists of only CH_4 and N_2 by keeping the same heating value with LCV gas 1. To characterize the

fuel distribution, a tracer of fuel, acetone was introduced to the fuel stream in the co-centric pipe. The gaseous acetone was introduced into the burner by bubbling fuels through liquid acetone, which is about 1% by volume in the MN, and LCV gas 1.

These fuels are fed by bottle gas produced by AGA Gas AB Company. The uncertainty of each gas composition is within $\pm 2.0\%$. The mass flow rates of fuels and air are monitored using Bronkhorst thermal mass meters and controllers installed in their respective feed lines. Before the experiments they were all calibrated. The calibrating conditions are 0.00°C and 101.325 kPa . The flow meters have accuracy $\pm 0.9\%$ of the measured values.

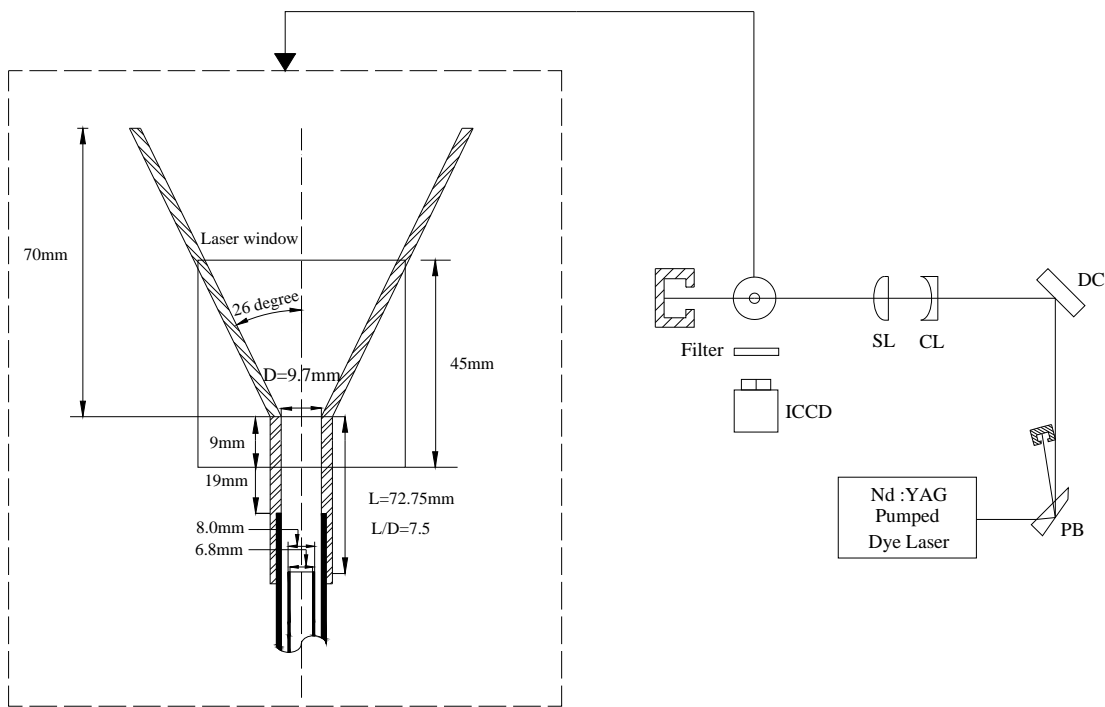


Figure.1 Burner details and experimental setup for simultaneous OH/acetone PLIF measurement: PB, Pellin-Broca prism; DC, dichroic mirror; SL, spherical lens; CL, cylindrical lens.

Table 1. The compositions and heating values of fuels

Vol	CO	H ₂	CH ₄	CO ₂	N ₂	LHV(MJ/Nm ³)
LCV gas 1	7.6	4.8	62.32	5.28	20	23.92
MN	0	0	66.44	0	33.56	23.92

The main setup is exactly the same as for OH PLIF measurement however acetone was excited and measured simultaneously with OH LIF by the same laser and camera system. And for this purpose, an image-doubling device, stereoscope, was mounted on the ICCD objective. Two different sets of optical glass filters (Scott, 3 mm) were employed in front of each entrance of the stereoscope, respectively, to filter the

laser scatterings and unwanted fluorescence. A long-pass WG305 and a short-pass UG11 worked together to collect the OH fluorescence signal at around 308 nm, while a WG345 filter was chosen to collect the broadband acetone fluorescence emissions from 350 to 500 nm.

Flame stabilization

Fig.2 shows six curves that denotes the stability behavior of the flames with and without the cone, and with different fuels. All the cases were at the same mixing condition of $L/D=7.5$. First, one can notice that without the cone (jet burner) the flames can be in different states depending on the overall equivalence ratio and jet velocity. The flames can be attached to the burner rim, regime A, or lifted from the burner rim, regime C, or blowout (flame total extinction), regime above C. The attached flame (regime A) occurs at low jet speed condition. For fuel MN the jet Reynolds number is typically below 2800; and it is fairly independent of the overall equivalence ratio. Blowout happens at much higher jet velocity, and it is depending on the overall equivalence ratio almost linearly. There is a regime B where the flames can be in attached mode or lifted mode, depending on the initial state of the flame. If the flame is initially attached to the burner rim, and increasing the jet velocity gradually, then the flames in regime B is in the attached mode; on the other hand, if the initial flame is in the regime C, i.e. lifted mode, then by gradually decreasing the jet velocity the flame in regime B is kept to be lifted until the jet Reynolds number is decreased to be lower than the reattached limit. The flames are then attached to the burner rim in regime A. The phenomenon that the modes of the flames depend on the initial state and the path at which the condition is changed is known as hysteresis [7, 8].

This phenomenon may be attributed to the significant difference in the distance between the nozzle exit and point of laminar to turbulent transition [9].

For the LCV gas 1 flames, the flames are in two modes only, attached to the burner rim, or blow-off. By blow-off it is meant that the flame is totally quenched starting from the attached mode and gradually increasing the jet velocity, whereas blowout refers to quenched flame starting from lifted mode and gradually increasing the jet velocity [10]. The fact that the stabilization behavior of the MN and LCV gas 1 flames shows that for jet flames the flame stability is very sensitive to the fuels. With LCV gas 1 where hydrogen is present, the flame is more stable and tends to be attached to the burner rim [11]. Similar observations have been reported in [3, 7, 8].

Finally, one can observe that with the cone, the stability characteristics of the flames with MN and LCV gas 1 are similar: the flame is stabilized inside the cone for large range of equivalence ratio and jet Reynolds number, and the blow-off limit is nearly linearly dependent of the overall equivalence ratio. For overall equivalence ratio higher than 5, it is very difficult to observe the blow-off mode with the current rig. The flames are more stable than the corresponding ones without the cone. The LCV gas 1 (biomass derived fuel containing hydrogen) flames is somewhat more stable than that of MN fuel. The difference is however much smaller than those without the cone.

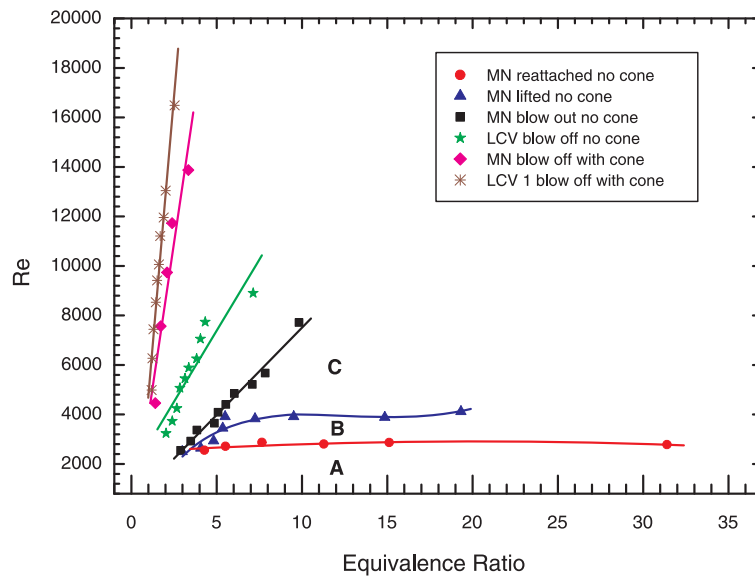


Figure 2. The stability curves of LCV gas 1 and MN with or without cone at $L/D=7.5$

Liftoff height and flame structures

Table 2 lists the four test cases studied using PLIF of acetone and OH. LCV gas 1 was used in these test cases. Two velocity conditions from the exit of the mixing tube (10 and 15 m/s) are considered; and the two equivalence ratios, 2.6 and 4 are considered. All these test flames have a mixing length L/D of 7.5.

From 1000 single-shot we obtain ensemble of simultaneous distribution of acetone and OH as illustrated in Fig. 3. Comparing Fig.3a and 3c, the lowest locations of OH distribution are almost at the same height. These locations correspond to the leading flame edges where the flame is stabilized. This result indicates that the flame stabilization of the conical flames is not sensitive to the exit flow Reynolds number.

When equivalence ratio is increased from 2.6 to 4, for L1F1 and L1F2 flames with a exit velocity equals to 10 m/s, it is shown that the richer flame stays slightly lower than the leaner flame (see Fig. 3a and 3b). For the exit velocity of 15 m/s flames, the richer flame and leaner flames have almost the same stabilization height (see Fig. 3c and 3d). In general, one can concludes that for the current four test flames the leading flame edge is rather insensitive to the exit flow velocity and the equivalence ratios. This is contrary to [7, 8, 11], where

it was reported that the liftoff height of jet flame increases with increase in the jet exit velocity.

Fig. 4 shows snap-shots of OH signals for the four test flames discussed above for LCV GAS 1 (see Table 1). As seen, the instantaneous OH images are fairly smooth. The thicknesses of the high speed flames (Fig.4c, 4d) are thinner than the low speed flames (Fig.4a and 4b). Based on dimensional analysis of length and time scales we could deduce the present four flames are all located in the thin reaction zone regimes.

Table 2. Flame cases studied using PLIF

Flame No	Q_F (l/min)	Q_A (l/min)	ϕ	Velocity (m/s)	Re	LHV (MJ/Nm ³)	Acetone concentration
L1F1	13	31.3	2.6	10	7158	23.92	1%
L1F2	17.3	27.0	4	10	7108	23.92	1%
L1F3	19.6	46.9	2.6	15	10745	23.92	1%
L1F4	26.0	40.5	4	15	10665	23.92	1%

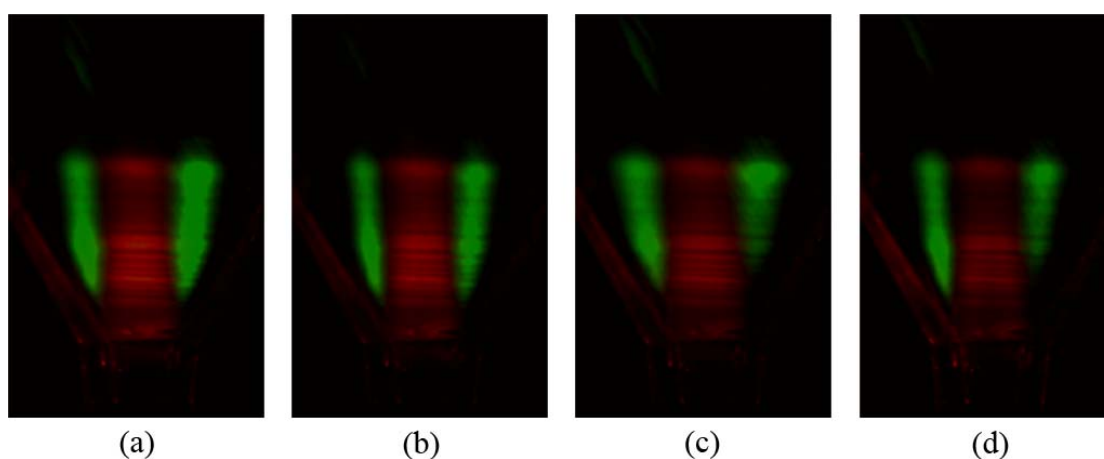


Figure 3. Ensemble averaged simultaneous PLIF signals of acetone (red) and OH (green) for various conditions: (a) LCV gas 1 Flame 1 (L1F1); (b) LCV gas 1 Flame 2 (L1F2); (c) LCV gas 1 Flame 3 (L1F3); (d) LCV gas 1 Flame 4 (L1F4).

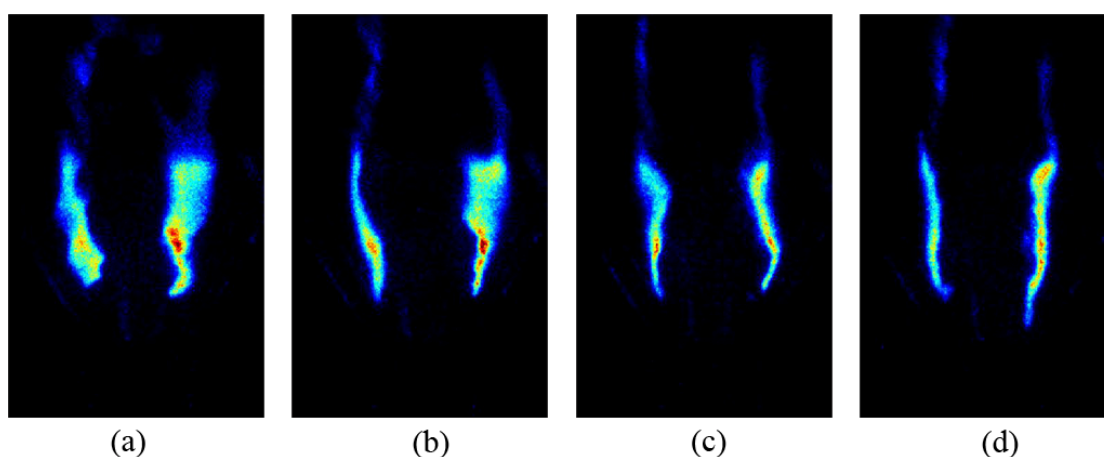


Figure 4. Snap-shots of PLIF signals of OH for various conditions: (a) & (b) LCV gas 1 Flame 1 (L1F1); (c) & (d) LCV gas 1 Flame 2 (L1F2).

Conclusions

The flame stability characteristics and flame structure of partially premixed turbulent flames in a conical burner has been studied using simultaneous PLIF of acetone and OH. The investigated gaseous fuels are a mixture of CH₄, CO, CO₂, H₂ and N₂, with a low heating value of 23 MJ/Nm³ simulating typical products derived from biomass gasification. Four flames at different equivalence ratio and Reynolds number have been investigated.

It was shown that the conical flame is much more stable than the corresponding flames without the cone (jet flames). The stability of the conical flames is not sensitive to the gas composition, equivalence ratio and exit flow velocity. This is significantly different from the jet flames. PLIF images of OH radicals show that the leading flame edges (where the chemical reactions start and the flame is stabilized) is fairly independent of the equivalence ratios and the burner exit velocity for the tested LCV gas flames. This is likely attributed to the flow vortices generated inside the cone which enhances the flame stabilization [5].

Acknowledgements

This work was sponsored by the Swedish Research Council VR, SSF and STEM through CeCOST. B.B. Yan, C.Y. Liu were sponsored by China Natural Science Foundation (grant no. 50428605) and CSC (China Scholarship Council).

Reference

- [1] H. Goyal, D.Seal, C. Saxena, *Renew. Sustain. Energy. Rev* 12 (2008) 504-517.
- [2] Wilson, K. Lyons, *Fuel* 87 (2008) 405-413.
- [3] S. Won, J. Kim, K. Hong, *Proc. Combust. Inst.* 30 (2005) 339-347.
- [4] F. EL-Mahallawy, A. Abdelhaffz, M. Mansour, *Combust. Sci. Technol.* 179 (2007) 249-263.
- [5] B. Li, E. Baudoin et al. *Proc Combust Inst.* 32 (2009) 1811-1818.
- [6] K. Stahl, L. Waldheim, M. Morris, U. Johansson, L. Gardmark, Biomass IGCC at Värnamo, Sweden – past and future, GCEP Energy Workshop, April 27, 2004, Frances C. Arrillaga Alumni Center, Stanford University, CA, USA.
- [7] S. Chung, B. Lee, *Combust. Flame* 86 (1991) 62-72.
- [8] B. Lee, S. Chung, *Combust. Flame* 109 (1997) 163-172.
- [9] M. Karbasi, I. Wierzba, *International Journal of Hydrogen Energy* 23 (1998) 123-129.
- [10] K. Wohl, N. Kapp, C. Gazley, *Symp. Combust. Flame. Explosion. Phenomena* 3 (1949) 3-21.
- [11] R. Chen, A. Kothawala, M. Chaos, *Combust. Flame* 141 (2005) 469-472.