Premixed conical flame stabilization

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Abstract. In the current work, stabilization of premixed laminar and lean turbulent flames for wide range of flow rates and equivalence ratios was performed. Methane–air mixture was ignited after passing through premixed chamber with beads and grids, and conical nozzle (Bunsen-type burner). On the edge of the nozzle a stabilized body–ring was mounted. Ring geometry was varied to get the widest stable flame parameters. This work was performed as part of the project on experimental investigation of premixed flames under microgravity conditions.

1. Introduction

Stabilization of premixed flames is one of the most vital issues for fundamental combustion research and in technological field. It helps to understand the fundamental aspects of NO\textsubscript{x} pollution, lean and rich flames, and to find new configuration and design of combustion devices and/or materials. The classic definition of a stable combustion—is that in reaction zone there is a dynamic equilibrium between flame striving to move towards the gas/air flow and tendency of fuel mixture flow to blow-off the jet flame. As usual blow-off limits estimates as function of mixture equivalence ratio and flow velocity. So the aim is to extend the flammability limits—to make stable flame under lower and higher velocities and for lean and rich combustible mixture.

There are several main principles of flames stabilization: swirling [1], bluff-body stabilization [2–7]. The main principle of all this methods—is to create recirculation zone to bring hot combustion products towards cold reactants, thereby heat them and reignite i.e. to keep flame at the same stagnation point. Also there are two other methods, which are of the similar nature using a pilot flame [8] and stabilization by burner rim [7]. In first case—flame under interest is surrounded by flow of stoichiometric mixture with “normal velocity” (velocity under which flame is stable) that is always burning, thus heating the main flow and keeping the flame. In the second case—rim is heated by the flame or by external means and it in its turn heats the flow and keeps the flame burning respectively. A completely different nature of flame stabilizations is by using ac and dc electric fields [9–11]. In literature they classified such influence in three different ways: first one—is the most studied and most significant—ionic wind, that influences boundary velocity gradient, thereby changes the blow-off velocity of the flow; the second one—influence of charged particles on associated reaction rates and the third one—increasing of charged particles diffusion flux. Despite of stabilization methods little variety, in each particular burner or engine configurations individual, even unique, combinations of methods are used. The aim of present work was to find the simplest way to stabilize conical premixed flame, as one of the preliminary steps for investigation of combustion process under microgravity conditions in Bremen Drop Tower [12], that in its term allows to grasp the fundamentals of combustion. As was mentioned
in the most previous microgravity experiments [13] a ring stabilizer was widely used, but almost no detailed information about flow characteristics and ring parameters was given. So, current work is devoted to detailed investigation of flow characteristics that are used for generation of stable conical premixed methane–air flame with wide range of flow velocities and mixture ratio.

2. Experimental setup

The experimental apparatus consisted of a conical nozzle, gas supply system, flow-seeding device, a power supply and measurement systems. The conical nozzle profile that is close to Vitoshinsky profile provides flat exit velocity. Outer and inner nozzle diameter are—15 mm and 30 mm respectively. Nozzle was set on cylindrical chamber, which was filled with glass beads ($d_b = 2–4$ mm) fixed in place with grids $\beta \approx 0.54$ all this system provided homogeneous mixture of fuel and oxidant, and turbulized the flow [13].

Drawing of nozzle with premixed chamber is presented in figure 1. The gas supply systems consisted of flow meters “Bronkhorst”, that provided required flow rates and mixture equivalence ratios. The experiments were performed both for cold flows and for flames. In case of flame the mixture equivalence ratio was determined as the ratio of the mole fraction of fuel in the experiment to the mole fraction of fuel in stoichiometric mixture:

$$\varphi = \frac{n_{CH_4}/n_{O_2}}{(n_{CH_4}/n_{O_2})_{stoich}}.$$

To extend flame parameters and at the same time to save conical shape of investigated flame, two suggestions were offered–to use heated burner rim and the ring as bluff-body. In case of rim the stabilization effect was not long-lived and efficient; parameters of stable flame were extended negligibly (for stoichiometric $\varphi = 1$ and rich $\varphi = 1.3$ flames Re = 500–1000, while there was no stable lean flames) and soon after disabling of rim heating the flame extinguished. Using of ring appeared much more efficient method. Thus as flame-holder the metal ring was used fixed
Figure 2. Mean velocity field. Horizontal axis is along the diameter of the nozzle edge section; vertical—along the nozzle symmetry axis. Top row—Re = 600, middle row—Re = 1000, down row—Re = 2250. Left column—gap 2 mm, middle—gap 1 mm, right—gap 0.3 mm.

in place by three tiny pins. Rings have the same inner diameter—10 mm, while out diameter was varied from 11 mm to 14.4 mm. Each ring was centered. All investigations were performed under atmospheric pressure.

Particle Image Velocimetry (PIV) system consisted of CCD camera, double-cavity 30 mJ Nd:YAG (Litron Nano L PIV 125-15) pulsed laser (pulse duration about 10 ns), a synchronizer and computer with “DaVis” software. The laser sheet passed through a symmetry axis of the flow. Thickness of the laser sheet in the area of interest was 1 mm. The time between a pair of laser pulses, determined displacement of the illuminated tracers in pairs of images, varied from 35 to 300 µs, depending on the flow velocity. The optical system was calibrated using single-level calibration plate (5 × 5 cm²), with anchor points-circles on a Cartesian grid with a pitch of 2.5 mm. Calibration consisted of binding experiment coordinate system to the camera coordinate system. The flow was seeded with oil soot particles (diameter ∼ 1 µm). Camera matrix resolution was 1600 × 1200 pix², field of view—21 × 16 mm². Camera axis had 90° with a laser sheet. The captured PIV images were processed by cross-correlation algorithm, a final interrogation area size of 32 × 32 pix². For each flow 170 instant velocity fields were measured.
Figure 3. Normalized velocity \( (u/u_{\text{mean}}) \) profiles along the radius of the nozzle edge section \( (r, \text{mm}) \) with different rings for \( Re = 600 \) (left-side); \( Re = 1000 \) (middle); \( Re = 2250 \) (right-side).

3. Discussions and results
In the figure 2 mean velocity flow fields are presented. In the first column for the ring with diameter of 11 mm, in the second—13 mm, and in the third—14.4 mm. In rows for different flow rates—left row corresponds to \( Re = 600 \), middle one for \( Re = 1000 \), and left one—\( Re = 2250 \). As was shown in [14], by means of thermoanemometry, for \( Re = 600 \) the flow is laminar, while from \( Re = 1000 \), the flow becomes weakly turbulent. Normalized velocity profiles for different rings are shown in figure 3. In the figure 4 vorticity are shown.

In such system, configuration stabilization takes place due to countercurrent flow formation. Flow in gap has lower velocity than main flow and its longitudinal dimension much less than...
lateral in spite of central main flow. Great velocity gradients occur due to impingement of such jet in to the stationary medium, that initialize vortex formation. Such vortexes are clearly shown in figure 2. Vortexes are “keeping” flame at the edge of nozzle exit. In case of rich flames the vortex also provides transport of additional oxidizer to the flame core that preventing flame from a flash back. Also this process improves combustion efficiency thus establishing conditions for reduction of NO\textsubscript{x} formation and pollutions. It is clearly shown in figure 2 and figure 3 that for the gap of 2 mm co-flow has too high velocity (profile central flow and co-flow have the same meaning for the case Re = 2250) for high Re numbers and vortex is almost not formed; for the case with ring 14.4 mm out diameter, co-flow is too weak and has not enough power for low flow rates to form sufficient big vortex. While for 13 mm ring height of co-flow is about 45–80\% of the main flow for wide range of flow rates. Nozzle with ring 13 mm outer diameter forms the flame that is the most stable to equivalence ratio changes. In case of a ring absence, conical flame existed only in narrow band of flame parameters: stoichiometric mixture with flow rate about 10 l/min. While using of ring allows to vary mixtures equivalence ratio and investigate both lean flame and rich: $\phi = 0.7$–1.3; and flow rate from 4 l/min to 21 l/min. In figure 5 photos of stoichiometric flames stabilized with ring are shown.

Figure 4. Vorticity field. Horizontal axis is along the diameter of the nozzle edge section; vertical—along the nozzle symmetry axis. Top row—Re = 600, middle row—Re = 1000, down row—Re = 2250. Left column—gap 2 mm, middle—gap 1 mm, right—gap 0.3 mm.
Figure 5. Stabilized methane/air premixed stoichiometric flames in laboratory conditions.

4. Conclusion
Stabilization of conical premixed methane–air flame by bluff-body ring was performed. The ring parameters with which it stabilizes the flame in the best way (allows to have the widest range of flow velocities and mixture ratio) was defined: inner diameter 10 mm, outer—13 mm. Without ring in this particular nozzle stable flame was only in narrow range of parameters (Re = 1000, $\varphi = 1$), while using of ring allows to extend operation range significantly (Re = 500–3000, $\varphi = 0.7–1.3$).

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