Diagnostics of Instantaneous Flow Structure in Swirling Premixed Flames by Optical Techniques

Sergey V. Alekseenko[1,2], Vladimir M. Dulin[1], Yuriy S. Kozorezov[1], Dmitriy M. Markovich[1,2], Sergey I. Shtork[1],

[1]Institute of Thermophysics SB RAS, Lavrentyev Avenue 1, 630090, Novosibirsk, Russia

[2]Department of Physics, Novosibirsk State University, Pirogova Street 2, 630090, Novosibirsk, Russia

1 Introduction

Presently, the structure and stability of a non-swirling hydrocarbon jet flame, is widely acknowledged for a wide range of inlet velocities and fuel-air ratios. Generally, the flame can be stabilized between two limiting values of the flow rate. The lower value is a flashback limit, below which the flame can't anchor itself to the lip of the burner rim and flashes back inside the burner. The upper value is a blow-off limit, for which the flow can't be longer stabilized in the region of interest and it is carried away by the upstream flow. Besides, when the flow rate exceeds a certain value, but before the blow-off event, a lifted combustion regime can be observed. In this case, the flame abruptly becomes detached from the burner lip remaining stably positioned at certain distance from the burner. In practice, modern combustion devices utilize lean premixed flames to achieve a low level of NOx emissions. However, lean premixed flames are sensitive to instabilities induced by various sources, including flame unsteadiness and blow-off [1]. Thus, the application of a relatively strong swirl with corresponding appearance of a vortex breakdown with recirculation zone is usually used for the flame stabilization. The vortex precession itself and intensive turbulent fluctuations, typical for the vortex breakdown, increase the flame stabilization via a high turbulent mixing rate of the fresh and burnt gases in the back-flow region. This allows to maintain the combustion at rather lean conditions. However, for the swirling flames and even for the isothermal swirling jets, substantially different flow regimes can be observed, depending on the swirl rate and on the manner in which the swirl is applied (e.g., [2]).

It is widely acknowledged by many authors that Kelvin–Helmholtz instability in shear layer leading to vortex rings formation, dominates non-swirling and weakly swirling jets. For a high enough swirl rate (but before pronounced vortex breakdown) strong helical waves were usually observed in the mixing layer of the jet. Further increase in a swirl rate leads to vortex breakdown appearance, which is known to have different states [3]: spiral, bubble, or conical, where the last two can be either symmetric or asymmetric (e.g., [2]). Obviously, the presence of combustion makes the structure of the swirling jets even more complex. Observations of different authors show that for the turbulent swirling flames a great variety of combustion regimes can exist resulting from a number of effects, like thermal expansion (strong buoyancy effect on a swirling jet was reported by [4]), and others. For the turbulent premixed combustion, depending on the ratio of characteristic scales of turbulence and flame, various

Correspondence to: aleks@itp.nsc.ru

effects can take place. Velocity fluctuations tend to increase propagation speed of the flame front, while thermal expansion effect suppresses the turbulence in the gas passing thru the flame layer (e.g., [5]). Besides, large-scale vortices interacting with the flame front result its intensive fluctuations and, consequently, fluctuations of the heat-release that leads to increase of acoustic noise [6]. Thus, such interaction can lead to harmful resonance effects in confined combustion facilities. At the same time, pressure waves form the flame/vortex interactions can result intensification of large-scale vortices in shear flows. In particular, the acoustic forcing is able to significantly increase combustion rate in non-swirling jet flames (see [7]). Similarly to the non-swirling jets, external forcing of inlet velocity can be used to control the development of large-scale vortices and thus the turbulent mixing in weakly and even in strongly swirling jets [8].

The present work is devoted to experimental study of flow/flame structure of premixed swirling jet flames at various combustion regimes. The swirl rate based on geometry of the swirlers was varied from 0 to 1.0. Stereo PIV technique combined with pressure probe was used for the measurements to investigate role of large-scale vortices in turbulent structure of the flames. Besides, chemiluminescence images were used to determine an average position of the flame front.

2 Experimental setup and measurement system

The measurements were performed in a combustion rig consisted of a burner, air fan, plenum chamber, flow seeding device, premixing chamber and section for the air and fuel (propane) flowrate control. The experiments were performed at the atmospheric pressure. During the study, Re_{air} number (based on the nozzle exit diameter d and flowrate velocity of the air and on viscosity of the air) was varied from 500 to 8,000. The equivalence ratio Φ of air-propane mixture was varied from 0.5 to 10. In order to provide PIV measurements of the instantaneous velocity, the flow was seeded by aluminum oxide particles with the average diameter of 5 μm. For external acoustic forcing of the flow, a system consisting of four loud speakers, parallel connected to an amplifier, function generator and electric power meter, was used. The normalized (by nozzle exit diameter d and the mean flowrate velocity U_0 of the mixture) forcing frequency, i.e. the Strouhal number, was varied from 0.1 to 3. The burner represented a profiled contraction nozzle with the same geometry as in the isothermal water jet experiments by [8]. The contraction nozzle was designed to provide a 'top-hat' velocity distribution at the nozzle exit for the non-swirling flow. The nozzle exit diameter d was 15 mm, and the area contraction rate was 18.8. For organization of the flows with swirl, smoothing grids in a plenum chamber of the nozzle were replaced by a swirl generator The definition of the swirl rate was based S on the swirler geometry was varied from 0 to 1.0.

For the instantaneous velocity measurements a "PIV-IT" Stereo PIV system consisting of a double-cavity Nd:YAG pulsed laser, couple of CCD cameras and a synchronizing processor was used. The cameras were equipped with narrow-bandwidth optical filters admitting emission of the laser (532 nm) and suppressing radiation of the flame. The system was operated by a computer with "ActualFlow" software. Measured images were processed by an iterative cross-correlation algorithm with an image deformation. Calculated instantaneous velocity fields were validated by using a signal-to-noise criterion for cross-correlation maxima and by an adaptive median filter. Stereo calibration was performed by using a plane calibration target. To minimize stereo calibration error connected with possible misalignment of the laser sheet and target plane, an iterative correction procedure was applied. All the measurements were performed in a central plane of the jet/flame. For the each combustion regime 2,500 instantaneous three-component velocity fields were measured.

For analysis of the flame front instantaneous shape, the CH* chemiluminiscence signal was captured by an UV sensitive ICCD camera equipped with a band-pass optical filter (430±5 nm).

3 Results

Figure 1 shows the typical combustion regimes and blow-off curves for non-swirling ($S = 0$) and strongly swirling ($S = 1.0$) premixed flames. For the $S = 0$ case, depending on Re and Φ values, various combustion regimes exist between an attached classical Bunsen flame and a remote from the nozzle lifted flame. For the flow with the high swirl, i.e. $S = 1.0$, (see Figure 1b), the lifted flame regimes were observed as well, and the range of Re, where stable lifted or attached flames were realized, was much more wider than for non-swirled flames. Generally, introduction of the swirl significantly increased blow-off limit and provides stable lean combustion at relatively high flow rates.

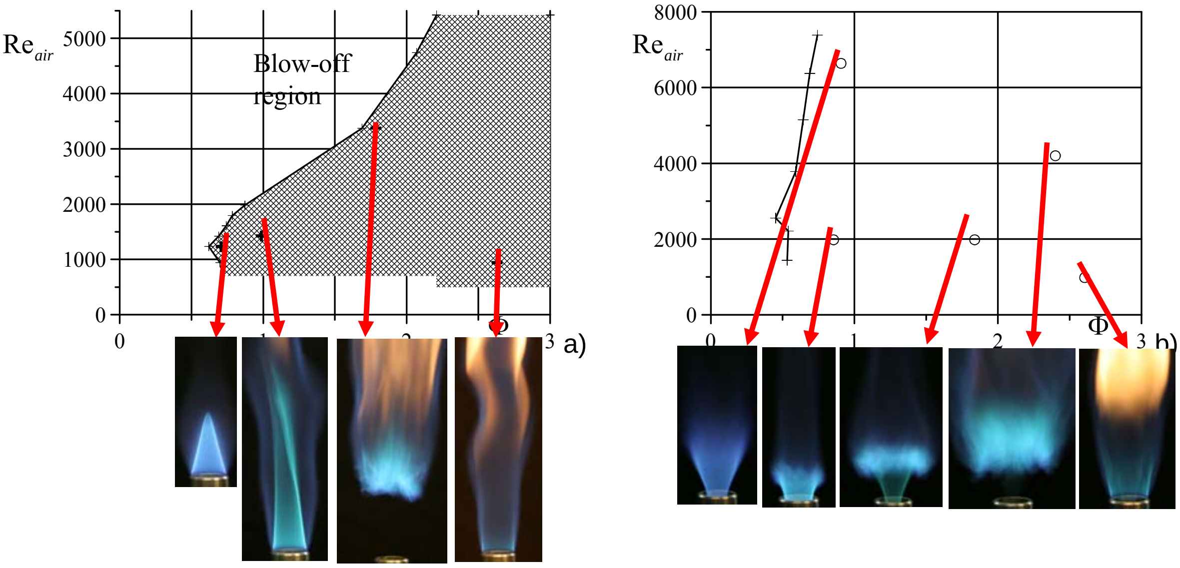

Figure 1. Re-Φ diagram with blow-off curve and examples of typical flame regimes for (a) S = 0, and (b) S = 1.0 cases.

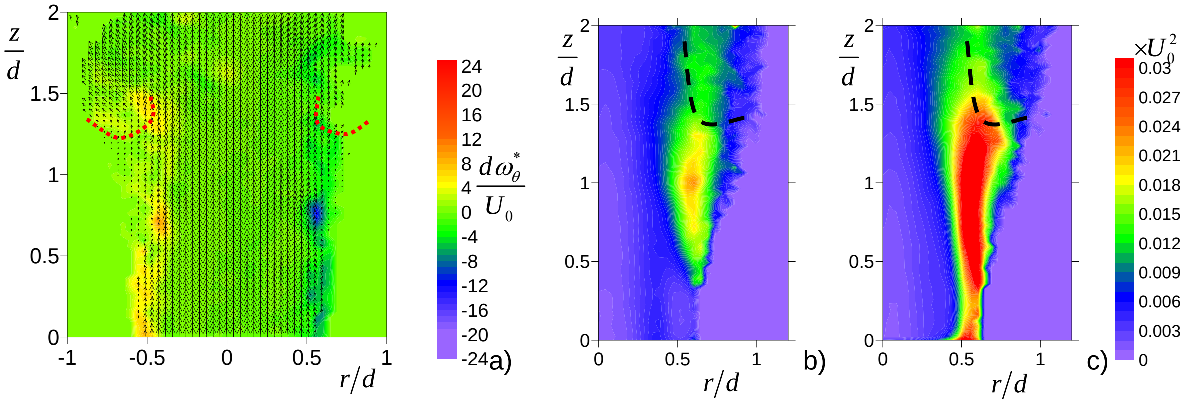

Figure 2. (a) Instantaneous velocity and vorticity fields. Spatial distributions of the (b) radial and (c) axial components of TKE for a lifted flame at S = 0; Re = 4,100; Φ = 2.0 U_0 = 4.6 m/s. Typical photography of the flame can be seen in Figure 1a.

Figures 2 show the instantaneous velocity and vorticity fields and the spatial distribution of turbulent kinetic energy (TKE) components for the non-swirling premixed lifted flame at Re = 4,100, Φ = 2.0, and U_0 = 4.6 m/s. For this regime, the flame front (schematically shown by the dashed line) was considered to represent the bottom of a torus and was oscillated around z/d = 1.3 position. By comprising the flows without (not shown in the paper) and with combustion, it was found that the vortices located above the flame boundary are rather suppressed (due to the thermal expansion effect) in the latter case. The suppression is clearly demonstrated at the distributions TKE components. Besides it was found that in the case of combustion the vortices before the front were more pronounced due to the pressure fluctuations (caused by the flame front deformation) effect on the shear layer of the jet. This was confirmed by application of an additional acoustic forcing.

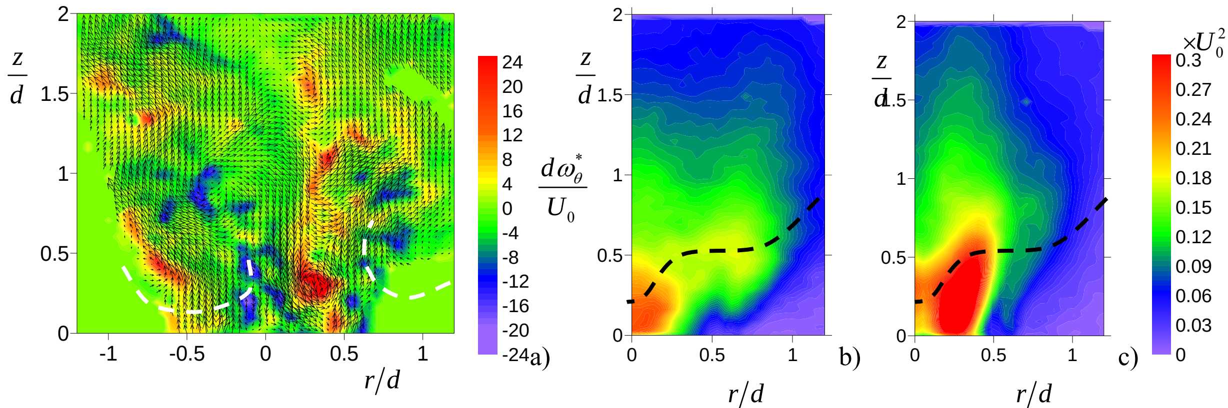

Figure 3. (a) Instantaneous velocity and vorticity fields. Spatial distributions of the (b) radial and (c) axial components of TKE for a lifted flame at S = 1.0; Re = 4,100; Φ = 2.3 U_0 = 4.7 m/s. Typical photography of the flame can be seen in Figure 1b.

Figure 3 shows the spatial distributions of the instantaneous velocity field and components of TKE for the swirling (S = 1.0) lifted flame. Large-scale helical vortices were observed in the inner and outer mixing layers of the jet, thus producing region of great values of TKE components. The flow structure before the flame boundary was found to be rather similar to the isothermal flow at the same nozzle configuration studied in [8], and as for the non-swirling lifted flame, a rapid suppression of vortices was observed after the gas passed thru the flame layer. Thus, the lifted premixed combustion regimes were associated with the flame stabilization in the region of strong velocity fluctuations caused by large-scale vortices developing in the 'cold' flow region before the flame front. On the other hand, the interaction of the large-scale vortices with the flame front resulted in intensive pressure fluctuations (in comparison to the attached flames) that can be very harmful in many practical cases.

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