Comparison of axial forcing effect on a strongly swirling jet and lifted propane-air flame

S.V. Alekseenko\textsuperscript{1,2}, V.M. Dulin\textsuperscript{1,2}, Yu.S. Kozorezov\textsuperscript{1}, D.M. Markovich\textsuperscript{1,2}

1: Institute of Thermophysics, Siberian Branch of RAS
Novosibirsk, Russia
2: Department of Physics, Novosibirsk State University
Novosibirsk, Russia

1 Introduction

The application of a swirl is often used for flame stabilization via increasing turbulent fluctuations upstream the flame and providing low-velocity or reverse flow region (for low or high swirl rates, respectively) at the jet axis [7], [9], [3]. The flow swirling can be used to reduce NOx formation of premixed flames, since it provides stable lean combustion regimes at a wide range of flow rates. Thus, the swirl application can be considered as the efficient ways to passively control flow structure of jets [1] and flames [3]. However, even for the isothermal swirling jets, substantially different flow regimes can be observed, depending on the swirl rate and the manner in which the swirl is applied (e.g., [10]). Another well-known efficient way to control turbulent structure (formation and downstream evolution of vortices) of non-swirling jet flows is periodical excitation of inlet velocity (e.g., [5]). In particular, the active forcing is known to strongly affect stabilization of a lifted non-swirling flame via controlling ring-like vortices developing upstream the flame [6]. Periodic forcing is also can be used to control the development of large-scale vortices and turbulent mixing in weakly [8] and even in strongly [1] swirling jets.

The present paper aims on experimental study of a rich strongly swirling lifted flame under high-amplitude forcing of the initial velocity for which a significant effect was recently observed [2]. The modification of turbulent reacting and also isothermal flows (at the same inflow conditions) was investigated by means of stereo Particle Image Velocimetry (PIV), and CH* chemiluminescence imaging was applied to visualize region of turbulent combustion for the reacting case.

2 Experimental setup and apparatus

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 atmospheric pressure. The burner represented a contraction nozzle with a swirler mounted inside. The swirl rate based on the swirler geometry corresponded to \( S = 1.0 \). The nozzle exit diameter \( d \) was 15 mm. During the present PIV study of the reacting flow, \( \text{Re}_{\text{air}} \) number (based on the nozzle exit diameter \( d \), mean flowrate velocity and viscosity of the air) was 4,100. The equivalence ratio \( \Phi \) of air-propane mixture issuing from the burner was 2.5. In order to provide PIV measurements, the main flow, issuing from the nozzle, was seeded by TiO\textsubscript{2} particles with...
the average diameter of 1 µm. The ambient air was seeded by a fog generator. For the external periodical forcing of the flow, a system consisting of four loud speakers (a similar system was used by [5]), 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 $St$, was varied from 0.1 to 3.

For the instantaneous velocity measurements, a "PIV-IT" Stereo PIV system consisting of a double-cavity 70 mJ Nd:YAG pulsed laser, couple of 4M CCD cameras and synchronizing processor was used. The cameras were equipped with narrow-bandwidth optical filters admitting the emission of the laser (532 nm) and suppressing the radiation of the flame. For each combustion regime, 1,500 instantaneous three-component velocity fields were measured.

For the analysis of turbulent combustion domain, the CH* chemiluminescence signal was captured by an UV-sensitive 1.5 Mpix ICCD camera equipped with a band-pass optical filter (430±5 nm). Five hundred 10-bit images of CH* chemiluminescence were captured, converted to floating point data, and then averaged for each combustion regime. For analysis of the spatial structure of turbulent combustion regions, an inverse discrete Abel transform ($A^{-1}$) was applied to the average images.

3 Results

From the example in Fig. 1a, one can observe that the lifted flame represented a domain of intensive turbulent combustion located less than one $d$ downstream the nozzle exit. Also, since the mixture coming from the nozzle was relatively rich ($\Phi = 2.5$) an extensive region of products afterburning was present further downstream, where soot luminescence was observed. Fig. 1b and c demonstrates the most pronounced effect of the axial velocity forcing (among tested frequencies and amplitudes) on the strongly swirling lifted flame. The considered forcing frequency 170 Hz corresponded to the Strouhal number $St = 0.6$. For this frequency and amplitude $a_f$ approximately above 25% of $U_0$, a considerable modification of lifted flame combustion was observed. In particular, a less soot luminosity was observed downstream of the domain of intensive turbulent combustion. It was concluded to be due to a turbulent heat and mass transfer enhancement in the initial region of the flow near the burner exit by the strong forcing.

![Figure 1. Direct images of a lifted strongly swirling flame (a) without periodic forcing and under forcing St = 0.6 (b) $a_f/U_0 = 20\%$ (c) $a_f/U_0 = 30\%$. $S = 1.0$, $Re_{air} = 4\,100$, $\Phi = 2.5$, $U_0 = 4.7$ m/s](image)

The integral CH* chemiluminescence images, averaged over 500 samples, are shown in Fig. 2 for the same cases. Analysis of the mean chemiluminescence distributions reveals that the high amplitude periodic forcing led to an increase in overall combustion intensity in the initial region of the lifted flame. The domain of turbulent combustion also slightly moved downstream and became wider. An inverse Abel $A^{-1}$ transform was applied to these integral chemiluminescence data in order to reconstruct the average CH* chemiluminescence source in the central plane of the flames.
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Figure 2. Time-average distributions of integral CH* chemiluminescence for a lifted strongly swirling flame (a) without periodic forcing and under forcing St = 0.6 (b) a_f/U_0 = 20% (c) a_f/U_0 = 30%. S = 1.0, Re_{air} = 4100, \( \Phi = 2.5 \), \( U_0 = 4.7 \) m/s.

Fig. 3 shows the spatial distributions of the mean velocity for the strongly swirling lifted turbulent flames. Length of the vectors shows the in-plane magnitude, while their colour scale corresponds to the magnitude of three-component vectors. For all the cases a bubble-type vortex breakdown took place. The main flow issued from the nozzle as a circular jet with a certain opening angle and propagated around the recirculation zone located around the jet axis (shown by a red heavy line in Fig. 3). Monotonous decrease of the recirculation zone longitudinal size with amplitude of the forcing can be seen, while its lateral size was almost constant (around 0.65d). As can be seen, the intensive combustion domain slightly shifted downstream towards the outer mixing layer when the forcing was applied. After the combustion domain, a growth of the jet spreading rate and increase of the gas velocity magnitude can be seen with a_f as the forcing intensified turbulent combustion.

Figure 3. Spatial distributions of the mean velocity and reconstructed CH* chemiluminescence in a central plane of the lifted strongly swirling flame (a) without periodic forcing and under forcing St = 0.6 (b) a_f/U_0 = 20% (c) a_f/U_0 = 30%. S = 1.0, Re_{air} = 4100, \( \Phi = 2.5 \), \( U_0 = 4.7 \) m/s. Red heavy line shows recirculation zone.

A substantial modification of the radial component of turbulent kinetic energy by the forcing can be outlined from Fig. 4. The main distinction for the case of a_f = 30% is that \( \langle v^2 \rangle \) magnitude was significantly smaller near the jet axis and nozzle exit (for r/d < 0.5 and z/d < 0.5). Similar changes in
the distributions of the azimuthal component of turbulent kinetic energy (TKE) (not shown in the paper) indicate that precession of the flow inside the recirculation zone was rather suppressed by the forcing with $St = 0.6$ and $af = 30\%$. As it is shown below, the suppression of vortex core precession was significant only for the reacting flow case, while for the isothermal flow at the same conditions there was no pronounced suppression.

![Figure 4](image-url)

Figure 4. Spatial distributions of the radial component of turbulent kinetic energy for the central plane of a lifted strongly swirling flame (a) without periodic forcing and under forcing $St = 0.6$ (b) $af/U_0 = 20\%$ (c) $af/U_0 = 30\%$. $S = 1.0$, $Re_{air} = 4\,100$, $\Phi = 2.5$, $U_0 = 4.7$ m/s. White solid line shows iso-level of $A^{-1} \langle \dot{I}_{CH} \rangle = 0.04$ a.u.

Fig. 5 represents the difference of the radial component of TKE between the reacting and isothermal flows at the same initial condition for the unforced and forced cases. For the strongly swirling lifted flame without forcing the combustion resulted in higher values of $\langle \nu^2 \rangle$ in the outer mixing layer between the main circular flow coming from the nozzle and ambient air.

![Figure 5](image-url)

Figure 5. Difference of the radial turbulent kinetic energy in the central plane of a lifted strongly swirling flame and isothermal jet flow. $S = 1.0$, $Re_{air} = 4\,100$, $\Phi = 2.5$, $U_0 = 4.7$ m/s. (a) No external forcing, forcing at St = 0.6 (b) $af/U_0 = 20\%$ (c) $af/U_0 = 30\%$. Black solid line corresponds to $\Delta \langle \nu^2 \rangle = 0$

This is expected to be due to an intensification of the large-scale vortices in the outer mixing layer caused by gas expansion and increase of the backflow inside the recirculation zone. It can be assumed that more intensive backflow produced higher radial velocity fluctuations near the stagnation point, where the backflow faced the mixture coming from the nozzle. For the case of forcing at $af/U_0 = 20\%$...
the overall effect of combustion seems to very similar. The application of forcing with $a_f/U_0 = 30\%$ amplitude results in substantially different effect of combustion on the radial velocity fluctuations near the nozzle exit than in two previous cases. It can be seen that the presence of the lifted flame for the forcing with $St = 0.6$ and 30% amplitude suppressed significantly the radial velocity fluctuations in the region $r/d < 0.5$ near the nozzle exit, while the velocity pulsation were intensified in the outer mixing layer $r/d > 0.5$. Thus, this demonstrates that the vortex core precession suppression was probably due to the forced vortices interaction with the lifted flame.

The next Fig. 6a and b show the instantaneous velocity and vorticity fields for the case of the strongly forced ($a_f = 30\%$) isothermal jet flow and lifted flame, respectively. This particular example, selected for the isothermal flow clearly indicate that the strong forcing induces (the amplitude for $St = 0.6$ in the present study was significantly greater than that in [1]) a couple of positive and negative nearly-symmetrical vortices in the outer mixing layer, while reverse flow wriggles inside the recirculation zone due to the core precession. Taking into account relatively large amplitude of the forcing, this couple of vortices might correspond to a ring-like vortex formed in the outer mixing layer by the flow pulsing. From the example for the reacting case (Fig. 6b), formation of a similar vortex couple can be seen very close to the nozzle rim. Another couple can be also seen inside the turbulent combustion zone for $z/d > 1.0$. In contrast to the isothermal flow at the same condition the radial velocity fluctuation inside the recirculation zone for $z/d < 1.0$ were rather small. Thus, the suppression of the reverse flow precession is expected to be due to the ring-like vortices integration with the lifted flame.

![Figure 6. Instantaneous velocity and vorticity fields in the central plane of an (a) isothermal jet and (b) lifted strongly swirling flame and under forcing $St = 0.6$, $a_f/U_0 = 30\%$. $S = 1.0$, $Re_{air} = 4100$, $\Phi = 2.5$, $U_0 = 4.7$ m/s.](image)

### 4 Conclusions

The flow structure of a strongly swirling lifted propane-air turbulent flame under periodical forcing was studied experimentally. Ensembles of the instantaneous velocity fields were measured by means of stereo PIV, and the spatial distributions of the mean velocity and intensity of turbulent fluctuations were calculated. In order to visualise the domains of intensive turbulent combustion, CH* chemiluminescence images were captured by ICCD camera.

The results demonstrate the strong axial forcing (with amplitude 30% of $U_0$) can provide an increase of the overall combustion rate for the lifted turbulent flame and also can suppress flow precession near the nozzle exit by forcing large-scale vortices in the jet mixing layer. By comparison the flow structure...
Alekseenko S. V.  

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for the reacting and isothermal flows under the strong forcing it was observed that significant suppression took place only for the reacting case.

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6 References