Numerical Simulation of Coaxial Swirled Lifted Propane-Air Flame under Buoyancy Conditions

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Abstract. Numerical simulation of gas dynamics and combustion in coaxial swirled lifted propane-air jets under buoyancy conditions is performed. Dependences of dimensionless flame length $L/d_0$, lift-off height $h/d_0$ as well as flame front surface area $S_f$ and mass rate of burn-out $U$ on orientation angle $\theta$ are obtained. The results of numerical simulation and experiment for different values of $\theta$ are compared. It is confirmed that in the angle range of $30^\circ < \theta < 60^\circ$ flame has the smallest surface area that provides the highest value of the mass rate of burn-out. The numerical solution closest to an experiment data can be obtained by using an additional differential transport equation for the ignition time or setting a delay time in the range of 0.05..0.25 s.

1. Introduction
Flow swirling is a generally accepted way to intensify gas dynamics, heat transfer and combustion in jet flows [1]. Due to the simplicity of implementation of jets and at the same time sufficiently high efficiency, such flows are found in almost all elements and operation processes of energy and gas turbine power plants. For this reason, it is considered promising to organize and search for optimal operating modes of jets with flow swirling.

One of the most effective ways of organizing the jet stream is a coaxial swirled flow, in the core of which an axial jet is realized, and the peripheral jet is swirled. Such combination of axial and peripheral swirled jet components is used in many applications like jet impingement for cooling surfaces [2, 3], coaxial swirl injectors [4] and combustion intensification [5-9]. Usually in coaxial non-premixed flames fuel jet is axial component and swirled air jet is peripheral one. However, there are different types of inverse jet flames with central oxidizer jet and annular fuel jet in a coaxial burner [10, 11]. This paper studies a classical configuration with swirled peripheral air jet [9, 12].

Previous studies have shown that combustion in coaxial swirled jet significantly depends on air-fuel ratio, Re numbers of components and buoyancy conditions. It has been shown that in contrast to burning a single fuel jet, the formation of the coaxial flame is accompanied by the 30% decrease in the relative curvilinear length. Moreover, noted decrease is different for different values of angle $0$ between vertical upward direction (direction of lift force) and initial direction of axial fuel jet. The range of the values of the angle $30^\circ < \phi < 45^\circ$ is characterized by maximum values of the mass rate of burn-out $U$ [9].

This study aims at finding reasons of maximum values of the mass rate of burn-out $U$ and defining the relation between flow structure and flame parameters. It requires a correct choice of numerical statement and careful analysis of results.
2. Numerical simulation details

The scheme of formation of a coaxial swirled lifted flame is shown in Figure 1. Numerical simulation was carried out for generator of coaxial jet and surrounding air of following dimensions: diameter of the propane nozzle $d_0 = 2\text{ mm}$, hydraulic diameter of the swirled air nozzle $d_{air} = 5\text{ mm}$, diameter of the surrounding air cylinder $d_{cyl} = 1\text{ m}$, and height of the surrounding air cylinder $h_{cyl} = 1\text{ m}$.

The calculation grid (Fig. 2) of the flow region was multiblock structured; the total number of elements was about 2.2 million. To calculate the gas flow, Reynolds-averaged Navier-Stokes equations were used. The turbulence was described by the k-ε-model with scalable wall-functions.

![Figure 1. Scheme of formation of a coaxial swirled lifted propane-air flame [9]: $x$ – flame width; $y$ – flame height; $l$ – curvilinear flame length; $h$ – lift-off height; $\theta$ – angle of jet’s orientation relative to vertical; $d_0$ – nozzle’s diameter; $u_0$ – initial speed of propane jet](image)

Modeling of combustion processes was carried out using Flamelet PDF model. Chemical transformations were described by G.Mech 1.220 mechanism for propane and air including 35 substances and 108 reactions. Simulation of lift-off height was carried out using Autoignition model with delay values from 0.01 s to 0.25 s. Buoyancy conditions were simulated by setting $X$, $Y$, and $Z$ components of acceleration due to gravity corresponding to the required angle $\theta$.

Total temperatures of propane and air at the domain inlets were constant for all the calculations and equal to 300 K. Propane mass flow rate was equal to 0.125 g/s that corresponds to Reynolds number $Re_f = 7000$. Air mass flow rate was equal to 0.23 g/s that corresponds to Reynolds number $Re_{air} = 2100$. Total temperature at the opening boundaries was also constant and equal to 300 K, as well as static pressure at these boundaries was equal to 101 kPa. The walls of the coaxial jet generator were considered to be adiabatic.

The results of calculations were summarized using the following dimensionless parameters:

- $Re_f = u_0 d_0/\nu_f$ – Reynolds number of fuel jet;
- $Re_{air} = u_{air} d_{air}/\nu_{air}$ – Reynolds number of air jet;
- $U = (G_{air} + G_f)/F_f$ – mass rate of burn-out which is equal to net mass flow rate of fuel and air supplied into domain divided by area of flame surface.

![Figure 2. Calculation grid.](image)
3. Results and discussion

Figures 3 and 4 show the positions of the flame front in the form of OH isosurfaces and velocity contours for operation mode $Re_f = 7000$ and $Re_{air} = 2100$ and values of orientation angle $\theta = 0^\circ; 22^\circ; 36^\circ; 43^\circ; 60^\circ; 75^\circ; 90^\circ$.

It is clearly seen that with increasing angle the flame becomes significantly curved, its length decreases, and the local thickness grows. At the same time, the change of velocity values along the curvilinear axis of the jet is insignificant. In addition, the observed blurring of the jet is almost the same for all the studied modes.

![Figure 3](image1)

**Figure 3.** Isosurfaces of OH mass fraction 0.0001 for operation mode $Re_f = 7000$ and $Re_{air} = 2100$: a) $\theta = 0^\circ$; b) $\theta = 22^\circ$; c) $\theta = 36^\circ$; d) $\theta = 43^\circ$; e) $\theta = 60^\circ$; f) $\theta = 75^\circ$; g) $\theta = 90^\circ$

![Figure 4](image2)

**Figure 4.** Velocity contours for operation mode $Re_f = 7000$ and $Re_{air} = 2100$: a) $\theta = 0^\circ$; b) $\theta = 22^\circ$; c) $\theta = 43^\circ$; d) $\theta = 60^\circ$; e) $\theta = 90^\circ$

Numerical studies of gas dynamics and combustion in coaxial swirled jets have shown that taking into account buoyancy conditions has a significant impact on the formation of the flame and its characteristics. It is obtained that the dimensionless curvilinear length of the flame $L/d_0$ decreases from 234 to 185, which practically corresponds to the experimental data ($L/d_0 = 288$ and 161, respectively). This was made possible by taking into account the stabilization features of the coaxial swirled flames based on the solution of an additional differential transport equation for the ignition time (autoignition delay). The results of testing of the mentioned statement on Flamelet PDF combustion model allowed drawing a conclusion that the solution closest to an experiment can be obtained in a delay time range...
0.05...0.25 seconds. At the operation conditions \( \text{Re}_f = 7000 \) and \( \text{Re}_{air} = 2100 \) the value of the dimensionless lift-off height \( h/d_0 \) varies from 37 at an angle of 0° to 28 at an angle of 90°. The experimental values corresponding to these conditions were 37 and 30, respectively [9].

The study of the flame front structure has confirmed the thesis that in the angle range of 30° < \( \theta \) < 60° the flame has the smallest surface area. In particular, for the above series of calculations, the minimum area was achieved at an angle of 60° and was 0.0539 m² (in the experiment 0.0447 m²), while the values 0° and 90° corresponded to 0.0793 m² and 0.0659 m² (in the experiment they were 0.0587 m² and 0.0643 m², respectively). These results defined the values of mass rate of burn-out \( U \) which has a maximum at the angle of 60° in numerical simulation \( (U = 0.0292 \text{ kg/(m}^2\cdot\text{s}) ) \) and at the angle of 36° in experiment \( (U = 0.0345 \text{ kg/(m}^2\cdot\text{s}) ) \). The difference between these two values of mass rate of burn-out can be explained by different approaches to definition of flame front surface area. In experiment, the area was defined using the soot luminosity in flame. Numerical simulation used the area of isosurface of OH-radicals’ mass fraction.

Dependences of dimensionless flame length \( L/d_0 \), lift-off height \( h/d_0 \) as well as flame front surface area \( S_{fl} \) and mass rate of burn-out \( U \) on orientation angle \( \theta \) are shown in Figures 5-8.

The reasons for the marked minimums of flame surface area and maximums of mass rate of burn-out may be as follows. The flame length decreases most intensively with increasing angle from 0° to 60°, while the greatest reduction of the lift-off height is achieved in the range from 30° to 90°. The mutual influence of these two factors on the combustion intensity leads to the fact that when the combined jet is oriented at an angle of 30-60° to the vertical, the flame volume is the smallest, which determines a 30-40% increase in the averaged mass rate of burn-out.

![Figure 5. Dimensionless flame length \( L/d_0 \) depending on orientation angle \( \theta \)](image)

![Figure 6. Dimensionless lift-off height \( h/d_0 \) depending on orientation angle \( \theta \)](image)

![Figure 7. Flame front surface area \( S_{fl} \) depending on orientation angle \( \theta \)](image)

![Figure 8. Mass rate of burn-out \( U \) depending on orientation angle \( \theta \)](image)
Figures 9-11 show a comparison of the calculated isosurfaces of OH mass fraction with experimental photographs. Figures 9 and 10 show instantaneous appearances of the flame front for orientation angles $\theta = 90^\circ$ and $0^\circ$. Figure 11 shows averaged appearance of the flame front for orientation angle $\theta = 0^\circ$. There is a good visual agreement between the calculated and experimental results for both values of angle $\theta$. Moreover, it is noticeable that instantaneous flame has a more curvilinear surface with developed turbulence while average flame can be characterized by sufficiently smooth surface. This is obvious for both computational and experimental studies and is associated with fluctuations in the flame length with a certain frequency. The value of this frequency can be found as a result of additional unsteady research.

**Figure 9.** Instantaneous appearance of the flame front for orientation angle $\theta = 90^\circ$: a) experimental photograph; b) numerical simulation of OH isosurface.

**Figure 10.** Instantaneous appearance of the flame front for orientation angle $\theta = 0^\circ$: a) experimental photograph; b) numerical simulation of OH isosurface

**Figure 11.** Averaged appearance of the flame front for orientation angle $\theta = 0^\circ$: a) experimental photograph; b) numerical simulation of OH isosurface.
Conclusion
The numerical simulation has revealed the relationship between gas dynamics and combustion in coaxial swirled propane-air jets. It is shown that flame length and lift-off height decrease with increasing orientation angle $\theta$. Reducing these quantities is not linear that defines a complex dependence of flame front surface area $S_{fl}$ and mass rate of burn-out $U$ on buoyancy conditions. It is experimentally and numerically confirmed that for the value of Reynolds numbers $Re_f = 7000$ and $Re_{air} = 2100$ mass rate of burn-out $U$ has a maximum in the range of orientation angle $30^\circ < \theta < 60^\circ$. The experimental and calculated values of $U$ differ by 15-25%. The possible reasons for this difference can be explained by different approaches to definition of flame front surface area. In experiment, the area was defined using the soot luminosity in flame. Numerical simulation used the area of isosurface of OH-radicals’ mass fraction.

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