Isothermal modeling of an adaptive burner for low-grade fuel combustion

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Abstract. This paper deals with an experimental study of the vortex structure of interacting coaxial swirling flows in an isothermal model of adaptive burner used for combustion of low-grade fuel. The working section consists of two consecutively connected tangential swirlers. Depending on the method of liquid flow supply to the second stage, both co-swirl and counter-swirl of two flows occur in the working section. In experiments, the effect of the flow swirl method on the resulting flow structure was studied with varying flow rates. Time-averaged distributions of axial and tangential velocity components along the entire region of the resulting flow were obtained using laser-Doppler anemometry. Experimental results have shown that counter-swirl is more preferable for the use in a two-stage burner because it promotes faster mixing of the burner jets of the first and second stages and more uniform filling of the internal volume of device.

1. Introduction

To date, flow swirl is the basis for operation of many technical devices used to mix liquids, stabilize flame and spray liquid fuels. When using this type of device, it is necessary to understand the flow structure. First, this is caused by the fact that the non-stationary vortex structures that contribute significantly to the transport processes and can serve as a source of noise are often formed in the swirling flows. Investigation of interacting co-axial swirling flows is important in terms of these flows application [1]. The need for such studies is caused in particular by the use of coaxial swirling flows for flame stabilization and improving mixing in many types of vortex combustion chambers and burners [2]. To improve mixing in such devices, double coaxial flows rotating in the same and opposite directions are widely used. This causes increased mixing between the hot reaction products, injected fuel and oncoming flow. In addition, the resulting strong negative pressure gradient causes recirculation necessary to stabilize the flame. To optimize the design of such devices, it is necessary to understand the flow structure and mechanisms of interaction between the coaxial swirling flows.

The presented work is devoted to the study of the aerodynamic flow structure in an adaptive burner used for combustion of low-grade fuel with application of isothermal modeling. This device is a vortex burner with two stages of flow swirl by tangential swirlers. In view of geometrical simplicity, such burners with tangential and vortex swirlers have found wide application in practice, for example, for combustion of fine pulverized coal fuels [3,4].

The isothermal modeling approach allows us to determine the direction of optimization of operation regimes and working section geometry with relatively little cost; it was widely used earlier for the development of power plants [5]. This approach remains relevant, and is now complemented by the capabilities of modern non-contact optical systems for the detailed analysis of internal structure
of the flows [6, 7]. The contactless technique of laser-Doppler anemometry allows obtaining information on the flow structure, as well as the vortex structure of interacting coaxial swirling flows in the model of an adaptive burner. Further studies will include experiments on fire setups to verify the validity of conclusions based on isothermal experiments.

2. Experimental setup

Isothermal modeling of the two-stage burner is carried out using water as a working liquid that gives more opportunities for visualization of the flow [8]. To ensure optical access, the working chamber is made of a transparent material: plexiglass. The stage of flow supply consists of two successively connected swirlers with the diameter of 185 mm, where the flow is swirled by means of tangential supply through the pipes with the internal diameter of 40 mm. Being swirled at the first stage (1), the liquid flow enters the region of mixing with the flow, swirled by second swirler (2), through nozzle (3). Depending on the way of liquid supply to the second swirler, there are both co-swirl (black arrows) and counter-swirl (white arrows) of two flows formed by the swirlers of the first and second stages of the working area. The resulting flow from a cylindrical region of 104 mm in diameter (4) enters the outlet section (5), from which it is withdrawn through four symmetrically located branch pipes with the internal diameter of 26 mm.

During the experiments, the flows with co- and counter-swirl between the first and second stages with the following flow ratios were studied: 4/4, 6/6, 8/8, 6/4, and 6/8 m$^3$/h. All these combinations of liquid flow rates were characterized by high Reynolds numbers of about $5 \cdot 10^4$ characteristic of the turbulent flow regime.

3. Results and discussion

To obtain quantitative information about the flow field, we used a two-component laser-Doppler anemometer (LDA) LAD-06i, which operates on backscattering. During the measurements, statistics of 1000 Doppler “bursts” (tracer passing through the measuring volume) was accumulated at each measuring point. The axial and tangential velocity components were measured alternately. To take into account the effect of ray refraction on the plexiglass-water boundary, the correction for the tangential velocity was taken into account by multiplying by factor $k = 1 + (n_1/n_2 - 1) \cdot (x/R)$, where $n_1$ is the refractive index of plexiglass, $n_2$ is the refractive index of water, $x$ is the distance from the wall to the axis, and $R$ is the radius of cylindrical region [9]. Thus, the maximal correction is achieved on axis $x = R$ and it is 14%.

At the first stage of experimental studies, the time-averaged axial and tangential velocity components were measured near the outlet of the second tangential swirler along the radius of the cylindrical region of sudden expansion. The co- and counter swirl regimes between two stages were studied at flow rates of 4/4, 6/6, and 8/8 m$^3$/h. The obtained velocity profiles are presented in figures 2 and 3. In the presented graphs, the distance from the center along axis $x$ is normalized to the radius of the cylindrical region of sudden expansion $R$. Superficial velocity $U_0$ in the cylindrical region, determined by the total flow through two stages of the swirlers was used as the velocity scale. Distributions of the axial velocity component show that in the case of flow co-swirl (figure 2 (a)), a central region of the reverse flow is formed along the axis of the chamber with an intense flow along the sidewall with the velocity twice exceeding superficial velocity $U_0$. At counter-swirl (figure 2 (b)), the flow pattern is characterized by an absence of recirculation zone and uniform distribution of the
Figure 2. Profiles of averaged axial velocity component for the regimes of flow co-swirl (a) and counter-swirl (b).

Figure 3. Profiles of averaged tangential velocity component for the regimes of flow co-swirl (a) and counter-swirl (b).

axial velocity. Comparison of the tangential velocity profiles for the flows with co- and counter swirl shows that in the counter-swirl regime, the level of resultant flow swirl decreases significantly, and the tangential velocity vector changes its direction near the wall of the cylindrical region.

At the second stage of experimental studies, the averaged axial and tangential velocity components were measured along the entire measuring cross-section at the center of the vortex chamber (figure 4). The measurements were carried out for two variants of the flow rate ratio between two stages of flow swirl: 1) $Q_1 = 6 \text{ m}^3/\text{h}, Q_2 = 4 \text{ m}^3/\text{h}$; 2) $Q_1 = 6 \text{ m}^3/\text{h}, Q_2 = 8 \text{ m}^3/\text{h}$. The characteristic flow patterns are shown in figures 5 and 6. For the first version of the flow ratio ($Q_1 = 6 \text{ m}^3/\text{h}, Q_2 = 4 \text{ m}^3/\text{h}$), the obtained distribution of the axial velocity component shows that in the cases with flow co-swirl (figure 5 (a)), the axial flow, non-uniform over the cross-section, with an intense flow along the sidewalls and extensive region of reverse flow along the chamber axis is formed. The jet flowing from the nozzle of the first stage of the swirler fills the central region, whereupon the axial velocity near the axis has the opposite direction. When the counter-swirl of two flows starts, the

Figure 4. Area of measuring the axial and tangential velocity components using the LDA system.
The recirculation region is reduced significantly (figure 5 (b)). The characteristic distributions of tangential velocity for this regime ($Q_1 = 6 \text{ m}^3/\text{h}$, $Q_2 = 4 \text{ m}^3/\text{h}$) show that velocity values are lower for the counter-swirl configuration.

Figure 6 presents velocity distributions for flow rates $Q_1 = 6 \text{ m}^3/\text{h}$, $Q_2 = 8 \text{ m}^3/\text{h}$ at two stages of swirl. At counter-swirl of the flows as compared to the co-swirl regime, the resulting flow structure is characterized by uniform distribution of the axial velocity along the entire longitudinal section. In the case of co-swirl, the flow is characterized by a high level of the tangential velocity component, which leads to the effect of vortex decay and generation of the precessing vortex core. In the case of counter-swirl, the second stage flow twists the resulting flow in the opposite direction. Due to the effect of mutual swirl suppression, the level of tangential velocities becomes lower. Moreover, swirl is localized near the sidewall, and the central region has a very weak level of swirl with a tendency to change the sign of rotation.
4. Conclusions

In this work, the averaged axial and tangential velocity components were measured using the two-component LDA system for the co-swirl and counter swirl flows in the isothermal model of an adaptive burner. In the regime with the co-swirling flows, formation of a zone of reverse flow was revealed. The regime with the counter-swirling flows showed that when the liquid flow rate at the second stage is higher than at the first one, the work section volume is uniformly filled in combination with pronounced moderate swirl of the flow and its stability.

Based on the results of isothermal experiments, it can be concluded that counter-swirl is more preferable for the use in a two-stage burner because it promotes faster mixing of the burner jets of the first and second stages and more uniform filling of the internal volume of device. This occurs in combination with stable pronounced swirl of the flow, which should increase the time of fuel particle stay in the zone of active combustion and, accordingly, more complete burnout. The latter factor is achieved without the development of strong hydrodynamic instability of the flow characteristic of the apparatus with strong flow swirl.

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