Investigation of the swirled flow structure in the improved four-vortex furnace model

E Yu Shadrin*, I S Anufriev and S V Alekseenko
Kutateladze Institute of Thermophysics SB RAS, Novosibirsk, Russia
*E-mail: evgen_zavita@mail.ru

Abstract. The flow structure in a model of promising four-vortex furnace is investigated using three-dimensional laser Doppler anemometry method (3D-LDA). Using the “minimum total pressure” criterion, a vortex flow structure was visualized: the core looks like a deformed elliptical cylinder. Results have been compared with early PIV experiments and showed good agreement. The mathematical model for full-scale furnace numerical studies can be verified using these data.

Introduction
Combustion of pulverized coal in an air stream is one of the common methods of generating energy [1]. By ensuring intensive swirling of the flow, it is possible to intensify the combustion process. There are a number of methods for creating swirling flow in furnaces. In most of them, pulverized coal is supplied with air to the combustion zone. Due to the orientation of nozzles, a swirled flow is formed in the combustion chamber [2-4]. This procedure of pulverized coal combustion ensures sufficient component mixing, combustion efficiency and less emission of harmful substances into the atmosphere in comparison with traditional combustion on a grate [5], used in "small energy".

Here we study the spatial structure of a swirled flow with the help of an isothermal four-vortex pilot furnace proposed in [6]. Previously, the method of Particle Image Velocimetry (PIV) was used to determine the zone of vortex localization and the optimal regimes for providing a symmetrical four-vortex flow pattern.

Experimental stand and methodology
The flow structure in a laboratory furnace model was experimentally studied using a test setup (Fig. 1), including the following elements: rectangle chamber, primary (side) and secondary (front) nozzles, ventilation. There is also a seeding device (the Involight 1500 DMX fog generator). The measuring system is used in conjunction with a coordinate-moving device to locate at the desired point. To evaluate three velocity components in the measuring area, the 3D-LDA technique was applied. A three-dimensional meter LAD-056, consisting of two two-dimensional devices, was used. These measurements were sufficient to ensure that the error in determining the mean value was not higher than 10% in the 95% confidence interval [7].
Figure 1. Photograph of the test setup.

Results
Experiments were carried out in the vortex localization region (40×240×75 mm), determined via the PIV results [6]. The measurements were performed only in one quarter of setup because of the features of the model and equipment. However, this was sufficient for analyzing the structure in the entire volume since the most symmetrical flow is implemented in the regime observed (4 and 2 m/s from primary and secondary nozzles, respectively) [6]. According to the velocity fields in horizontal cross-sections obtained with the 3D-LDA (figure 2 a-c, figure 3), the flow is swirled. Vector fields in various vertical cross-sections are presented in Fig. 2 d-f; this pattern illustrates an ascending translational motion of the flow. The flow moves vertically upward throughout the entire investigated region, starting from y = 90 mm (y = 0 mm is the center of bottom tier).
Figure 2. The 3D-LDA measurements of the vector velocity field in the vortex localization region: (a) $y = 95$ mm; (b) $y = 120$ mm; (c) $y = 145$ mm; (d) $x = 40$ mm; (e) $x = 60$ mm; (f) $x = 80$ mm.

Let us note that in the velocity minimum region there are “false” vectors (Fig. 3-a). The presence of such vectors is associated with a feature of 3D-LDA equipment: the Vx component is not measured directly, but is restored. Figure 3 shows a comparison of the LDA and PIV measurements, which nevertheless agree well. Thus, the knowledge of three velocity components allows visualizing the vortex flow structure. The vortex structures can be visualized using various approaches [8]: $\lambda_2$- or Q-criteria, etc. But there is a simpler way to determine vortex location: criterion of "minimum total pressure". This criterion works well in similar problems [8]. According to [9], it is reduced to the velocity modulus minimum, assuming the static pressure constant on the model scale.
Velocity isosurface $V=0.3$ m/s measured with 3D-LDA is shown in Fig. 4. Measured vortex is shown in blue. Three other vortices (gray) are mirrored for better visual perception (assuming symmetry for investigated mode [6]). The vortex looks like a deformed vertical elliptical cylinder. In the entire investigated volume, the cross-section of the vortex zone is large; in practice, this contributes to an increase in the time of coal particle burning, thus, ensuring their more complete burnout.

**Figure 3.** 3D-LDA and PIV results [6] comparison: (a) vector velocity field ($y = 120$ mm); (b) $V_z$ profile ($z = 140$ mm; $y = 120$ mm).

**Figure 4.** Velocity modulus isosurfaces ($V = 0.3$ m/s).
Conclusion
The spatial distribution of velocity in the vortex localization region was obtained by the 3D-LDA method. The vortex structure of the flow was visualized using the criterion of "minimum total pressure": it is a deformed vertical elliptical cylinder. The cross-section of the vortex zone is large; in practice, this contributes to an increase in the time of coal particle burning, thus, ensuring their more complete burnout.

Acknowledgments
Visualization of the vortex core structure by means of 3D-LDA was funded by the Russian Science Foundation (Project No. 19-19-00443), the study of average velocity distribution was carried out within the state contract with IT SB RAS (AAAA-121031800229-1).

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