Investigation of aerodynamics of improved four-vortex furnace device

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Abstract. In this work, the inner aerodynamics of a perspective vortex furnace device with a four-vortex burner layout scheme is experimentally investigated. Using the contactless optical flow diagnostics method (PIV), the averaged velocity distributions are obtained in a number of cross sections of the furnace model for various modes. The spatial structure of the flow is studied. It is found that the flow consists of four vertical vortices with curved rotation axes.

1. Introduction

According to the forecasts of various energy agencies, the use of solid fuel (coal) as a source of energy in thermal power plants will soon increase steadily [1]. The use of vortex technologies for burning such fuels is of interest, since it allows solving a number of problems. Swirling the flow increases the residence time of fuel particles in the combustion chamber, which is necessary for their complete combustion, and it allows using “non-project” coals as fuel, which, due to the lack of combustion technologies, are still not in demand. In addition, the presence of a swirling allows achieving intensive mixing of the supplied fuel-air mixture, which provides the best ignition. At the same time, the possibility of using staged combustion allows achieving a homogeneous temperature field with a lower average temperature, which in turn leads to a decrease in the level of toxic combustion products. The scientific substantiation of ways to optimize the aerodynamics of combustion devices using laboratory modeling is the key stage in their development and modernization.

Current work is a continuation of the authors’ work [2] and is devoted to the study of the flow structure in the model of an improved four-vortex combustion device for burning pulverized coal. The main difference of this furnace from existing boilers [3] is the symmetrical arrangement of the front nozzles. This change, according to the authors, will ensure the symmetry and stability of the four-vortex combustion scheme for flexible control of the structure of the swirling flow.

2. Experimental setup and technique

The experimental study of the inner aerodynamics of an improved four-vortex furnace was performed on a laboratory isothermal model made of 10 mm thick plexiglas on a scale of 1:25 (for optical measurements). Two nozzles (corresponding to burner embrasures) are installed on the side walls in three tiers at an angle of 6°, directed toward the center of the furnace. Front nozzles (corresponding to the supply of secondary air) are also installed in three tiers on the front and rear walls directed toward the side walls at an angle of 20°. This arrangement of the burners provides the possibility of creating a swirling flow in the combustion chamber with a four-vortex flow pattern.

The studies were carried out on an experimental stand [4], the main elements of which (Fig. 1) are: an automated system for controlled supply of compressed air; isothermal laboratory model of the four-
vortex furnace; control and measuring devices. The stand is connected with the compressed air supply and ventilation system; it is equipped with a device for seeding the flow with tracers - microdrops of oil.

![Figure 1. Scheme of the experimental stand with the four-vortex furnace model: 1 – compressed air supply, 2 – valve, 3 – regulator, 4 – flow meter, 5 – control cabinet, 6 – manometers, 7 – tracer generator (Laskin nozzle), 8 – four-vortex furnace model, 9 – ventilation, 10 – PIV-system, 11 – computer.]

In this work, the PIV-system “Polis” was used for simultaneous measurement of two components of velocity in the entire section under study. Measurement of the instantaneous velocity field in a given cross section is based on the detection of the movement of particles between two laser flashes. The displacement value is determined using correlation methods applied to the tracer images, when the entire measurement area is divided into regular elementary zones. The PIV measuring system [5] includes: the QuantelEVG dual pulse Nd:YAG laser with a pulse energy of 145 mJ and a pulse duration of 10 ns; lens to generate a laser sheet; ImperX B4820 CCD camera with a resolution of 4904×3280 pixels; Nikon 50 mm lens; synchronizing processor; computer with software ActualFlow and software package PIV Kit; and an assembly kit based on Newport elements. A coordinate-displacement device was used to move the measuring system (positioning accuracy – 0.1 mm).

PIV measurements were performed in several horizontal sections. For each section, the system recorded a series of 1000 pairs of frames taken at a frequency of 1.25 Hz (the time delay in a pair of frames is 100 μs). Data processing was performed using an iterative cross-correlation algorithm to calculate the velocity field: the measurement area is divided into cells with a size of 64×64 pixels and spatial overlap of 50%. Background illumination created by the reflection of light from model elements was eliminated by digital filtering of the image (“background subtraction”).

3. Results
Figure 2 shows the fields of time-average velocities in the four-vortex furnace model for three horizontal cross-sections passing through the centers of each tier, as well as streamlines constructed along these fields. A flow regime in which the ratio of average flow rates at the exit from the side and front nozzles was 2.5 (5 and 2 m/s, respectively) is presented. The characteristic value of the Reynolds number calculated for the length of the vortex chamber at these velocities is \(\text{Re} > 10^5\), i.e. lies in the range that provides the self-similar flow regime [6], and the results of the studies are applicable to flow analysis in full-sized furnaces. It should be noted that due to the geometric features of the model, only half of the furnace volume was available for optical measurements. Therefore, for clarity, the fields obtained by the mirror reflection of the measurement results relative to the plane of symmetry...
passing through the centers of the front nozzles are shown. Thus, a better spatial resolution and a shorter computation time were achieved due to the image capture for only half of the horizontal section (290 × 365 mm). The minimum spatial grid step was 5 mm.

![Figure 2](image_url)

**Figure 2.** Vector fields of time-averaged velocity (a-c) and streamlines (d-f) for the flow regime with 5 and 2 m/s from side and front nozzles correspondingly in horizontal cross-sections: (a, d) bottom nozzles; (b, e) middle nozzles; (c, f) top nozzles.

As one can see, the flow has a complex spatial structure. For the specified ratio of velocities in all three tiers, a swirling flow with four vertical vortices is formed. The position of the center of the vortex changes with height, which indicates the curvature of the vortex axes. Figure 3 presents the measurement results for the mode when the speed ratio was 1.0 (4 and 4 m/s, respectively). This mode is characterized by a pronounced absence of flow symmetry and four vortices, which allows us to conclude that a decrease in the ratio of average flow rates leads to the destruction of the four-vortex structure.
Figure 3. Vector fields of time-averaged velocity (a-c) and streamlines (d-f) for the flow regime with 4 and 4 m/s from side and front nozzles correspondingly in horizontal cross-sections: (a, d) bottom nozzles; (b, e) middle nozzles; (c, f) top nozzles.

Conclusion
Using the PIV method, information on the distribution of the components of the averaged velocity in the isothermal laboratory model of an improved four-vortex combustion device was obtained. The flow structure is presented in the form of four conjugated closed vortices with vertical axes of rotation. It is shown that a change in the ratio of average flow rates through the side and front nozzles (in the direction of increasing flow through the front nozzles) leads to the destruction of the four-vortex flow structure, which in practice is a negative factor. The results will be used in further experimental and numerical studies.

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