THREE-COMPONENT DIAGNOSTICS OF SWIRLING FLOW IN THE MODEL OF AN IMPROVED FOUR-VORTEX FURNACE

by

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The spatial structure of a swirling turbulent flow has been investigated based on the three-component laser Doppler anemometry method in an isothermal laboratory model of a four-vortex furnace. The structure of the vortex cores of the flow with the shape of a deformed vertical elliptical cylinder is visualized using the "minimum total pressure" criterion. The spectrum of velocity pulsations indicates the absence of unsteady periodic vortex structures, which means the occurrence of a stable vortex flow in the volume of the combustion chamber.

Key words: *four-vortex furnace, laser Doppler anemometry, swirling flow, flow structure*

Introduction

Coal-fired power plants still dominate on the market of electricity generation [1-3]. However, the coal industry faces stricter regulations that limit emissions of pollutants such as NO_x, CO, CO_2, SO_x, and PM as compared to other fuels [4], as well as the challenge of involving cheaper low-grade coals. To solve these problems, it is necessary to research fundamental processes and develop new types of boilers that meet modern and advanced standards of energy efficiency and environmental safety.

The common approach in coal power engineering is combustion of pulverized fuel in an air-flow [5]. The organization of vortex movement ensures the effective control of the combustion processes. There are many ways to create swirling flow in combustion chambers. Let us consider only some of them that are of interest for this problem. In many versions of vortex combustion, the fuel, crushed to fine dust, is fed into the combustion zone together with the transporting air, where a swirling stable flame is formed [6-8]. Swirling is carried out due to the fact that the main air-flow enters the burner in the form of an intense swirling flow, which dilutes the air-fuel mixture to the required concentration ratio. Such a flowchart of the process of pulverized fuel combustion is characterized by better mixing of components, increased combustion efficiency, and lower emissions of pollutants into the atmosphere as compared to traditional grate combustion [9], used in *small energy*.

Another direction is the use of low temperature vortex burners [10], which reduce NO_x emissions due to the lack of an oxidant in the re-circulation zone. The influence of secondary air on NO_x formation during coal combustion in a swirling flow was studied in [10, 11]. The tests were carried out using a special vortex burner installed at the bottom of the vertical furnace. In addition to the fuel-air mixture, secondary air was supplied along the pe-

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riphery, which, according to the authors, improves fuel burnout. However, the results showed that the secondary air supply does not significantly affect the quality of fuel particle burnout. The vortex method of fuel and air supply contributed to NO_x reduction, which was confirmed by the experiment without peripheral injection of additional oxygen.

One more technology for burning fuel in a swirling flow is cyclone-type furnaces [12, 13]. Such cyclones are attractive for the needs of *small energy*, since they allow solving the issue related to modernization of outdated boilers, as well as in relation to *large energy*, where the task is to use *non-project* cheaper fuels. The disadvantages of such furnaces are the need to take into account the place where they will be installed, and together with the boiler unit, the design of such installations must be carried out for a specific fuel.

Another method of implementing vortex combustion of energy fuels is the use of vortex furnaces [14-18], where an intensely swirling flow is formed due to the furnace design. Such furnaces allow the use of *non-project* coals and simultaneously minimize harmful emissions without additional costs for treatment devices due to the features of the inner construction. Unlike the methods previously described, organization of the swirling flow inside the boiler does not require the use of special injectors (for swirling the flow of the fuel-air mixture) and installation of an auxiliary device for ignition. However, combustion in such furnaces is complicated by the fact that due to the loss of stability of the swirling flows, various 3-D non-stationary structures of various kinds are formed (for example, precessing vortex core, *etc.*). These structures have a negative impact on all processes in vortex devices. Thus, the study of the structure and dynamics of vortex flows in combustion chambers is an important scientific task, the solution of which is necessary for the design of new furnaces.

This work deals with the study of the 3-D structure of the swirling flow in the isothermal model of a four-vortex furnace, proposed in [18]. Earlier in this work, the particle image velocimetry (PIV) method was used to study two-component velocity fields in the horizontal sections of the model at different regime parameters and to determine optimal regimes with a stable symmetric four-vortex flow structure.

Experimental set-up and method

The experiments were carried out on an isothermal model of an improved four-vortex furnace (290 × 1200 × 730 mm), whose scheme is shown in fig. 1. The main elements of the model are: rectangular combustion chamber – 1, 18 frontal – 2, side – 3, and nozzles installed in three tiers and outlet – 4, for ventilation. The side nozzles are directed diagonally to the center of the model at an angle of 6°. The front nozzles are oriented to the side walls at an angle of 20° to the front wall using separators. This orientation of nozzles ensures formation of four symmetrical vortices, fig. 1(a), in the volume of the model. The model is connected to the system of adjustable compressed air supply from the main line. A more detailed description of the experimental set-up is given in [18].

Laser Doppler anemometry (LDA) was used to study the velocity distribution in the volume of the model. For this purpose, a three-component anemometer LAD-056 (developed at the IT SB RAS), consisting of 2-D devices LAD-05 and LAD-06 with mutually orthogonally polarized laser beams, was used. The device – 5, was mounted on a coordinate-moving device – 6, opposite one of the front walls, fig. 1. The flow was seeded with evaporated glycerin particles using a fog generator Involight 1500 DMX as tracers. The method was used to measure three velocity components in the volume of the model. The experiments were carried out at the nodes of the spatial grid with a step of 5 mm in the region of vortex localization determined in preliminary two-component PIV studies [18]. Vertically, the area – 7, was situated between the centers of the lower and upper tiers of the burners, and this was limited to one passage of the coordinate device (240 mm). The measurements were carried out for 60 seconds at each point, which provided a set of at least 5000 measurements for each component. This number of measurements provided an error of no more than 10% of the measured average value in the 95% confidence interval [19].

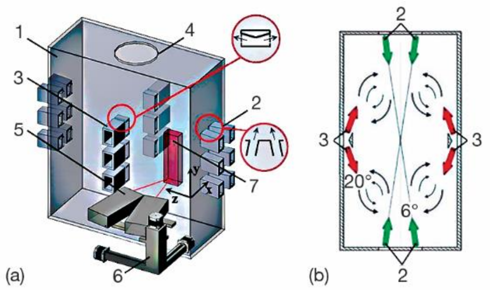


Figure 1. Diagram of the four-vortex furnace model; (a) *1 – combustion chamber, 2 – side nozzles, 3 – central nozzles, 4 – outlet, 5 – LDA velocimeter, 6 – co-ordinate-moving device, 7 – measuring area,* **(b) The scheme of the flow organization in a horizontal cross-section**

Results and discussion

To study the 3-D structure of the swirling flow in the model of an improved four-vortex furnace, a series of experiments was carried out to measure three velocity components in the area of vortex localization (40 × 240 × 75 mm, marked in red in the fig. 1). Since, due to the geometric features of the model and the dimensions of measuring equipment, the entire volume of the furnace was not available for measurements, they were carried out only in one quarter. This is sufficient to analyze the structure of the entire flow while observing the operating parameters that implement a symmetric four-vortex scheme [18]. The velocity vector fields obtained by the LDA method in different horizontal and vertical cross-sections are shown in fig. 2. The regime with velocity values at the outlet of the side and central nozzles of 4 m/s and 2 m/s, respectively, is presented there (total air flow rate of 350 m^3 per hours, average flow rate velocity at the nozzle outlet of 3 m/s). This regime is chosen based on the fact that it implements the most symmetrical flow [18]. From the presented velocity fields in horizontal cross-sections, figs. 2(a)-2(c), fig. 4 it follows that the flow is swirling. At that, the position of vortex depends slightly on the vertical co-ordinate. Figures 2(d)-2(i) shows vector fields in various vertical cross-sections which illustrate the upward translational motion of the flow. Figure 3 shows the profiles of the vertical velocity component in vertical cross-sections. According to them, the flow moves in the up vertical direction at approximately the same velocity in the entire studied area, starting from the level y = 90 mm. At the same time, in the vortex region with the lowest velocity, there are so called *false* vectors, fig. 4(a). The appearance of inaccurate data in some areas of the flow is caused by the fact that one of the vortex components, V_x, is not measured directly when using LDA, *i.e.* it is reconstructed from indirect measurements. Thus, in the area with a V_x value close to 0, velocity determination is erroneous. This conclusion can be confirmed by comparing the LDA and PIV velocity fields [18], shown in fig. 4(a). *False* vectors are those whose direction does not coincide with the direction of the PIV vectors, which are considered reliable because the procedure for filtering false vectors and restoring them was carried out in [18]. The profiles of the z-component of velocity along line z = 140 mm in the central cross-section, obtained by two independent methods that have a good qualitative and quantitative correspondence, are compared in fig. 4(b). On the x-axis, the vortex axis is located at a distance of approximately 60 mm from the front wall. Along the z-axis, it is difficult to determine the position of the vortex axis because the vortex core has an

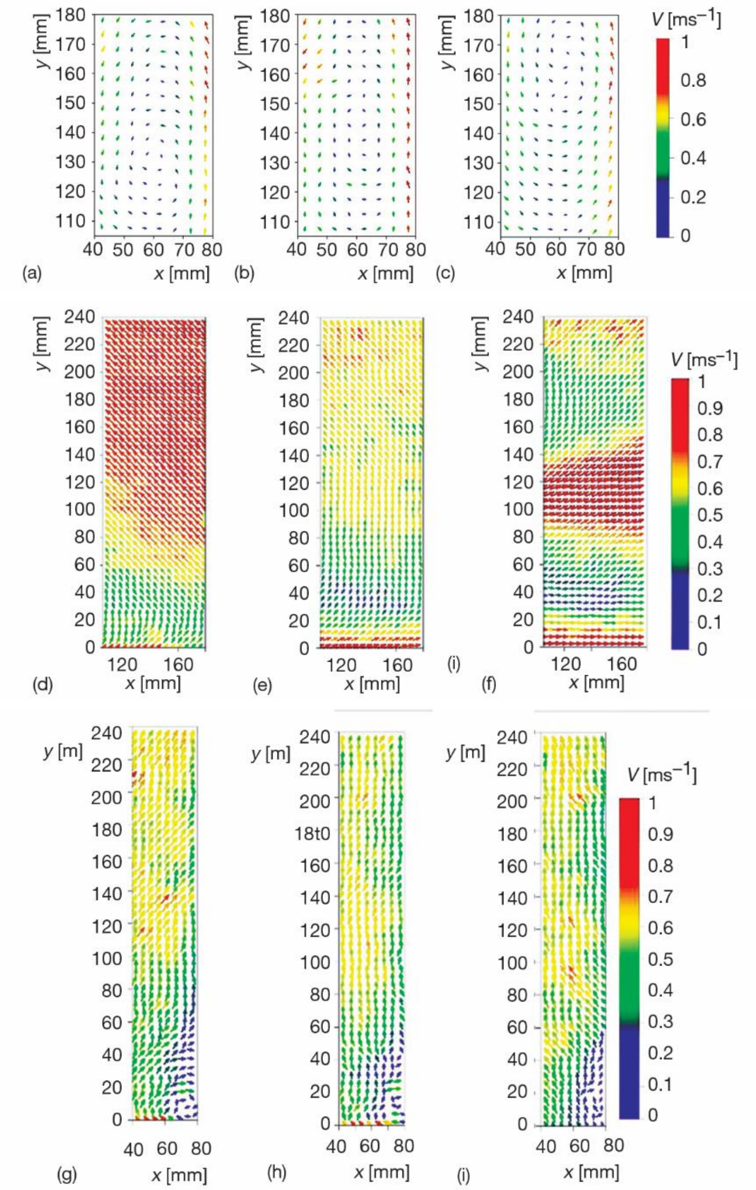


Figure 2. The vector velocity field obtained by the LDA method in the vortex localization region; (a) below the central tier (y = 95 mm), (b) in the central tier (y = 120 mm), (c) above the central tier (y = 145 mm), (d) in vertical cross-section x = 40 mm, (e) in vertical cross-section x = 60 mm, (f) in vertical cross-section x = 80 mm, (g) in vertical cross-section z = 105mm, (h) in vertical cross-section z = 140 mm, and (i) in vertical cross-section z = 175 mm

elongated shape in this direction. Thus, the characteristic structure of the vortex zone can be determined from the LDA results. Various approaches are used to visualize vortex structures [20], for example, the λ_2- or Q-criteria, *etc.* However, a complex calculation method of their determination, taking into account erroneous velocity measurements, can lead to unpredicta-

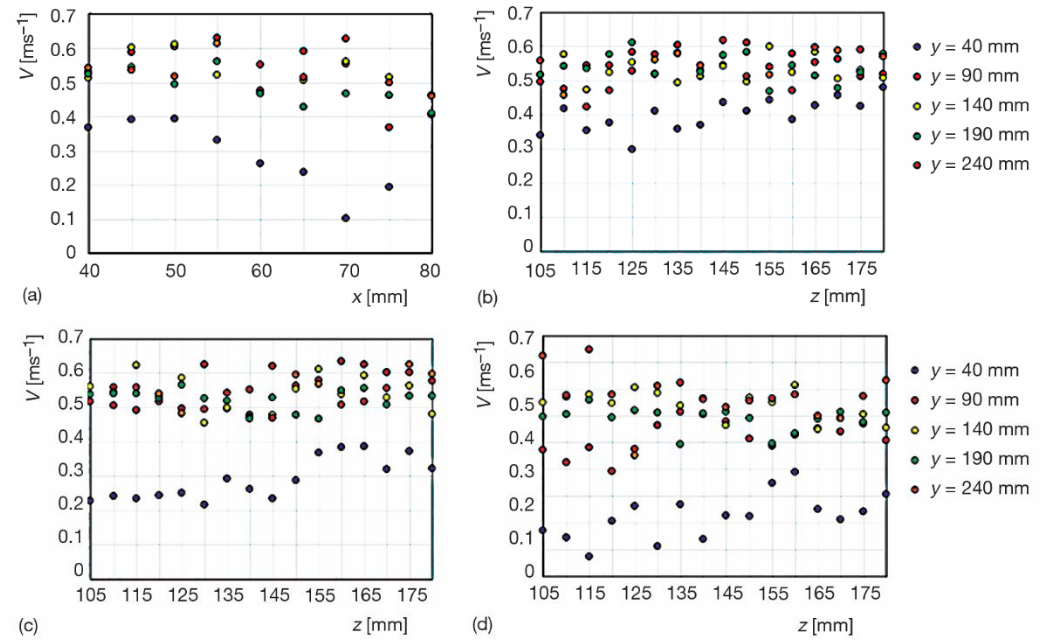


Figure 3. Profiles of the vertical velocity component in vertical cross-section; (a) z = 140 mm, (b) x = 40 mm, (c) x = 60 mm, and (d) x = 80 mm

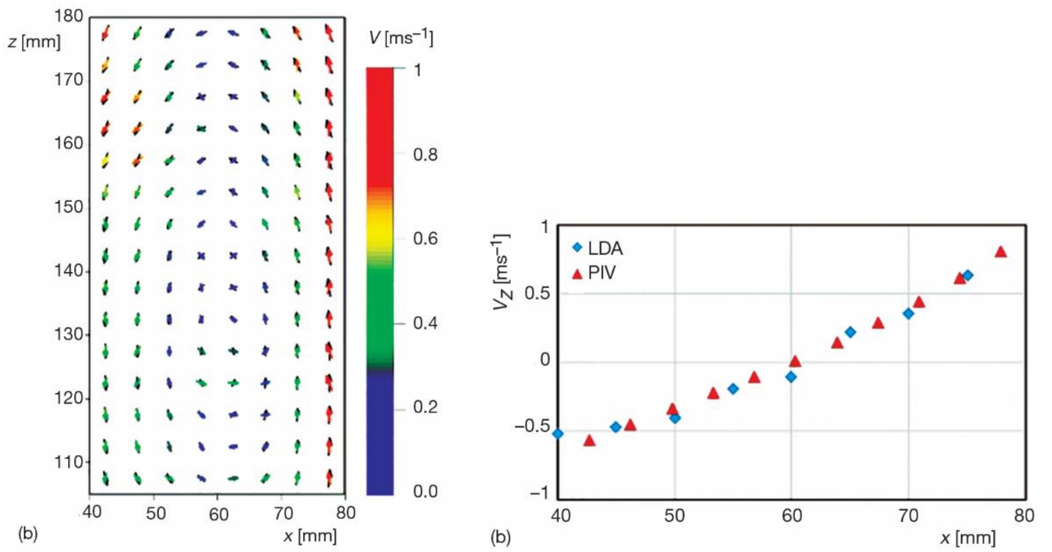


Figure 4. Comparison of LDA and PIV measurements [19]; (a) vector velocity field in horizontal cross-section (y = 120 mm) and (b) profile of the z-component of velocity along line z = 140 mm (y = 120 mm)

ble consequences. Nevertheless, there is an alternative, simpler way to determine the location of the vortex zone, called the *minimum total pressure* criterion, which also performs well enough in similar problems [20]. As it was shown in [21], the minimum of the total pressure is reduced to the local minimum of the dynamic pressure, which in turn is proportional to the square of the velocity modulus $P_{\text{dyn}} = \rho V^2/2$. Thus, assuming that the static pressure is constant at the scale of the laboratory model, the vortex region can be determined by finding out the location of the velocity minimum.

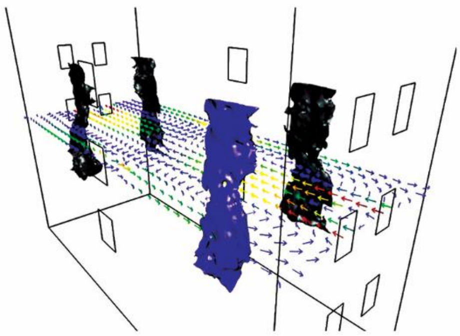
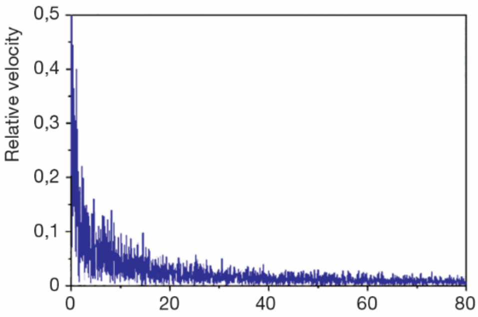


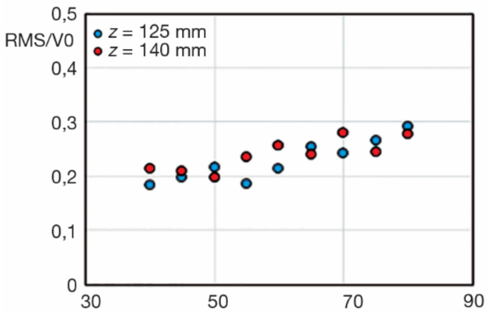
Figure 5. Isosurfaces of velocity V = 0.3 m/s; Ffor clarity, the vector velocity field is plotted in the central section

Figure 5 shows the velocity isosurface V = 0.3 m/s, based on the results of LDA measurements. For the purpose of visual representation, taking into account the symmetry of the flow for this regime [18], the measurement results for one vortex (blue in fig. 5) are duplicated for three other vortices (gray in fig. 5) by mirror reflection. The figure also shows a vector velocity field in a horizontal cross-section passing through the middle of the central tier. The vortex zone has the shape of a deformed elliptical cylinder with a vertical orientation. The smallest *diameter* is located in the area of the central tier of the nozzles, *i.e.*, the vortex is clamped there due to the high values of input velocities. At the same time, in the rest volume of the model, the vortex zone has a large cross-section, which in practice will contribute to the long-term retention of coal particles in the combustion chamber, and as a result, more complete fuel burnout.

The regime of implementation of the symmetric flow structure is analyzed using the *minimum total pressure* criterion. At the same time, especially from a practical point of view, the stability and stationarity of such a vortex structure is of interest. To identify possible non-stationary effects, the velocity pulsations were analyzed (based on the results of 3D-LDA measurements) using the fast Fourier transform, by analogy with [22], where this technique was used to analyze velocity pulsations in a model of a vortex furnace with a horizontal axis of flow rotation. The spectrum of pulsations the z-component of velocity at the point (x, y, z) = (55 mm, 120 mm, 125 mm), normalized to average flow rate velocity V = 3 m/s, is shown in fig. 6(a). The absence of pronounced peaks indicates the absence of pronounced



(a)



(b)

Figure 6. (a) The spectrum of pulsations of the z-component of velocity at the selected point of vortex with co-ordinates (x, y, z) = (55 mm, 120 mm, 125 mm) and (b) profile of RMS deviation of the z-component of velocity normalized to the superficial velocity (3 m/s)

fluctuations in the flow and indicates the relative stability (absence of precession and other large-scale phenomena) of the flow vortex structure. At the same time, there are pulsation modes with a value of up to half of the local average velocity. In addition, fig. 6(b) shows the profile of the RMS of the *z*-component of the velocity, normalized to the average flow rate velocity. A high level of pulsations should be noted (18-28% of the average flow rate), as well as a fairly uniform distribution of the value of the RMS velocity over the vortex cross section, which provides efficient mixing and is a positive property for the processes of pulverized coal combustion.

Conclusions

Velocity fields are measured in an isothermal laboratory model of a four-vortex furnace using the method of three-component LDA. The results of experimental studies allowed visualization of the spatial structure of the flow vortex core based on the *minimum total pressure* criterion. This structure is a deformed elliptical cylinder of vertical orientation. The spectral analysis of velocity pulsations indicates the stability (stationary position) of the flow vortex core in this design of the furnace. For other types of vortex furnaces with a vertical axis of the swirling flow and tangential supply of the fuel-air mixture, the precession of the vortex core is characteristic, and under certain conditions, it is possible to excite powerful thermoacoustic vibrations. Preventing this potentially dangerous effect involves additional restrictions imposed on the operating parameters (such as flow rate and flow swirl) that determine the energy efficiency and environmental characteristics of the furnace. Thus, the absence of non-stationary periodic vortex structures means the presence of a stable vortex structure inside the furnace chamber. At the same time, a sufficiently high level of velocity pulsations in a wide range of frequencies should lead to effective mixing and provide efficient combustion of pulverized coal in a combustion chamber of a similar design.

The results of the study can be used to verify the mathematical model as applied to the processes of fuel combustion in a real furnace with subsequent recommendations for the design of vortex-type combustion chambers.

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Nomenclature

P_{dyn} – dynamic pressure, [Pa]
V – velocity, [ms^{-1}]

Acronyms

LDA – laser Doppler anemometry
PIV – particle image velocimetry

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