Aerodynamics and convective heat transfer processes in cyclone chambers with external recirculation of gases

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Abstract. The paper presents the results of an experimental and theoretical calculation study of aerodynamics and convective heat transfer on the side surface of cyclone recirculation furnace devices. The possibility of controlling the main aerodynamic characteristics without changing the geometric parameters of the cyclone devices by organizing external gas recirculation is shown.

1. Introduction
Cyclone fuel burning devices have a number of advantages over other types of devices of a similar purpose (the ability to achieve high values of heat liberation rate in the furnace volume, a smaller volume of the furnace working space, efficient dust recovery, etc.). The aerodynamics of the cyclonic flow in heating furnaces, cyclone furnaces, dryers and other devices with swirling gas movement [1] can be controlled by changing their basic dimensionless geometric and operating characteristics: the total area of the flow inlet \( \frac{f_{in}}{D_c^2} \), where \( D_c \) is the inner diameter of the cyclone chamber; outlet diameter \( \frac{d_{out}}{D_c} \); working volume length \( \frac{L_c}{D_c} \); input Reynolds number \( \frac{v_{in}D_c}{\nu_{in}} \). The aerodynamics can be also controlled by organizing of external recirculation of gases [2, 3, 4, 5] with a recirculation coefficient for the flow rate \( \frac{Q_{rec}}{Q_{in}} \). The relevance and novelty of the research is determined by the low level of knowledge of the cyclone flow control when organizing external recirculation of furnace gases under the influence of a radial pressure gradient between the wall and axial zones of the cyclone furnace chamber without changing the main design parameters. This principle was used to increase the efficiency of cyclone heating devices and can be used as the basis for the operation of cyclone furnaces and pre-furnaces with a flare-layer method of burning combustible waste from the forest and woodworking industry of the North Arctic region [2].

2. The scheme of the experimental installation
The study of the aerodynamics of the cyclone recirculation device was carried out on a model of a cyclone chamber with an inner diameter \( D_c = 201 \text{ mm} \) and a length \( L_c = 316 \text{ mm} \). The dimensionless total area of the flow inlet \( \frac{f_{in}}{D_c^2} \) was equal to 3,9-10^{-2}. Air was removed from the cyclone chamber through pinching of the outlet end, the dimensionless diameter of which \( \frac{d_{out}}{D_c} \) could take values from 0,2 to 0,4, and the recirculated gas was taken through one or more radial pipes on the side surface of the working volume with \( \frac{f_{rec}}{D_c^2} \) from 0 to 7,2-10^{-2} and connecting channels with the axial zone of the chamber (Figure 1).
Measurements of the fields of velocities and pressures in the working volume of the installation were carried out with a three-channel cylindrical probe, the flow rates of recirculated gas $Q_{\text{rec}}$ were determined with rotameters of constant pressure drop, average in the inlet channels $Q_{\text{in}}$ with a pre-calibrated normal diaphragm in accordance with GOST 8.586-2005.

3. The study of aerodynamics
The distributions of the dimensionless tangential $\bar{w}_\theta = w_\theta / v_{\text{in}}$ (where $v_{\text{in}}$ is the average air velocity in the inlet channels) and axial $\bar{w}_z = w_z / v_{\text{in}}$ of velocities along the chamber radius for the value is shown in Figure 2. As it can be seen from the presented data, the use of external circulation of gases practically does not lead to changes in the velocity fields in the near-wall region, but at the same time it significantly changes the flow in the flow core. Thus, an increase in the recirculation ratio $k_c$ in the investigated range of values 0 ... 0.51 and $d_{\text{out}}=0.3...0.4$ leads to decrease of $\bar{w}_{\text{out}}$ by 1.6 with only a slight displacement of the radius $r_{\text{out}}$ to the peripheral region.

Figure 3 shows the distributions of the axial component of the velocity $\bar{w}_z$ along the radius of the chamber at various values of $d_{\text{out}}$ and $k_c$. From the analysis of the profiles $\bar{w}_z$, it can be concluded that when external recirculation is used, the axial reverse current is eliminated and a forward axial flow is formed, the maximum velocity in which depends on $d_{\text{out}}$ and reaches values commensurate with the input, and with $d_{\text{out}} = 0.2$ it exceeds $v_{\text{in}}$ by 20%.
Figure 2. Radial distribution of dimensionless tangential velocity at different values of $k_c$

It was found in the experiments that by adjusting $k_c$ from 0 to 0.53, it is possible to change the level of the dimensionless (referred to $v_{in}$) tangential velocity $\bar{w}_\psi$ with $\bar{d}_{out} = 0.2$ – by 2, with $\bar{d}_{out} = 0.3$ – by 1.59 and at $\bar{d}_{out} = 0.4$ – by 1.34 times in the conditions of suppression of the axial reverse flow ($k_c \approx 0,1...0,2$).

The analytical distribution $w_\psi$ is found [3, 6, 7] by the joint solution of the equations of motion and continuity; the radial turbulent Reynolds number $Re_{tb}$ was used as a criterion:

$$\bar{w}_\psi = \frac{4\xi}{Re_{tb}(1-\xi^2)+4}$$ (1)
where \( \xi = \frac{r}{r_c} \) - is the dimensionless radius, \( Re_n = 3.7 \left( \frac{f_{in}}{f_{out}} (1-k) \right)^{0.5} \).

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{Radial distribution of dimensionless axial velocity at different values of \( k_c \).}
\end{figure}

Numerical modeling of aerodynamics was performed on the OpenFoam platform using the Launder-Gibson (GL) turbulence model, discretization schemes for differential equations of the second order of accuracy, and a non-stationary solution algorithm. A comparison of the profiles of the
dimensionless tangential velocity $\overline{w_\phi}$, obtained in numerical and physical modeling for a cyclone chamber without recirculation ($k_c = 0$) and with external recirculation ($k_c > 0$) is shown in Figure 4. As can be seen from the data presented, the calculated and experimental values of $\overline{w_\phi}$ are in satisfactory agreement with each other. The maximum discrepancy between the compared values does not exceed $6 \ldots 10\%$.

Figure 4. Comparison of radial profiles $\overline{w_\phi}$: a) 1,3,5 – experimental data with $\overline{d_{\text{out}}} = 0,2, 0,3, 0,4; 2, 4, 6$ – calculated values ($k_c = 0$); b) 1 – experimental data with $\overline{d_{\text{out}}} = 0,3; 2$ – calculated values ($k_c = 0,51$)

4. The study of heat transfer

An experimental study of convective heat transfer on the side surfaces of the cyclone chamber in one- and two-phase conditions has been carried out [4]. The problem of convective heat transfer on the lateral surface of the working volume in two-phase conditions was solved on the basis of the Reynolds analogy using the integral relation [8, 9]

$$\frac{d}{dr_{c,0}} \int_{0}^{\delta_1} w_\phi \theta dy = \frac{q_e}{\rho_g c_{ef}},$$

(2)

where $r_{c,0}$ is the radius of the flow core in the inlet section; $\delta_1$ - thickness of the thermal boundary layer; $\theta$ - excess temperature of the medium; $y$ – coordinate directed along the normal to the wall; $q_e$ – heat flux density on the heat exchange surface; $c_{ef}$ – the effective specific heat of the gas-solid system, $c_{ef} = c_g (1 + c_p / c_g \mu)$; $c_g$ – the average isobaric heat capacity of gases; $c_p$ is the heat capacity of the particles.

As a result of the solution, the calculation formula was obtained

$$\text{Nu} = \frac{1}{2} \frac{Pr}{Pr_{\text{th}}} \frac{\text{Ko Re}_{c,0}^{n_2} \psi^{-0.4}}{\text{Ko Re}_{c,0}^{n_1} \psi^{-0.4}}.$$

(3)

where $n_1 = 1 - \frac{1}{n_2}$, $n_2$ is an exponent depending on surface friction $C_e = A \text{Re}_{c,0}^{n_2}$; $\text{Re}_{c,0} = w_{c,0} D / \nu$ is the Reynolds number built from the tangential velocity at the boundary of the flow core in the inlet section $w_{c,0}$; $Pr$, $Pr_{\text{th}}$ - molecular and turbulent Prandtl numbers; $A$ and Ko are dimensionless complexes that take into account the geometry of the cyclone device and reflect the influence of the longitudinal coordinate and the concentration of the solid phase on surface friction and heat transfer; $\psi$ is the temperature factor.
Figure 5. Comparison of the calculated dependence for heat transfer on the side surface of smooth-walled cyclone chambers with experimental data: lines – calculation according to equations (3), (4); points – experimental data [6, 8, 10]

Equation (3) with \( m = 1/14, \ z = 2/15, \ Pr = 0.7, \ Pr_{th} \approx 0.95, \ A_1 = 0.0486 k_{cl}^{-3.6} \) can be written in a more convenient form, replacing with accuracy \( \pm 5\% Ko/Al \) factor by 0.84 \( k_{cl}^{1.8} \).

\[
\frac{1}{n} \lg \frac{\text{Nu}}{0.5 \text{Pr} \text{Pr}_{th}^{0.4} \psi} - \frac{\text{Ko}}{A_1} = 0.015 k_{cl}^{-1.8} R_{m}^{0.875} \psi^{-0.4}. \tag{4}
\]

The law of the change in the Nusselt number with an increase in the mass concentration of the suspension was established

\[
\text{Nu}_{\mu} = \text{Nu}/\text{Nu}_{\mu=0} = (1 + c \mu) [(1 + A_1 \mu) k_{\mu}]^{p/(n+1)/(2n+1)}, \tag{5}
\]

where \( \text{Nu}_{\mu=0} \) is the Nu number by \( \mu = 0; \ c = c_p/c_g \) - ratio of specific heat capacities of particles and gases; \( A_1, p \) - experimental coefficients; \( k_{\mu} \) is a correction factor that takes into account the influence of \( \mu \) on \( r_{min} \).

The dependence (5) is in satisfactory agreement with the experimental data of the authors [11] and other researchers [12, 13] (Figure 6). From the presented results, it follows that the effect of dustiness of the flow on heat transfer at a mass concentration of dust and fine waste up to 0.05 kg / kg, typical, for example, for ventilation and aspiration systems of enterprises of the pulp and paper and woodworking industries, is insignificant [14].
Figure 6. Comparison of experimental (points) and calculated (lines) values of Nusselt numbers at different mass concentration of solid particles; points: 1 - [11]. 2, 3 - [12]; calculation: according to (5): 4 - \( A_1 = 1 \); 5 - \( A_2 = 0 \) (in the absence of the influence of \( \mu \) on \( c_{fc} \)); 6 - according to [13]; 7 - according to (5) at \( A_1 = 0.5 \) (taking into account the influence of \( \mu \) on \( r_{pm} \)).

The assessment of the aerodynamic and energy efficiency of cyclone devices [2, 5, 10, 15, 16, 17, 18] is based on the analysis of energy consumption for the creation of rotational motion

\[
\Delta \overline{p}_{cr} = \left( \frac{2\pi}{0} \int_0^R \left( \frac{w_0^2}{2} \right) \rho dz \right) / \Delta p_t,
\]

aerodynamic efficiency ratio

\[
\zeta_{pm} = \zeta_{in} / \overline{W}_{pm}^2,
\]

and dimensionless complex

\[
K_c = \frac{\text{Nu}}{\text{Re}_{in}^{n} \zeta_{in}}.
\]

where \( \Delta p_t \) is the total pressure drop in the cyclone; \( n \) is the exponent in the thermal similarity equation, \( \zeta_{in} \) is the ratio of aerodynamic resistance of the cyclone device, calculated according to the input conditions, \( \zeta_{in} = 2\Delta p_t / (\rho v_{in}^2) \).

Calculations using (6) - (8) make it possible to obtain recommendations on the choice of optimal geometric and operating parameters of cyclone furnace and recirculation devices, which ensure a decrease in aerodynamic resistance and energy consumption for blast, air heating due to heat exchange with the side surface of the furnace space.
5. Conclusions

1) Based on the results of the work, it can be concluded that by adjusting the recirculation ratio and aerodynamic resistance of the recirculation channel (channels), it is possible to control the main aerodynamic characteristics without changing the geometric parameters of the cyclone device.

2) An experimental study of the aerodynamics of an unloaded cyclone combustion device with external gas recirculation in a wide range of varying input and output conditions has been carried out. Numerical modeling of gas movement was performed on the Open-Foam platform using the Launder-Gibson (GL) turbulence model. The analytical distribution $\bar{w}_\phi$ is found by the joint solution of the equations of motion and continuity using the radial turbulent Reynolds number $Re_b$ as a criterion.

3) On the basis of the integral relation for the thermal boundary layer, the problem of calculating convective heat transfer on the lateral surface of the working volume of a cyclone combustion device in one- and two-phase flow conditions has been solved.

4) Criteria for assessing the aerodynamic and energy efficiency of cyclone devices, applicable to cyclone furnaces with external gas recirculation, were proposed.

6. References

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