Thermophysical fundamentals of cyclonic recirculating heating devices

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Abstract. This report presents the results of experimental and theoretical research of aerodynamics and convective heat transfer in cyclone devices with the new system of external recirculation of heating gas under the influence of radial pressure gradient in a heat carrier’s swirling turbulent flow. The dynamic problem of tangential velocity distribution in a clearance volume is solved at various re-circulation ratio values including limiting quantities (k_r = 0; 1) and variations in cyclonic combustion chamber’s design parameters and operating conditions (Re); the integrated calculation ratios for fundamental aerodynamic characteristics of a recirculation device are derived. The first experimental and numerical studies of convective heat transfer on internal and external surfaces of a hollow shaft in a swirling recirculation flow are derived through the instrumentality of OpenFOAM, these studies are also conducted for a setting of several cylindrical solid inserts. The external surface heat problem of a hollow cylindrical insert is solved with integral and digital methods; generalized similarity equations for the internal and external surfaces extended in range of Reynolds number are derived. The experimental data is in reasonable agreement with the derived curves and the results of mathematic modelling of convective heat transfer. Calculation recommendations for optimal selection of k_r values at various ratios of their geometric characteristics and products utilization rate are obtained.

1. Introduction
The use of cyclone furnaces for metal heating and heat treating of fabricated metal products is one of the prospective directions for furnace heat engineering. Due to intensification of convective heat transfer on surfaces of work pieces and sidewall, temperature drop required for heating is decreasing. Large-scale implementation of cyclone heating devices into metallurgy and engineering industries promotes energy performance of heating equipment stock and decreases consumption of gaseous fuel. Further developing of cyclone combustion chamber configuration is related to the removal of following disadvantages: non-uniform heat supply towards internal and external hollow cylindrical surfaces due to paraxial reverse flow, which draws cooled gases from exhaust vent, nonoptimality of flow distribution in furnace body and others [1].

2. Problem Formulation
In the authors’ investigation a new method of enhancing aerodynamic and energy performance of cyclone heating devices through establishing an external flow of heating agent from a near-wall zone
to a paraxial zone on account of occurring radial differential pressure is proposed and studied [2, 3].

Figure 1 shows the diagram of cyclone heating device with external recirculation of heating gas and various load ratios of clearance volume.

3. Aerodynamics

Addressing a problem of distribution of tangential velocity component $w_\varphi$ in a furnace volume at a wide range of dimensionless geometric parameters: diameter of outlet duct $d_{out} = d_{out}/D$, total inlet area $f_{in} = 4f_{in}/(\pi D_d^2)$ and recirculation ratio $k_r = Q_{rec}/Q_{in}$ ($Q_{rec}$ and $Q_{in}$ are gas volumetric flow rates through a recirculation system and total flow rate[1] with the involvement of experimental and numerical investigations [2] enables to develop a calculation procedure based on aerodynamic characteristics of recirculation devices. Radial distribution of tangential velocity could be found through solving the system of equations for tangential velocity component and continuity equation in cylindrical coordinates [1, 3] under the following conditions: 1) the flow is axially symmetrical, steady-state, incompressible 2) turbulent viscosity $\nu_t$ doesn’t change radially and far exceeds the molecular viscosity $\nu$.

The solution is carried out in two different ways: 1) on the presumption that $w_z$ in nuclear interior area ($0 < r < r_{out}$) increases in linear fashion at the height of cyclone chamber from a blank end to diaphragm outlet, when in exterior area ($r_{out} < r < r_c$, where $r_c$ – radius of swirling flow’s core) $w_z$ is equal to zero; 2) given that the flow’s core is of spiral nature with permanent torque angle, that is $a = w_r/w_\varphi = \text{const}$. The validity of these presumptions is proved with numerical simulation in OpenFoam based on the Gibson-Launder turbulence models for unloaded cyclone devices and on the Menter models (corrected to curvature of streamline) when loaded with a hollow insert.

In the first instance the dependences are established that are similar to Goldshtick solutions [4] for swirling chambers:

$$\frac{-w_\varphi}{\psi} = \frac{1}{\psi} \left( \frac{e^{\psi r_{out}} - 1}{e^{\psi r} - 1} \right) \text{ when } r \leq r_{out};$$

(1)

$$\frac{-w_\varphi}{\psi} = \frac{1}{\psi} \left( \frac{\text{Re}_r e^{\psi r_{out}} (\psi r_{out}^2 - 1)}{e^{\psi r^2} - 1 (\text{Re}_r + 2)} + 1 \right) \text{ when } r_{out} \leq r \leq r_c;$$

(2)
where \( \psi = r/r_{\text{out}} \), \( \vec{w}_\theta = w_{\theta,\text{out}}/w_{\phi,\text{out}} \) – nondimensional radius and tangential velocity; \( \text{Re}_r = w_r r_c/\nu \) – radial turbulent Reynolds number; \( w_{\text{in}} \) \( w_{\phi,\text{out}} \) – radial and tangential velocity component at radius of \( r_c \) and \( r_{\text{out}} \) respectively.

In the second instance the analytical expression is derived:

\[
\vec{w}_\theta = \frac{4\xi}{\text{Re} \left(1 - \xi^2\right)^{1/4}},
\]

where \( \xi = r/r_c \) - nondimensional radius.

The both methods give the comparable results deviation from the empirical data when \( f_{\text{in}}/f_{\text{out}} = 0.25...2.0 \). However, when \( f_{\text{in}}/f_{\text{out}} > 0.5 \) and making the assumption of constant spin angle, \( w_\phi \) cut-out is highly dependent on \( |\text{Re}_r| \) so a fractional \( |\text{Re}_r| \) error leads to a significant deviation of calculated velocity values from experimental values. Therefore, in the present study it is recommended to use the expressions (1, 2). The comparison of experimental and calculated \( w_\phi \) cut-outs is given in figure 2.

In the equations (1...3), the radial turbulent Reynolds number \( \text{Re}_r \) is used as similarity criteria.

The \( \text{Re}_r \) calculation method for swirling chambers \([3]\) is not applicable for cyclone devices, since: 1) prevents from calculating \( w_\phi \) cut-out when \( r_{\text{min}} > r_{\text{out}} \) and is used only with large \( f_{\text{in}} \) values; 2) due to geometrical distinctions between swirling chambers and cyclone devices at \( |\text{Re}_r| = 3...6 \), noticeable divergence between estimated and experimental data is occurring (figure.3). \( |\text{Re}_r| \) values, which are received from a comparison between experimental \( w_\phi \) cut-outs and calculated in (1, 2), are summarized by the dependence

\[
|\text{Re}_r| = 3.7 \left( \frac{f_{\text{in}}}{f_{\text{out}}} \left(1 - k_r\right) \right)^{0.5}.
\]

External recirculation has low influence on tangential velocity cut-out in peripheral area, thus, in order to calculate aerodynamic characteristics at the edge of flow’s core \( (w_c, r_c) \), it is appropriate to use the current methods for common cyclone chambers \([5,7]\) with the following correction multiplier: \( w_{\phi,\text{in}}/w_{\phi,\text{cr},k_r=0} = (1 - 0.15k_r) \) and \( r_c/r_{\text{cr},k_r=0} = (1 - 0.1k_r) \).
When a cyclone recirculation device is loaded with a hollow shaft, characteristic maximums of tangential velocity in exterior \( w_{\phi_{m1}} \) and interior \( w_{\phi_{m2}} \) areas of flow cloud be found with reasonable accuracy from the cut-out for the unloaded chamber at radiuses \( r_{\text{ins ext}} \) and \( r_{\text{ins int}} \) with the factor of reduction in rotational velocity \( \gamma \) [1,3].

The \( p_{s.w.} \) calculation is conducted through integration of radial equilibrium equation:

\[
\bar{p}_{s.w.} = \gamma^2 \int_{r_{p_{s.w}}}^{r_{\text{ins ext}}} 2 \frac{w_{\phi_{m}}}{} \, dr + \int_{r_{\text{ins ext}}}^{\bar{r}_{c}} \frac{w_{\phi_{m}}}{} \, d\bar{r}.
\]  

When pressure on the side surface of chamber ( \( \bar{p}_{s.c} \) ) and the correlation between \( p_{s.w.} / p_{s.in} \) [7] are found, total aerodynamic resistance coefficient of the recirculation device \( \zeta_{\text{in}} \) can be defined. The comparison between experimental and estimated \( \zeta_{\text{in}} \) values for unloaded and loaded with a hollow shaft cyclone chambers shows that discrepancy does not exceed ±12% and ±8% respectively.

4. Convective heat transfer

This section explores heat transfer in a cyclone recirculation device loaded with a hollow shaft and a setting of several work pieces. It is experimentally proved that the use of external recirculation of gases has low impact on intensity of convective heat transfer. The largest change amounts to 13%, it is observed on the interior surface when \( d_{\text{out}}=0.2 \). With increase in Reynolds number, the intensity of convective heat transfer raises faster on the internal rather than external surface, which is determined by highly turbulent flow that develops in the external area of insert; that flow is similar to the flow of a swirling jet in a pipe of uniform cross section.

In figure 4 heat flux distribution (q), attributed to the average values (q_{avg}), obtained through numerical simulation within an external and internal shaft length are given. As figures 4a and 4b demonstrates, irregularity of distribution on the exterior surface of the cylindrical shaft is relatively small (at most ±10%). On the internal surface, minimum and maximum heat flows might vary by up to 40%; the change of q/q_{avg} within hollow shaft length resembles the similar q distribution for swirling flow of gas in a pipe; progressively as approaching a diaphragm end of cyclone chamber, q/q_{avg} is monotonically decreasing until axial coordinate \( zd_{\text{ins ext}}=2.5...3 \), upon which it is monotonically increasing because of intensifying flow influence.

In figure 4c, distribution of local heat-transfer coefficients on the surface of one of the setting’s work pieces are shown, attributed to the average values in cyclone devices for both: with and without external recirculation of gases. The averaged \( \alpha/\alpha_{\text{avg}} \) values are depicted with lines.
Figure 4. Heat flux distribution on the external (a) and internal (b) surfaces of a hollow shaft ($k_r=0.33$, $d_{ins.out}=0.64$ и $d_{ins.in}=0.34$; $d_{out}=0.4$) and distribution of peripheral heat-transfer coefficients $\alpha/\alpha_{avg}$ along the insert(c) in a setting of 6 work pieces ($d_{ins}=0.16$, $d_{set}=0.5$); cyclone chamber: 1 – $k_r=0$, 2 – $k_r>0$.

As can be seen in figure 4, heat-transfer rate along the perimeter of work piece changes more than twofold, two peaks are observed: the first one at coordinate angle of 150°, corresponding to swirling flow attachment point in the external area; the second one – at angle of 30°, at the attachment point of forced paraxial vortex.

Distributions of $\alpha/\alpha_{avg}$ in the chamber are almost identical with recirculation of gases or without it ($k_r=0$).

Therefore, the calculation of convective heat transfer in a setting of several work pieces in cyclone recirculation devices should be conducted according to methods designed for common cyclone chambers in ASTU – NArFU [5, 7]. In this case, external recirculation equalizes temperature pattern in a setting by means of flow of hot gases from a peripheral area of heating furnace to a paraxial area.

In the present paper it is demonstrated on the basis of empirical analysis that the following generalized similarity equation, obtained through integral method, might be used for convective heat transfer calculation on the external surface of inserts, despite of various impact on aerodynamics of a cyclone device as the consequence of clearance volume loaded with hollow and solid shafts at high diameters of inserts ($d_{ins.out}>0.4$) [6]:

\[
\text{Nu}_{ins.out} = 0.064 D(\eta_{ins}) Re_{\phi_m}^{0.24}, \text{ when } Re_{\phi_m} = w_{\phi_m} d_{ins.out} / \nu = 4.5 \times 10^3 ... 1.7 \times 10^5, \tag{6}
\]

\[
\text{Nu}_{ins.out} = 0.464 D(\eta_{ins}) Re_{\phi_m}^{0.556}, \text{ when } Re_{\phi_m} = 8.5 \times 10^3 ... 4.5 \times 10^4, \tag{7}
\]

where $D(\eta_{ins}) = 1 - k_{ins} \eta_{ins}^{m}$; $k_{ins}$ – coefficient dependent upon dimensionless external diameter of insert $\eta_{ins}=r_{ins.out} / r_{phi}$. When comparing the experimental data to dependence calculation (6, 7), discrepancy does not exceed ±7.5%.

Integration of experimental data on the external surface of a hollow shaft is conducted on the basis of the following correlation dependence

\[
\text{Nu}_{z,int} = 0.029 Re_{z}^{0.8} Pr^{0.4} \epsilon_T \epsilon_{\phi}, \tag{8}
\]

where $\text{Nu}_{z,int}= \alpha z / \lambda$ – Nusselt number; $Re_{z}=w_{z,avg} z / \nu$ – Reynolds number; $w_{z,avg}$ – average axial velocity in the internal area a hollow shaft; $z$ – axial coordinate; $Pr$ – Prandtl number; $\epsilon_T = (2/(T_w/T_{in}))^{0.5} + 1)^{1.6}$ – anisothermality parameter; $\epsilon_{\phi} = f(\Phi_{\phi})$ – parameter that shows how stream swirl impacts rate of heat exchange, where $\Phi_{\phi}$ - integral swirling parameter:
\[ \varepsilon_0 = 1 + 0,079 \Phi^{1.8}. \]  

Deviation of experimental data from the dependence (8) does not exceed \( \pm 12.5\% \).

5. Aerodynamic and energy performance

Evaluation of aerodynamic efficiency of recirculation is carried out, whereby total resistance of cyclone is divided into pressure loss at entrance \( \Delta p_{\text{in}} \), exit loss \( \Delta p_{\text{ext}} \) and energy consumption to cause rotational motion \( \Delta p_{\text{rot}} \):

\[
\Delta p_{\text{rot}} = \left( \frac{2\pi}{R_c} \int_0^{R_c} r \frac{w_r^2}{2} dr dz \right) / \Delta \rho; \quad \Delta p_{\text{in}} = \frac{p_{\text{in,rot}} - p_{\text{in,w}}}{\zeta_{\text{in}}}; \quad \Delta p_{\text{ext}} = 1 - \Delta p_{\text{in}} - \Delta p_{\text{rot}},
\]

where \( \Delta p_{\text{in}}, \Delta p_{\text{ext}} \) – dimensionless total pressures in inlet ducts and chamber’s sidewall. Estimates suggest (10) that \( k_i \) increase raises aerodynamic cleanliness of cyclone chamber: \( \Delta p_{\text{in}} \) is decreasing and \( \Delta p_{\text{rot}} \) costs are growing.

Dimensionless number \( K_e \) is used to evaluate energy performance of cyclone recirculation device loaded with a hollow shaft:

\[
K_e = \frac{\text{Nu}_{l,0}}{\text{Re}_{l,0} \zeta_{l,0}},
\]

where \( \text{Nu}_{l} \) – Nu number, calculated for an internal (\( \text{Nu}_{\text{in,rot}} \)) or external (\( \text{Nu}_{\text{ext,rot}} \)) surface of a hollow shaft; \( n \) — index of power in similarity equation.

The higher intensity of heat transfer on a heat transfer surface at specified \( \text{Re}_{\text{in}} \) value plus the lower aerodynamic resistance of cyclone chamber are, the higher becomes energetical cleanliness of device.

In the present work in order to determine the optimal \( k_{i,\text{opt}} \) value, \( K_e \) number is relegated to the analogous index of cyclone chamber without external recirculation \( (k_i=0) \). In all reviewed cases, the use of external recirculation leads to increase in energy performance due to significant decrease in aerodynamic resistance with its low impact on heat transfer.

The rate of \( K_{e,\text{ext}} / K_{e,\text{ext,k}=0} \) index is monotonically increasing with \( k_i \) increase: \( K_{e,\text{ext}} / K_{e,\text{ext,k}=0} \) curves have strongly pronounced peak at optimal \( k_{i,\text{opt}} \) value. The optimal \( k_{i,\text{opt}} \) value can be calculated within the accuracy of \( \pm 15\% \) within the range of \( d_{\text{ext}}=0.2...0.4, \; f_{\text{in}}=0.042...0.122 \) and \( d_{\text{in}}=0.1...0.6 \) through integrated dependence:

\[
k_{i,\text{opt}} = \left( 0.0126 f_{\text{in}} \left( \frac{7d_{\text{ext}}}{0.7} - 0.2 \right) \left( \frac{d_{\text{in}}}{-1} \right) + 1. \right)
\]

The impact of external recirculation of gases on aerodynamic characteristics of cyclone heating device and duration of heat treatment of products in the form of a hollow shaft is assessed. It was demonstrated, that the use of external recirculation of the proposed kind allows to decrease aerodynamic resistance of furnace by 15% and duration of heat treatment by 22% due to increasing uniform heating of products.

References

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