Aerodynamics, convective heat exchange and energy efficiency of cyclone devices with large relative length

D A Onokhin, A N Orekhov, S V Karpov, and M I Konoplev
Northern (Arctic) Federal University named after M V Lomonosov
Russia, 163002 Arkhangelsk, Severnaya Dvina embankment, 17

Abstract. The main purpose of the work was to optimize the design of the cyclone devices with large relative length. Studies of aerodynamics and convective heat exchange in cyclone devices have been performed to determine their optimal parameters. Two methods for determining the aerodynamic and thermal efficiency of cyclone chambers are proposed. The analysis according to the proposed methods was carried out and the optimal geometrical and regime parameters of cyclone chambers were determined, ensuring minimal energy costs and an increase in efficiency.

1. Introduction
Cyclone chambers found a use in manufacturing and energy industries as heating and furnace systems [1,2], separators [3], waste heat recovery units, air-heaters and other industrial heat-exchanging installations [2]. It is driven by their high technical and economic features, utilisation flexibility and simple design, which is essential for high intensity of heat and mass transfer within cyclone chamber space.

Originally, the working volume of chambers was relatively short. The expansion of industrial use and increase in productivity resulted in the need to increase the working volume length and to conduct additional research aimed at developing recommendations for the calculation and construction of cyclone chambers.

2. Research methodology
Structure optimisation with the most appropriate geometrical and performance characteristics of cyclone chambers has the objective of attaining the maximum aerodynamic and energy-technological efficiency. The key dimensionless design factors (which vary in experiments) of cyclone heating devices are: length of working volume \( \frac{L_v}{D_v} = 1.00...17.25 \) (\( L_v, D_v \) are the length and diameter of working volume), area of inlet duct \( \frac{f_{in}}{\pi D_v^2} = 0.02...0.21 \), diameter of outlet duct \( \frac{d_{out}}{D_v} = 0.2...1.0 \) and diameter of workpiece \( \frac{d_{wp}}{D_v} = 0.31...0.69 \). The main performance characteristic that determines the type and regime of a cyclone flow is Reynolds number \( Re_{in} = \frac{\nu_{in} D_v}{\nu} \) (where \( \nu_{in}, \nu \) are the average speed and kinematic coefficient of viscosity in inlet ducts).

Different dimensionless factors were proposed as an evaluation criteria of cyclone chamber efficiency [2, 3]. For example, coefficient of aerodynamic efficiency \( \frac{\Delta p_{in}}{\rho \nu_{in}^2} \) was applied in works by E. N. Saburov [2], S. V. Karpov[3], A. N. Orekhov and others; this coefficient represents the correlation between available head at the chamber inlet and dynamic head, which is calculated.
based on the maximum tangential velocity in the working volume. However, according to the analysis of conducted research, values of geometric parameters that are drawn on the minimum value of $\zeta_{\psi_{\text{em}}}$ coefficient are not always optimum for cyclone chambers of large relative length due to more complicated structure and rearrangement of a flow inside them.

3. Results of study

Earlier studies [4, 5] suggest that in the working volume of cyclone chambers of large relative length the flow core is one of the main flow regions; alongside, formulae for flow characteristics at the edge of flow core were deduced:

$$\bar{r}_c = 0.96L_c^{-0.24}f_{\text{in}}^{0.03},$$

$$\bar{w}_{\psi_{\text{c}}} = 6.23L_v^{-0.24}f_{\text{in}}^{0.76}d_{\text{out}}^{-0.18},$$

where $\bar{r}_c = R_c/r_c$ is dimensionless radius of flow core;

$\bar{w}_{\psi_{\text{c}}} = w_{\psi_{\text{c}}}/V_{\text{in}}$ is dimensionless tangential speed at the edge of flow core;

$R_c$ is radius of working volume.

Consequently, it appears that coefficient of cyclone friction calculated on the basis of tangential velocity at the edge of flow core $\zeta_{\psi_{\text{c}}} = 2\Delta p / \rho w_{\psi_{\text{c}}}^2$ is a more reasonable way to measure aerodynamic efficiency of relatively large cyclone chambers. Figure 1 shows the change dependences between $\zeta_{\psi_{\text{c}}}$ coefficient and geometrical parameters of cyclone chambers studied in this paper.

![Figure 1](image)

**Figure 1.** Effect of geometrical parameters of cyclone chambers on friction factor $\zeta_{\psi_{\text{c}}}$ depending on $L_v$ (a), $f_{\text{in}}$ (b), $d_{\text{out}}$ (c). Keys: ○—unloaded chamber, □—$d_{\text{wp}} = 0.31$, $\Delta = 0.47$

Study of distributions of $\zeta_{\psi_{\text{c}}}$ coefficient has shown that the optimum dimensionless length is in the range of 2.5...3.0, where the maximum productivity and good energy-technological parameters are achieved. Further increase in $L_v$ leads to lower aerodynamic values of the flow, primarily, the overall level of rotational speeds. Friction factor is growing and approaches its maximum value asymptotically when $L_v = 21.5$.

The influence of the relative inlet area on the creation and maintenance of specific predetermined degree of whirling is definite, regardless of loading efficiency of the working volume. The optimum value is $f_{\text{in}} = 0.08$. A decrease in $f_{\text{in}}$ to the values lower than 0.04 leads to the fall in the degree of whirling and abrupt growth of $\zeta_{\psi_{\text{c}}}$. An increase in $f_{\text{in}}$ above 0.08 has no significant influence over the level of tangential velocities.

The study [2] confirms that for unloaded cyclone chambers at any length of the working volume the optimum $d_{\text{out}}$ is 0.4...0.6. When chamber is loaded with a workpiece, it is recommended to
measure the efficiency of cyclone chamber by correlation between the inlet and outlet areas as well as relative diameter \( \frac{D_{wp}}{D} \).

Nevertheless, the proposed methodology of the aerodynamic efficiency evaluation of cyclone devices based on the coefficient of friction \( \zeta_{qc} \) has its drawbacks and is not always applicable. For instance, the cyclone flow at high \( \frac{D_{wp}}{D} \) values is similar to the axial flow inside a circular duct which leads to dwindling of the flow core. At the same time, the optimum geometric parameters for cyclone heating devices should be selected bearing in mind both the aerodynamic and thermal efficiency.

In accordance with generalized empirical data the heat problem of boundary level on the inner surface of the working load is solved; the equation for local heat-transfer coefficients is derived:

\[
Nu = 0.088Re_{\phi}^{0.75} \zeta^{-0.29},
\]

where \( Nu = \frac{\alpha D_v \Delta}{\lambda} \) is Nusselt number;
\( \alpha \) is heat transfer coefficient;
\( \lambda \) is thermal conductivity of gases;
\( Re_{\phi} = \frac{w_\phi D_v}{\nu} \) is Reynolds number;
\( \zeta = \frac{\phi}{D_v} \) is longitudinal coordinate directed alongside working volume from the end wall towards the outlet.

The degree of energy efficiency of cyclone devices can be measured with the help of special dimensionless number [3]:

\[
K_e = \frac{Nu}{Re_{\phi}^{0.75}} \zeta_{in},
\]

where \( \zeta_{in} = 2\Delta p_1/\rho V_{in}^2 \) is aerodynamic drag coefficient calculated based on the inlet conditions.

Thus, the higher the intensity of convective heat transfer (to the side wall or workpiece) at the final value \( V_{in} \) (and \( Re_{in} \)) and the lower the energy costs of blast air, which are \( \zeta_{in} \)-dependent, the bigger is the energy efficiency of a cyclone device.

Correlations between \( K_e \) and \( \tilde{f}_{in} \), \( \tilde{d}_{wp} \) are shown in figure 2. Icons depict experimental data, lines are calculated curves, (3) is taken into account.

![Figure 2](image)

**Figure 2.** Influence of \( \tilde{f}_{in} \) (a) and \( \tilde{d}_{wp} \) (b) on \( K_e \). Keys: a) \( \times \)--- \( \bar{L}_v = 1.00 \), \( \circ \)---7.25, \( \circ \)---12.75, \( \Delta \)---17.25; b) \( \square \)--- \( \tilde{f}_{in} = 0.04 \), \( \circ \)---0.08, \( \Delta \)---0.21

The estimation made with (4) is consistent with the conclusions reached using the \( \zeta_{qc} \) coefficient. Hence, \( \bar{L}_v = 10...18 \) and \( \tilde{f}_{in} = 0.04...0.10 \) can be considered optimum. In such a case, maximum \( K_e \) is:

\[
K_{e,\text{m}} = 0.059L_v^{0.11}.
\]

4. Conclusions
As a result, based on the analysis and generalisation of the empirical and calculation data we put forward two evaluation methods of aerodynamic and thermal efficiency of cyclone heating devices with a large relative length. Choosing the optimum geometric parameters for cyclone heating devices can greatly reduce energy costs of the creation and maintenance of the optimum degree of flow whirling, and, consequently, increase the device efficiency and lower heating-up fuel consumption.

References

[1] Knorre G F and Nadzharova M A 1958 Cyclone furnaces (Moscow: Publishing House of State Energy)
[2] Saburov E N Cyclone Heat Devices with Intensive Convective Heat Exchange. (Arkhangelsk: North-East Publishing House)
[3] Karpov S V and Saburov E N 2002 High-efficiency cyclone devices for treatment and thermal utilization of gaseous emission (Arkhangelsk: Publishing House of Arkhangelsk State Technical University)
[4] Onokhin D A and Saburov E N 2018 Aerodynamics and convective heat transfer in cyclone chambers of large relative length (Proc. of 7th Russian National Heat Exchange Conference 22–26th October 2018 Moscow) (Moscow: Publishing House of Moscow Power Engineering Institute) 3 pp 431–433
[5] Saburov E N and Onokhin D A 2018 Aerodynamics and stability of the flow in relatively long cyclone chambers (Energy. News of Universities and CIS Power Energy Associations) 61 (6) pp 527–538