Research of the convective heat exchange of relatively long cyclone chamber with use gradient heat flux sensors

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Abstract. The aim of study is research of features of convective heat transfer in relatively long cyclone chamber. The research of heat exchange was carried out in a wide range of Reynolds numbers using gradient heat flow sensors. In the experiments, the value of the entrance area was changed by the flow and the diameter of the outlet. The results obtained were presented in the form of similarity equation. It was proposed to use the possibilities of gradient thermometry for studying the processes of heat exchange in cyclone chambers.

1. Introduction
One of the tasks of developing the fuel and energy complex in Russia is to increase the productivity and energy efficiency of industrial equipment, which can be achieved through the intensification of work processes and the creation of fundamentally new designs.

The highly turbulent swirling heat carrier flows, which generated in cyclonic devices allows to achieve the significant intensification of heat and mass exchange processes. Cyclone chambers possess versatility and simplicity of design, which allows achieving a high level of intensification of one of the main components of working processes—convective heat transfer.

Most studies on convective heat transfer in cyclone chambers are performed on their models with a small relative length \( \bar{L}_k = L_k/D_k \) (\( L_k, D_k \)—the length and diameter of cyclone chamber working volume) of 1–2 and in a relatively narrow range of Reynolds numbers. Such devices were originally widely used in industry [1,2]. The expansion of the industrial use of cyclone chambers and the increase in their productivity have necessitated an increase in the length of the working volume and the conduct of corresponding studies on aerodynamics and convective heat transfer.

The first systematic studies of the aerodynamics of cyclone chamber models with a relative length over a wide range of changes \( \bar{L}_k = 1–11.5 \) have shown that the aerodynamics of long chambers have certain characteristics in comparison with the aerodynamics of short chambers [1]. Therefore, there must be different heat exchange processes in relatively long chambers.

This paper is a continuation of earlier studies [3–5]. The aim of the work was to study the features of convective heat transfer in a cyclone chamber of large relative length over a wide range of Reynolds numbers and under various conditions of input and output of a flow, and also to develop recommendations for the calculation of heat transfer.

2. Research methodology
The experimental setup was a model of a cyclone chamber [4,5] with a working volume \( D_k = 160 \text{ mm} \) (millimeters) и длиной \( L_k = 2040 \text{ mm} \) (figure 1). The air into the chamber curler entered tangentially from diametrically opposite sides with two input channels. The withdrawal of air was organized from the opposite end of chamber. The change in air flow was carried out by frequency control of the speed.
rotation of the blower. The cross-sectional area of the inlet channels (inlet flow area) $f_{in}$ was changed by special inserts, and the diameter of the chamber outlet hole $d_{out}$ was varied with replaceable diaphragms.

![Diagram](image)

**Figure 1.** The scheme of the cyclone chamber (dimensions point out in millimeters).
1—swirler, 2—entrance channel (slot), 3—static pressure fitting, 4—aerodynamic probe fitting, 5—steam calorimeter with installed heat flux sensors, 6—mobile section.

The study of heat transfer was carried out using gradient heat flux sensors [6], established along the perimeter of the inner surface of the calorimeter (figure 2). The calorimeter previously used for similar experiments [3,4]. The internal diameter of the calorimeter is equal to the diameter of the working volume of the cyclone chamber. The sectional design of the chamber made it possible to change the position of the calorimeter with the installed sensors along its length. The longitudinal coordinate $\zeta = z/D_k$ determining the location of the sensors was measured from the deaf end of the twist along the axis of the working volume of the chamber.

Gradient heat flow sensors from the French firm Captec Enterprice measuring 5×10 mm and thickness 0.5 mm were used in the studies. The sensors with the help of hot-melt glue were installed in specially cut grooves so that the external surface of the sensors coincided with the inner surface of the calorimeter. The location of the sensors is shown in figure 2.
Figure 2. The scheme of the calorimeter (dimensions point out in millimeters).

1 — the inner cylindrical wall, 2 — guard area, 3 — outer cylindrical wall, 4 — hose inlet of the steam, 5 — working area, 6 — purge fitting, 7 — flange of the calorimeter to the camera, 8 — fitting the condensate to the drain, 9 — nipple of the condensate dimension, 10 — heat flux sensor.

Heating steam from the electric boiler through the superheater entered the working area of the calorimeter. The removal of excess steam was carried out to the guard area of the calorimeter, and from there to the drainage. The surface temperature of the calorimeter was monitored by means of thermocouples built into the sensors. The arrangement of the sensors along the perimeter of the calorimeter and the previously obtained data [4,5] made it possible to determine the average value of the heat transfer coefficient at any part of the working surface of the cyclone chamber.

3. Results of study

The executed studies varied the value of the relative inlet area \( \hat{f}_\text{in} = \frac{f_\text{in}}{\pi D_k^2} = 0.02; 0.04; 0.08; 0.21 \).

The relative diameter of the outlet hole was \( \hat{d}_\text{out} = \frac{d_\text{out}}{D_k} = 0.2; 0.43; 0.59; 0.74; 1 \). In all variants, the experiments were carried out at 15 values of the input Reynolds number \( \text{Re}_\text{in} = \frac{\nu_{\text{in}} D_k}{\nu_{\text{in}}} \), where \( \nu_{\text{in}} \) — the flow velocity at the entrance to the chamber (in the slots), \( \nu_{\text{in}} \) — the kinematic viscosity of the flow in the slots. A total of about 1500 experiments were performed with good repeatability of the results.

The generalization of the experimental data was carried out in the form of the similarity equation:

\[
\text{Nu} = A \text{Re}^n_{\text{in}} \varepsilon \varepsilon_z,
\]

where \( \text{Nu} = \alpha D_k/\lambda_{\text{in}} \) — local Nusselt number;
α—local coefficient of heat transfer;
λ_{oa}—heat conductivity coefficient of air;
ε_g —factor take into account geometric characteristics of cyclone chamber;
ε_z —factor takes into account the change of Nusselt number along the length of chamber;
A—factor of proportionality.

It has been established that in relatively long cyclone chambers, in contrast to short chambers, the conditions for the withdrawal of gases (outlet diameter) have practically no effect on the heat transfer of the side surface of the chamber. The greatest influence on the intensity of heat transfer from the geometric characteristics is exerted by the area of the inlet of the stream, therefore:

\[ \varepsilon_g = f_{n}^{0.4}. \]  

(2)

As the flow moves to the outlet (with increasing longitudinal coordinate \( z \)), the local heat transfer coefficients on the side surface of the chamber decrease. Thus, the factor \( \varepsilon_z \) has the form:

\[ \varepsilon_z = \frac{z^k}{z}. \]  

(3)

\[ k = -0.14 f_{n}^{-0.24}. \]  

(4)

The results of the generalization of the experimental data are given in figure 3 (the designations are given in the table 1) and the results are described by the equation:

\[ \text{Nu} = 0.203 \text{Re}_{n}^{0.72} \varepsilon_g \varepsilon_z. \]  

(5)

Figure 3. Resulting relation (drawing symbols shows in table 1).
Table 1. Drawing symbols.

| $\tilde{f}_{in}$ | 1.5 | 3.0 | 6.0 | 10.5 | 12.0 |
|------------------|-----|-----|-----|------|------|
| 0.02             | ◇  | ◇  | ◇  | ◇   | ◇   |
| 0.04             | □  | □  | □  | □   | □   |
| 0.08             | ◇  | ◇  | ◇  | ◇   | ◇   |
| 0.21             | △  | △  | △  | △   | △   |

4. Conclusions

The equation (5) is applicable in the range $Re_{in} = 5.18\times10^4$–$1.2860\times10^6$. The deviation of the majority of experimental data from the generalizing curve (5) does not exceed ± 11%. Comparison of the results of the calorimetric method [4] and using gradient heat flux sensors shows that their discrepancy does not exceed 12%.

Thus, the performed studies have shown that gradient heat flow sensors are a fairly accurate and convenient method for studying convective heat transfer.

References

[1] Saburov E N 1995 Cyclone Heat Devices with Intensive Convective Heat Exchange. (Arkhangelsk: North-East Publishing House)

[2] Saburov E N and Karpov S V 1993 Cyclone devises in Pulp-and-Paper Production (Moscow: Publishing House “Ecology”)

[3] Zaytseva M L, Orekhov A N and Saburov E N 2013 Research of convective heat exchange in relatively long cyclone chambers The Problems of Gas Dynamics and Heat Exchange in New Energy Machines (Proc. of XIX School-Seminar of Young Scientists and Experts Under Command the Member of the Academy of Science of Russia A I Leontyev 20–24th may 2013 Orekhovo-Zuyevo) (Moscow: Publishing House of Moscow Power Engineering Institute) pp 148–51

[4] Onokhin D A and Saburov E N 2017 Research of convective heat exchange in relatively long cyclone chambers (Proc. of XIX School-Seminar of Young Scientists and Experts Under Command the Member of the Academy of Science of Russia A I Leontyev 22–26th may 2017 St. Petersburg) (Moscow: Publishing House of Moscow Power Engineering Institute) 2 pp 353–6

[5] Onokhin D A and Saburov E N 2017 Research of convective heat exchange in cyclone chamber The Conditions and Prospects of the Development of Electrotechnology and Heat Technology (Proc. of XIX International Science-Technical Conf. “XIX Benardos Readings” 31st may–2nd june 2017 Ivanovo) (Ivanovo: Publishing House of Ivanovo State Power University) 2 pp 203–7

[6] Sapozhnikov S Z, Mityakov V Yu and Mityakov A V 2003 Gradient Heat Flux Sensors (St. Petersburg: Publishing House of St.Petersburg Polytechnic University)