Heat exchange of a mixture of gases with different Prandtl numbers under a swirl flow in a circular heated channel

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Abstract. The results of experimental studies of hydrodynamics and heat transfer in a swirl air flow (Pr = 0.7) and a helium-xenon mixture (Pr = 0.2) in heated circular channels with original screw inserts in a wide range of Reynolds numbers are presented. The efficiency analysis of heated channels with a swirl of the flow is compared with the efficiency analysis of the channels without swirling the flow using the energy necessary for pumping the gas through the heated channel.

1. Introduction
Swirled flows are widely used in technical applications such as heat exchangers, vortex energy separators, vortex chambers, burners, etc. This is due to such properties of a swirling flow that distinguish it from axial flow as the presence of commensurable values of axial, rotational and radial velocity components, gradients pressure in the longitudinal and transverse direction of the flow, the action of centrifugal forces on the flow. There are a lot of the ways of the flow swirl. In this paper, we propose new screw inserts that swirled the gas flow and simultaneously ensured the reciprocating motion of the gas mixture from the wall to the core of the flow and back. The study of hydro-gas dynamics and heat transfer in the swirling flow of a gas mixture with a low Prandtl number in a heated channel with such a screw insert is due to the fact that such mixtures are considered as the promising heat carriers in power plants.

2. Experiment
To swirl the flow of gas in a circular pipe, the screw inserts of the original design were used. Screw inserts, in addition to their direct purpose, aimed at spiral twisting of the gas flow, provided reciprocating motion of the gas mixture from the wall to the core of the flow and back because, in contrast to the known and used screw type vortexers, where the spiral generatrix approaches the wall channel at a right angle, in the screw inserts used, the spiral generates a wall at an angle of about 45°, which leads to a flow component in the direction from the wall to the core of the flow. It should be noted that it is possible to change the angle of approach of the generator to the channel wall in a wide range (from 10 to 170°). A change in the angle results in a change in the proportion of flow from the wall to the core of the flow. At the same time, for the angles of the approach of the spiral forming to the channel wall, more than 90°, the flow regime with the component from the flow core to the channel wall will be realized. Various screw inserts were made with different spiral widths, pitch of the screw, and angle of approach of the forming spiral to the channel wall. Schematic representation of
a screw insert where its main parameters are indicated is shown in figure 1. Here: $L$ is the pitch of the screw, $s$ is the width of the helix, $\alpha$ is the angle of approach of the helix forming to the channel wall, $D$ is the internal diameter of the channel, $d$ is the thickness of the channel wall.

In the experiments, a screw insert with a screw pitch $L = 16$ mm, a helix width $s = 1.6$ mm and an angle of approach of the helix forming to the channel wall $\alpha = 45^\circ$ was used. The screw insert is made of stainless steel, the thickness of the spiral is 0.1 mm.

The insert was placed in a nichrome thin-walled pipe with an internal diameter $D = 5.4$ mm, a wall thickness $d = 0.3$ mm with an electric heated area of 450 mm. The hydraulic diameter of the channel with the insert was $d_h = 4.82$ mm. Due to the large contact resistance at the points of contact between the screw insert and the pipe wall, the electric current flowing through the insert is negligible and all of the thermal power is released only from the pipe wall. The screw insert was continued to the unheated input initial section of the pipe 100 mm long, which provided a steady vortex gas flow at the entrance to the heated section of the channel. Nine copper-constantan thermocouples with a diameter of 100 μm were mounted at the distances from the start of heating point of 10, 20, 40, 90, 150, 250, 350, 410 and 430 mm to measure the temperature of the wall of the heated channel by contact welding. The gas temperature at the inlet and outlet of the channel was measured by chromel-alumel thermocouples with an isolated junction located in the core of the flow. The differential pressure was measured on the basis of $H = 545$ mm. To study the effect of the Prandtl number on the heat exchange process, air ($\text{Pr} = 0.73$) and a helium-xenon mixture with a mass content of helium of 7.2% ($\text{Pr} = 0.23$) were used as coolants in the experiments. To analyze the heat transfer efficiency of a screw-threaded flow in comparison with a straight flow, some of the experiments were carried out in a heated pipe without an insert.

3. Result and Discussion

The results of the experiments are shown in figures 2 and 3. Figures 2 and 3 show the dependences of the resistance coefficient and the Nusselt number on the modified Reynolds number for air flow and helium-xenon mixture in a round pipe without swirling and with a swirl of the flow. When considering flow with a swirl, as shown in [1], it is logical to use the flow velocity along the generatrix of the screw insert, which is defined as:

$$V_s = \frac{G}{\rho} \left[ 1 + \left( \frac{\pi}{2y} \right)^2 \right]^{1/2},$$

where $y$ is defined as the ratio of the half-step screw to the inner diameter of the pipe ($y = L/2D$), $G$ is the mass flow rate of the gas, and $\rho$ is the gas density. In this case, the modified Reynolds number is defined as:

$$Re_s = \frac{\rho V_s}{\mu} d_h,$$

where $d_h$ is the hydraulic diameter of the pipe with the insert, $\mu$ is the dynamic viscosity of the gas. Accordingly, the coefficient of resistance is determined through the length of the screw current and the effective screw speed as:
Figure 3. The Nusselt number vs the modified Reynolds number for air flow and helium-xenon mixture in a circular pipe without swirling and with a swirl of the flow.

The Nusselt number is defined as:

\[
Nu = \frac{(htc)_m d_b}{\lambda},
\]

where \( \lambda \) is the coefficient of thermal conductivity of the gas mixture, \((htc)_m\) is the arithmetic mean value of the wall heat transfer coefficient, determined from the seven values of the local heat transfer coefficients \((htc)_i\) in the cross sections \(i\) of the last thermocouples.
Figure 4. The wall heat transfer coefficient vs the energy necessary for pumping gas through a heated channel with a screw insert and without it.

\[(hct)_m = \frac{1}{7} \sum_{i=3}^{9} (hct)_i, \quad (hct)_i = \frac{Q}{S(U_{ti} - T_{fi})}\]

Here: \(Q\) is the electric power output, taking into account the heat losses, \(S\) is the internal heat dissipation surface, \(T_{wi}\) is the channel wall temperature in the \(i\) section, \(T_{fi}\) is the average mass flow temperature \(i\) cross-section, calculated from the heat balance.

For a pipe without a screw insert, the complex \((\pi/2y)\) is 0, since the half-step of the screw is infinite. The obtained data in these dimensionless criteria show that the resistance coefficient for a gas flow with a swirling flow exceeds the coefficient of resistance without swirling from one and a half to two times for air and one and a half times for a helium-xenon mixture. Using a screw insert leads to intensification of heat transfer, which reflects the data shown in figure 3. The Nusselt number for a gas flow with a swirling flow exceeds the Nusselt number without swirling from one and a half to two times, both for air and for a helium-xenon mixture.

Figure 4 shows the dependence of the wall heat transfer coefficient on the energy necessary for pumping gas through a heated channel with a screw insert and without it \(E = \frac{1}{2} \mu^3 f_s \frac{d_0^3}{d_s^3} Re_s^3\). The efficiency of a circular channel with a screw insert significantly increases as compared to a channel without an insert. At the same time, efficiency with the helium-xenon mixture of gases as a coolant is somewhat higher as compared with the flow of air.

4. Summary
Experimental studies of hydrodynamics and heat transfer in the spiral air flow and helium-xenon mixture in heated channels of circular shape with original screw inserts in a wide range of Reynolds numbers are carried out. An analysis of the efficiency of heated channels with a swirl of the flow in comparison with the channels without swirling the flow using the energy necessary for pumping the gas through the heated channel showed that the efficiency of the circular channel with the screw insert is significantly increased as compared to the channel without the insert.

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References
[1] Bejan A, Kraus A D 2003 *Heat Transfer Handbook* (Published by John Wiley & Sons, Inc.)