Heat transfer in helium-xenon mixture flowing in straight and twisted tubes with square cross-section

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Abstract. The article considers heat transfer in a flow of helium-xenon mixture in straight and twisted tubes with square cross sections. The main attention is paid to the heat transfer at large Reynolds numbers for tubes with small effective diameter. Such flows are often found in compact heat exchangers, assemblies of heat-generating elements, and energy-separating devices. CFD simulation data serve to analyze the influence of the cross-section shape and the twist step of the tube on hydraulic resistance and heat transfer. Various methods of generalization of heat exchange data are analyzed, taking into account the effect of gas compressibility on the flow acceleration in the tube and dissipative effects on the equilibrium wall temperature.

1. Introduction
Rare gas mixtures are increasingly offered as coolants in power equipment, for example, in closed gas turbine units (CGTU), operating in the Brighton cycle [1], in compact nuclear reactors designed to provide energy to spacecraft [2], and in devices of machine-free gas-dynamic energy separation [3-5] (in Leontiev tubes). On some characteristics (compressor turbine efficiency, mass of heat exchanger, refrigeration capacity), a helium-xenon mixture with helium mass fraction ranging within 5...10% ($Pr = 0.2...0.3$) is a more efficient heat carrier than pure gases or other mixtures [1]. For example, when working on a helium-xenon mixture, Leontiev tubes have an order of magnitude greater cooling capacity than when working on air or pure gases. The use of helium-xenon mixture in CGTU leads to an increase in the system efficiency by 4-5% compared to the efficiency in case of pure helium. A low Prandtl number leads to a more uniform heating of the coolant and a decrease in thermal deformations of the flow zone of the fuel assemblies, which somewhat likens properties of the mixed-gas coolant to the liquid metal coolant. The thermodynamic and transport properties of such mixtures have been studied quite well [6], but the data on the laws of heat transfer are not widely presented in the literature [3, 7]. Often the channels of power equipment, through which the coolant flows, have a complex shape. Acute angles and convergences can lead to uneven flows around the heat exchange surface and, as a consequence, uneven heat removal, which in turn can result in local overheating of the surface. Various spiral inserts [8], holes and fins [9, 10], various types of eddy generators [11, 12] and channel twisting [13, 14] are used to intensify heat transfer.

This work presents new results of numerical simulation of heat transfer in helium-xenon mixture flowing in straight and twisted tubes with square cross-sections. The influence of tube twist on the development of secondary vortex structures and their influence on heat transfer are studied. Various
methods of generalization of heat exchange data are analyzed, taking into account the effect of gas compressibility on the flow acceleration in the tube and dissipative effects on the equilibrium wall temperature.

2. Problem formulation

The conjugate heat exchange in the helium-xenon mixture flow, pumped through a thin-walled nickel tube with a hydraulic diameter of 6.2 mm (wall thickness of 0.15 mm) was investigated. At the inlet and outlet of the tubes there were adiabatic areas of circular cross-section and a length of 120 mm. The total length of the studied work area was 1030 mm, and the twist step $s$ was taken equal to $\infty$ (no twist), 200, 100 and 50 mm. The properties of the wall material were: density – 8900 kg/m$^3$, heat conductivity – 91.74 W/m-K, and specific heat – 460.6 J/kg·K. The shape of the studied tubes and the flow pattern are shown in figure 1 (from top to bottom: a tube with circular cross section; a straight tube with square cross-section; twisted tubes with square cross-section and twist step of 200, 100 and 50 mm).

The properties of helium-xenon mixture were calculated by the parameters of flow deceleration at the tube inlet [6] and were taken constant in length (table 1).

Along the entire length of the twisted part of the tube, a heat flux of 6000 W/m$^2$ was supplied to the outer side of the wall. The gas stagnation temperature at the tube inlet was taken equal to 300 K. The pressure at the outlet was 1 atm. The mass flow rate of the gas is 0.015 kg/s, which corresponded to the range of Reynolds numbers $Re_d$ from $10^5$, approximately.

Numerical simulation of the flow and heat transfer dynamics was carried out using the ANSYS Fluent CFD package under the license of the Siberian Supercomputer Center. For turbulence modeling, the Reynolds stress model (RSM) with nonequilibrium wall functions was used. The system of differential equations was solved by the SIMPLE method.

3. Results

The simulation has resulted in obtaining temperature and velocity fields and local values of heat transfer coefficients on the walls of twisted tubes. Figure 2 presents an example of data visualization in different sections along the length of a straight tube with square cross section. In the corners of the channel, areas with a low coolant rate are formed, and heat removal from the surface in these areas is difficult compared to the middle of the wall. At a large thermal load, this can lead to local overheating of the wall. Secondary low-intensity flows are directed from the flow core to the angles along the diagonal of the square and back along its side.
Figure 2. Fields of longitudinal velocity and projections of velocity vectors on section planes (top) and temperature fields (bottom) for the straight square tube under heat load of 6000 W/m² and flow rate of the helium-xenon mixture through the tube of 0.015 kg/s in sections: a – 0.014, b – 0.14, c – 0.47, d – 0.88 and e – 1 m, respectively.

Figure 3. Fields of longitudinal velocity and projections of velocity vectors on section planes (top) and temperature fields (bottom) for the square twisted tube with a twist step of 50 mm; the boundary conditions and notations are given in figure 2.

The structures formed in the heated area remain in the end adiabatic part of the tube. This flow pattern is in good agreement with the known literature data [16]. Twisting leads to some intensification of the coolant entrainment from the channel corners and to more uniform mixing of the coolant inside the channel (figure 3). In the final adiabatic section, the flow of the coolant retains the swirling nature.

With an increase in the twist step the hydraulic resistances of tubes increases (figure 4). The greatest increase in resistance is observed at the transition from twist step of 100 to 50, which is associated both with the development of the surface area, and with the intensification of secondary flows. It is important to note that the effect of tube twist should be estimated on changes in the average coefficient of hydraulic resistance, i.e., the pressure drop between the tube inlet and the considered section along the tube length. In compressible flows, a significant pressure gradient necessitates
choosing the conditions for determining the characteristic gas density. In our studies, the gas density was determined by the temperature and pressure in the considered section of the tube:

\[ \rho = \frac{P_{in} - P}{x} \]

From figure 4 it is apparent that the resistance of tubes does not become constant, which indicates the absence of hydrodynamic stabilization of the flow at more than 120 calibers, while in the flow of incompressible media at turbulent flow regime the stabilization area does not exceed 50 calibers. This can be explained by a significant acceleration of the gas flow due to the volume expansion at higher temperatures and lower pressure in the tube. With twist step decrease, the drop in resistance along the tube length becomes less pronounced.

![Figure 4. Changes in the coefficient of average hydraulic resistance in circular and square tubes with different twist step.](image)

It is known that in gas flows with a significant impact of compressibility, determining the heat transfer coefficient and generalizing data is more difficult than in incompressible flows [15]. Thus, as the flow rate increases, its thermodynamic temperature decreases, but this does not mean an automatic heat transfer enhancement as in incompressible flows. The decrease or increase in the wall temperature depends on the Prandtl number of gas. At \( Pr > 1 \) the wall will be heated, and at \( Pr < 1 \) it will be cooled. On the basis of simulation data in [7] various methods of generalizing data on heat exchange for air and helium-xenon mixture at flowing in small-diameter circular tubes have been analyzed. It is shown that selecting the mean mass recovery temperature as the defining temperature in the calculation of the Nusselt number, the range of applicability of the Mikheev formula can be expanded:

\[ \overline{Nu} = \frac{q}{T_w - T_{def}}, d_d = 0.021 \cdot Re_d^{0.8} \cdot Pr_d^{0.31}, \quad T_{def} = T_r \]

Figure 4: Changes in the coefficient of average hydraulic resistance in circular and square tubes with different twist step.

The defining recovery temperature was calculated using the formulas [7]:

\[ T_{def} = T_r \]
This approach (red lines and dots in Fig. 5-7), along with the approach from [15] (blue lines, green and blue dots in figures 5-7), has been also adopted for the analysis of heat exchange in square cross-section tubes. In the work [15] generalization of data on heat exchange at the sound air flow from a small-diameter tube was achieved using the recovery temperature, obtained in the experiment with adiabatic air flow with the same flow rate, as the determining one.

\[ T_r = r \frac{T}{T} + (1-r) \bar{T}, \quad r = 0.9 \cdot Pr^{0.1} \]  

(3)

Figure 5. Changes in recovery temperature along the length of circular and square tubes with various twist steps.

Figure 6. Nusselt numbers for circular and square tubes with various twist steps.

Figure 7. The Nusselt number, averaged for the length of heated parts of tubes with triangle and square cross section, depending on the Reynolds number.

The application of the approach from [15] has shown that the heat exchange data are well generalized, but the Nusselt number along the tube length decreases (figure 6). It is thought that this approach allows us to correctly consider the effect of the pressure gradient (flow acceleration), which occurs due to friction pressure losses and the associated gas expansion, on the recovery temperature. However, the gas expansion due to heat supply and the actual change in the stagnation temperature of the heated gas remains unaccounted for in this case. Formula (3) allows taking into account the
influence of these factors, but the expression for determining the recovery factor requires a
modification to consider the effect of the pressure gradient. Fig. 7 presents a comparison of the known
correlations [3] and the Nusselt number averaged for the tube length, obtained using the approaches of
[7] and [15], depending on the Reynolds number for triangle and square twisted tubes. It is seen that
depending on the choice of the defining temperature in the Nusselt number calculation, the
generalization of data leads to different correlations. Thus, the calculation of the defining temperature
by formula (3) gives results close to the Mikheev correlation, and the approach from [15] gives results
close to the correlation [17].

Conclusion
The influence of the twist of the tubes with a square cross section on the hydraulic resistance and heat
transfer rate at the outflow of helium-xenon mixture with a low Prandtl number has been analyzed. It
is shown that the known approaches to determine the Nusselt number by mass-average recovery
temperature do not allow fully taking into account the effect of the volume gas expansion and the
associated effect of the pressure gradient on the heat exchange at large Reynolds numbers. The
obtained data on heat transfer have not resulted in clear detection of the influence of the tube twist step
on the heat transfer intensity. The flow cooling due to increasing outflow rate when approaching the
speed of sound has a more significant effect on heat transfer than the presence of secondary flows due
to the shape of the tube cross section and the flow twist.

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Nomenclature

\( c_p \) – specific heat at constant pressure, [J/kg·K];
\( d_{ef} \) – effective hydraulic diameter of a tube, [m];
\( K_{He} \) – helium mass fraction in mixture, [kg/kg];
\( M \) – molar mass of gas mixture, [g/mole];
\( r \) – recovery factor, [-];
\( \text{Pr} \) – Prandtl number, [-];
\( \text{Re}_d \) – Reynolds number defined by the \( d_{ef} \), [-];
\( s \) – twist step, [m];
\( q \) – specific heat flux, [W/m\(^2\)];
\( T_{def} \) – defining temperature, [K];
\( T_{as} \) – thermodynamic temperature at the axis of
tube, [K];
\( \bar{T}, \bar{T}^*, \bar{T}_r \) – mass-average: thermodynamic, total
and recovery temperature, accordingly, [K];
\( \mu \) – dynamic viscosity, [Pa·s];
\( \lambda \) – heat conductivity, [W/m·K].

References
[1] El-Genk M S, Tournier J-M 2008 Energy Conv. Manag. 49 1881
[2] Peters C D 2006 A 50-100 kWe Gas-Cooled Reactor For Use on Mars SAND 2006–2189 p 87
[3] Nakoryakov V E, Makarov M S, Petukhov Yu I, Vitovsky O V and Elistratov S L 2015
Teplovye processy v potokah gasovyh smesej s malym chislom Prandtlya (Akademizdat,
Novosibirsk) [in Russian]
[4] Leontiev A I, Lushchik V G and Yakubenko A E 2006 High Temp. 44 (2) 234
[5] Lushchik V G, Makarova M S 2016 High Temp. 54 (3) 377
[6] Tournier J-M, El-Genk M S 2008 Energy Conv. Manag. 49 (3) 469
[7] Vitovsky O V, Makarov M S, Nakoryakov V E and Naumkin V S 2017 Int. J. Heat Mass
Transf. 109 997
[8] Yakovlev A B, Tarasevich S E, Giniyatullin A A and Shishkin A V 2013 J. Enhanced Heat
Transf. 20 (6) 511
[9] Dreitser G A, Lobanov I E and Isaev S A 2005 High temp. 43(2) 214
[10] Isaev S A, Schelchkov A V, Leontiev A I, Baranov P A and Gulcova M E 2016 Int. J. Heat
Mass Transf. 94 426

[11] Popov I A, Shchelchakov A V and Yarkaev M Z 2013 Rus. Aero. 56 83
[12] Popov I A, Shchelchakov A V and Yarkaev M Z 2016 High Temp. 54 842
[13] Carlos A, Ribeiro D and Francisco J. de Souza 2017 Wear 380–381 176
[14] Manikanta R V, Prabhakar D V N and Shankar N V S 2017 IJOER 3 (5) 58
[15] McAdams W H, Nicolai L A and Keenan J H 1945 Measurements of recovery factors and coefficients of heat transfer in a tube for subsonic flow of air NACA-TN-985 p 30
[16] Petukhov B S, Genin L G and Kovalev S A Teploobmen v yadernyh energeticheskih ustanovkah 1974 (Atomizdat) [in Russian]
[17] Kirov V S, Kozhelupenko Yu D, Tetel'baum S D 1975 J. Eng. Phys. Thermophys. 26 (2) 152