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Heat transfer in a small diameter tube at high Reynolds numbers

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ABSTRACT

Investigation results on heat transfer in low-Prandtl helium-xenon gas mixture and air, flowing in a small diameter tube, are presented. New experimental data on the heat transfer coefficient in the flow of helium-xenon mixture are obtained; results of numerical simulation are compared with the experimental data and known empirical correlations. Based on the simulation data it is shown that in a heated tube an increase in the Reynolds number due to an increase in the flow rate intensifies the heat transfer, and it may be due to the flow acceleration. It is shown that the high flow velocity and significant acceleration have a considerable effect on heat transfer in a tube, and the use of mean-mass stagnation temperatures as the determining one for generalization of data on heat transfer is insufficient. For the studied conditions, the known correlations give a significant error in determination of the heat transfer coefficient: the lower the Prandtl number and gas density, the higher the error.

1. Introduction

Determination of heat transfer intensity on the tube wall is a classical problem of the heat transfer theory. The engineering methods for determining the heat transfer coefficient in the fully-established turbulent flow, based on correlations of Dittus–Boelter, Mikheev, Petukhov–Popov, and others are widely known. The basis for the construction of such correlations is the data of numerous experiments and numerical simulations [1–5]. Applying these correlations for the analysis of thermal processes in the tubular heat exchangers of traditional configurations for the flow of air, steam or water is well-founded. The transition to the compact heat exchangers makes it necessary to reduce the flow cross-section of the tubes and, as a result, to increase the speed of coolant pumping. High pumping speed at simultaneous use vapor or gas mixture as a coolant leads to a significant increase in the effects of compressibility, Prandtl number and flow acceleration on heat transfer intensity, which was not taken into account at derivation of the above correlations. The relevance of the effect of these factors on heat transfer is also confirmed by the fact that the mixed gas coolants are increasingly used at various power plants [6]. The projects of compact nuclear reactors, providing energy for the research equipment on the surface of Mars, are known [7]. The equipment for flameless heating and cooling of gas pipelines are being developed [8]. By some characteristics (for example, efficiency of compressor turbine, heat exchanger mass) the helium-xenon mixture with helium mass concentration of 5–10% is more effective coolant than pure gases or mixtures of different composition [9]. The properties of helium-xenon mixture have been studied in detail [10,11]. The main feature of helium-xenon mixture of this composition is the low Prandtl number (0.23). In literature there are few experimental data and data of numerical simulation on heat transfer in such mixtures [12–15]. The working media in most other papers, dealt with heat transfer in the substances with low-Prandtl number, are liquid metals [16,17]. Gas heat-transfer agents, in contrast to liquid metals, are the compressible media. Gas heating causes it expansion, which in turn leads to a significant acceleration of the flow in tubes with a small cross-section and, as a consequence, to a change in heat transfer conditions.

The modern numerical models and methods of heat transfer investigation allow sufficiently accurate calculation of the velocity and temperature fields in a compressible flow and determination of the local and length-average heat transfer coefficient on the tube wall. The numerical experiment allows us to extend the range of tested parameters and complete the full-scale experiment. For the mixed gas heat-transfer agents with low molecular Prandtl number Pr, it is crucial to choose the model for the turbulent Prandtl number Pr_t. According to the data of direct numerical simulation (DNS) at $\mathrm{Pr} = 0.1$, Pr_t can be an order of magnitude higher and have substantial non-uniformity in the cross-section of the

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Nomenclature

c_p	specific heat at constant pressure [J/kg·K]
d	tube diameter [m]
G	mass flow rate [kg/s]
K	mass concentration
L	tube length [m]
M	Mach number
Nu	Nusselt number
p	pressure [Pa]
Pr	Prandtl number
Pr_t	turbulent Prandtl number
Q	heat load [W]
q	heat flux [W/m^2]
r	tube radius [m]
r_f	recovery factor
Re_d	Reynolds number
S	cross-sectional area [m^2]
T	temperature [K]
u_x, u_r	axial and radial velocity [m/s]
x	axial coordinate [m]
α	heat transfer coefficient [W/m^2·K]
λ	thermal conductivity [W/m·K]
μ	dynamic viscosity [Pa·s]
ρ	density [kg/m^3]

Indexes

ax	at the axis
in	at the tube inlet
out	at the tube outlet
r	recovery
t	turbulent
w	at the wall
‾	mass-average value
*	stagnation value

wall boundary layer [18,19]. Heat transfer in the flow in the wide range of molecular Prandtl numbers was studied in [20–24]. The dependence of the turbulent Prandtl number on the Reynolds number and molecular Prandtl number was derived in [20]. It is shown that for low Reynolds and Prandtl numbers, the value of Pr_t can be higher than one. By increasing Re_d and Pr, the value of Pr_t decreases and tends to the constant value of 0.7.

This paper presents the results of numerical studies of heat transfer in the flow of helium-xenon mixture and air in a small diameter tube in the wide range of Reynolds numbers, covering the areas of gas compressibility influence on the flow dynamics and heat transfer. The used mathematical model and method for solving the heat transfer problems take into account the changes in the turbulent Prandtl number over the tube cross-section and they are verified by the data of the experiment under the conditions similar to the considered ones.

2. Problem statement and main features of the flow

Heat transfer was studied in a circular tube with diameter $d = 5.5$ mm and length L from 0.75 to 1 m. The flow scheme is shown in Fig. 1a. The helium-xenon mixture with helium mass concentration $K_{He} = 5\%$ (Pr = 0.23) or air (Pr = 0.71) was used as a coolant. The properties of helium-xenon mixture were calculated by dependences suggested in [10]. The properties of air were determined by the data of [25]. In all calculations, excluding the test cases, specific heat flux q_w of 2895 and 5790 W/m^2 was fed to the wall along the entire tube, and for the tube of 1-m length it corresponded to heat power $Q = 50$ and 100 W. The stagnation temperature of gas at the channel inlet was $T^*_{in} = 293$ K. At numerical simulation, mass flow rate G was determined by the gas parameters at the tube inlet, at that, total pressure p^*_{in} was varied from 0.5 to 2 atm, and Mach number M_{in} was varied from 0.003 to 0.31. Total pressure p^*_{out}, stagnation temperature of the flow T^*_{out}, and Mach number M_{out} at the tube outlet were determined through calculations. For the flow velocity at the tube outlet close to the sonic one, the maximal tube length corresponded to zero pressure at the outlet. During the full-scale experiment, the mass flow of gas through the tube of a constant length was regulated; the static pressure and temperature were measured at the tube inlet and outlet by the pressure gauges and thermocouple converters. To verify the computational model, the tube geometry and gas parameters at the inlet and outlet were chosen as close as possible to the experimental conditions.

For the flows at a high Reynolds number, the drop of static pressure along the tube and change in the gas temperature lead to a substantial change in the flow velocity even in the area of fully-established flow, as can be seen from the characteristic velocity profiles in Fig. 1b. The gas flow velocity at the outlet is substantially higher than the flow velocity at the inlet and can reach the local sound velocity, and the flow in the tube is accelerated. The solid lines represent the changes in the boundary layer thickness δ, thickness of displacement δ^* and momentum thickness δ^{**} along the tube. The line marked with letter δ corresponds to the distance from the tube axis, where the longitudinal flow velocity is 0.995 of its value on the axis. For the initial section, this parameter corresponds to the thickness of the wall boundary layer. It is evident that in the initial section, the boundary layer increases according to the law for the laminar flow, followed by the transition to the turbulent flow and boundary layer closing. At low Reynolds numbers, an incompressible flow downstream is established with the power velocity distribution. As it can be seen, at high Reynolds numbers, a compressible flow can be called established only conditionally. The near-axial section with almost uniform velocity distribution increases downstream together with substantial increase in the longitudinal velocity. We can speak about flow acceleration due to the changes in displacement thickness, momentum thickness and distributions of transverse velocities along the tube radius in different cross-sections (see Fig. 1c). In the accelerated flow, δ^* and δ^{**} values decrease and transverse velocity changes the sign [26]. Increasing the momentum thickness at the beginning of the tube and its reduction at the end leads to a change in aerodynamic curvature of the tube wall and an expansion of the gas flow at the tube outlet at high Reynolds numbers.

3. Mathematical model and method of solution

To describe all features of the gas mixture flow with low Prandtl number in a small diameter tube at high Reynolds numbers and their effect on heat transfer, the following mathematical model was used. The problem was considered in 2D axisymmetrical statement. Fluid dynamics and heat transfer are described by the following equation set of the boundary layer type [27]:

Continuity equation