EXPERIMENTAL-CALCULATED INVESTIGATION OF FORCED CONVECTION NANOFLUID IN A CHANNEL WITH ARTIFICIAL ROUGHNESS

D V Guzei[1,2], A V Minakov[1,2], I A Popov[3]

[1] *Siberian Federal University, Krasnoyarsk, Russia*
[2] *Kutateladze Institute of Thermophysics, SB RAS, Novosibirsk, Russia*
[3] *Kazan National Research Technical University named after A.N.Tupolev, KNRTU-KAI, Kazan, Russia*
E-mail: gudimas@yandex.ru

Abstract. The experimental-calculated investigation of turbulent forced convection in a channel with artificial roughness of nanofluids with ZrO_2 nanoparticles was carried out. Nanoparticle concentration in the experiments was equals 4 vol. %. The nanoparticle size ranged from 44 to 105 nm. Numerical simulation of turbulent forced convection of nanofluids in a channel with annular knurls was carried out. A homogeneous model with experimentally determined transport coefficients was used to describe the nanofluid.

1. Introduction

One of the most common ways of heat transfer enhancement in turbulent convection is the use of surfaces with artificial roughness. Roughness structure may be both an inherent part of heat-exchange surface or a wire element or part of other inserts. In the first case this is uniform or discrete two- or three-dimensional gutters or protrusions applied by mechanical treatment. Therefore, the comparison of thermal-hydraulic efficiency of the artificial roughness, as well as the use of nanofluids for heat transfer enhancement and also the possibility of their application in channels with artificial roughness is an important issue.

One way of solving heat transfer enhancement problem is the use in heat-exchange equipment of shaped heat-transfer surfaces such as annular knurling, spherical protrusions, etc. [1, 2]. At the same time, studies related to the use in heat exchange devices of fluids with admixtures of nanoparticles of different composition called "nanofluids", are developing extremely fast.

A huge number of works appeared in this area over the last two decades. Most studies revealed the increase in heat transfer when using nanoparticles. However, there are publications demonstrating the reduction of heat transfer when adding nanoparticles [4-5].

The simulation and experimental study of forced convection of nanofluid in channels with annular knurls was performed.

2. Experimental investigation

Experimental study of forced turbulent convection of water-based nanofluids with nanoparticles of zirconium oxide (ZrO_2) was carried out in smooth tubes and channels with wall heat transfer enhancers. The experimental-calculated investigation of turbulent forced convection in a channel with artificial roughness of nanofluids with ZrO_2 nanoparticles was carried out. Nanoparticle concentration in the experiments was equals 4 vol. %. The nanoparticle size ranged from 44 to 105 nm. Experiments

were carried out with the use of installation, previously employed for similar purposes and repeatedly tested in our works [6–7].

The experiments have shown that the nanofluid with ZrO_2 particles 44 nm in size enhances heat transfer by 35% as compared to heat transfer in pure water at a fixed Reynolds number. In the turbulent flow regime at a fixed Reynolds number, with increasing particle size, the rate of enhancement decreases, and for the nanofluid with particle size of 105 nm this decrease is 20% [8].

It is revealed that the increments in the heat transfer coefficient and the pressure drop when using nanofluids depend on the surface shape of the channel. When using tubes with heat transfer enhancers, the increment of the heat transfer coefficient in nanofluids decreases, while the increment of the pressure drop, on the contrary, increases. In our opinion, this is caused by a change in the local concentration of nanoparticles in the vortices formed behind the artificial roughness.

It is shown that nanofluids allow reaching thermal-hydraulic efficiency comparable to that of the channels with artificial heat transfer enhancers. The use of nanofluids in channels with artificial enhancers appeared to be ineffective in terms of thermal-hydraulic efficiency [9].

A numerical simulation of the forced convection of nanofluids in a smooth and a channel with annular knurls was carried out during to the obtained experimental data.

3. Mathematical model and numerical method

For a better understanding of the processes of heat transfer mathematical model was built. There are different approaches to describe the nanofluids. The uniform (homogeneous) nanofluid model suggests that fluid dynamics and heat transfer can be described by standard Navier-Stokes and the heat transfer equations with corresponding physical parameters of this dispersion medium. There are also two-component nanofluid models, which are considered the nanofluids as a binary mixture. The one of the objectives of this article is to analyze the applicability of the homogeneous nanofluid model to describe the heat transfer by forced convection in circular cross-section channels. The necessity of using the numerical simulation due to the fact that for a correct description of heat transfer in laminar regime, the temperature dependence of the medium properties (especially viscosity) must be considered. In this case, classical analytical relations do not work, and the known variable viscosity adjusted empirical formulae are too rough to use them for quantitative analysis. A previously developed algorithm based on the finite volume method for structured multiblock grids to simulate the flow and heat transfer was used [10]. The nanofluid is considered as an incompressible homogeneous Newtonian fluid, which is described by the Navier-Stokes equations:

$$\nabla \cdot (\rho \vec{u}) = 0$$

$$\frac{\partial \rho \vec{u}}{\partial t} + \nabla \cdot (\rho \vec{u}\vec{u}) = -\nabla p + \nabla \cdot T + \rho g \tag{1}$$

where ρ – fluid density, p – pressure, $\vec{u}$ – velocity vector, T – is the viscous stress tensor:

$$T_{\mathrm{ij}} = \mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right),$$

where μ – coefficient of molecular viscosity, u_i – velocity vector components.

The energy-conservation equation is considered as follows:

$$\frac{\partial \rho h}{\partial t} + \nabla \left(\rho \vec{u} h \right) = \nabla \left(\lambda \nabla T \right), \tag{2}$$

where λ – thermal conductivity coefficient of fluid, h – the enthalpy of the medium, which is defined as follows:

$$h(T) = \int_{T_0}^{T} C_p dT, \tag{3}$$

where C_p is the specific heat capacity.

The density of nanofluids was calculated as:

$$\rho = \frac{\rho_0}{1 + \beta \cdot (T - T_0)}, \tag{4}$$

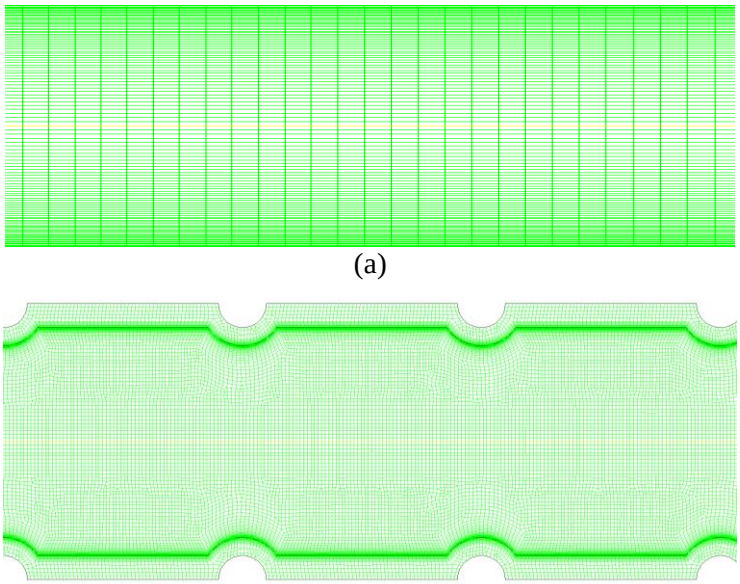
there ρ_0 is the density of the nanofluid at room temperature T_0, which is defined as $\rho_0 = (1-\phi) \cdot \rho_f + \phi \cdot \rho_p$, ϕ is the volume fraction of nanoparticles and β is the coefficient of thermal expansion of the nanofluid, which is defined as follows:

$$\beta = \frac{(1-\phi) \cdot \rho_f \beta_f + \phi \cdot \rho_p \beta_p}{\rho_0}, \tag{5}$$

where β_f and β_p are coefficients of thermal expansion of transport fluid and nanoparticles.

The transfer coefficients (viscosity and thermal conductivity) for the model were determined from the experiment [9].

A two-dimensional axisymmetric formulation was used. A part of the calculated grid for a smooth channel and a channel with annular knurls are presented in Figures 1 (a) and (b) respectively. The total nodes of the grid was 500,000. At the inlet of the channel, a parabolic velocity profile and a uniform temperature of the liquid were set. At the heated parts of the computational domain, the constant heat flux condition that corresponding to the experiments was set. At the outlet of the channel the Neumann conditions (zero normal derivative to the outlet plane) for all quantities were set. The two-zone two-parameter Menter SST model was used as the basic to model the turbulent flow [11, 12].



(a)

(b)

Figure 1. A calculated grid of a smooth channel (a) and a channel with annular knurls (b).

4. Result and Discussion

Numerical simulation of turbulent forced convection of nanofluids in smooth channel and a channel with annular knurls was carried out. The calculations were based on experimental data for a nanofluid with zirconium oxide particles for average particle size of 105 nm. Figure 2 shows the vector velocity

fields in a smooth channel and a channel with annular knurls for a Reynolds number of 7000. The annular knurls lead to significant changes in the flow structure in the channel. As is obvious the recirculation zones of the flow are formed behind the annular knurls. Vortex structures mix the fluid near the channel walls, this leads to more intensive heat exchange. Figure 3 shows the temperature fields of the fluid in the channel for a smooth and profiled channel.

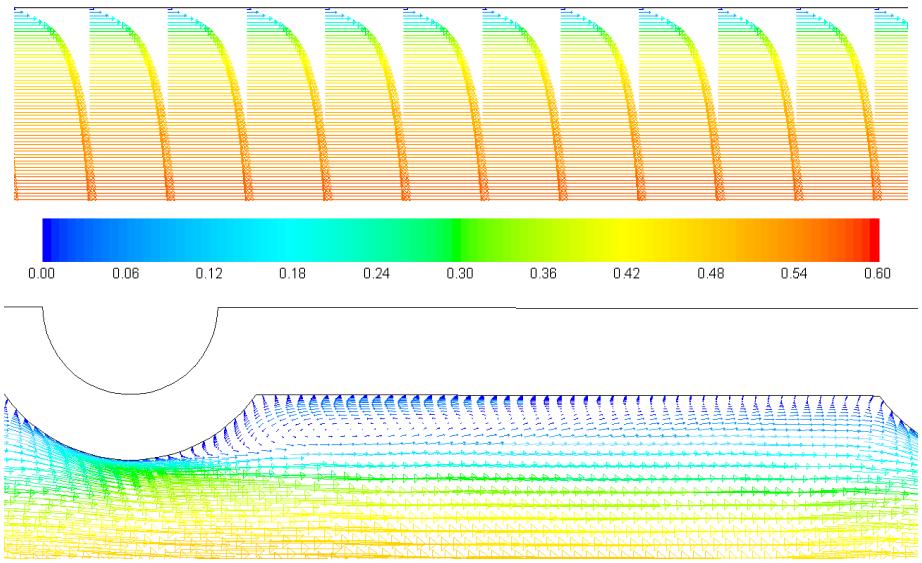


Figure 2. Vector velocity fields.

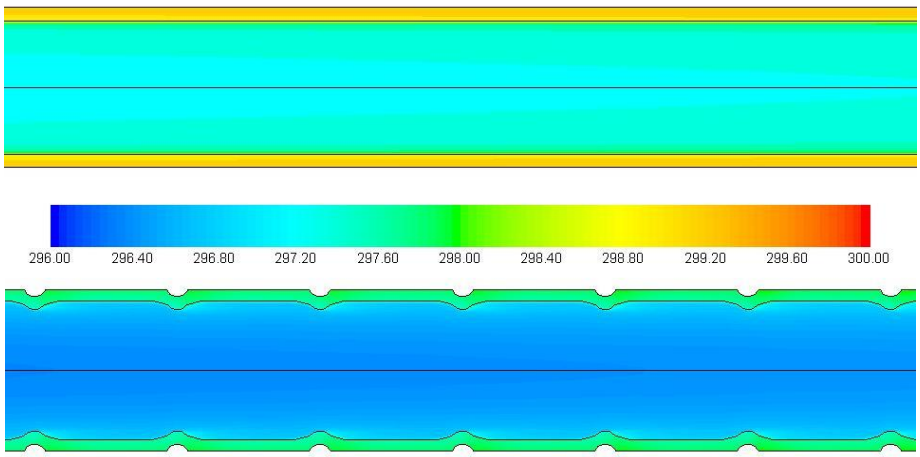


Figure 3. Temperature distribution fields.

The dependence of the average heat transfer coefficient on the Reynolds number was used to compare the numerical simulation results with the experiments results. This dependence is shown in Figure 4.

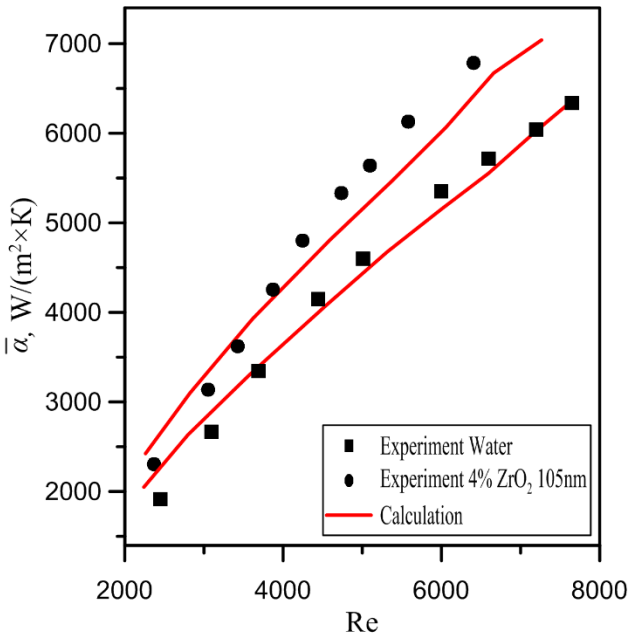


Figure 4. The average heat transfer coefficient as function of the Reynolds number.

The numerical simulation well described the forced convection of a pure fluid in a channel with annular knurls for a Reynolds number above 3000. The discrepancy between the calculated and experimental values did not exceed 3% for a pure fluid. Calculations of forced convection of a nanofluid in a channel with annular knurls were also performed. A comparison of the calculated and experimental data for dependence the average heat transfer coefficient from the Reynolds number is shown in Figure 4. A numerical simulation based on a homogeneous model for the nanofluid well describes the forced convection of nanofluids in a smooth channel, both qualitatively and quantitatively. As follows from calculations the channels with annular knurl the homogeneous model qualitatively describes the forced convection of a nanofluid in a channel with annular knurl, but the calculated values are quantitatively less the experimental data. The homogeneous model does not account for changes in the nanoparticles concentration in the vortex zones formed behind the annular knurls. These zones are visible in Figure 2 (b). This leads to decrease of determination accuracy of hydrodynamics and heat transfer of the nanofluid since the properties of the nanofluid essentially depend on the nanoparticles concentration, and the homogeneous model does not account for changes in the concentration in the flow. In future, we plan to perform a numerical simulation of forced convection of nanofluids in the channels with annular knurling using two-component model of nanofluid.

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