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Experimental study of turbulent forced convection of nanofluid in channels with cylindrical and spherical hollows

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ABSTRACT

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. Nanopowders with average particle size of 44 and 105 nm were used in the experiments. The Reynolds number ranged from 3000 to 8000. 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. It is shown that nanofluids allow reaching thermal-hydraulic efficiency comparable to that of the channels with artificial heat transfer enhancers.

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.

The problem of convective heat transfer enhancement and the related issues of experimental and theoretical studies are currently becoming an independent and fast growing field in heat exchange doctrine. All machines, equipment and technologies need for intensive heat removal that can be carried out using various kinds of heat exchangers. The urgency of this problem is determined by the desire to achieve maximum compactness with minimum materials consumption, and increase heat exchange performance factor combined with reducing energy costs.

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].

In Refs. [3–5] it was shown that heat transfer enhancement in tubes with annular knurling within the range of Reynolds numbers $600\ldots3.8\cdot10^3$ may reach the factor of 1.06… 14.01. At that, the pressure loss may increase by 0.92…19.7 times. In Ref. [6] at $Re_D = 10^4\ldots4\cdot10^5$ and $Pr = 0.7\ldots50$ within a wide range of dimensionless geometric parameters $d/D = 0.9\ldots0.87$, $t/D = 0.25\ldots1$ heat transfer in such channels was enhanced by $1.2 \div 2.2$ times at the growth of the pressure loss by $1.05 \div 10.5$ times.

In order to improve thermal-hydraulic performance of heat exchanger tubes, in Refs. [7–13] it is proposed to use spherical protrusions located along circular or spiral lines inside the tubes, rather than solid annular knurling. These studies were conducted within the following ranges of Re and Pr numbers $5\cdot10^3 < Re_D < 10^5$ and $Pr = 2.9–100$, relative parameters of the protrusions $0.017 < h/D < 0.16$; $0.09 < t/D < 1.706$ and $0.16 < s/D < 0.55$. The increase in heat transfer coefficients was up to 1.5–5 times as compared with a smooth tube. At that, pressure loss increased by 1.2–4.5 times.

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. Experiments on laminar and turbulent forced convection of

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water-based nanofluids have shown that nanofluids can improve the heat transfer coefficient within the range from a few percent up to 350% for carbon nanotubes [14–34]. 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.

The research carried out by Pak and Cho [21] apparently should be considered the first work dealing with turbulent heat transfer of nanofluids. The results of this work have shown that the Nusselt number in nanofluids increases with increasing volume concentration of particles and the Reynolds number. However, in this work it was also shown that at high concentrations of nanoparticles the heat transfer coefficient may be lower than that of pure water (by 12% for three-percent nanofluid).

Duangthongsuk and Wongwises [22] obtained 32% improvement of heat transfer at concentration of nanoparticles equal to just 1%, and 14% decrease in heat transfer coefficient at concentration of nanoparticles equal to 2% as compared to the base fluid.

In Ref. [23] increase in the heat transfer coefficient with an increase in the concentration of nanoparticles to 3% inclusive is shown, a further increase in the concentration of nanoparticles leads to a decrease in the heat transfer coefficient.

The results of the experiments [24] showed that the addition of nanoparticles into the coolant significantly increases heat transfer efficiency (by 60% for two-percent nanofluid), while the friction factor was almost the same as for pure water.

In Ref. [25] it was found that the heat transfer coefficient definitely increases with increase in the concentration of nanoparticles in laminar and turbulent regimes at fixed Reynolds number. The maximum rate of enhancement of the heat transfer coefficient, recorded in the experiment, was 40% for 1.1% nanofluid. At that, the pressure drop in the channels for nanofluids was very close to that for pure fluid. In addition, the authors investigated the effect of particle size. No effect of particle size on heat transfer was found in this work.

Fotukian and Hasr Esfahany [26] recorded a definite increase in heat transfer coefficient and pressure drop with increasing particle concentration. The maximum increase in heat transfer coefficient amounted to 48% at a negligible volume fraction of the nanoparticles equal to 0.054%. In the next paper [27], the same authors investigated turbulent heat transfer of water-based nanofluid with particles of CuO in a circular pipe. The authors found that the heat transfer coefficient is almost independent of nanoparticles concentration.

The work [31] allowed answering partly some questions regarding turbulent heat transfer of nanofluids. It is shown that heat transfer enhancement due to the use of nanofluids in the turbulent regime is not a trivial task. The effect which is beneficial for heat transfer enhancement depends on the ratio between viscosity and thermal conductivity of nanofluid, and therefore the material of the particles and their size. It is shown that with increasing concentration of nanoparticles the local and average heat transfer coefficients at a fixed Reynolds number increase. Heat transfer coefficient may decrease with the increase of particles concentration at a constant flow rate of the coolant. When conducting investigations with nanofluid and their analysis, it is necessary to take into account and control many factors and parameters. Apparently, this fact explains extremely broad variations and inconsistency of data on turbulent heat transfer obtained by various authors.

From this brief review it follows that currently in the field of turbulent heat transfer of nanofluids there are still many unresolved issues. In particular, most of the works do not discuss in principle the issue of thermal-hydraulic efficiency of nanofluids, though in the meantime this problem is crucial from the viewpoint of the practical application.

As concerns the studies of turbulent convection in nanofluids flowing in channels with shaped surfaces, they are very few, and usually limited just by measurements of the heat transfer coefficient. Thus, for example, in the work of Liu [33] it is shown that the nanofluid with 2% volume concentration of ZnO particles enhances heat transfer by 33% relative to that in pure water at a constant Reynolds number. Suresh [34] has shown that the use of nanofluids based on distilled water with CuO particles allows enhancing heat transfer coefficient in a channel with dimples. At the 0.3% volume concentration of nanoparticles this enhancement reaches 39% relative to that in pure water.

Currently, no comprehensive analysis of thermal-hydraulic efficiency when using nanofluids in channels with shaped surface is available. Also, there are virtually no data allowing direct comparison of the thermal-hydraulic efficiency of nanofluids with that of traditional methods of heat transfer enhancement. Exactly this point is the objective of the present study.

2. Description of the setup and experimental technique

The diagram of the setup for conducting research on forced convection is shown in Fig. 1. The setup is a closed loop with a circulating coolant. Working fluid is pumped through a heated measuring area from where it flows to the heat exchanger, where it is cooled by the thermostat. The flow rate of the working fluid in the loop is adjusted by changing the pump power. Pump output is regulated by laboratory transformer. Power supplied to the pump is measured by Omix D4-MX meter.

Heated section is a stainless steel tube 6 mm in diameter and 1 m long. Thickness of the tube wall is 0.5 mm. Before entering the measuring section, the flow was stabilized at a length of 0.8 m. The length of the hydrodynamic stabilization section does not exceed 0.14 m in the Reynolds number range from 3000 to 10,000. The length of the hydrodynamic stabilization section was determined by the formula $l_h = 1.45\mathrm{Re}^{1/4}d$ [35], where d – is the diameter channel; Re – is the Reynolds number. The thermal stabilization section in turbulent flow regimes is approximately equal to the region of hydrodynamic stabilization. The tube is heated by supplying electric current directly to the tube wall. This heating method allows providing heat at a constant heat flux density at the tube wall. In addition, this heating method is universal and easily applicable to tubes of any cross section. The tube is insulated by multi-layered insulation. Heating power is controlled by a transformer. Six chromel-copel thermocouples are fixed at the tube wall at an equal distance from each other to measure the local temperatures of the tube. Temperature measurements were carried out by OWEN TRM-200 meters. In addition, temperatures at the inlet and outlet of the heated section were measured by means of thermocouples. At that, the thermocouple designed to measure the outlet temperature was located at a considerable distance from the end of the heated section to ensure temperature uniformity in the measurement point. The part of the loop between the heater and the cross section, in which the flow temperature was measured, was also insulated. Measurements of pressure drop were conducted using a differential pressure meter OWEN PD200. For flowrate measurement was used turbine flowmeter YF-S201. The precision multimeter GwInstek GDM-8261 was used for measuring the current signal from the pressure transducer and flowmeter.

Designed setup was tested based on known empirical data for heat transfer in pure water. A series of experiments was carried out for turbulent flow regime. The water flow rate was varied within the range from 0.65 to 2 L/min that corresponds to the range of Reynolds numbers from 2300 to 8000. In experiments, the liquid temperature at the entrance to the working reach was