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Study of turbulent heat transfer of the nanofluids in a cylindrical channel

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ABSTRACT

The experiment investigation of turbulent forced convection of nanofluids with SiO_2 and Al_2O_3 nanoparticles was carried out. Nanoparticle concentration varied in the range from 0.5 to 2 vol.% in the experiments. The nanoparticle size ranged from 10 to 100 nm. The dependence of heat transfer coefficient and pressure drop from the concentration, size, material of the nanoparticles and temperature was studied. It was shown that adding nanoparticles to the coolant significantly influences the heat transfer coefficient in the turbulent flow regime. It is shown that with increasing nanoparticles concentration, the local and average heat transfer coefficients at a fixed Reynolds number increase. Decrease in heat transfer coefficient with increasing particles concentration may take place at a fixed flow rate. It is shown that, the heat transfer coefficient of the nanofluid in turbulent regime increases with increasing nanoparticles size at a fixed flow rate, while has a certain maximum at a fixed Reynolds number. The effect of nanoparticles material on the heat transfer coefficient and pressure loss has been also demonstrated. It is found that the inlet temperature is another factor having a significant effect on turbulent heat transfer performance of nanofluids.

1. Introduction

The enhancement of convective heat transfer and the related experimental and theoretical research become at present an independent, important and rapidly developing field of heat transfer theory. High heat flux removal is a major consideration in the design of many machines, equipment and technologies, and can be accomplished using various kinds of heat transfer equipment. The urgency of this problem is determined by driving to enhance the performance of heat exchange devices, reduce energy costs and achieve maximum compactness with minimum material consumption. One of the solutions to the problem of heat transfer performance enhancement could be the use of so called nanofluids, which are fluids containing nanoparticles of various composition. The first experiments have shown that even very small additions of nanoparticles to the fluid (a fraction of volume concentration) may lead to increase in thermal conductivity and heat transfer of the nanofluid by tens of percent, whereas the critical heat flux may be increased several times ([1–5]). Over the last two decades, a great number of works have been emerged in this area. Most of them were focused on the study of thermal conductivity and viscosity of nanofluids. Actually, the study of heat transfer was performed in a relatively few research works, and the results presented are extremely controversial (see the review [5]). Most works reveal an increase in heat transfer when using nanoparticles. The increase in heat transfer coefficient in nanofluids as compared to base fluids can range from a few percent to 350% for carbon nanotubes. However, there are publications showing the deterioration of heat transfer when adding nanoparticles. Most of these works are dealt with the study of convection of nanofluids in laminar flow regime [6–9]. Turbulent convection is explored to a substantially lesser degree.

The first work, in which the turbulent heat transfer of nanofluids was studied, is apparently the work of Pak and Cho [10]. They experimentally studied the turbulent heat transfer in water-based nanofluids, containing Al_2O_3 and TiO_2 nanoparticles, and flowing in a horizontal circular pipe with a constant wall heat flux. The results have shown that the Nusselt number in nanofluids increases with increasing both bulk concentration of the particles and the Reynolds number. However, in the same paper [10] it has been revealed also that at high concentrations of nanoparticles the heat transfer coefficient may be lower than that in pure water (by 12% in a nanofluid with particles concentration of 3%).

Convective heat transfer in turbulent flow regime of nanofluids containing copper nanoparticles was experimentally investigated

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Nomenclature

Nu	is the Nusselt number	μ	are fluid viscosity coefficient
α	is the average heat-transfer coefficient	U	is the superficial velocity
G	mass flow rate	d	is the tube diameter
C_p	is the specific heat of the fluid	L	is the test section length
S	is the area of the lateral surface of the channel	ΔP	is the measured pressure drop
T_{out}, T_{in}	are fluid temperatures at the channel inlet and outlet	ξ	is the friction factor
$\bar{T}$	is the average fluid temperature	μ_n	are nanofluid viscosity coefficient
T_w	is the arithmetic mean of the channel wall temperature, obtained by averaging of the values of six thermocouples	μ_w	are water viscosity coefficient
		λ_n	are nanofluid thermal conductivity coefficient
		λ_w	are water thermal conductivity coefficient
Pr	is the Prandtl number;	λ_p	are particles thermal conductivity coefficient
Re	is the Reynolds number;	φ	volume concentration of particles
λ	are fluid thermal conductivity coefficient		

in the subsequent work [11]. The experimental results have shown that adding nanoparticles to the base fluid significantly improved the heat transfer efficiency of base fluid (by 60% in a nanofluid with particles concentration of 2%), while the friction factor remained almost the same as for water.

In [12] the efficiency of heat transfer in water-based nanofluids containing titanium oxide nanoparticles was investigated in laminar and turbulent flow regimes in vertical tube under constant wall heat flux boundary condition. The results have shown that the heat transfer coefficient definitely increases with increase of nanoparticles concentration in both laminar and turbulent regimes at a fixed Reynolds number. The maximum intensification of heat transfer coefficient, recorded in the experiment, was 40% for 1.1% nanofluid. In this case, the pressure drop in nanofluids, when flowing in the channel, was very close to that in pure fluid. In addition, the authors investigated the effect of particles size, though no effect of size on the heat transfer coefficient was detected, possibly, because the particles were large enough (95–210 nm).

Duangthongsuk and Wongwises [13] experimentally studied turbulent heat transfer and pressure drop in water-based nanofluids with TiO_2 particles. And again the results were extremely controversial. They revealed a 32% enhancement in thermal performance at particles concentration of 1%, and 14% reduction in the heat transfer coefficient at particles concentration of 2% as compared with the pure fluid.

Fotukian and Nasr Esfahany [14] studied turbulent convective heat transfer in nanofluids with a very low concentration of Al_2O_3 nanoparticles in water flowing in a circular pipe. They recorded a clear increase in heat transfer coefficient and pressure drop with increasing concentration of particles. The maximum increase of heat transfer coefficient equal to 48% was reached at negligibly small volume concentration of the nanoparticles (0.054%). In a subsequent paper [15] the same authors studied turbulent heat transfer of water-based nanofluids containing CuO nanoparticles in a circular pipe. They achieved a 25% increase in the heat transfer coefficient and a 20% increase in pressure drop at a concentration of nanoparticles equal to 0.24%, as compared to pure water. Besides, they revealed that the heat transfer coefficient was almost independent of the concentration of nanoparticles within the observed range of volume percent change from 0.039 to 0.24.

Nguyen et al. [16] experimentally investigated the heat transfer coefficient in the liquid cooling system of microprocessors using water-based nanofluid containing nanoparticles of Al_2O_3 at a turbulent flow regime. They found that nanofluid significantly increases the heat transfer coefficient as compared to base fluid (by 40% at particles concentration of 6.8%). Besides, they investigated the effect of particle size on turbulent heat transfer. The authors revealed that the nanofluid containing particles of 36 nm in size provided a higher heat transfer coefficient as compared to the nanofluid with particles size of 47 nm.

Extensive experimental studies of turbulent convective heat transfer in the annular channel for several water-based nanofluids containing Al_2O_3, SiO_2, and MgO particles was carried out in [17]. The authors revealed considerable increase in heat transfer coefficient with increasing particles concentration (by 46% in a 4% nanofluid containing particles of SiO_2), and argued that in general the heat transfer coefficient increased with decreasing particle size. However, the authors used in their study particles of substantially different shapes (cylinders with sizes of 28–110 nm and spheres with diameter of 6.5 nm). Thus, such a comparison seems incorrect.

Heat transfer in nanofluid based on the mixture of water and ethylene glycol with particles of silicon carbide was experimentally investigated in [18]. The particle size ranged from 16 to 90 nm. It was shown that with increasing particle size at other conditions being equal the heat transfer coefficient increased significantly.

In addition, it should be noted that there are a huge number of computational studies of turbulent heat transfer in nanofluids. Though, in our view, these studies are not self-containing because they require experimental data on transport coefficients. Therefore, analyzing these works, which are characterized by the inconsistency of the experimental data, apparently does not make much sense.

Thus, the analysis of the literature shows that in the available works there is neither quantitative nor qualitative consensus in terms of turbulent heat transfer performance of nanofluids. In the meantime, almost all scientists note that the effect of nanoparticles on the heat transfer in the turbulent flow regime is much more complicated than that in laminar flow regime. This circumstance requires additional systematic experimental study of turbulent heat transfer of nanofluids.

2. Description of the experimental setup

The diagram of the installation to study the heat transfer coefficient is shown in Fig. 1. The installation is a closed loop with a circulating coolant [7–9]. The working fluid is pumped through the heated test section to the heat exchanger, where heat is removed by the thermostat. The flow rate of the working fluid in the loop is controlled by controlling the pump power by means of laboratory transformer. Power input to the pump is measured through Omix meter.