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EXPERIMENTAL INVESTIGATION OF FREE CONVECTION OF GLYCOL-Al_2O_3 NANOFLUID FROM HORIZONTAL TUBE

Nanofluids are considered to be a new generation of coolants, both in single- and two phase systems. Furthermore, nanofluids or nanocomposites may be used as a media in thermal energy storage (TES) in such systems as sensible heat storage (SHS) and phase change materials (PCM). In the SHS systems the dominating mechanism of the heat transfer is natural convection. However, in the literature only a few investigations of free convection of nanofluids have been discussed. This paper presents preliminary results of the experimental investigation of natural convection heat transfer of glycol-Al_2O_3 nanofluid from horizontal tube.

Keywords: thermal energy storage, sensible heat, nanofluids, free convection

1. Introduction

The shortage of fossil fuels and environmental considerations – first of all the reduction of carbon dioxide emission, motivated the use of alternative energy sources. However, utilization of renewable sources of energy may be limited due to a mismatch between energy supply and energy demand and intermittent performance of the renewable energy sources. Therefore, thermal energy storage plays essential role in heat recovery and contributes considerably in improving the performance of the thermal systems. There are two main physical ways for thermal energy storage: a change in internal energy of a material as sensible heat or latent heat during phase change processes and thermochemical reactions. Energy storage based on chemical reactions has much

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higher thermal capacity than sensible heat but is not widely commercially viable.

Large volume sensible heat systems are promising technologies with low heat losses and attractive prices. However, low thermal conductivity of liquids leads to a slow charging and discharging rate. The charging and discharging rate can be enhanced by applying nanofluids, i.e. mixtures of a base fluid and nanoparticles with a typical size smaller than 100 nm [1]. The fact that thermal conductivity of the suspensions is higher than that of the base liquids results from the higher - even orders of magnitude, thermal conductivities of solids than that of liquids [2, 3]. Moreover, crucial in sensible heat storage specific heat of the storage material (fluid) can be enhanced by use of nanoparticles [4]. Natural convection is the dominating mechanism of the heat transfer in the SHS systems. However, in the literature – contrary to forced convection or boiling heat transfer of nanofluids, little attention was paid to study free convection of nanofluids. Putra et al. [5] studied heat transfer of aqueous CuO and Al_2O_3 nanofluids inside a horizontal cylinder with ID of 40 mm and 100 mm long. The concentration of nanoparticles was 1% and 4% by volume. Experiments at Rayleigh number ranging from 106 to 109 showed a systematic and significant deterioration of heat transfer. The deterioration increased with an increase of nanoparticle concentration and was more pronounced for CuO nanofluids. Wen and Ding [6] investigated heat transfer behaviour of water-TiO_2 nanofluid inside a bottom-fired cylindrical gap with a diameter of 240 mm and a thickness of 10 mm. The concentration of nanoparticles was 0.19%, 0.36% and 0.57% by volume. The results showed a systematic decrease of heat transfer coefficient with increasing particle concentration. Li and Peterson [7] studied heat transfer behavior of water-Al_2O_3 nanofluid inside a bottom-fired cylindrical gap of 20 mm in diameter and thickness of 2.5 mm. The concentration of nanoparticles ranged from 0.5% to 6% by volume. A deterioration of heat transfer coefficient was observed with an increase of the volume fraction of the nanoparticles. Mahrood et al. [8] conducted experiments with Al_2O_3 and TiO_2 aqueous solution of carboxymethyl cellulose (0.5 wt.%). Tested nanofluids exhibit the properties of non-Newtonian fluids. Experiments were carried out in the vertical cylinder (enclosure) with three aspect ratios (length to diameter) of 0.5, 1.0 and 1.5. The nanoparticle concentration was 0.1, 0.2, 0.5, 1.0 and 1.5 by volume. The numerical simulations of natural convection of nanofluids show enhancement of heat transfer [9-11]. However, the results presented in the literature are devoted to the enclosed spaces when the liquid's thermal conductivity is very important.

This paper aims to evaluate the potential of glycol-Al_2O_3 nanofluid as a sensible heat storage material in a natural convection system. The test chamber consists of a cubical vessel that simulates SHS container and a horizontal tube is as a heating element. Alumina nanoparticles are tested at the concentration of 0.1% by weight.

2. Experiment

The test chamber consists of a cubical vessel made of acrylic glass (PMMA) with inside dimensions of 160 mm x 160 mm x 500 mm. Commercially available stainless steel tube with an outside diameter of 10 mm and 0.6 mm wall thickness is used to fabricate the test heater. The effective length of the tube was 150 mm. The ends of the tube are soldered to cooper joints in order to minimize any additional electrical resistance. The test specimen is heated by using the tube itself as a resistance heater. The power supply can be adjusted with an electrical transformer. The inside temperature of the test tube is measured using two resistance thermometers Pt100. Twelve thermometers type Pt100 - located at various levels inside the vessel are used to determine the average fluid temperature. The scheme of the experimental rig is shown in Fig. 1.

In the present study Al_2O_3 nanoparticles were applied while as a base fluid pure ethylene glycol was used. In order to prepare stable nanofluids and reduce the occurrence of agglomerates the sonication is applied using an ultrasonic washer for 4 h. Alumina nanoparticles are tested at the concentration of 0.1% by weight. Used nanoparticles have a spherical form and their diameter is in a range from 5 nm to 250 nm, while their mean diameter is 47 nm according to the manufacturer (Sigma-Aldrich Co.). Heat flux is calculated as

$$q = \frac{P_{el}}{\pi D_o L} \tag{1}$$

where: P_{el} - electrical power, D_0 - the outside diameter, L - the length of the tube.

The inside temperature of the tube is calculated as an arithmetic mean of the measured two inside temperatures:

$$t_{in} = \frac{t_{in1} + t_{in2}}{2} \tag{2}$$

where: t_{in1}, t_{in2} - the inside temperatures of the tube.

According to Fourier's law, the mean temperature of the outside surface of the tube was determined from the formula [12]:

$$t_w = t_{in} - UI \frac{\ln\left(\frac{D_o}{D_{in}}\right)}{2\pi \lambda_t L} \tag{3}$$

where: U - voltage, I - current intensity, D_i - the inside diameter, λ_t - thermal conductivity of the tube material.

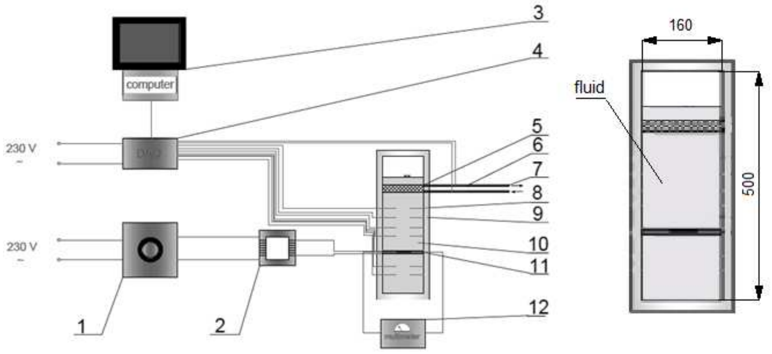

Fig. 1. Scheme of the experimental setup (left) and geometry of the vessel (right): (1) variac, (2) transformer, (3) PC-aided data acquisition system, (4) DAQ-module, (5) cooler, (6) cooling water system, (7) cooling water outlet, (8) Pt100 resistance thermometers, (9) insulation, (10) test vessel filled with a fluid, (11) heating section, (12) multimeter

The wall-to-fluid temperature difference is estimated as:

$$\Delta T = t_w - t_f \tag{4}$$

where: t_f - the mean fluid temperature, t_w - the outside surface temperature.

The mean fluid temperature t_f is calculated as the arithmetic mean of the eight fluid temperatures (measured above the heating tube (Fig. 1).

$$t_f = \frac{1}{8}\sum_{i=1}^{i=8} t_f \tag{5}$$

The inside tube temperature and the distribution temperature of the fluid were recorded during established steady states. For the measurement of the temperatures the resistance thermometers Pt100 with a diameter of 3 mm and the accuracy ±(0.3+0.0050·t), where t is a current temperature, were used. The heat transfer coefficient is estimated as:

$$\alpha = \frac{q}{\Delta T} \tag{6}$$

where: q - heat flux, calculated from Eq. 1,
ΔT - wall-to-fluid temperature difference, calculated from Eq. 4.

Nusselt and Rayleigh numbers are calculated from the formulas:

$$Nu = \frac{\alpha D_o}{\lambda} \tag{7}$$

$$Ra = \frac{g\beta\Delta T D_o^3}{\nu a} \tag{8}$$

where: g - gravitational acceleration, a - thermal diffusity, β - coefficient of thermal expansion, ν - kinematic viscosity, λ - thermal conductivity.

Due to low nanoparticle concentration, there were taken the same thermophysical properties of the nanofluid as for pure ethylene glycol. The accuracy of calculated parameters is estimated with the mean square method. The uncertainty of the heat flux was estimated as follows:

$$\Delta q = \sqrt{\left(\frac{\partial q}{\partial P}\Delta P\right)^2 + \left(\frac{\partial q}{\partial P}\Delta D_o\right)^2 + \left(\frac{\partial q}{\partial P}\Delta L\right)^2} \tag{9}$$

The absolute measurement errors of the electrical power ΔP, the outside tube diameter ΔD_o and active length of the tube ΔL are 1 W, 0.1 mm and 0.5 mm, respectively. The maximum error for the heat flux was estimated to ±1.2%. The experimental uncertainty for average heat transfer coefficient is calculated as:

$$\Delta\alpha = \sqrt{\left(\frac{\partial\alpha}{\partial q}\Delta q\right)^2 + \left(\frac{\partial\alpha}{\partial\Delta T}\delta T\right)^2} \tag{10}$$

The absolute measurement error of the wall superheat δT is 0.1 K. The maximum error for average heat transfer coefficient was estimated to ±1.2%.

During the experimental runs the inside tube temperature, the distribution temperature of the fluid, the voltage and current intensity were measured by using a Lab View system. All these data were recorded during established steady states. Steady state was reached when the emf reading varied by less than 5 μV over a 15 min period. The time to establish a steady state was usually about 1.5 h. A new steady state was reached by increasing the voltage and simultaneously increasing the cooling water flux in the cooler.

3. Results

In order to validate the apparatus as well as the experimental procedure, the present data for pure glycol are compared with those predicted with the use of Churchill and Chu correlation [12]. The Nusselt number Nu_{ch} was determined from the correlation:

$$Nu_{ch} = \left\{ 0.6 + \frac{0.387 \cdot Ra^{\frac{1}{6}}}{\left[1 + \left(\frac{0.559}{\Pr} \right)^{\frac{9}{16}} \right]^{\frac{8}{27}}} \right\}^2 \tag{11}$$

where: Pr - Prandtl number

Figure 2 shows the comparison of the predicted results and measured data during three independent runs. The results show satisfactory agreement. Figure 3 shows preliminary results of heat transfer from horizontal tube obtained for glycol-Al_2O_3 nanofluid with nanoparticle concentration of 0.1% by weight. Contrary to the experimental results reported in the literature slight enhancement of heat transfer compared to the pure glycol on the same stainless steel tube was recorded.

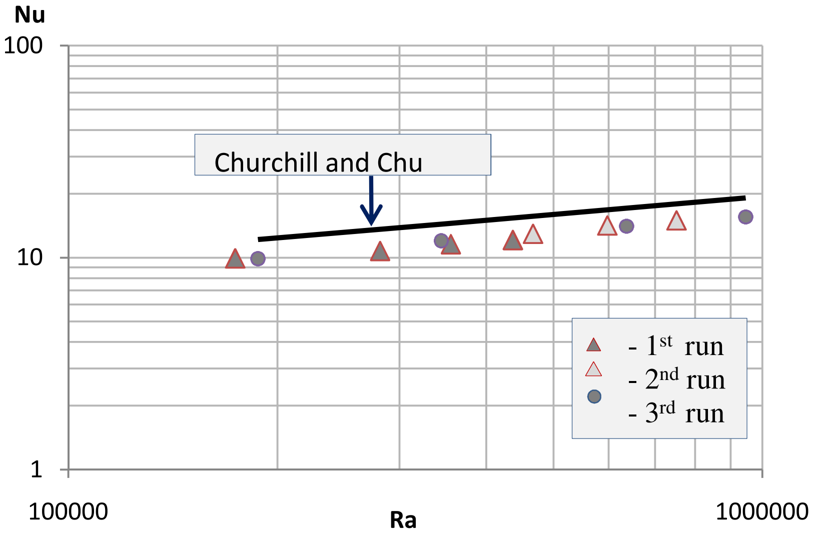

Fig. 2. Nu-Ra relationship of pure ethylene glycol

4. Conclusions

- Heat transfer behavior of glycol-Al_2O_3 nanofluid during free convection from horizontal stainless steel tube was investigated.
- Present results for pure glycol show satisfactory agreement with predictions made by recognized Churchill and Chu correlation, however the correlation overpredicts the experimental data for all free conducted runs.

- Contrary to the results reported in the literature slight enhancement of heat transfer for glycol-Al_2O_3 nanofluid compared to the pure glycol was recorded.

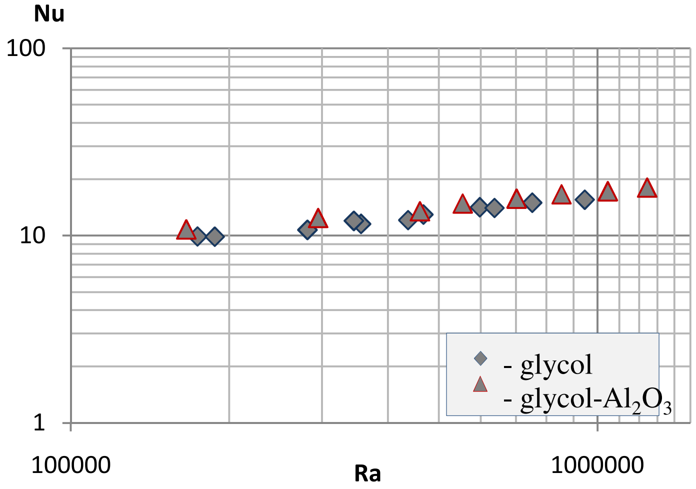

Fig. 3. Nu-Ra relationship of glycol-Al_2O_3 (0.1%) nanofluid

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BADANIA EKSPERYMENTALNE KONWEKCJI SWOBODNEJ NANOCIECZY GLIKOL-Al_2O_3 NA POZIOMEJ RURCE

Streszczenie

Nanociecze uważane są za nową generację czynników chłodzących w układach jednofazowych oraz dwufazowych. Ponadto, nanociecze i nanokomponenty mogą być użyte jako środki magazynowania energii cieplnej (TES) w takich systemach jak SHS czy PCM. W systemach wykorzystujących ciepło jawne dominującym sposobem wymiany ciepła jest konwekcja swobodna. Mimo tego, jak dotąd, przeprowadzono niewiele badań eksperymentalnych i numerycznych dotyczących zjawiska konwekcji swobodnej nanocieczy. W pracy zaprezentowano wstępne wyniki badań eksperymentalnych wymiany ciepła podczas konwekcji swobodnej nanocieczy glikol-Al_2O_3 na poziomej rurce.

Słowa kluczowe: magazynowanie energii cieplnej, ciepło jawne, nanociecze, konwekcja swobodna

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