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Heat transfer and pressure drop of Al_2O_3 nanofluid as coolant in shell and helically coiled tube heat exchanger

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In this investigation, the heat transfer and pressure drop analysis of Al_2O_3/ water nanofluid in a shell and helically coiled tube heat exchanger are studied. The Al_2O_3/water nanofluid at 0.1%, 0.4%, and 0.8% particle volume concentration was prepared by two-step method and characterized. It was found that the enhancement of experimental inner Nusselt numbers of 0.1%, 0.4% and 0.8% nanofluids are by 21%, 28% and 42%, respectively, higher than in water under laminar flow condition. This may be due to better mixing of the flow particles and higher effective thermal conductivity of the nanofluid. The inner Nusselt number correlation was proposed based on the experimental data. It is found that the deviation between the predicted and experimental Nusselt numbers in the range of ±7.5 %. The pressure drop in 0.1 %, 0.4% and 0.8% nanofluids was by 8%, 12% and 20%, respectively higher than that in water. This is due to the improved viscosity of the nanofluids. It is concluded that the Al_2O_3 nanofluid can be applied as coolant in a helically coiled tube at 0.1% and 0.4% particle volume concentrations without significant pressure drop.

Keywords: Al_2O_3/water nanofluid, Dean number, effective thermal conductivity, helical coil, inner Nusselt number, particle volume concentration.

INTRODUCTION

As conventional heat transfer fluids have exhausted their cooling capacity, nanotechnology is trying to overcome the hurdles faced by the existing conventional heat transfer fluids. Choi [1] introduced a new class of heat transfer fluids with 1-100 nm sized suspended nanoparticles in a base fluid and conceived the concept of heat transfer nanofluids in 1995. Subsequently, it was reported that thermal performance of nanofluids is better than that of water. Wang *et al*. [2], Lee *et al*. [3], Das *et al*. [4], and Li *et al.* [5] reported the effect of a nanofluid on the friction factor. Based on the aspect of enhanced heat transfer of the nanofluid, many researchers tried recently to apply a nanofluid as coolant. The nanofluid has a higher convective heat transfer coefficient than water, which increases with increasing mass flow rate [6]. The results were validated by simulations with empirical equations. The use of CuO and TiO_2/water nanofluids can significantly enhance the convective heat transfer in laminar flow regime.

The viscosity of Al_2O_3/water nanofluids significantly decreases with increasing temperature. The viscosity of the Al_2O_3–water nanofluid is in nonlinear relation with the concentration even in the low (0.01%–0.3%) volume concentration range. It is found that the measured value of nanofluid viscosity agrees well with the values predicted by the model of Lee *et al.* [7]. They observed that the heat transfer coefficient in the nanofluids is higher than that in water. Rea *et al.* [8] found that the pressure loss for nanofluids is much higher than for pure water. They suggested that the rotational Brownian motion of nanoparticles enhances heat transfer. For a nanofluid to be an efficient coolant, the nanoparticles should have a spherical shape and higher critical dilution limit of nanoparticle volume concentration [9].

The effective viscosity of Al_2O_3/water nanofluid nonlinearly increases with the volume concentration of nanoparticles even in the very low range (0.02–0.3 vol %) and strongly depends on the ratio of the nanoparticle diameter to the tube diameter [10]. The nanofluids with low concentrations can enhance the heat transfer efficiency up to 45% in comparison with pure water

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[11]. The use of a nanofluid gives better thermal performance than pure water [12]. A liquid metal with low melting point and high thermal conductivity is expected to act as an ideal solution for ultimate coolant [13]. An experiment with a multi-channel heat exchanger (MCHE) carried out by Jwo *et al*. [14] showed the nanofluids have a considerable potential for use in electronic chip cooling systems. Most of the studies have been done on a straight tube, as the flow pattern is simple. In case of a helically coiled tube, the flow pattern is complex. A dimensionless Dean number relates inertia force and centrifugal force in a flow through a curved pipe or channel. Dean number measures the secondary flow and the effect of curvature of bend/coil [15]. Correlations for Nusselt number (Nu), incorporating Dean number (De), and helical number (He) have been proposed by Salimpour [16]. Prabhanjan *et al*. [17] have found the helically coiled tubes are superior to straight tubes when employed in heat transfer applications using conventional fluid and the curvature of the tube plays an important role in enhancing heat transfer rate. The Reynolds number was replaced by the Dean number which takes into account the curvature effect [18]. The experiment was carried out on a residual heat removal system using helically coiled tube [19]. The friction factor of a helical coil tube was studied by Srinivasan [20] on varying the coiled tube diameter. The critical Reynolds number in a curved tube flow relates the coil pitch and the coil diameter. The formation of a secondary flow depends on the curvature radius and the Dean number. The addition of nanoparticles to the base fluid enhances the heat transfer coefficient [21]. The nanoparticles volume concentration does not affect the secondary flow, axial velocity and skin friction factor [22]. The heat transfer enhancement has a positive effect due to the presence of nanoparticles [23].

Very few works have been reported on helical coils with nanofluids. Moreover, the pressure drop plays an important role in the heat exchanger. Therefore, in this investigation, the effect of an Al_2O_3/water nanofluid on the heat transfer and pressure drop of a helically coiled tube heat exchanger is examined.

MATERIALS AND METHODS

Preparation of Al_2O_3 / water nanofluids

The Al_2O_3 nanoparticles was purchased from Alfa Aesar, USA. The Al_2O_3 nanoparticles were characterized by XRD (Rigaku Cu- $k_{\alpha 1}$ X ray diffractometer). The average particle size was calculated from the XRD pattern of the nanoparticles to be between 45 and 50 nm with an error within ±5 nm. In this investigation 0.1%, 0.4%, 0.8% Al_2O_3/water based nanofluids were prepared by a two-step method. The required amount of nanoparticles was dispersed in distilled water. Ultrasonic bath (Toshiba, India) generating ultrasonic pulses of 100 W at 36±3 kHz was switched on for 9 hours to get uniform dispersion and stable suspension of nanoparticles. Fig.1 illustrates the scanning electron microscope (Jeol JSM 6360 SEM) image of the agglomerated nanoparticles in the base fluid.

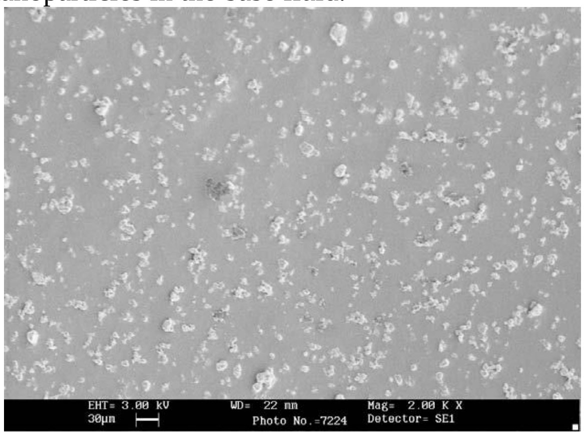

Fig. 1. SEM image of Al_2O_3 nanoparticles

The SEM image was obtained after ultrasonicating the nanoparticles to achieve stability, placing the sample on the sample holder, and rapid drying for getting solid conductive particles. The SEM image shows that the nanoparticles are uniformly dispersed, stable, less agglomerated and spherical in shape.

Experimental setup

Fig.2. illustrates the scheme of the experimental setup. The set-up has shell side loop and helical coiled tube side loop. Shell side loop handles hot water. Helical coiled tube loop handles Al_2O_3/water nanofluid. The shell side flow and the coiled tube side flow are in counter flow configuration. Shell side loop consists of a storage vessel with a heater of 1.75 kW capacity, magnetic pump and thermostat. The tube side loop consists of mono block pump, valve to control the flow on the tube side, test section, cooling unit and storage vessel of five liter capacity. The helical tube is made up of copper and shell is made up of mild steel. The temperature of the hot water in the shell side storage vessel is maintained by a thermostat. Four 'K'-type thermocouples of 0.1°C accuracy are used to measure the inlet and outlet temperatures of shell and tube side. Four 'K'-type thermocouples of

0.1ºC accuracy are placed on the outer surface of the coiled tube to measure the tube wall temperatures. U-tube mercury manometer is placed across the helical tube to measure the pressure drop. The shell is insulated with fiber wool. A valve is provided in the flow pipe connecting the cooler section and the reservoir for flow rate measurements and cleaning the system between experimental runs.

The dimensions of the test section are: helical tube internal diameter (di) – 10 mm, external diameter of helical tube - 11.5 mm, shell external diameter - 124 mm, effective length (L) of the coil -170 mm, coil pitch (B) – 17 mm, length of calming section – 70 mm, coil diameter (D) - 93 mm.

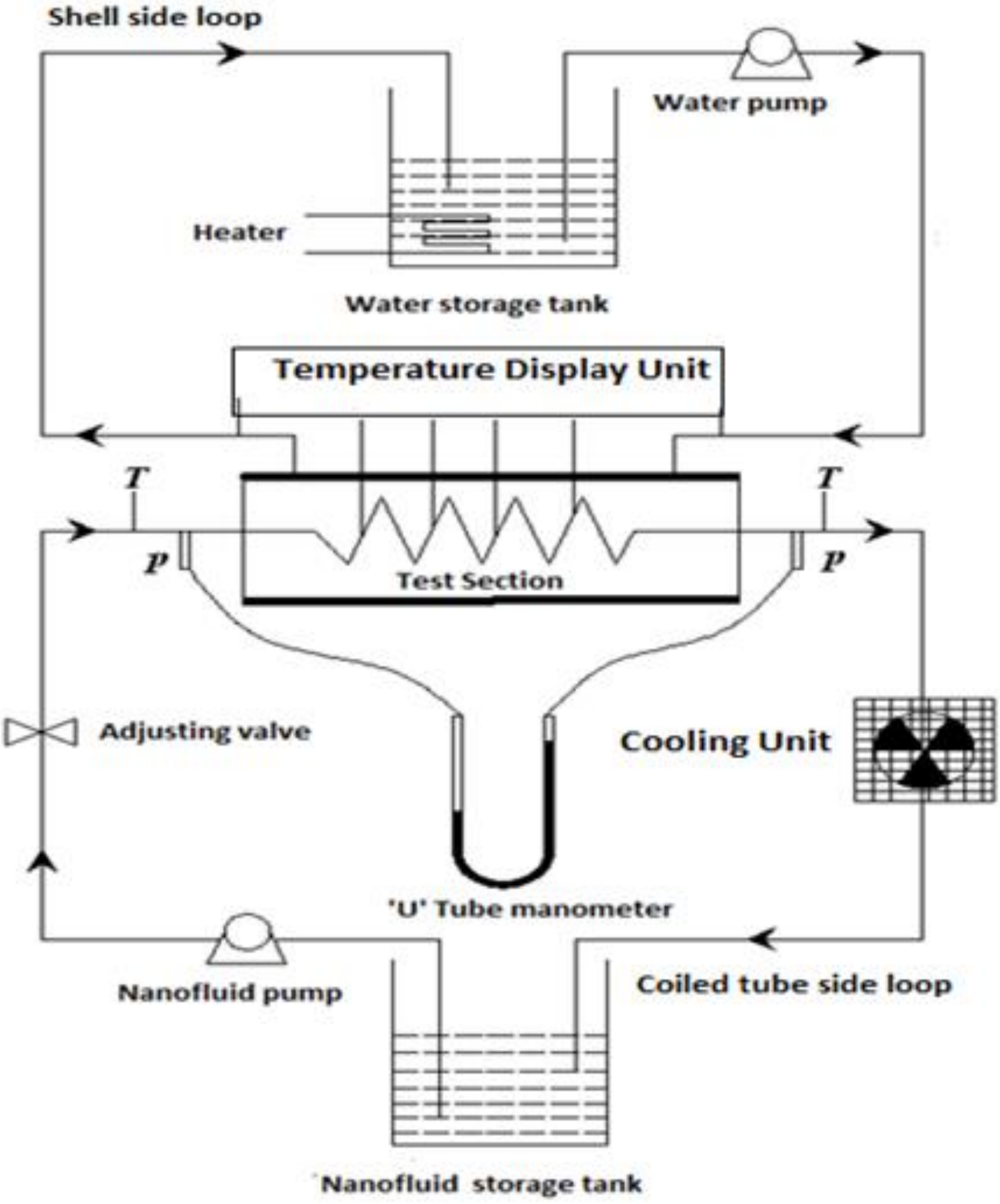

Fig. 2 . Schematic diagram of the experimental setup**.** T- Thermocouple, P-Pressure measuring port, Ts-Thermocouple for measuring surface temperature

Experimental procedure

Hot water and cold water were supplied to the shell side and the tube side, respectively, to check for leakages and test the accuracy of thermocouples and thermostat. Hot water was circulated to the shell side at a constant flow rate. The nanofluid with 0.1%, particle volume concentration was circulated through the tube side. The corresponding observations were made. The tube side flow was varied to attain the specified Dean number by using valve arrangement. Flow rate on the shell side was kept constant (0.15 kg/sec). The flow rate on the tube side was in the range of 0.03-0.05 kg/sec in laminar flow. The coil pitch was maintained constant throughout the test. The same procedure was followed for the 0.4% and 0.8% nanofluids. The uncertainty analysis was carried out by the Coleman and Steele method [24] and ANSI/ASME standards [25] considering measurement errors. The uncertainties involved in the measurements were about ±3% and ±2.5% for the Nusselt number and the Dean number, respectively.

Estimation of thermo-physical properties of the nanofluid

The specific heat capacity of the Al_2O_3 /water nanofluid was estimated using Eqn. (1) given by Xuan and Roetzel [26].

$$(\rho c_p)_{nf} = (1-\phi)(\rho c_p) + \phi(\rho c_p)_s \quad (1)$$

The thermal conductivity of Al_2O_3/water nanofluids was measured at 30°C with a KD2 Pro thermal analyzer. It is seen in Fig.3 that thermal conductivity increases with increasing particle volume concentration.

The measured thermal conductivity holds decent agreement with the estimated nanofluid thermal conductivity model proposed by Chandrasekar *et al*. [27]. The viscosity was measured at 30°C with a Brookfield cone and a plate viscometer (LVDV-I PRIME C/P). It is seen in Fig.4 that the viscosity increases with increasing particle volume concentration.

The measured viscosity holds decent agreement with the estimated viscosity of the nanofluid model proposed by Chandrasekar *et al*. [27].

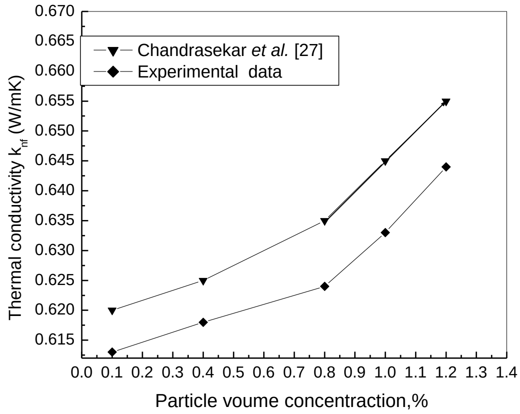

Fig. 3. Variation of the thermal conductivity of the Al_2O_3/water nanofluid with particle volume concentration

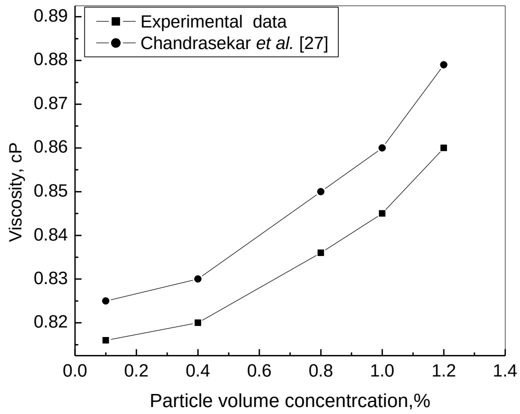

Fig. 4 Variation of viscosity with particle volume concentration.

Calculation of experimental inner Nusselt number and friction factor

The heat transfer for water and nanofluid was estimated from Eqns. (2) and (3). The inner heat transfer coefficient was calculated from Eqn. (4).

$$Q_{nf} = m_{nf} c_{p,nf} (T_{in} - T_{out})_{nf} \quad (2)$$

$$Q = h_i A_i (T_{wall} - T_{bulk}) \quad (3)$$

$$Q_w = m_w c_{p,w} (T_{in} - T_{out})_w \quad (4)$$

$$Nu_i = h_i d_i / k_{eff} \quad (5)$$

The experimental tube side Nusselt number was estimated from Eqn. (5) and it measures the convective heat transfer in the helical tube. It is a function of Dean number (De) and Prandtl number (Pr), coil pitch and curvature radius.

RESULTS AND DISCUSSION

Heat transfer coefficient

Fig.5 shows the effect of increasing the particle volume concentration on the tube side experimental Nusselt number under laminar flow.

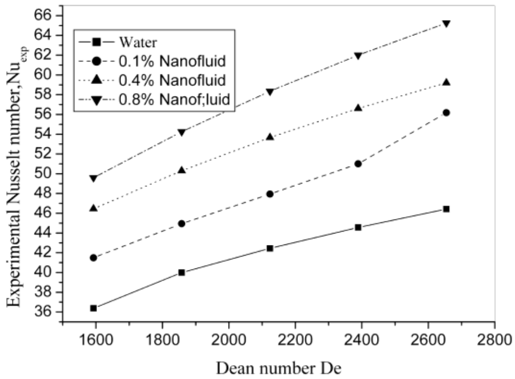

Fig. 5. Experimental inner Nusselt number *versus* inner Dean number

It is clear that the tube Nusselt number increases with particle volume concentration and Dean number. At a fixed Dean number, the enhancement of tube side experimental Nusselt number for 0.1%, 0.4% and 0.8% nanofluids is by 21%, 28% and 42% than water. This may be due to the better mixing of Al_2O_3 nanoparticles and the higher effective thermal conductivity of nanofluid. The Nusselt number increases with Dean number, as the formation of secondary flow is getting stronger and thinning of the boundary layer takes place. The increasing nanofluid conductivity and decreasing thermal boundary thickness are the reasons for enhancing heat transfer coefficient in a shell and tube heat exchanger when a nanofluid is passing through the coiled tube.

Based on the experimental data, a Nusselt number correlation (Eqn. 6) was developed for a laminar flow in the range of 1600 < De < 2700. Fig. 6 shows the comparison between experimental and predicted Nusselt number.

$$Nu_i = 1.12 De^{0.45} \Pr^{0.1} \delta^{0.06} \phi^{0.07} \quad (6)$$

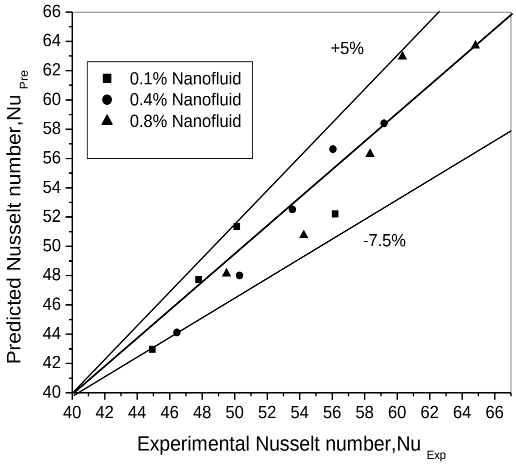

Fig. 6. Comparison between experimental and predicted inner Nusselt number

The deviation between the predicted and the experimental Nusselt number was found to be in the range of ±7.5 under laminar flow conditions.

Effect of pressure drop

Fig. 7 shows that the pressure drop increases with increasing particle volume concentration and mass flow rate.

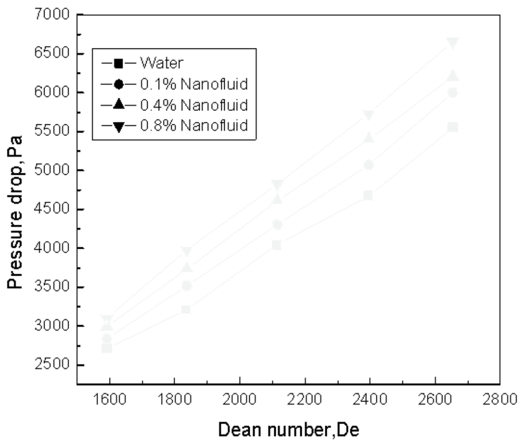

Fig. 7. Variation of experimental pressure drop with Dean number in a laminar flow

The pressure drop in 0.1 %, 0.4% and 0.8% nanofluids is higher by 8%, 12% and 20%, respectively, than in water at De = 2650. This is due to the increased density and viscosity at higher particle volume concentrations. It is observed that the rate of pressure drop increased when Dean number increased. The rate of increase of pressure drop at De = 1600 is smaller than at De = 2650 because the effect of viscosity dominates at low velocity.

CONCLUSION

In this paper, heat transfer and pressure drop studies of a shell and helically coiled tube heat exchanger with Al_2O_3/ water nanofluid were carried out under laminar flow. The increase in Nusselt number was found to be 21%, 28% and 42% at 0.1%, 0.4% and 0.8% of Al_2O_3/water nanofluid particle volume concentration respectively, when compared with water. The main reason is the higher effective thermal conductivity of nanofluid. Based on the experimental data, a Nusselt number correlation was developed for a helically coiled tube. The deviation between the predicted and experimental Nusselt number was found to be in the range of ±7.5%. It is found that the pressure drop increases with increasing particles volume concentration and Dean number. It is concluded that the Al_2O_3/water nanofluid can be applied as coolant in a shell and helical coiled tube heat exchanger at 0.1% and 0.4% low particle volume concentration without significant pressure drop with heat transfer enhancement.

NOMENCLATURE

A	Surface area , m^2
C_p	Specific heat capacity J/kg K
d_i	Inner Diameter of tube, m
De	Dean number = $Re_i (d_i / 2R_c)^{0.5}$
h	Convective heat transfer coefficient, $W/m^2 K$
k	Thermal conductivity, W/m K
Nu	Nusselt number $=h_i d_i / k_{eff}$
Pr	Prandtl number $=C_{p,nf} \mu_{nf} / k_{eff}$
Q	Heat transfer rate, W
Rc	Curvature radius, m
T	Temperature, K
v_i	Velocity, m/s

Greek letters

ρ	Density, kg/m^3
φ	Particle volume concentration (%)
μ	Dynamic viscosity, kg/m^2s
δ	Inner tube radius /mean coil radius R

Subscripts

cr	Critical
eff	Effective
in	Inlet
nf	Nanofluid
m	mean
out	Outlet
s	Surface
w	Water

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АНАЛИЗ НА ТОПЛООБМЕНА И ХИДРАВЛИЧНОТО СЪПРОТИВЛЕНИЕ НА НАНОФЛУИД ОТ Al_2O_3 КАТО ОХЛАДИТЕЛ В КОЖУХО-ТРЪБНИ И СПИРАЛНИ ТОПЛООБМЕННИЦИ

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(Резюме)

В тази работа са изследвани топлообмена и хидравличното съпротивление на нанофлуид от Al_2O_3 като охладител в кожухо-тръбни и спирални топлообменници. Обемните концентрации на частиците от 0.1%, 0.4% и 0.8% са приготвени по двустепенен метод. Беше установено, че повишаването на числото на Нуселт за вътрешността на топлообменника спрямо водата като топлоносител са 21%, 28% and 42% при добавени съответно 0.1%, 0.4% и 0.8% нанофлуид при ламинарно течение. Това може да се дължи на по-доброто смесване и по-високата топлопроводност на нанофлуида. Предложена е корелация за числото на Нуселт на основание на експериментални данни. Установено е отклонение от ±7.5 % между предсказаните и опитните стойности на числото на Нуселт. Хидравличното съпротивление при наличие на 0.1%, 0.4% и 0.8% нанофлуиди е с 8%, 12% и 20% по-високо, отколкото във вода. Това се дължи на повишения вискозитет на смесите с нанофлуиди.Установено е, че нанофлуидите с Al_2O_3 може да се прилагат като охлаждащи течности в спирални топлообменници без значимо повишаване на хидравличното съпротивление.