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Effects of Cooling Process of Al_2O_3-water Nanofluid on Convective Heat Transfer

Research has been done to investigate the convective heat transfer and pressure drop of nanofluid, using alumina-water nanofluid under laminar flow regime. The test section was using 1.1 m long and 5 mm inner diameter tube of a double- pipe heat exchanger with constant wall temperatures. The hot nanofluid is flowing inside tube, while the cold water flows outside. The volume concentration of the nanoparticles varied from 0.15%, 0.25% and 0.5%. Experiment shows that the convection heat transfer increases remarkably with the increase of the nanoparticles concentration under various values of Reynolds number. The Nusselt number increases about 40.5% compared to pure water under 0.5% volume concentration. The pressure drop of nanofluid increases slightly with increasing volume concentration. However, compared with using pure water the difference of the pressure drop is insignificant, so that the use of nanofluid has little penalty on pressure drop.

Keywords: *Nanofluid, alumina, laminar flow, Nusselt number, convective heat transfer, pressure drop.*

1. INTRODUCTION

Various methods that have been done to enhance heat transfer, such as modifying surface roughness as turbulence promoter, flowing fluids through micro channels, and using nanofluids. In the past 20 years many researchers have been studying the properties of nanofluids, and it's expected to be the next generation of heat transfer technology due to the better thermal performances compared to that of traditional heat transfer fluid [1]. Nanofluid can be defined as a fluid in which solid particles with the sizes under 100 nm are suspended and dispersed uniformly in a fluid. The base fluid used the same as traditional heat transfer fluids, e.g, water, oil, and ethylene glycol.

Many researchers observed the phenomenon of higher thermal conductivity of various nanofluids compared to that of the base fluids. However, differences between the results were observed, i.e., some showed that the increase of thermal conductivity of nanofluids is an anomaly that cannot be predicted by the existing conventional equation [2,4]; while some others showed that the increase is not an anomaly and can be predicted by using the existing conventional equation [5]. Regarding the convection heat transfer, Li and Xuan [3] reported that in laminar and turbulent flow regime in forced convection, the heat transfer coefficient of Cu-water nanofluids flowing inside a uniformly heated tube remarkably increased. The heat transfer coefficient increased by around 60% for 2 vol.% nanoparticle concentration compared to that of pure water. Furthermore, it was observed that the increase of nanoparticle concentration would also increase the heat transfer coefficient. Interestingly, the experimental results showed that there is no significant increase in pressure drop compared to that of water. Thus, it is no need to be worried about the drawback of pumping power increase.

Experimentally, enhancement of laminar flow convection coefficient of Al_2O_3-water nanofluids under constant wall temperature in heating process is much higher than that predicted by single phase heat transfer correlation used in conjunction with the nanofluids properties, as in [6]. It was also concluded that the heat transfer enhancement of nanofluids is not merely due to the thermal conductivity increase of nanofluids which means other factors may contribute to this phenomenon.

Duangthongsuk and Wongwises [7] have presented the heat transfer and flow characteristics of nanofluid consisting of water and TiO2 nanoparticles at 0.2% volume concentration in double-tube heat exchanger. The result showed that the convective heat transfer coefficient of nanofluid was only slighty higher than of the base fluid by about 6-11% and has little increase in pressure drop.

Anoop et al [8] carried out convective heat transfer experiments with Al_2O_3-water nanofluids in the developing region of pipe flow with constant heat flux to evaluate the effect of particle size on convective heat transfer coefficient. In their work, two particle sizes (45 nm and 150 nm) were used and it was observed that the nanofluid with 45 nm particles showed higher heat transfer coefficient than that with 150 nm particles.

Hojjat et al [13] conducted experiments to investigate heat transfer of Al_2O_3, TiO_2 and CuO in aqueous solution of carboxymethyl cellulose (CMC) was used as the base fluid tested in fully developed turbulent flow regime. The results showed that all nanofluids have higher heat transfer coefficient than

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those of the base fluid. Enhancement of heat transfer coefficient increases with an increase in both of the Peclet number and the nanoparticle concentration. The heat transfer coefficient enhancement is much higher than attribute to the thermal conductivity.

The goal of the experiment by Asirvatham et al [10] is to investigate heat transfer of silver-water nanofluid which was varied from 0.3 % to 0.9 % volume concentration in double tube heat exchanger. The result showed the enhancement of heat transfer coefficient by 28.7% and 69.3% for 0.3% and 0.9% volume concentration, respectively, and [11] investigated heat transfer and pressure drop of TiO_2-water nanofluid in circular tube at 0.05% to 0.25% volume concentrations. The results indicated that addition of small amounts of nanoparticles to the base fluids, heat transfer coefficient of nanofluids increased. At the Reynolds number of 5000, for 0.25% volume concentration, there was increase of about 22% in the heat transfer coefficient. The pressure drop of nanofluid increased with increasing the volume concentrations of nanoparticles. The maximum pressure drop was about 25% greater than of pure water which occurred in 0.25% volume concentration at the Reynolds number of 5000.

In this study, the enhancement of convective heat transfer and pressure drop was done using Al_2O_3-water nanofluid flowing in a concentric double pipe heat exchanger with counter flow. The effect of the rate of cooling process of nanofluid, concentration of Al_2O_3 nanoparticles, thermal resistance and flow rates on convective heat transfer and pressure drop were investigated.

2. EXPERIMENTAL METHODS

2.1 Nanofluid preparation

The γ Al_2O_3 nanoparticles size of 20-50 nm produced by Zhejiang Ultrafine powder&Chemical Co, Ltd China were used. Nanofluid was prepared by dispersing Al_2O_3 nanoparticles with different volume concentrations in distilled water as base fluid. The mechanical mixer (magnetic-stirring) was used for dispersing nanoparticles. The solutions of water-alumina nanoparticles were prepared by the equivalent weight of nanoparticles according to their volume and was measured and gradually added to distilled water while being agitated in a flask. No sedimentation was observed after 5 hour in the low concentrations used in this work.

2.2 Thermo-physical properties of nanofluid

The thermo-physical properties as such as density, viscosity, specific heat and thermal conductivity of the nanofluid are calculated using the following correlations:

Density [15]:

$$\rho_{nf} = \varphi\rho_p + (1-\varphi)\rho_b \tag{1}$$

Viscosity [12]:

$$\mu_{nf} = \mu_f \left(1 + 7.3\varphi + 123\varphi^2\right) \tag{2}$$

Specific heat [16]:

$$(\rho Cp)_{nf} = (1-\varphi)(\rho Cp)_b + \varphi(\rho Cp)_p \tag{3}$$

Thermal conductivity [17]:

$$\frac{k_{nf}}{k_b} = \frac{k_{p+}2k_b + 2(k_p - k_b)(1+\beta)^3\varphi}{k_p + 2k_b - (k_p - k_b)(1+\beta)^3\varphi} \tag{4}$$

Where φ is the volume particles concentration, and the subscript *b*, *p* and *nf* represent the base fluid, nanoparticle and nanofluid, respectively.

In this study, Al_2O_3–water nanofluids with particle volume concentrations of 0.125%, 0.25%, and 0.5% are used to evaluate the heat transfer performance of nanofluids. Table 1 shows the lists of the thermo-physical properties of these nanofluids at the characteristic temperatures of 40^{o}C.

Table1. Thermophysical properties of Al_2O_3–water nanofluids at 40^{o}C

φ (%)	ρ (kgm^{-3})	k ($Wm^{-1}K^{-1}$)	μ ($kg\ m^{-1}s^{-1}$)	Cp ($Jkg^{-1}C^{-1}$)	Pr
0	992	0.633	0.00065	4174	4.300
0.15	995	0.636	0.000657	4158	4.293
0.25	997	0.639	0.000662	4148	4.299
0.50	1002	0.645	0.000676	4123	4.318

2.3 Experimental apparatus

The experimental system used for this study is shown schematically in Figure 1, which comprises two flow circuits, cold water and hot nanofluid. It consisted of a flow loop, a heating unit, a cooling unit, a flow measuring unit and a pressure drop measuring unit. The flow loop contained a reservoir, pump, valve for controlling the flow rate and a test section. The test section made from smooth brass tube is a 1.1 m long with 5 mm inner diameter and a 6.24 mm outer diameter, while the outer tube is a stainless steel tube and with 38.5 mm outer diameter and 3 mm thickness.

The experiments were done using a counter flow mode in a horizontal double pipe heat exchanger, with hot nanofluid flowing inside the inner tube while cold water flows through the annulus. The temperature of the nanofluid at the inlet was maintained at 40^{o}C. The stainless steel outer tube was thermally isolated using Aeroflex tube 35 mm diameter and 10mm thickness. Four K-type thermocouples were mounted at differential longitudinal positions on tube surface of the wall, two K-type thermocouples were inserted into the flow at the entrance and exit of the test section to measure the bulk temperatures of nanofluid and two K-type thermocouples were measured the flow the entrance and exit of the cold water flows in the annular temperatures. A differential pressure transducer from Brand Omega PX 409-005DWU5V was used for measuring the pressure drop along the test section. The electric heater with a PID controller was installed to keep the temperature of the nanofluid constant.

The cooler tank with a thermostat is used to keep the nanofluid temperature constant. The nanofluid flow rate and cold water were controlled by adjusting the bypass flow valve, which was measured by Dakota rotameters. To create constant wall temperature boundary condition, the cool water was circulated with high flow rate. During all experiments, the inlet and outlet temperature of the nanofluid, the wall temperature at the various positions were measured and recorded using the thermocouple data acquisitions module (Omega TC-08). The average of all data was used in the present study.

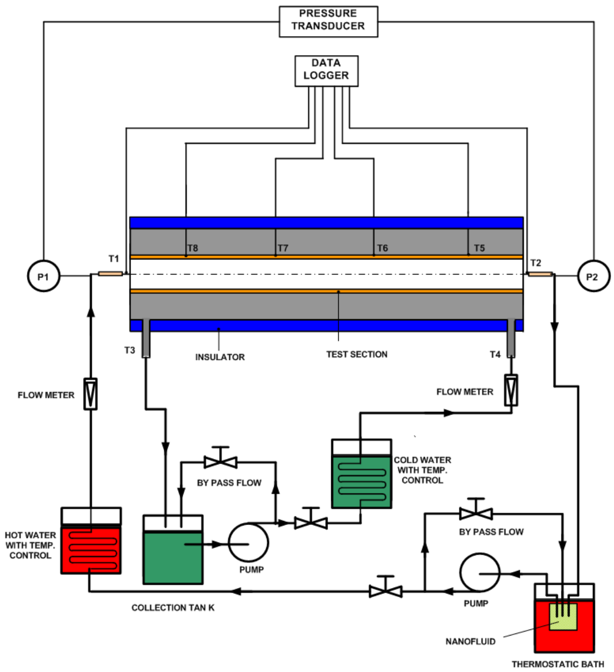

Figure 1. Schematic diagram of the experimental apparatus

2.4 Data Analysis

The heat transfer performance of nanofluid through tube was defined in terms of the convective heat transfer coefficient calculated as follows:

$$Q_{nf} = \dot{m}_{nf}\, Cp_{nf}\left(T_i - T_o\right) \tag{5}$$

$$\bar{h}_{nf} = \frac{Q_{nf}}{\pi d L \Delta T_{LMTD}} \tag{6}$$

$$\Delta T_{LMTD} = \frac{\left(T_w - T_o\right)-\left(T_w - T_i\right)}{\ln\left(T_w - T_o\right)/\left(T_w - T_i\right)} \tag{7}$$

$$\overline{Nu}_{nf} = \frac{\bar{h}_{nf} d}{k_{nf}} \tag{8}$$

where Q_{nf} is heat transfer rate of nanofluid, $\dot{m}_{nf}$ is the mass flow rate of nanofluid, T_i is temperature inlet of the nanofluid, T_o is temperature outlet of the nanofluid, T_w is the temperature of the wall, $\bar{h}_{nf}$ average heat transfer coefficient of the nanofluid, $\overline{Nu}_{nf}$ is average Nusselt number of the nanofluid, d is the inner diameter of the test tube and k_{nf} thermal conductivity of the nanofluid.

2.5 Uncertainty analysis

Uncertainty of experimental results was determined by measurement deviation of the parameters, including weight, temperature, flow rate and pressure drop. The weight (W) of nanoparticles was measured by a precise electronic balance with the accuracy of ± 0.001 g, the precision temperature data acquisitions (T) is ± 0.1o C, flow rate (V) was measured by a rotameter with the full scale accuracy of ±5% and pressure drop (P) was measured by a pressure transducer with the accuracy of 2%. The uncertainty of experimental results could be expressed as follows [20]:

$$u_m = \pm\left[\left(\frac{\Delta W}{W}\right)^2 + \left(\frac{\Delta T}{T}\right)^2 + \left(\frac{\Delta V}{V}\right)^2 + \left(\frac{\Delta P}{P}\right)^2\right]^{1/2} \tag{9}$$

Therefore, the uncertainty of the experiment was less than ± 6.0%.

3. EXPERIMENTAL RESULT AND DISCCUSIONS

3.1 Convective heat transfer

To make the comparison for the results of convective heat transfer using nanofluid, similar experiment was done using pure water as the working fluid. Figure 2 shows the experimental results of the pure water in laminar flow regime prediction from Seider and Tate [9], which is defined as:

$$\overline{Nu}_{nf}(th) = 1.86\left(Re\ Pr\frac{d}{L}\right)^{1/3}\left(\frac{\mu_s}{\mu}\right)^{0.14} \tag{10}$$

Very good agreement between experimental data and the Seider Tata equations results were obtained, which emphasizes the accuracy and reliability of the experiments. It should be in equation (10) the *Re* and *Pr* are the Reynolds number and Prandtl number, respectively which are defined as follows:

$$\mathrm{Re} = \frac{\rho \bar{U} d}{\mu} \tag{11}$$

$$\mathrm{Pr} = \frac{Cp\ \mu}{k} \tag{12}$$

where, *Nu* is the Nusselt number, $\mu_w, \mu, \rho, C_p, \bar{U}$ and *k* are the viscosity of fluid at wall, the viscosity of water, density, specific heat, average velocity and thermal conductivity, respectively.

As shown in Figure 3 the Nusselt number increases with increases in the Reynold number as well as in the particle volume concentration. It can be clearly seen that the Nusselt number of the nanofluid is higher than that of the base fluid (water) at a given Reynold number. For example, at the Reynolds number 2000 the Nusselt number increases from 6.12 to 8.6 (40.5%), for volume concentration 0% (pure water) to 0.5%. The thermal conductivity enhancement according equation (4) is about 1.9% for the same volume concentration. It can be concluded from this figure that other mechanism beside thermal conductivity increase can be responsible for heat transfer enhancement.

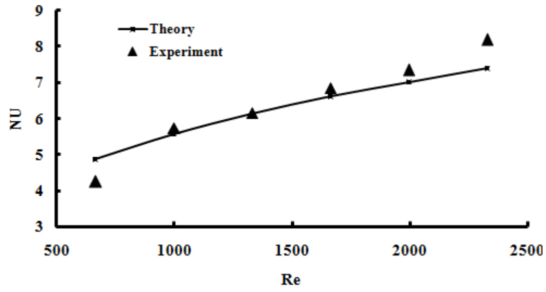

Figure 2. Comparison between experimental data of pure water and calculated from Seider and Tate equations

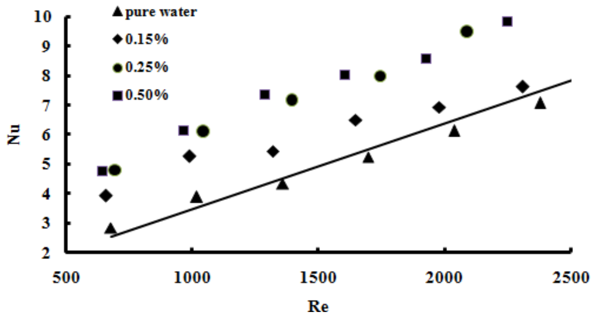

Figure 3. The Nusselt vs Reynolds number for pure water and Al_2O_3-water nanofluid at different volume concentration.

The convection heat transfer caused by the presence of nanoparticle is speculatively attributed to the interactions of nanoparticle with the wall as well as with the surrounding fluids. It is considered by [18] that the interactions between nanoparticles and solid wall play an important role in the convection heat transfer nanofluid. The nanoparticles, serving as 'heat carrier', frequently collide with the wall tube. With the increase in the nanoprticles concentration, the interaction and collisions between nanoprticles and the wall become frequent, and thus cause a much higher heat transfer and the Nusselt number.

The experimental results obtained in this study using Al_2O_3–water nanofluid with laminar flows, were then compared with two other correlations with forced convective heat transfer under laminar flow which are, an empirical correlation by Li and Xuan [3] and a numerical correlation in tube by Maiga et al [14] in equations (13) and (14).

$$Nu = 0.4328(1+11.285\varphi^{0.754})^{0.14}\,\mathrm{Re}_{nf}^{0.33}\,\mathrm{Pr}_{nf}^{0.4} \quad (13)$$

$$Nu = 0.28\,\mathrm{Re}_{nf}^{0.35}\,\mathrm{Pr}_{nf}^{0.36} \quad (14)$$

As can be seen in Figure 4, at volume concentration 0.5% of Al_2O_3–water, experiment study lies between those prediction from Maiga and Li& Xuan correlations.

Figure 5 shows, the variation of the thermal resistance versus the Reynolds number for the nanofluid with different particle volume concentration. It is found that for both the pure water and the Al_2O_3–water nanofluids, the thermal resistance decreased with increasing in the Reynolds number.

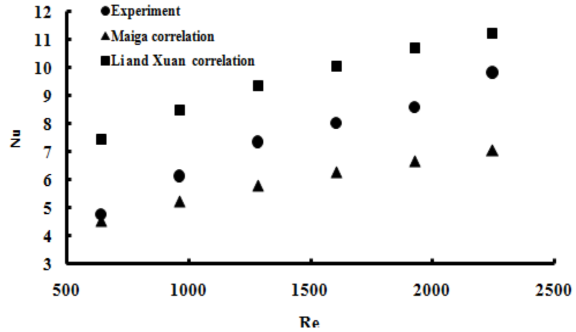

Figure 4. Comparison of measured Nusselt number with those predicted from Li and Xuan and Maiga correlation for 0.5% volume concentration.

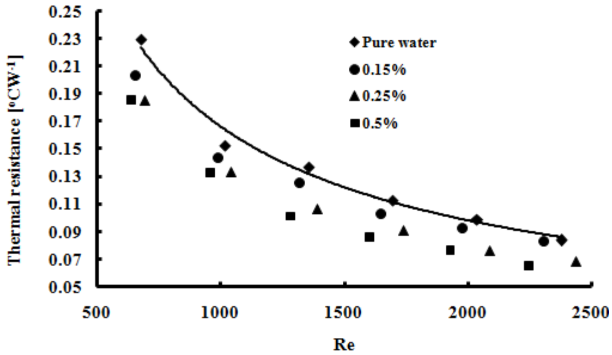

Figure 5. Thermal resistance pure water and Al_2O_3-water nanofluid vs Reynold number at different volume concentration.

The decreasing rate thermal resistance with increasing Reynold number was relatively fast at the lower Reynold number, but became slow with the increase in the Reynold number. At the same Reynolds number (Re=2000), the thermal resistance decreased with increase in the particle concentration. As can be seen, the nanofluid with volume concentration of a 0% (pure water) to 0.5%, the thermal resistances decrease from 0.105^{o}CW^{-1} to 0.083^{o}CW^{-1} (20.9%).

3.2 Pressure drop of nanofluid

The accuracy of fluid flow in experimental method, the predicted pressure drop for laminar flow was compared to the correlation the Heggen-Poiseuille as follows:

$$\Delta P = \frac{32\bar{U}\mu L}{d^2} \quad (15)$$

Figure 6 shows the pressure drop of the hot water inside the tube as a function of the Reynold number at 40^{o}C temperature. Good agreement exists between experimental data and the theoretical model for laminar flow.

Figure 7 shows the variation in the pressure drop with the Reynolds number for the nanofluid with different particle volume concentration. It can be clearly seen that the hot water flow has insignificant effect on the pressure drop of the Al_2O_3–water nanofluid. This is due to the increase in the hot water flow rate having a slight effect on the viscosity in the nanofluid, which leads to a tiny change in the measured pressure drop at low volume concentration Al_2O_3–water nanofluid.

The pressure drop is dependent on viscosity of the working fluid inside the tube. With increasing in the particle concentration in the nanofluid the viscosity increases, but temperature gradient on radial axis of the working fluid causes the viscosity distribution of the nanofluid, and it is an important parameter in pressure loss. Especially, viscosity at the wall significantly affects pressure loss. Since, the viscosity of nanofluid is a strong function of temperature, the pressure drop of nanofluid depends on temperature of the working fluid.

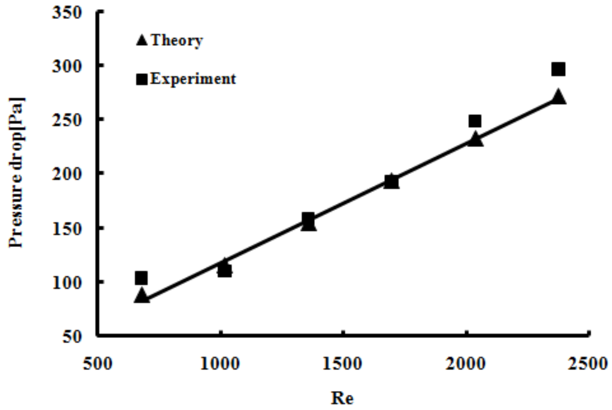

Figure. 6 Comparison between experimental data and theory of pressure drop.

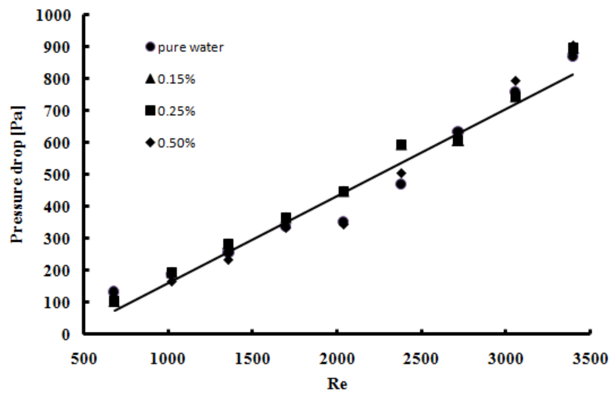

Figure 7. Pressure drop and Reynold number for nanofluid with different volume concentration.

4. CONCLUSIONS

The convective heat transfer and pressure drop characteristics of three nanofluids flowing in a circular tube in the laminar flow regime was experimentally investigated. The effects of the flow on the Reynolds number and the volume concentration of nanofluid were important point. The following conclusions have been obtained. (1) Convective heat transfer of the Al_2O_3–water nanofluids are significantly higher than those of the pure water. (2) The convective heat transfer increases with increasing both the Reynolds number and volume concentration. (3) The pressure drop of the Al_2O_3–water nanofluids are approximately the same as those of pure water in the given conditions. This implies that the nanofluid incurs no penalty of pump power and may be suitable for practical application.

NOMENCLATURE

Re	Reynolds number
Nu	Nusselt number
Pr	Pandtl number
A	Cross section area, [m^2]
Cp	Spesific heat, [J kg^{-3} K^{-1}]
d	Diameter of tube, [m]
f	Friction factor, [-]
h	Heat transfer coefficient, [W m^{-2} K^{-1}]
k	Thermal conductivity, [W m^{-1} K^{-1}]
L	Length of the test tube, [m]
Δ P	Pressure drop,[Pa]
Q	Heat transfer rate, [W]
q_s	Heat flux, [W m^{-2}]
r	Radius [m]
T	Operating temperature, [K]
$\overline{U}$	Average velocity, [m s^{-1}]

Greek symbols

μ	Dynamic viscosity [Pa s]
φ	Volume concentrations [%]
ρ	Density [kg m^{-3}]

Superscripts

b	Base fluid
o	Outlet
f	Fluid
i	Inlet
nf	Nanofluid
o	Outlet
p	Particle
w	Wall

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УТИЦАЈ ПРОЦЕСА ХЛАЂЕЊА НАНОФЛУИДОМ САСТАВЉЕНОГ ОД ВОДЕ И AL_2O_3 НАНОЧЕСТИЦА НА ПРЕНОС ТОПЛОТЕ КОНВЕКЦИЈОМ

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Рад приказује истраживање преноса топлоте конвекцијом и пад притиска у нанофлуиду коришћењем нанофлуида који се састоји од воде и алуминијум оксида у условима режима ламинарног струјања. Испитивање је вршено помоћу цеви дужине 1,1 м и унутрашњег пречника 5 мм код измењивача топлоте са двоструком цеви при константним температурама зида. Загрејани нанофлуид тече кроз унутрашњу цев а расхладна вода опструјава споља. Запреминска концентрација наночестица је варирала: 0,15%; 0,25% и 0,5%. Експеримент је показао да се пренос топлоте конвекцијом значајно повећава са повећањем концентрације наночестица при различитим вредностима Рејнолдсовог броја. Нуселтов број се повећава око 40,5% у односу на чисту воду при запреминској концентрацији од 0,5%. Пад притиска у нанофлуиду незнатно расте са порастом запреминске концентрације. Међутим, у поређењу са коришћењем чисте воде разлика је безначајна, тако да коришћење нанофлуида има малог утицаја на пад притиска.