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SCIENTIFIC PAPER

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HEAT TRANSFER PERFORMANCE OF AN Al_2O_3-WATER-METHANOL NANOFLUID IN A PLATE HEAT EXCHANGER

Article Highlights

- Al_2O_3/Methanol/ Water mixed nanofluid were prepared using a high-pressure homogenizer
- The heat transfer performance of Al_2O_3 suspended base fluid was studied in a plate heat exchanger
- Individual and overall heat transfer coefficients were determined and analyzed by varying flow rate

Abstract

A plate heat exchanger is one of the smallest and most efficient heat exchangers on the market. This experiment aims to assess the performance of methanol-water as a base fluid in a plate heat exchanger that affects the heat transfer performance. For this study, aluminum oxide (Al_2O_3) nanoparticle was used in various ratios (0.25, 0.5, and 0.75 vol. %) in a base fluid (10 vol.% methanol & 90 vol.% water) to prepare a nanofluid. At two different temperatures, such as 55 °C and 60 °C, with varying flow rates (2 to 8 L/min) and varying nanoparticle concentrations (0.25 to 0.75%), thermo physical characteristics and convective heat transfer studies were performed, and the results are presented. The overall inference was that there was a notable enhancement in the hot side, cold side, and overall heat transfer coefficient by the combination of Al_2O_3 nanoparticle and methanol-water-based fluid. It was noted that utilizing Al_2O_3/methanol-water nanofluid could significantly reduce the temperature gradient in the heat exchanger and improve its performance. Maximum hot fluid coefficient of 4300 W/m^2 °C, cold fluid coefficient of 4600 W/m^2 °C, and overall coefficient of 2200 W/m^2 °C were noted for 0.75 vol.% nanoparticle concentration and at a flow rate of 8 L/min.

Keywords: Al_2O_3, base fluid, heat transfer, methanol, nanofluid, plate heat exchanger.

Particles with a size of less than 100 nm are known as nanoparticles. Nanoparticles naturally occur in the environment but are artificially synthesized [1]. Nanoparticles are inorganic materials. The human eye cannot see nanoparticles. They can be classified into different types based on their shapes, properties, and sizes. Nanoparticles have unique physical and chemical properties because of their nanoscale size and high surface area. Their unique size, shape, and structure play a major role in reactivity, toughness, and other properties. Due to their special characteristics, these minuscule particles are well suited for high chemical reactivity, bio mobility, and energy absorption [2]. Nanomaterials are classified into 0D, 1D, 2D, and 3D based on their overall shape. Nanoclusters have a modest size distribution with at least one dimension between 1 and 10nm. Industrial manufacturing processes involve heat exchangers for heating and cooling [3] the fluids. The most common base fluids in heat transfer applications are glycols, methanol, engine oil, and water [4]. Thermal conductivity and heat transfer properties of these fluids must be improved to improve heat transfer performance [5,6].

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There has been a recent advancement in energy reduction using nanofluids, as evidenced by a sizable number of technical community research articles. A new engineering fluid, this nanofluid is known for its special applications and capacity to reduce costs in heat transfer operations based on altering suitable base fluids [7]. A complete review of synthesis, stability, thermophysical properties, and heat transfer applications of nanofluid was performed by Mehta *et al.* and was useful for framing the experimental conditions of the present study [8,9].

Researchers have developed nanoparticle-sustained heat transfer fluids in different heat transfer equipment [10,11]. Various metal oxides were utilized by many researchers, such as CuO nanoparticles added to water [12], aluminum oxide/water [13–17], Al_2O_3 in water-ethylene glycol [18], TiO_2, ZnO in water-ethylene glycol [19], Fe_2O_3 in engine oil-water mixture [20], Al_2O_3 and CuO nanoparticle suspension in engine oil, vacuum pump fluid, distilled water, and ethylene glycol [21] and the results showed that this addition considerably increases the thermal conductivities of fluid mixtures and heat transfer coefficient.

A heat transfer study was made to determine Nusselt number, pressure drop, and energy efficiency factor by Ajeeb *et al.*, and the results indicated a heat transfer enhancement of 27% at 0.2 vol% for DW-based Al_2O_3 nanofluid and 19.1% at 0.2 vol% for 30% of EG based Al_2O_3 nanofluid [22]. The experimental results of Al_2O_3 nanoparticle addition show that the Nusselt number increased significantly with respect to different volume fractions [23]. Heat transfer results on experimental and numerical investigations performed by Singh *et al.* with DW-Al_2O_3, graphene nanoplatelet (GnP), and multi-walled carbon nanotubes (MWCNT) nanofluids showed that at 1 Vol.% nanoparticle concentration, around 10, 15 and 18 % maximum enhancement in an average heat transfer rate observed with Al_2O_3, GnP and MWCNT nanofluids, respectively[24]. Pang *et al.* [25] used methanol-based nanofluids with 0.5 vol% at 293.15 K and reported 14.29% and 10.74% thermal conductivity enhancement for SiO_2 and Al_2O_3 nanoparticles, respectively. Methanol was used as a base fluid, and silver nanoparticles were added to the water in a thermo siphon heat exchanger [26]. Using Al_2O_3/water nanofluid, the heat transfer study was made numerically by Kumar *et al.* in a flat plate heat exchanger and bubble fin plate heat exchanger. Investigation on the effect of mass flow rate and volume fraction on heat transfer coefficient (HTC), Nusselt number, and pressure drop was performed, and it was reported that HTC increased with an increase in mass flow rate and volume concentration of nanofluid [27]. The result of the heat transfer effect showed energy savings of around 32% for cooling. Methanol has recently been used for various heat transfer applications [28] and different types of heat pipes vapor-dynamic thermosyphons, and conventional and micro heat pipes.

Many studies have examined these innovative fluids' unique characteristics and capacities since using nanofluids in various industries. Aluminum oxide (Al_2O_3) is a non-toxic, economically viable nanomaterial with good thermophysical and heat transport characteristics. For instance, Al_2O_3 and TiO_2 nanofluids were prepared to perform heat transfer analysis of prepared nanofluids flowing inside a compact plate heat exchanger. A study compared the experimental and numerical results (CFD analysis) and found a better correlation between the results of improved thermal performance [29]. A stable nanofluid of γ-Al_2O_3 was prepared by Mehta *et al.* to evaluate thermo physical properties (viscosity and thermal conductivity). The study was also performed with the addition of surfactant and found that there will be 20% and 8% enhancement in viscosity and thermal conductivity at 0.75% volume fraction. It also revealed that surfactant addition shows an average rise of 2% in viscosity and a drop of 3% in thermal conductivity for all volume fractions [30]. Using a two-step method and CTAB surfactant, a stable aqua-Al_2O_3 nanofluid was synthesized by Mehta *et al.*, and studies on thermo physical characteristics were made with prepared nanofluid. Experimental results show an enhancement of 76.2% in dynamic viscosity and 8.5% in thermal conductivity at 1% volume fraction [31].

There is potential to examine the heat transfer capabilities of this material in real-time heat exchangers. However, most studies are primarily interested in thermal conductivity investigations. While there are many benefits to using nanofluids, there are also some drawbacks, including fouling, surface erosion, and instability. While preparing a nanofluid, methanol offers a way to reduce fouling and prevent nanoparticle aggregation. Compact plate heat exchangers were chosen in our investigation since the literature also shows that compact plate heat exchangers are effective and perform better with nanofluids [32–34]. The heat transfer performance of a nanofluid mixture of Al_2O_3-water (W)-methanol (M) has not been investigated in a plate heat exchanger in the literature. Hence, heat transfer characteristics of Al_2O_3 nanoparticle addition in a base fluid (methanol + water) was performed by varying the nanoparticle concentration (0.25% to 0.75%), hot fluid inlet temperature (55 °C to 60 °C) and flow rate (2 L/min to 8 L/min) for a base fluid volume fractions of (10:90) and the results are presented.

MATERIALS AND METHODS

Preparation and properties of nanoparticle

Agglomerates of ultrafine particles, nanoparticles, or nanoclusters are called nanopowders. Nanoparticles comprise three layers: the surface, shell, and core. Nanoparticles are converted into nanofluids using two-step methods. In this study, the Al_2O_3 nanoparticle size of 50 nm was suspended in a water-methanol mixture using a two-step (sol-gel) technique. Base fluids with volume fractions (10% methanol + 90% water) were created using the amounts calculated by Eq. (1).

$$\varphi = \frac{(m/\rho)_{Al_2O_3}}{(m/\rho)_{Al_2O_3} + (m/\rho)_{W:M}} \quad (1)$$

A high-pressure homogenizer was utilized to ensure the stability of the prepared nanofluid, which was used as a cold fluid in the plate heat exchanger. The preparation of nanofluid using a homogenizer is shown in Fig. 1

Figure 1. Preparation of Al_2O_3-water-methanol nanofluid.

Because of the high-pressure homogenizer, the prepared nanofluid was uniformly suspended throughout the base fluid. The thermal conductivity of heating or cooling fluids was an essential attribute to consider when designing energy-efficient systems. One of the primary qualities considered while developing and regulating the process was the fluid's heat conductance. The ease of availability, prices, heat conductance, and inclination of the particles to keep them in the base fluid with little agglomeration are all important considerations. Metal oxide nanoparticles have a higher tendency to agglomerate despite their superior thermal conductivity. Aluminum oxide (Al_2O_3) nanofluid was used for the present heat transfer investigation.

SEM images of aluminum oxide nanoparticle

SEM is widely used to identify the microstructure and chemistry of materials. It projects and scans the focused stream of electrons over the surface to produce an image. The electrons in the beam interact with the sample and produce various signals to obtain details about the surface's composition. Fig. 2 shows the SEM Images of Al_2O_3 nanoparticles.

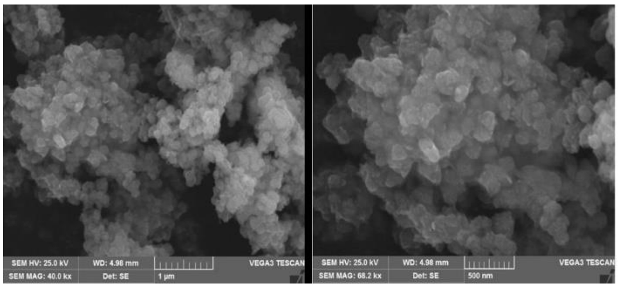

Figure 2. SEM image of Al_2O_3 nanoparticle.

Experimental setup and estimation of thermophysical properties

The experiments were carried out on a plate-type heat exchanger described in the previous work [35,36]; the experimental setup is shown in Fig. 3. Methanol-based nanofluids using Al_2O_3 nanoparticles were prepared for various volume concentrations, such as 0.25%, 0.5%, and 0.75%. The density, dynamic viscosity, heating value, and heat conductance were then computed [37,38] premised on experimental results.

Figure 3. Photographic view of the experimental setup.

Determination of Nusselt number, convective and overall heat transfer coefficient of Al_2O_3/water-methanol nanofluid

Eq. (2) was used to determine the Nusselt number of nanofluid [39] (Kim model), and Eq. (3) was used to find the heat transfer coefficient of hot and cold fluid. Eq. (4) was used to find the overall heat transfer coefficient.

$$Nu = 0.295(N\text{Re})^{0.64}(N\text{Pr})^{0.32}\left(\left(\frac{\Pi}{2}-\beta\right)\right) \quad (2)$$

$$h = \frac{NuD_H}{K} \quad (3)$$

$$U = \frac{Qavg}{A\nabla Tlmtd} \quad (4)$$

RESULTS AND DISCUSSION

Effect of flow rate on hot fluid heat transfer coefficient (h_h) at 55 °C

Before conducting detailed experiments with selected nanofluids, the study was performed with de-ionized water to ensure reliability. Figure 4 represents the influence of flow rate on hot fluid heat transfer coefficient (h_h) at a hot fluid inlet temperature of 55 °C for different nanofluid concentrations and water.

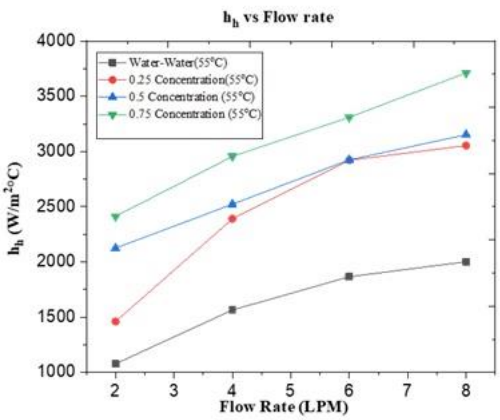

Figure 4. Effect of flow rate on hot fluid heat transfer coefficient (h_h) at 55 °C.

According to Fig. 3, ranges of heat transfer coefficient on the hot side (h_h) vary from 1700 W/m^2°C for water-water, and this value is increased to 3300 W/m^2°C at a flow rate of 6 L/min for a nanofluid with a nanoparticle concentration of 0.75 vol.%. When the flow rate increased to 8 L/min, the heat transfer coefficient range also increased to 1850 W/m^2°C for water-water and 3800 W/m^2°C for 0.75 vol.%. It shows that flow rate has a significant effect on heat transfer enhancement.

Effect of flow rate on cold fluid heat transfer coefficient (h_c) at 55 °C

The flow rate variations on the cold side heat transfer coefficient at 60 °C are presented in Fig. 5. A similar trend of heat transfer enhancement was also observed on the cold side fluid, as shown in Fig. 4. It was noted that, at a low flow rate (2 L/min) and low nanoparticle concentration (0.25 vol.%), the heat transfer coefficient was almost the same for water as a base fluid; however by increasing the flow rate gradually, the rate of heat transfer starts increasing gradually. For instance, at a flow rate of 4 L/min, the heat transfer coefficient increased to 2400 W/m^2°C (for 0.75 vol.%) from 1250 W/m^2°C (for water).

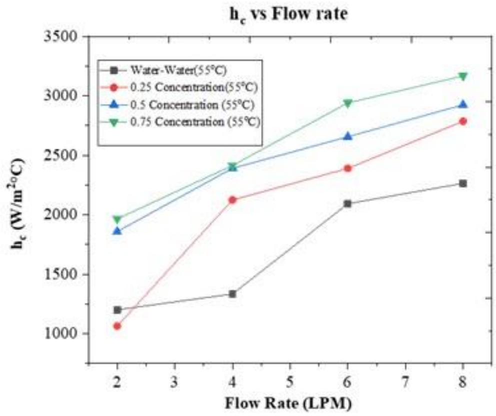

Figure 5. Effect of flow rate on cold fluid heat transfer coefficient (h_h) at 55 °C.

Results showed that the convective heat transfer coefficient and Nusselt number for Al_2O_3/methanol-water nanofluid were comparatively higher than those for the base fluid. This effect was due to the heat transport by thermally conductive nanoparticles, which was enhanced through the interfacial layers of fluids. Finally, the maximum enhancement was observed at 8 L/min with a heat transfer coefficient value of 3300 W/m^2°C (for 0.75 vol.%); however, the rate of enhancement was decreased by the flow rate. Hence, the flow rate needs to be optimized to utilize nanoparticles efficiently.

Effect of flow rate on overall heat transfer coefficient (U) at 55 °C

Although the heat transfer coefficient was calculated individually, it is very useful to calculate the overall heat transfer coefficient for extracting the benefits from nanoparticles. Hence, the result concerning an overall heat transfer coefficient at 55 °C is presented in Fig. 6.

Fig. 5 shows that, at the flow rate of 4, 6, and 8 L/min, the range of U was 850, 990, and 1100 W/m^2°C (for 0.25 vol. % nanoparticle) and 1350, 1440, and 1720 W/m^2°C (for 0.75 vol. %). Hence, it may be concluded that the individual and overall heat transfer coefficients were enhanced notably because of the nano-sized solid particles.

Effect of flow rate on hot fluid heat transfer coefficient (h_h) at 60°C

Since temperature plays a major role in heat

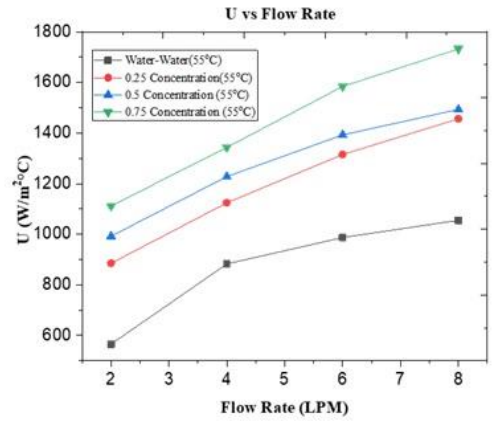

Figure 6. Effect of flow rate on overall heat transfer coefficient (h_h) at 55 °C.

transfer, the study was repeated by increasing the hot fluid temperature by 60 °C, and the effect of flow rate on the hot fluid heat transfer coefficient can be seen in Fig. 7.

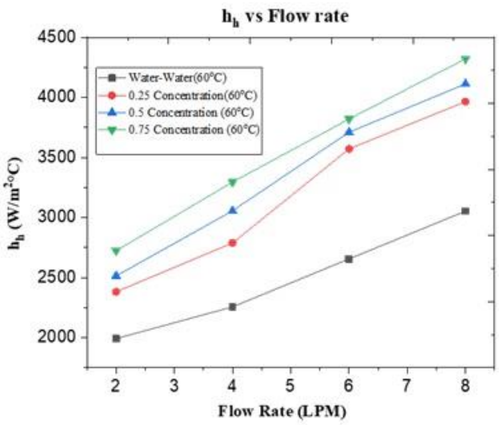

Figure 7. Effect of flow rate on hot fluid heat transfer coefficient (h_h) at 60 °C.

The experimental results in Fig. 6 point that for the concentration of 0.25 vol.% through 0.75 vol.%, the heat transfer coefficient on the hot side was 1950 W/m^2°C (for water), 2310 W/m^2°C (for 0.25 vol.%), and 2790 W/m^2°C (for 0.75 vol.%) at a flow rate of 2 L/min and 2700 W/m^2°C (for water), 3600 W/m^2°C (for 0.25 vol.%), and 4300 W/m^2°C (for 0.75 vol.%) at a flow rate of 8 L/min. This result again supports the ability of nanoparticle suspension to help in heat transfer enhancement.

Effect of flow rate on cold fluid heat transfer coefficient (h_c) at 60 °C

The effect of flow rate on the cold-side heat transfer coefficient at 60 °C is presented in Fig. 8. The effect on the cold-side heat transfer coefficient shows an increase from 2600 (for water) to 4600 W/m^2°C (for 0.75 vol.% nanoparticle concentration). When comparing the coefficient at 55 °C, the enhancement was significantly high. It shows a similar increasing pattern on the heat transfer rate, and the increment was linear with respect to nanoparticle concentration and temperature.

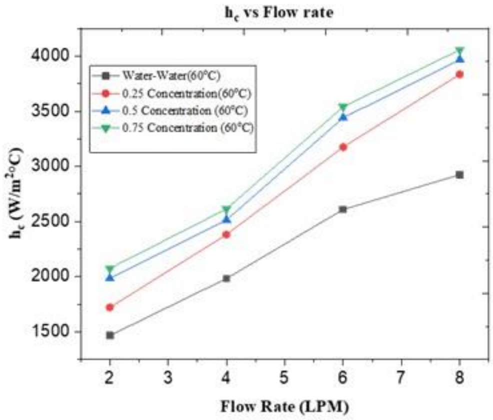

Figure 8. Effect of flow rate on cold fluid heat transfer coefficient (h_h) at 60 °C.

Effect of flow rate on overall heat transfer coefficient (U) at 60 °C

The effect of the flow rate variations on the overall heat transfer coefficient at 60 °C is presented in Fig. 9.

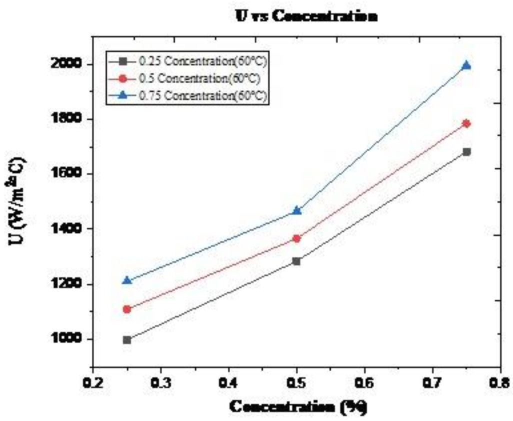

Figure 9. Effect of flow rate on overall heat transfer coefficient (h_h) at 60 °C.

Fig. 9 shows that the increase in temperature favors heat transfer; however, the temperature cannot increase more than the boiling point of methanol. Hence, a study was performed up to 60 °C. The result shows a uniform enhancement in the overall heat transfer rate with respect to all the concentrations (0.25, 0.5, and 0.75 vol. %) and all the flow rates. The ranges were 1380 to 2200 W/m^2°C (for 0.25 vol. % and 0.75 vol. % nanoparticle concentrations, respectively) at a flow rate of 8 L/min.

It shows that flow rate significantly affects heat transfer enhancement due to the relative increase in thermal conductivity because of the highly conducive solid nanoparticle to the prepared base fluids. Other significant factors for this heat transfer enhancement are Brownian motion, interfacial layer between base and nanofluid, thermo physical properties other than thermal conductivity (Viscosity, density, and specific heat capacity), and fluid flow rate [40]. The results are consistent with the reported results that the thermal conductivity, viscosity, and density of the Al_2O_3 nanofluids increase with nanoparticles in the base fluid [41–43].

CONCLUSION

The following conclusions were derived from the present study. The overall inference was a significant improvement in heat transfer with the addition of nanoparticles because the high conductive solid nanoparticle augments the heat transfer rate of base fluids. Utilizing the Al_2O_3/methanol-water nanofluid could significantly reduce the temperature gradients in the heat exchanger and improve the performance of heat exchangers. As temperature and nanoparticle concentration increase, the heat transfer coefficient also increases at various flow rates; the maximum hot fluid coefficient of 4300 W/m^2°C, cold fluid coefficient of 4600 W/m^2°C, and overall coefficient of 2200 W/m^2°C were noted for 0.75 vol.% nanoparticle concentration and at a flow rate of 8 L/min. The minimum fluid flow rate is sufficient to get the maximum enhancement for heat transfer rate since 8 L/min provides considerable improvement in heat transfer. Because of the addition of methanol, some drawbacks, including fouling, surface erosion, and instability, were rectified. Hence, future studies will be explored with alcohol-based base fluids to extract further benefits from the nanofluids.

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NOMENCLATURE

Al_2O_3	Aluminum Oxide
TiO_2	Titanium dioxide
ZnO	Zinc Oxide
Fe_2O_3	Iron Oxide
CuO	Copper Oxide
SiO_2	Silicon dioxide
CNT	Carbon Nano Tubes
D	Dimension
D_H	Hydraulic diameter, m
ΔT_{LMTD}	Logarithmic Mean Temperature Difference
M	Methanol
W	Water
m	Mass, kg
U	Overall Heat transfer coefficient, W/m^2 °C
N_{Nu}	Nusselt number, dimensionless
N_{Pr}	Prandtl Number, dimensionless
N_{Re}	Reynolds number, dimensionless
Q	Heat Flux, W
Cp	Specific heat capacity, J/(kg °C)
PHE	Plate Heat Exchanger
Pr	Prandtl number, dimensionless
H	Heat transfer coefficient, W/m^2 °C
H_h	Hot Fluid Heat transfer coefficient, W/m^2 °C
Hc	Cold Fluid Heat transfer coefficient, W/m^2 °C
vol. %	Volume %
Greek symbols	
β	corrugation angle, °
ρ	density, kg/m^3
μ	dynamic viscosity, Pa s
ø	nanoparticle volume fraction, dimensionless
k	thermal conductivity, W/(m K)

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NAUČNI RAD

UTICAJ NANOFLUIDA Al_2O_3-VODA-METANOL PRENOS TOPLOTE U PLOČASTOM IZMENJIVAČU TOPLOTE

Pločasti izmenjivač toplote je jedan od najmanjih i najefikasnijih izmenjivača toplote na tržištu. Ova studija ima za cilj da proceni uticaj metanol-vode kao osnovnog fluida na prenos toplote u pločastom izmenjivaču toplote. Za ovu studiju, nanočestice aluminijum oksida (Al_2O_3) su korišćene u različitim odnosima (0,25, 0,5 i 0,75 vol. %) u baznoj tečnosti (10 vol.% metanola i 90 vol.% vode) za pripremu nanofluida. Na dve različite temperature (55 °C i 60 °C), sa različitim brzinama protoka (2 do 8 L/min) i različitim koncentracijama nanočestica (0,25% do 0,75%), istražene su termofizičke karakteristike i konvektivni prenos toplote. Opšti zaključak je da je kombinacijom nanočestica Al_2O_3 i tečnosti na bazi metanola i vode došlo do značajnog poboljšanja na toploj i hladnoj strani i u ukupnom koeficijentu prenosa toplote. Primećeno je da korišćenje nanofluida Al_2O_3/metanol-voda može značajno smanjiti temperaturni gradijent u izmenjivaču toplote i poboljšati njegove performanse. Maksimalne vrednosti koeficijenta sa strane toplog fluida od 4300 V/m^2°C, koeficijenta sa strane hladnog fluida od 4600 V/m^2°C i ukupnog koeficijenta od 2200 V/m^2°C određene su za koncentraciju nanočestica od 0,75 vol.% pri brzini protoka od 8 L/min.

Ključne reči: Al_2O_3, bazni fluid, prenos toplote, metanol, nanofluid, pločasti izmenjivač toplote.