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TECHNICAL PAPER

Hydrothermal performance of plate heat exchanger with an alumina–graphene hybrid nanofluid: experimental study

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Abstract

An experimental investigation is conducted with graphene–Al_2O_3 hybrid nanofluid as a coolant in corrugated surface plate heat exchanger to study energetic performance. The combinations studied are Al_2O_3–graphene in 4:1 nanoparticle ratio and 100% Al_2O_3 nanoparticle with 0.01 v % concentration in DI water. Effect of coolant flow rates (2.0–4.0 lpm) and coolant inlet temperatures (10–25 °C) on various factors like coolant outlet temperature, heat transfer rate, convective heat transfer coefficient, pressure drop, and heat transfer coefficient to pressure drop ratio has been investigated. Maximum enhancements of around 2.5%, 5.34%, 25.36%, and 23.8% are observed in the coolant outlet temperature, heat transfer rate, heat transfer coefficient, and heat transfer coefficient to pressure drop ratio, respectively, for Al_2O_3–graphene hybrid nanofluid.

Keywords Plate heat exchanger · Coolant · Hybrid nanofluids · Graphene · Heat transfer coefficient · Heat transfer rate

Abbreviation

Al_2O_3	Alumina
CTAB	Cetyl trimethyl ammonium bromide
DI	Deionized water
HEX	Heat exchanger
HTC	Heat transfer coefficient
MWCNT	Multiwalled carbon nanotube
PG	Propylene glycol
PHE	Plate heat exchanger
TiO_2	Titania
v %	Percentage volume concentration

List of symbols

B	Channel spacing [m]
c_p	Specific heat [J.kg^{-1}.K^{-1}]
D_h	Hydraulic diameter [m]
G	Mass velocity [kg.s^{-1}.m^{-2}]
H	Heat transfer coefficient [W.K^{-1}.m^{-2}]
k	Thermal conductivity [W.K^{-1}.m^{-1}]
L_w	Width of plate [m]
N	Number of channels [dimensionless]
M	Mass [kg]
$\dot{m}$	Mass flow rate [kg.s^{-1}]
Nu	Nusselt number [dimensionless]
Pr	Prandtl number [dimensionless]
Q	Heat transfer rate [W]
Re	Reynolds number [dimensionless]
t	Thickness of the plate [m]
T	Temperature [°C]
U	Overall heat transfer coefficient [W.K^{-1}.m^{-2}]
V	Volume [m^3]

Greek symbols

Δp	Pressure drop [Pa]
μ	Dynamic viscosity [Pa.s]
Ω	Volumetric flow rate [m^3 s^{-1}]
ρ	Density [kg.m^{-3}]

Subscript

c	Cold
h	Hot
i	Inlet
o	Outlet

1 Introduction

In the present state, as the plate heat exchanger (PHE) is used for various purpose so, many attempts have been made in improving its performance by changing its surface texture

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(adding corrugations). It intensifies the heat transfer coefficient and thermal performance of the heat exchanger (HEX) [1] that makes plate heat exchanger suitable for various heat transfer applications. The heat transfer characteristics of PHE can also be made better by using the working fluid with enhanced thermal properties. It can be made possible by introducing single or multiple types of nanoparticles in the base fluid. The addition of nanoparticles leads to an increase in the thermal conductivity of the fluid and hence enhances the heat transfer characteristics. Therefore, hybrid nanofluid was innovated by suspending more than one nanoparticles in the base fluid that improves thermal conductivity and provides the gist to begin research in this field [2–4].

During the last era, several surveys were done on the plate heat exchanger using mono nanofluids resulting in the augmented performance of the plate-type heat exchanger [5–8]. But, research on the combination of hybrid nanofluid and PHE is inadequate. This fact created a zeal inside the researcher community to work with hybrid nanofluid in the plate heat exchanger to see the heat transfer performance. Huang et al. [9] observed a rise in heat transfer coefficient and pressure drop while using hybrid nanofluid in plate-type HEX. Kumar et al. [10, 11] performed an analysis with different water-based hybrid nanofluids and observed enhanced performance in terms of energy and exergy parameters. Bhattad et al. [12] carried a numerical investigation with Al_2O_3–MWCNT/water hybrid nanofluid on the corrugated plate heat exchanger performance. Bhattad et al. [13–15] observed better performance using brine-based hybrid nanofluids in plate-type heat exchanger. Kumar and Tiwari [16] performed numerical investigation with hybrid nanofluid in a plate heat exchanger and observed augmented performance. Bhattad et al. [17, 18] performed research with different alumina hybrid nanofluids and with varying ratios of the particle and found better performance characteristics than base fluid. Table 1 shows the comparative study conducted till now with the application of hybrid nanofluid in the PHE.

The above survey shows that the use of hybrid nanofluids enhances the heat transfer performance of heat exchangers. But, the author found some loopholes like less work has been done with hybrid nanofluids in the plate heat exchangers with a *particular particle volume ratio*. Moreover, for low-temperature applications, the research is even less using hybrid nanofluids as coolant. Nobody used *alumina–graphene hybrid nanofluid in the plate heat exchanger as a coolant*. So the author focused on the influence of graphene–alumina–water hybrid nanofluid (*in 1:4 particle ratio*) as a *coolant* on the plate heat exchanger performance for *sub-ambient temperature*. The hybrid nanofluid prepared was of 0.01 v % concentration. Alumina has been selected

Table 1 Comparative study using hybrid nanofluid in plate heat exchanger

References	Operating variables	Nanofluid characteristics	Findings
Huang et al. [9]	Hybrid nanofluid hot side and water at cold side. $Re=182–956$, $T_{hi}=28$ ℃, $T_{ci}=14$ ℃.	Hybrid nanofluid: MWCNT/water (0.0111 v %) and Al_2O_3/water (1.89 v %) in ratio 1:2.5.	Convective coefficient of heat transfer augments.
Kumar et al., [10]	Hybrid nanofluid as coolant, $T_{ci}=20$ ℃, $T_{hi}=50$ ℃, $\Omega_c=\Omega_h=3$ lpm.	MWCNT/Al_2O_3, TiO_2, CeO_2 and ZnO (0.25–2.0v %)	Observed reduction in exergy loss up to 24.75%.
Kumar et al. [11]	Hybrid nanofluid as coolant, $T_{ci}=20$ ℃, $T_{hi}=50$ ℃, $\Omega_c=\Omega_h=3$ lpm, $b=2.5–10.0$ mm.	Cu + Al_2O_3 hybrid nanofluid/DI water, (0.5–2.0 v %), surfactant: CTAB.	Exergy destruction was minimum, and exergetic efficiency was maximum for 5 mm spacing at 0.75 v %.
Bhattad et al. [12]	Hybrid nanofluid as coolant, $T_{ci}=20$ ℃, $T_{hi}=40$ ℃, $\Omega_c=\Omega_h=3$ lpm	Al_2O_3–MWCNT/water	Improvement in heat transfer characteristics with hybrid nanofluid.
Bhattad et al. [13, 14]	Hybrid nanofluid as secondary refrigerant, $T_{nfi}=-10, 0$ & 20 ℃, $T_{nfo}=-25, -15$ & 5 ℃, $T_{hi}=40$ ℃, $Q=50$ kW,	Cu + Al_2O_3, Ag + Al_2O_3, MWCNT + Al_2O_3/EG water, PG water, $CaCl_2$–water, KAC water (0.8 v %)	Brine-based hybrid nanofluids are good options as secondary refrigerants.
Bhattad et al. [15]	Hybrid nanofluid as coolant, $T_{ci}=0$ ℃, $T_{hi}=30$ ℃, $T_{ho}=5$ ℃, $\Omega_c=3–7$ lpm	Ag + Al_2O_3, Ag + MgO/EG water, PG water, (0.0–2.0 v %)	Brine-based hybrid nanofluids are good coolant for milk chilling unit.
Kumar and Tiwari [16]	Hybrid nanofluid as coolant, $T_{ci}=20$ ℃, $T_{hi}=75$ ℃	MWCNT + TiO_2, (0.0–1.5 v %)	Discrete phase method gives good result.
Bhattad et al. [17]	Hybrid nanofluid as coolant, $T_{ci}=10–25$ ℃, $T_{hi}=35$ ℃, $\Omega_h=3$ lpm, $\Omega_c=2–4$ lpm	Al_2O_3–MWCNT/water, (5:0, 4:1, 3:2, 2:3, 1:4, and 0:5) and 0.01 v %	Heat transfer coefficient improves up to 15.2%.
Bhattad et al., [18]	Hybrid nanofluid as coolant, $T_{ci}=10–25$ ℃, $T_{hi}=35$ ℃, $\Omega_h=3$ lpm, $\Omega_c=2–4$ lpm	Al_2O_3 + SiC, AlN, MgO, CuO and MWCNT (4:1)/water, 0.1 v %	Al_2O_3 + SiC hybrid combination gives the best energetic performance.

because of easy availability at a cheaper rate with better chemical stability, and graphene possesses high thermal conductivity that enhances the heat transfer characteristics [19–22] and makes graphene nanofluid suitable as a coolant in the plate heat exchanger [23]. As graphene costs more hence, it is taken in less quantity. The energy parameters discussed are coolant outlet temperature, heat transfer rate, convective heat transfer coefficient, coolant pressure drop, and heat transfer coefficient to pressure drop ratio.

2 Preparation and property measurement

2.1 Hybrid nanofluid preparation

The two-step method was used for preparing the nanofluid/hybrid nanofluid [18]. The calculated amounts of Al_2O_3 and graphene nanoparticles were purchased, weighed by a digital weighing balance, and the required quantity was mixed with DI water. The mixture was mechanically stirred for 1 h and afterward ultrasonicated for 5 h at 40 °C in an ultrasonication system to maintain excellent stability and homogenization. Cetyl trimethyl ammonium bromide (CTAB) in a 1:5 ratio of nanoparticle volume has also been used to prevent the nanoparticles' deposition.

2.2 Hybrid nanofluid properties

For the experimental study, different properties have been obtained from various equipment. Hot disk thermal properties analyzer, Brookfield digital viscometer, and digital weighing machine were used for measuring the thermal conductivity, specific heat, dynamic viscosity, and mass of various fluids. The density was measured through the expression $\rho = m/V$. Multiple measured properties of fluids used in the present investigation are listed in Table 2.

3 Experimental procedure

Geometrical dimensions of the plate-type HEX are given in Bhattad et al. [12]. The experimental setup and its block diagram are shown in Figs. 1 and 2, respectively. The setup consists of two fluid loops: one for hot fluid and another for a cold one. The coolant loop contains an isothermal bath, a float-type flowmeter, and a manometer. Here, hybrid nanofluid is acting as a coolant. The hybrid nanofluid is stored and cooled in an isothermal bath to maintain the constant inlet temperature. Then, it goes to the heat exchanger via flowmeter. The flow rate is varied with a control valve, and a differential manometer is used to measure the pressure drop of hybrid nanofluid. The hot loop contains an insulated hot water tank, a float-type flow meter to measure flow rate, a differential manometer to measure the pressure drop of DI water, and a hot water pump to circulate the hot DI water. The desired temperature of the hot water inlet is maintained through a temperature controller. Water is stored and heated in the tank, and then through a hot fluid water pump goes to the heat exchanger via flowmeter. The temperatures of the hybrid nanofluid and hot water streams are measured using thermocouples.

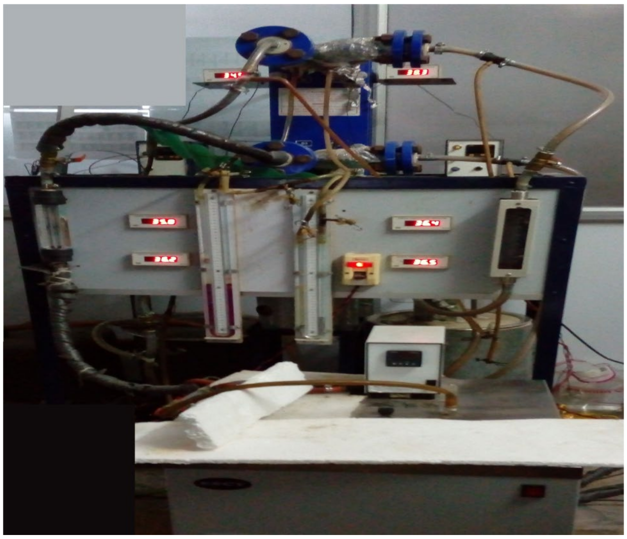


Fig. 1 Experimental setup

Here, DI water, Al_2O_3–DI water nanofluid, and graphene–Al_2O_3–DI water hybrid nanofluid are performing as a coolant. The terminal temperatures (T_{hi}, T_{ho}, T_{ci}, and T_{co}) are measured through thermocouples, flow rates through flowmeters and pressure drop in both the loops (hot and cold) using differential manometers. The formulation for the calculation of different parameters is given in Bhattad et al. [18]. The heat transfer rate of hot fluid, Q_h, and cold liquid, Q_c, is calculated from Eq. (1):

Table 2 Thermo-physical properties of different fluids at ambient temperature

Different fluids	Thermal conductivity (W/m.K)	Specific heat (J/kg.K)	Density (kg/m^3)	Viscosity (Pa.s)
DI water	0.5964	4183.0	996.8	0.0008706
Al_2O_3 (5:0)	0.6004	4170.0	999.5	0.0008786
Hybrid (4:1)	0.6063	4174.0	1008.2	0.0008792

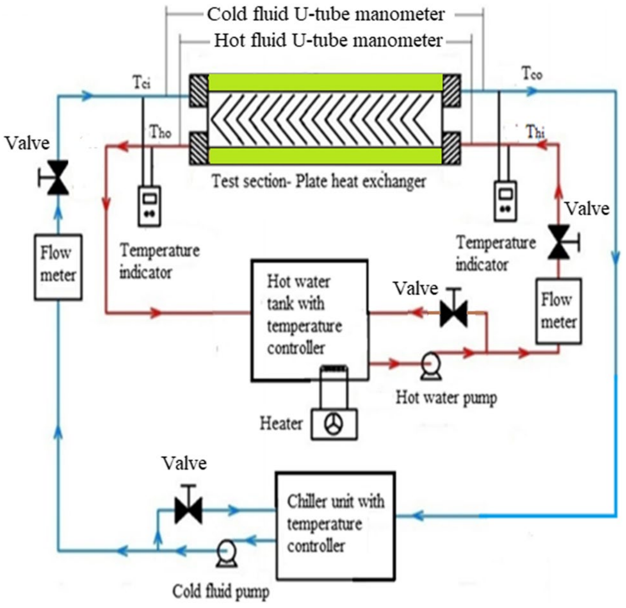


Fig. 2 Block diagram of the experimental setup

$$Q_h = \dot{m}_h c_{p,h}(T_{hi} - T_{ho}) \text{ and } Q_c = \dot{m}_c c_{p,c}(T_{co} - T_{ci}) \tag{1}$$

where $\dot{m}$ is the mass flow rate (kg.s^{-1}) and c_p is the specific heat (J.kg^{-1}.K^{-1})

Due to the variation in hot and cold heat transfer rates, the average heat transfer rate (Q) needs to be calculated:

$$Q = (Q_c + Q_h)/2 \tag{2}$$

The correlation for calculating the hot fluid heat transfer coefficient is given in Eq. (3) [18]:

$$Nu = 0.358\mathrm{Re}^{0.57}Pr^{0.3} \tag{3}$$

where

$$Nu = \frac{HD_h}{k} \tag{4}$$

$$\mathrm{Pr} = \frac{\mu c_p}{k} \tag{5}$$

$$\mathrm{Re} = \frac{GD_h}{\mu} \tag{6}$$

Channel mass velocity (G) of hot water and cold hybrid nanofluid is given by:

$$G = \frac{\dot{m}}{NbL_w} \tag{7}$$

The heat transfer coefficient of cold hybrid nanofluid (H_c) is obtained from the overall heat transfer coefficient (U) and the heat transfer coefficient of hot DI water (H_h):

$$\frac{1}{U} = \frac{1}{H_h} + \frac{1}{H_c} + \frac{t}{k_w} \tag{8}$$

where k_w = thermal conductivity of the plate (W/m.K)

t = thickness of the plate (mm)

On putting the formula of heat transfer coefficient, the expression obtained for the overall heat transfer coefficient is as follows:

$$\frac{1}{U} = \frac{1}{\frac{k_h.a.\mathrm{Re}_h^b\,\mathrm{Pr}_h^c}{D_h}} + \frac{1}{\frac{k_c.a.\mathrm{Re}_c^b\,\mathrm{Pr}_c^c}{D_h}} + \frac{t}{k_w} \tag{9}$$

On solving Eqs. 3–9, we get the value of the heat transfer coefficient of hybrid nanofluid. Values of a, b, and c can be taken from Bhattad et al. [18]. The results obtained during the present investigation agree with the result obtained by Tiwari et al. [24] for the water. During the study, flow rates, temperatures, and pressure differences were measured with suitable instruments. The instruments were calibrated before conducting the experiments. The thermocouple was calibrated with the help of a PT-100 temperature measuring instrument. Data at various temperatures (5 °C to 70 °C) were recorded simultaneously through thermocouple and PT-100 devices. Further, the deviation in both the data was recorded. Flowmeter was calibrated by recording the time taken to collect the amount of fluid in a beaker (1 L to 5 L). U-tube manometer was calibrated by measuring the pressure drop between the inlet and outlet of a fluid stream simultaneously with U-tube manometer and a digital pressure gauge in a stream. The calibration data are as follows: thermocouple—0.2%, flowmeter—2.5%, and manometer—2.3%. Each test was done five times, with error ranges within ± 5%, as shown in the figures. The uncertainties occurring in the measured and calculated parameters are calculated from the formula given in Bhattad et al. [18]. Uncertainties in various parameters are as follows: temperature—0.2%, mass flow rate—2.5%, pressure drop—2.3%, heat transfer rate—4.5%, heat transfer coefficient—6.3%, and heat transfer coefficient to pressure drop ratio—6.7%.

4 Results and discussion

Hybrid nanofluid consists of 80% alumina nanoparticle and 20% graphene nanoparticle suspended in DI water with 0.01 v % concentration. Hot water flow rate and inlet temperature are taken as 3 lpm and 35 °C, respectively. Various performance parameters considered are cold outlet temperature, heat transfer rate, heat transfer coefficient, pressure drop, and heat transfer coefficient to pressure drop ratio. Effect of different coolant flow rates and inlet temperatures has been investigated.

4.1 Effect of varying coolant flow rate

Figures 3, 4, 5, 6, and 7 show the variation of performance variables with a coolant flow rate for 15 °C coolant inlet temperature. Various coolant flow rates considered are 2, 2.5, 3, 3.5, and 4 lpm. In figures, notation 2, 2.5, 3, 3.5, and 4 represents the coolant flow rates in lpm, whereas 10, 15, 20, and 25 describes the coolant inlet temperatures in °C. Also, DI represents DI water, alumina represents alumina nanofluid, and hybrid (8:2) represents DI water-based hybrid nanofluid containing 80% alumina nanoparticles and 20% graphene nanoparticles, respectively. Figure 3 shows that the coolant outlet temperature decreases with an increase in the coolant flow rate because as the flow rate increases, the time for exchanging the heat decreases. Hence, the rise in temperature (temperature difference) is less. Also, outlet temperature increases with the addition of nanoparticles and is highest for hybrid nanofluid due to Brownian motion and thermophoresis effects [2]. It enhances the maximum by 2.38%. Figure 4 shows enhancement in the heat transfer rate with the coolant flow rate due to direct dependency on the mass flow rate (Eq. 1). It increases with an addition of nanoparticles giving maximum enhancement of 5.06% for hybrid nanofluid due to interaction and collision between the nanoparticles, micro-turbulence, etc. It gives rise to the thermal conductivity that increases the heat transfer rate. Figure 5 shows that the heat transfer coefficient enhances with the volumetric flow rate. With the increase in the mass

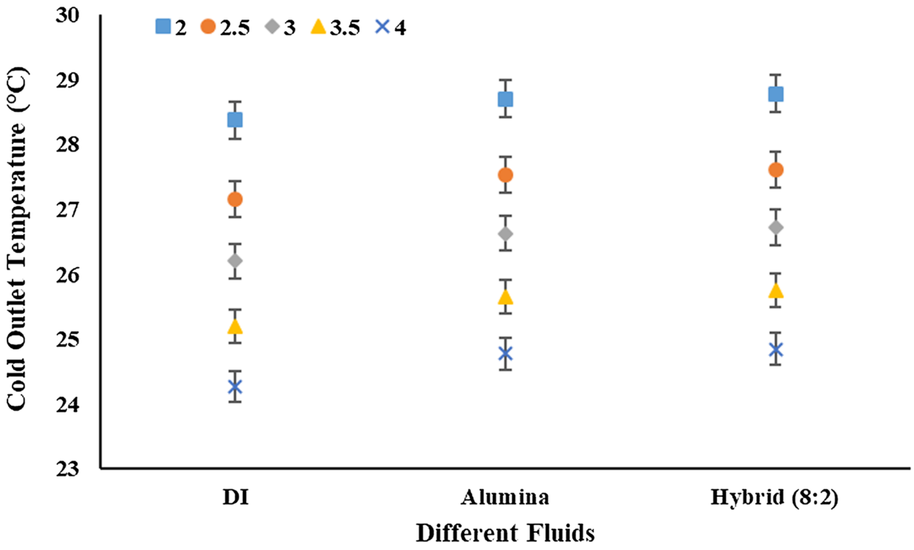


Fig. 3 Variation of cold outlet temperature for different flow rates

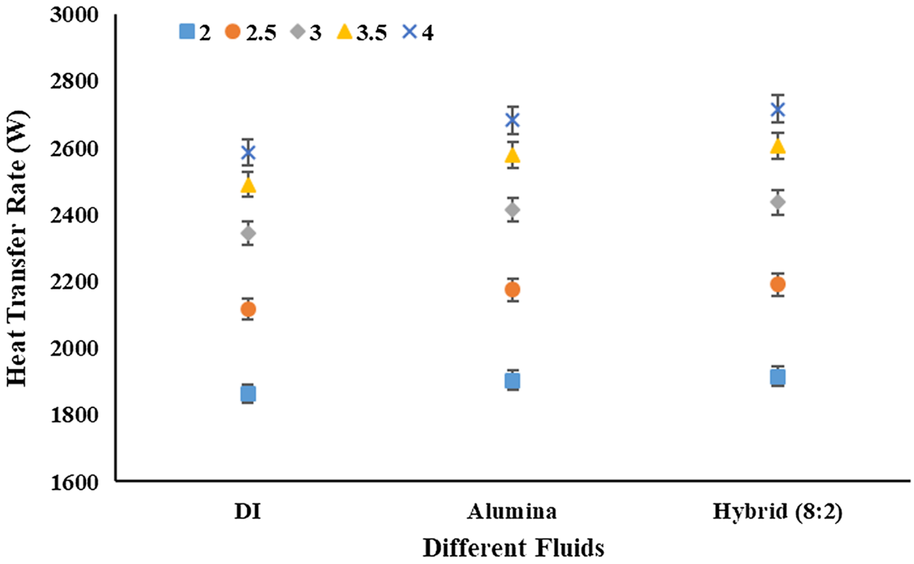


Fig. 4 Variation of heat transfer rate for different flow rates

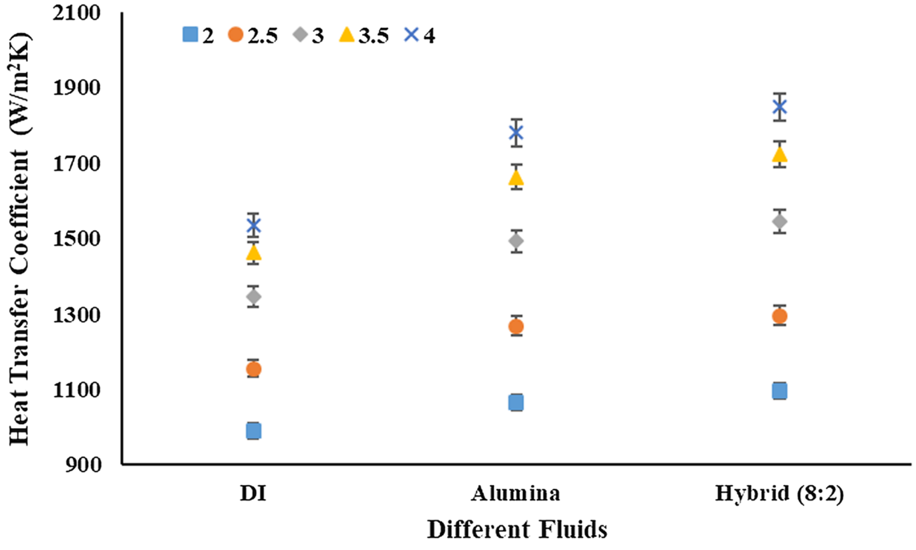


Fig. 5 Variation of heat transfer coefficient for different flow rates

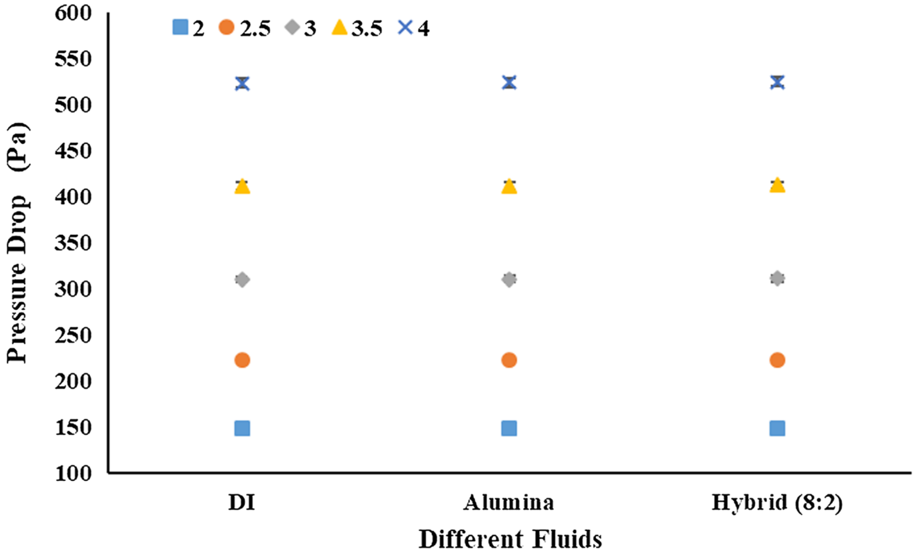


Fig. 6 Variation of pressure drop for different flow rates

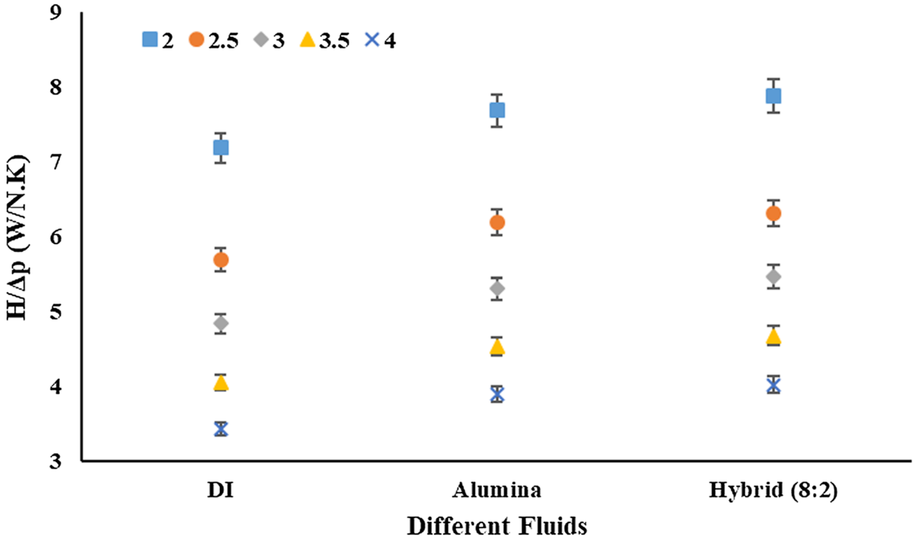


Fig. 7 Variation of heat transfer coefficient to pressure drop ratio for different flow rates

flow rate, the Reynolds number and, hence, HTC increase. It also augments with hybrid nanofluid due to the relative motion between the base fluid and nanoparticle, resulting in the self-circulation of the nanoparticles acting as a heat carrier [25]. A maximum enrichment of 20.4% has been observed in HTC for the hybrid nanofluids. The enhancement of using hybrid nanofluid is comparatively less than the alumina nanofluid because the amount of other nanoparticle (Graphene) used is very less. So, one cannot find significant enhancement with the use of hybrid nanofluid.

An insignificant increment has been witnessed in the pressure drop by adding nanoparticles and increasing the fluid flow rate (Fig. 6). By dispersing the nanoparticles in the base fluid, its viscosity and density change that cause a rise in the pressure drop. The dominance of the heat transfer coefficient over the pressure drop is shown in Fig. 7. The ratio of heat transfer coefficient to pressure drop has been maximum for hybrid nanofluid (19.3%) due to better enhancement in the heat transfer coefficient than the pressure drop. Its value drops with a rise in the flow rate.

4.2 Effect of varying coolant inlet temperature

Figures 8, 9, 10, 11, and 12 show the variation of performance parameters with coolant inlet temperature (10–25 °C) at 3 lpm coolant flow rate. An increase in the coolant outlet temperature has been observed with an increase in the coolant inlet temperature and suspension of nanoparticles in the base fluid (Fig. 8). A maximum enhancement of 2.5% has been observed for hybrid nanofluid. Figure 9 depicts a drop in the heat transfer rate with an increase in the coolant inlet temperature. It occurs due to a decrease in the temperature difference between the outlet and inlet of the fluid. Moreover, the heat transfer rate enhances by 5.34% for hybrid nanofluid. An increase in the heat transfer coefficient (maximum 25.36%) has been observed for hybrid nanofluids (Fig. 10). Also, the heat transfer coefficient rises with the coolant inlet temperature due to the rise in the mean temperature of the fluid.

Further, the pressure drop declines with a rise in the coolant inlet temperature (Fig. 11). It occurs due to a drop in density and viscosity of the fluid with an increase in the temperature. But the hybrid nanofluids increase the pressure drop (0.35% negligible). On the other hand, the ratio of heat transfer coefficient to pressure drop increases with an increase in coolant inlet temperature as shown in Fig. 12. It is because an increase in the temperature gives rise to the heat transfer coefficient and declines pressure drop. Also, this ratio augmented with the suspension of nanoparticles in DI water and was found the maximum (23.8%) for hybrid nanofluid.

The study was carried out, thinking of the futuristic scope of hybrid nanofluids. A considerable enrichment in the heat transfer coefficient was observed using hybrid nanofluid with an inconsiderable increase in the pressure drop due to less concentration of the nanoparticles. As the nanoparticles are costly, they are presently not used in industrial applications. Singh and Sarkar [26] suggested that the hybrid nanofluids are desirable at lower concentrations because they provide an early payback period at such intensity. In the present investigation, the combined cost of nanoparticle and stabilizer was around Rs. 40,000. By spending this extra amount, the author obtained enhancement in the heat transfer coefficient of 25.36% in the time interval of 5 days (daily 8 h). But, in the long run, the problem of stability of the solution arises that needs enormous research. One has to work in the area of reducing the cost of the nanoparticle by innovating the manufacturing technology of nanoparticles and by increasing the stability of nanofluids so that it can be used in industries frequently.

Fig. 8 Variation of cold outlet temperature for different inlet temperatures

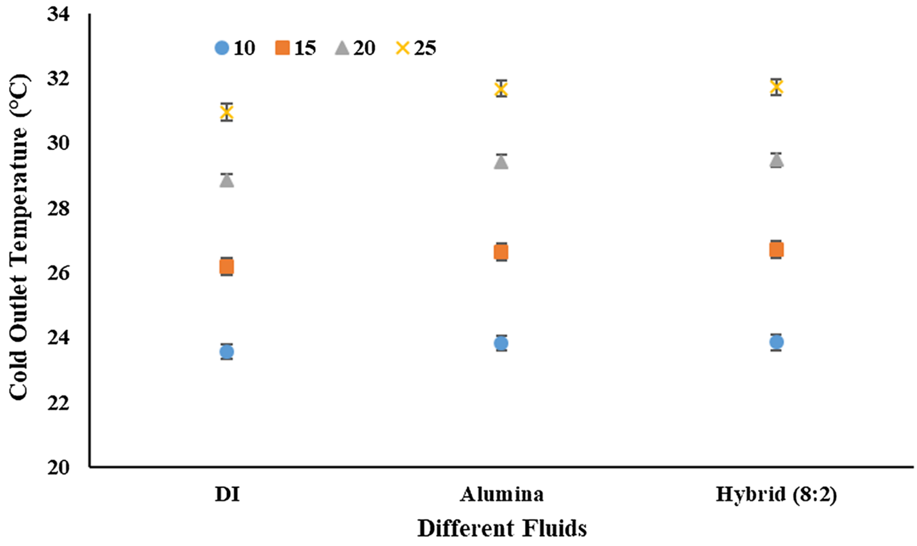


Fig. 9 Variation of heat transfer rate for different inlet temperatures

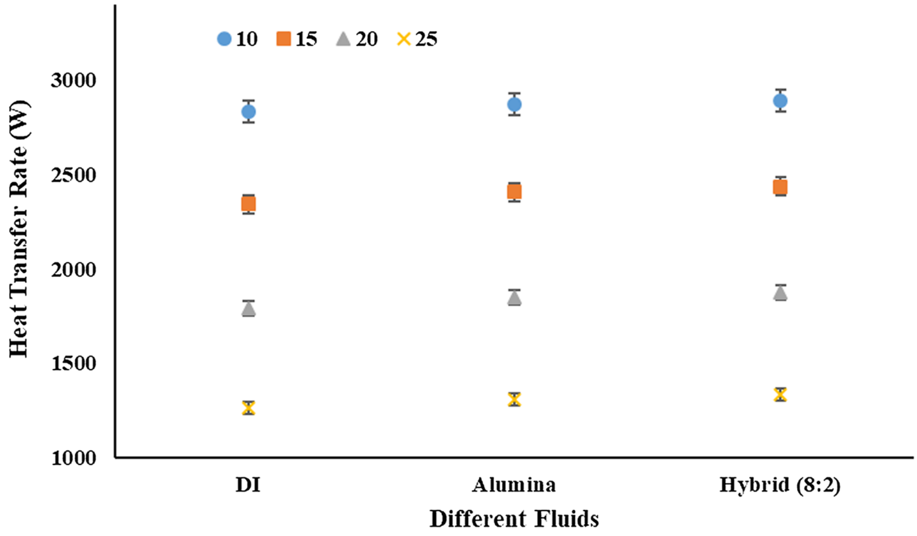


Fig. 10 Variation of heat transfer coefficient for different inlet temperatures

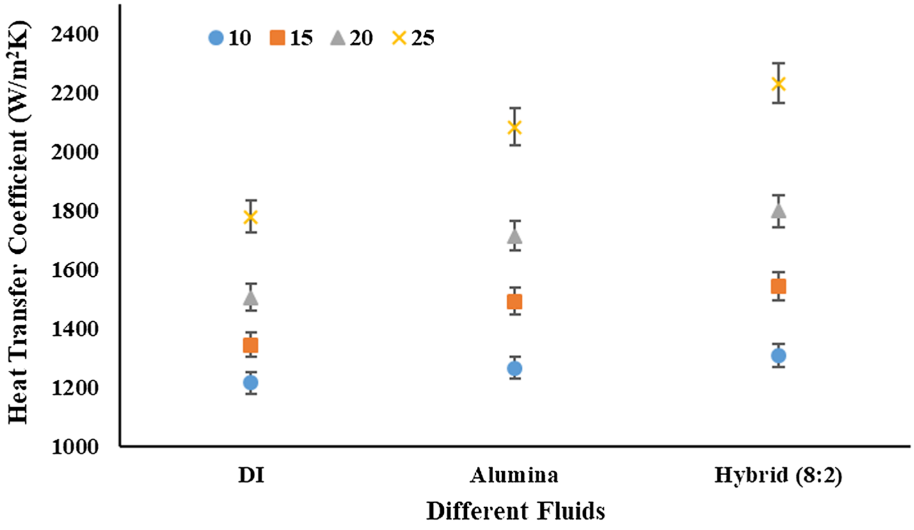
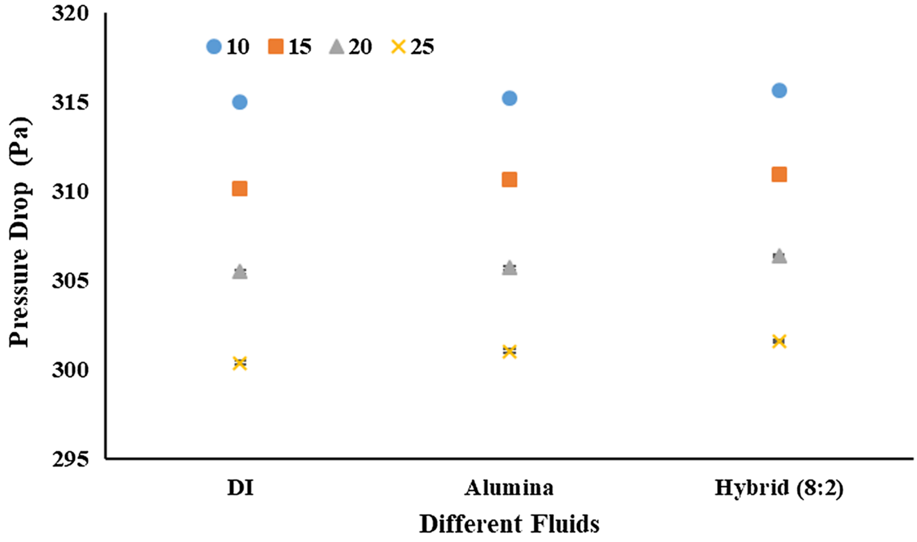


Fig. 11 Variation of pressure drop for different inlet temperatures



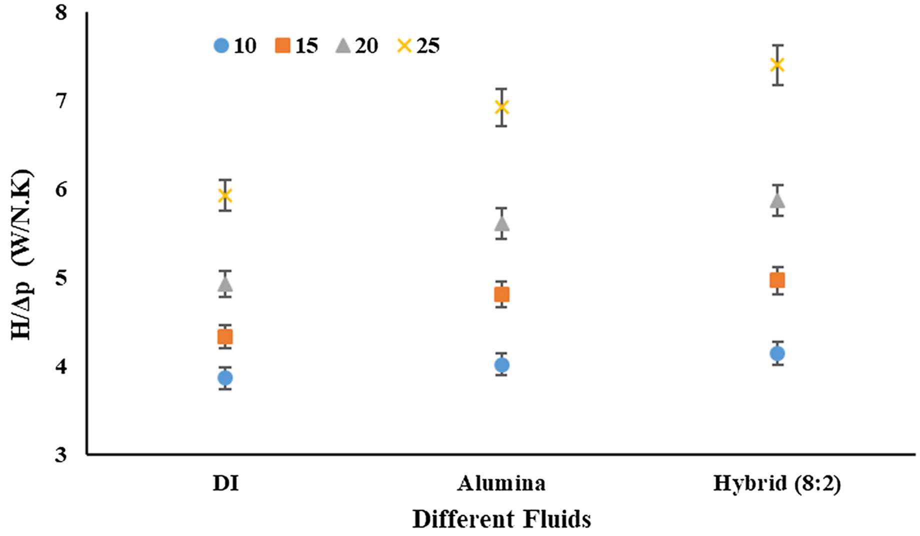


Fig. 12 Variation of heat transfer coefficient to pressure drop ratio for different inlet temperatures

5 Conclusions

In the current study, the energizing attributes of Al_2O_3–graphene–DI water hybrid nanofluid have been experimentally investigated in a counterflow plate heat exchanger. The tests were conducted for 0.01v % particle concentration having a 4:1 particle volume ratio. The following conclusions can be made from the results obtained:

- Hybrid nanofluid displays better hydrothermal performance than other studied fluids.
- Heat transfer rate increases by 5.34% for Al_2O_3–graphene–DI water hybrid nanofluid as compared to DI water.
- The heat transfer coefficient enhances up to 25.36% for hybrid nanofluid as compared to DI water with a negligible increase in pressure drop. Heat transfer coefficient enhances and pressure drop reduces with operating temperature.
- The ratio of heat transfer coefficient to pressure drop enhances by 23.8% for hybrid nanofluids as compared to DI water and increases with operating temperature.
- Hybrid nanofluid is suggested as a suitable replacement as a coolant for low-temperature applications at low nanoparticle volume concentration.

References

1. Elmaaty TMA, Kabeel AE, Mahgoub M (2017) Corrugated plate heat exchanger review. Renew Sustain Energy Rev 70:852–860
2. Sarkar J, Ghosh P, Adil A (2015) A review on hybrid nanofluids: recent research, development and applications. Renew Sustain Energy Rev 43:164–177
3. Huminic G, Huminic A (2018) Hybrid nanofluids for heat transfer applications—A state-of-the-art review. Int J Heat Mass Transf 125:82–103
4. Babar H, Ali HM (2019) Towards hybrid nanofluids: preparation, thermophysical properties, applications, and challenges. J Mol Liq 281:598–633
5. Javadi FS, Sadeghipour S, Saidur R, BoroumandJazi G, Rahmati B, Elias MM, Sohel MR (2013) The effects of nanofluid on thermophysical properties and heat transfer characteristics of a plate heat exchanger. Int Commun Heat Mass Transf 44:58–63
6. Kumar V, Tiwari AK, Ghosh SK (2015) Application of nanofluids in plate heat exchanger: a review. Energ Convers Manage. 105:1017–1036
7. Goodarzi M et al (2015) Investigation of heat transfer and pressure drop of a counterflow corrugated plate heat exchanger using MWCNT based nanofluids. Int Commun Heat Mass Transf. 66:172–179
8. Sarafraz MM, Hormozi F (2016) Heat transfer, pressure drop and fouling studies of multi-walled carbon nanotube nano-fluids inside a plate heat exchanger. Exp Therm Fluid Sci 72:1–11
9. Huang D, Wu Z, Sunden B (2016) Effects of hybrid nanofluid mixture in plate heat exchangers. Exp Therm Fluid Sci 72:190–196
10. Kumar V, Tiwari AK, Ghosh SK (2016) Effect of variable spacing on performance of plate heat exchanger using nanofluids. Energy 114:1107–1119
11. Kumar V, Tiwari AK, Ghosh SK (2018) Exergy analysis of hybrid nanofluids with optimum concentration in a plate heat exchanger. Mater Res Express 5:065022
12. Bhattad A, Sarkar J, Ghosh P (2018) Discrete phase numerical model and experimental study of hybrid nanofluid heat transfer and pressure drop in plate heat exchanger. Int Commun Heat Mass Transf 91:262–273
13. Bhattad A, Sarkar J, Ghosh P (2017) Exergetic analysis of plate evaporator using hybrid nanofluids as secondary refrigerant for low temperature applications. Int J Exergy 24(1):1–20
14. Bhattad A, Sarkar J, Ghosh P (2018) Energy-Economic analysis of plate evaporator using brine based hybrid nanofluids as secondary refrigerant. Int J Air-Cond Refrig 26(1):1850003–1850012
15. Bhattad A, Sarkar J, Ghosh P (2020) Energetic and exergetic performances of plate heat exchanger using brine based hybrid nanofluid for milk chilling application. Heat Transf Eng 41(6–7):1–14

16. Kumar D, Tiwari AK (2018) CFD simulation of plate heat exchanger using hybrid nanofluid. Int J Mech Eng Technol 9(9):1411–1418
17. Bhattad A, Sarkar J, Ghosh P (2019) Experimentation on effect of particle ratio on hydrothermal performance of plate heat exchanger using hybrid nanofluid. Appl Therm Eng 162:114309
18. Bhattad A, Sarkar J, Ghosh P (2020) Hydrothermal performance of different alumina hybrid nanofluid types in plate heat exchanger. J Therm Anal Calorim 139: 3777–3787
19. Ghozatloo A, Rashidi A, Niassar MS (2014) Convective heat transfer enhancement of graphene nanofluids in shell and tube heat exchanger. Exp. Therm. Fluid Sci. 53:136–141
20. Sadeghinezhad E, Mehrali M, Saidur R, Mehrali M, Latibari ST, Akhiani AR, Metselaar HSC (2016) A comprehensive review on graphene nanofluids: recent research, development and applications. Energ Convers Manage 111:466–487
21. Contreras EMC, Oliveira GA, Filho EPB (2019) Experimental analysis of the thermohydraulic performance of graphene and silver nanofluids in automotive cooling systems. Int J Heat Mass Transf 132:375–387
22. Bahiraei M, Heshmatian S (2019) Graphene family nanofluids: a critical review and future research directions. Energ Convers Manage 196:1222–1256
23. Wanga Z, Wua Z, Hanc F, Wadsöd L, Sundén B (2018) Experimental comparative evaluation of a graphene nanofluid coolant in miniature plate heat exchanger. Int J Therm Sci 130:148–156
24. Tiwari AK, Ghosh P, Sarkar J (2015) Particle concentration levels of various nanofluids in plate heat exchanger for best performance. Int J Heat Mass Transf 89:1110–1118
25. Bhattad A, Sarkar J, Ghosh P (2018) Improving the performance of refrigeration systems by using nanofluids: a comprehensive review. Renew Sustain Energy Rev 82:3656–3669
26. Singh SK, Sarkar J (2018) Energy, exergy and economic assessments of shell and tube condenser using hybrid nanofluid as coolant. Int Commun Heat Mass Transf 98:41–48