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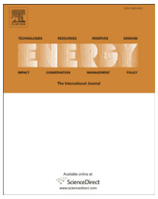

Effect of variable spacing on performance of plate heat exchanger using nanofluids

Vikas Kumar [a,*], Arun Kumar Tiwari [b], Subrata Kumar Ghosh [a]

[a] Department of Mechanical Engineering, Indian School of Mines, Dhanbad 826004, India
[b] Department of Mechanical Engineering, Institute of Engineering and Technology, GLA University, Mathura 281406, India

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ABSTRACT

This paper presents details of an experimental investigation into the effect of different spacings ($\Delta X = 2.5$ mm, 5.0 mm, 7.5 mm and 10.0 mm) in plate heat exchanger (PHE) on the basis of its combined energetic and exergetic performance by using various nanofluids, i.e., TiO_2, Al_2O_3, ZnO, CeO_2, hybrid ($Cu+Al_2O_3$), graphene nanoplate (GNP) and multi-walled carbon nanotube (MWCNT). On the basis of experiment data, various energetic and exergetic performance parameters have been evaluated and their inter-relationship has been discussed. The optimum heat transfer characteristics in the nanofluids and their exergetic performance have been found to be achieved with a spacing of $\Delta X = 5.0$ mm. Based on these data, it has been found that the MWCNT/water nanofluid, with a spacing of $\Delta X = 5$ mm in PHE, has the maximum heat transfer coefficient, which is 53% higher compared to water at 0.75 vol % (optimum). Nanofluids significantly improve heat transfer capacity with a nominal rise in pressure drop at 0.75 vol %. This study will help to understand the process of heat transfer augmentation by using various nanofluids in the PHE on the basis of energetic and exergetic performance of the system.

1. Introduction

The phenomenon of heat transfer is common in many engineering applications which are carried out with the help of various appliances, including plate heat exchanger (PHE). A PHE consists of a number of thin corrugated plates. Each plate has port holes providing a passage for flowing fluids. The corners of the plates are sealed with gaskets to support the interplate channels directing fluids into alternate channels.

The plates of a PHE are held together between a fixed frame plate and a moving pressure plate. They are clamped together by compression with a bolt which compresses the gaskets, thus, making a seal. The transferring of heat takes place through the plate between the channels. The objective behind corrugation of the plates is to enhance the turbulence, thereby increasing heat transfer and strengthening the plate pack [1,2].

The efficacy of heat transfer in a heat exchanging equipment greatly depends on the thermophysical properties of working fluids [3]. Due to inherent properties of high thermal conductivities, enhanced heat transfer coefficient (HTC) and a small penalty of pressure drop, nanofluids have been widely used as coolant for the last two decades [4–9].

Picon-Nuñez et al. [10] studied designing of plate fin heat exchanger (PFHE) with two different surfaces (Plain-fin and louvered fins), based on the volume performance index at various Reynolds numbers. The effect of the plate geometry (angles, depth and types of corrugation) of a PHE on heat transfer characteristics under turbulent conditions for different Reynolds numbers and Prandtl numbers was investigated by Khan et al. [11]. They found a significant effect of plate geometry on the heat transfer performance. Faizal and Ahmed [12] studied the process of optimum heat transfer by varying the spacing between the plates in PHE. Their findings revealed that the optimum heat transfer occurred at a minimum spacing for water-water stream in PHE. Abed et al. [13] carried out a numerical study on the heat transfer performance in corrugated trapezoidal PHE. They used various nanomaterials (Al_2O_3, SiO_2, CuO and ZnO) with volume fractions 0–4.0% and particle diameter 20–80 nm under turbulent flow conditions. Their results established that the heat transfer rate increases with an increased volume fraction of nanofluid. However, the pressure drop increases with decreased diameter of nanoparticles.

The performance of heat transfer of nanofluid (Al_2O_3/water) as a cooling medium in corrugated PHE was examined by Tiwari et al. [14,15]. Pandey and Neema [16] observed that addition of

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* Corresponding author.
E-mail address: vikaskumar.iitbhu@gmail.com (V. Kumar).

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nanoparticles (Al_2O_3) in a base fluid (water) improves the effectiveness of PHE, thereby decreasing the overall heat transfer coefficient (OHTC). Maré et al. [17] experimentally compared the thermal performance of Al_2O_3/water and carbon nanotubes/water (CNTs/water) at low temperatures in a PHE. Their results revealed a significant enhancement in HTC with the aforementioned nanofluids.

Khoshvaght-Aliabadi et al. [18] carried out a numerical investigation to study the effect of geometrical parameters on heat transfer characteristics of Cu/water nanofluid in a PHE with vortex-generator channels. Pantzali et al. [19] studied both experimentally and numerically the effect of nanofluid (4 vol% CuO/water) as a working fluid in a PHE. They observed that nanofluid increases the rate of heat transfer more as compared to water. Ray et al. [20] investigated the performance of three types of nanofluid in a PHE both experimentally and numerically. They used Al_2O_3, CuO and SiO_2 nanoparticles dispersed in a mixture of ethylene glycol (EG) and water. When measured, the mixture showed rise in HTC. Hence, less pumping power was required for a fixed amount of heat transfer in the PHE in each of the three cases. Khoshvaght-Aliabadi [21] studied the heat transfer and flow characteristics of sinusoidal-corrugated channel with different parameters (i.e. height/length of channel, length/amplitude of wave and phase shift) using Al_2O_3-water ($\phi = 0–4.0$ vol %) nanofluid at $Re = 6000–22000$ numerically. Their results revealed that values of Nusselt number and friction factor were highly influenced by channel height and wave amplitude respectively. An experiment was conducted to study the HTC in Al_2O_3/EG and CuO/EG nanofluids in PHE and double pipe by Zamzamian et al. [22]. They found a significant rise in HTC ranging from 3.0%–49.0% when compared with base fluid. Jokar and O'Halloran [23] analyzed the heat transfer process in Alumina/water (1.0–4.0 vol %) nanofluid by using computational fluid dynamic (CFD) under the laminar condition. Their results showed that the dispersion of nanoparticles in the base fluid caused reduction in the total heat transfer in the PHE. Khoshvaght-Aliabadi et al. [24] performed an experiment to study the thermal – hydraulic performance of different plate fin channels (plain/perforated/offset strip/louvered/wavy/vortex generator and pin) using CuO/water nanofluid. The HTC and pressure drop values were increased with weight concentration of tested nanofluid for all channels considered in their experimentation. However, the vortex generator channel provided the appropriate thermal–hydraulic performance and reduced surface area.

Khairul et al. [25] analyzed the heat transfer and exergy of CuO/water (0.5%–1.5 vol %) nanofluid in PHE. In their experimentation, the HTC increased from 18.5%–27.2% while the exergy loss decreased by 24% due to the use of nanofluid. Kabeel et al. [26] studied the thermal effect of Al_2O_3 nanoparticles on PHE. Their results revealed a 13% rise in HTC for 4.0% vol. concentration of Al_2O_3/water nanofluid. Javadi et al. [27] compared the thermal properties and performance of heat transfer in various nanofluids (Al_2O_3, TiO_2, and SiO_2) with base fluid (liquid nitrogen) flowing in PHE. They found that the addition of nanomaterials in base fluid improved the thermal conductivity (TC). Moreover, the value of TC in Al_2O_3 and TiO_2 was almost equal but higher than SiO_2 nanomaterial. The HTC was found to be the least in SiO_2 nanomaterials in their experimentation. Chen et al. [28] studied the effect of chevron angles in PHE on the performance of heat transfer by using lithium bromide (LiBr) solution and Al_2O_3 nanoparticles dispersed in LiBr solution at different mass flow rates. They demonstrated that the heat transfer characteristics were excellent at chevron angle $60^\circ/60^\circ$ in PHE as compared to other chevron angles for LiBr solution. The HTR, however, was augmented by about 3–8% with 3.0 vol % of LiBr/Al_2O_3 nanofluid in all cases. The effect of chevron angles ($\beta = 30^\circ/30^\circ$, $60^\circ/60^\circ$ and $30^\circ/60^\circ$) on heat transfer performance using different nanofluids (Al_2O_3/water and SiO_2/water) with $\phi = 0–1.0$ vol % in a PHE was investigated experimentally by Elias et al. [29]. Their findings revealed the HTR, HTC, pressure drop and pumping power increased with volume concentration and these parameters were higher at $\beta = 60^\circ/60^\circ$. Abed et al. [13] conducted a numerical investigation to study the heat transfer in trapezoidal PHE by using nanofluids (Al_2O_3, SiO_2, CuO and ZnO) with $\phi = 0–4.0$ vol % and $d_p = 20–80$ nm for turbulent flow. Their results revealed that as the ϕ of nanofluid increases, d_p decreases followed by increment in the Nusselt number and pressure drop. Sarafraz and Hormozi [30] conducted an experiment to investigate the heat transfer performance and pressure drop of multi-walled carbon nanotube (MWCNT) in a PHE under the following operating conditions: volume concentration ($\phi = 0.5–1.5$ vol %) of MWCNT, inlet temperature of MWCNT (50–70 °C) and Re (700–25000). Their experiment data demonstrated that the addition of the aforesaid nanofluid intensified the HTC with a little penalty in pressure drop. The TC also increased approximately from 21%–68%. Anoop et al. [31] studied the thermal performance of SiO_2/water in shell, tube and PHE. In their experimentation, they found no anomalous rise in the value of HTC while using nanofluids. An investigation on the heat transfer and pressure drop characteristics of CeO_2/water nanofluid in PHE was carried out by Tiwari et al. [32]. The authors observed a rise in HTC by 39% in the nanofluid as compared to water. A few other authors [33–36] also reviewed the application of various nanofluids in the heat exchangers.

Askari et al. [37] examined thermal performance of MWCNTs and graphene nanofluids in cooling tower for counter flow arrangement. In their experimentation, the rise in TC was found to be 20% and 16% for MWNTs and graphene nanofluids, respectively, at 45 °C. Huang et al. [38] conducted an experiment on the effect of hybrid nanofluid (HNF) on heat transfer and pressure drop characteristics in PHE. In their experimentation, they added MWCNTs/water nanofluid in Al_2O_3/water nanofluid to prepare the HNF. After comparing the experiment results of HNF with Al_2O_3/water nanofluid and water, the value of HTC was reported to be higher in HNF than that of Al_2O_3/water nanofluid and water. The pressure drop in HNF was less than Al_2O_3/water nanofluid but higher than water. HNF of GNP–Ag was investigated by Yarmand et al. [39]. They found that TC and viscosity of HNF ($\phi = 0.1$ wt %) increased by 22.22% and 30%, respectively, as compared to base fluid at 40 °C temperature. Suresh et al. [40] synthesized the HNF (Al_2O_3+Cu/water) with different volume concentration (0.1–2.0 vol %) by a two-step method to study its thermo-physical properties. The experiment data of TC showed an improvement of 12.11% for $\phi = 2.0$ vol %.

Nimmagadda and Venkatasubbaiah [41] numerically analyzed the heat transfer phenomenon in HNF (Al_2O_3 + Ag/Water) in micro-channel. They reported that while employing HNF, the heat transfer increased by 143% than base fluid.

Madhesh et al. [42] investigated the heat transfer and rheological characteristics of hybrid nano-composite Cu-TiO_2 (0.1%–2.0 vol %) in a tube and a tube heat exchanger. Their study revealed that the heat transfer rate and the overall HTC increase by 52% and 68%, respectively, up to a concentration of 1.0 vol % of hybrid nano-composite. Till now, these authors are not aware of the availability of sufficient information regarding the effect of spacing ΔX between the PHE plates on the heat transfer characteristics and exergetic performance. However, the performance of PHE is affected by the spacing ΔX between the plates. Thus, the authors of the present article were motivated to conduct an experiment on this aspect. The aim of the present study has been to investigate the effect of spacing ΔX between the plates of PHE on HTR, HTC, OHTC, pressure drop ratio, pumping power ratio, exergy destruction and