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Original Article

Heat Flow Analysis in Corrugated Plate Heat Exchanger using MWCNT Nanofluid at Various Corrugated Angles, Volume Flow Rate, Phi.

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Abstract - *A comprehensive Study investigates thermal performance in a Corrugated Wavy plate heat exchanger utilizing Multi-Walled Carbon Nanotube (MWCNT)-based nanofluids, with a focus on the combined effects of flow-rate, nano-particle concentration, and corrugation angle on efficiency. Experiments were conducted across varying flow rates (2–4 LPM), MWCNT concentrations, phi (ϕ,, 0,0.01,0.03,0.05,0.07,0.09%), and plate angles (0°–60°) to evaluate their individual and synergistic impacts on heat transfer. The results show that an increase in Volume Flow Rate(lpm) increases both heat transfer rate, Q(Watts), and pressure drop (Pascal). Elevating nanoparticle concentration to 0.09% leads to increased heat transfer rate and unwanted pressure drop. Inclination angle markedly influences performance, with optimal(maximal) heat-transfer-rate at 40 ° with optimal(minimal) pressure-drop at 0 ° inclination angle. Corrugated angle, lpm, nanoparticle concentration elevates Q at the cost of pressure drop. An attempt is made to find optimum parameters that enhance the heat transfer rate and reduce the pressure drop. With water as test fluid, maximum HTR is 2060.847W at 30º ° cphe' angle, at 3lpm. For MWCNT nanofluid as test fluid, max HTR is 2431.613W at 50º 'cphe 'angle,4lpm. An 18% increase in HTR is observed. Minimum pressure drop is 7.328871pascal at 0º,2 lpm with water as test fluid, and 7.49995 pascal at 0.01% phi,2lpm at 0 ° corrugated angle with nanofluid as test fluid. Pressure drop almost remained constant for water and 0.01% nanofluid. Optimal response from designxpert software is found to be 7.5pascal pressure-drop,2431.6Watts HTR at 50 degrees, 4lpm,0.01% nanoparticle concentration with 0.7 overall desirability.*

Keywords *- Corrugated Wavy Plate Heat Exchanger, Corrugated Angle, HTR, Optimum, Phi, MWCNT.*

1. Introduction

Over the previous fifty years, rapid advancements in science and engineering technologies related to fossil and nuclear energy, electric power generation, electronic chip cooling, and inkjet printing have driven extensive research in heat transfer enhancement. Among these, improving heat-transfer efficiency in Corrugated-Plate Heat Exchangers (CWPHEs) has been a key focus due to their widespread industrial applications, including HVAC systems, food processing, and chemical industries. Heat exchangers play a crucial role in thermal management systems, where the need for efficient, high-performance, compact designs continues to rise. One practical approach to enhancing heat transfer performance is the application of nano-fluids-solid particles of nano size suspended in base fluid - which was first introduced by Choi. These fluids exhibit superior thermal conductivity, enhanced convective heat transfer, and improved stability in comparison to conventional base fluids. Among various nanofillers, Multi-Walled Carbon Nanotubes (MWCNTs) have gained significant attention due to their extraordinary thermal conductivity, 'high aspect ratio', and excellent dispersion properties, making them ideal candidates for heat transfer applications. Additionally, the corrugated plate design in PHEs further improves thermal performance by inducing turbulence, increasing surface area, and reducing fouling effects. The combination of nanofluids and corrugated plate heat exchangers presents a promising strategy to optimize heat transfer efficiency while maintaining compact system designs.

The study aims to analyse the impact of MWCNT/water-based nanofluids on the heat-transfer characteristics of corrugated-wavy-plate heat exchangers. The study aims to analyse key parameters such as heat transfer rate and pressure drop, to evaluate the feasibility of nanofluids in enhancing PHE performance. The Critical Heat Flux (CHF) was increased by approximately 160% due to Al_2O_3 nanoparticle coatings on the heating surface. But prolonged operation resulted in decreased efficiency due to deposition and fouling of the heating surfaces [1]. The importance of controlling nanoparticle accumulation was emphasized to maintain the efficiency of heat transfer. Strategies to minimize the negative impact of particle buildup, such as periodic cleaning or using more stable nanofluids, were suggested.

Any discussion on heat transfer and heat exchangers might not be able to produce a rational judgement without mentioning nano-fluids. [2]. In both turbulent and laminar conditions, in comparison to Al_2O_3/water, Al_2O_3 +Copper/water hybrid nano-fluid had a higher average Nusselt number [3, 4]. Al_2O_3 + MWCNT hybrid aqueous nano-fluid outperformed Al_2O_3 mono aqueous nanofluid because of the greater thermal-conductivity of MWCNT than Al_2O_3 [5].

As the Peclet number, Pe, rises, the heat-transfer coefficient rises. Peclet number is correlated to working fluid volume-flow-rate and thermal diffusivity. [6-8]. Water has the lowest Nusselt-No, while Nano-fluids have substantial Nusselt-No. [9]. The friction factor reduces with the rise in Peclet number [10, 11]. Higher pressure drop is observed for viscous and dense nano-fluids.[10]. Nanoparticles rise pumping power. [7, 12]. Temperature and nano-particle volume fraction are directly related to thermal exchange.[13]. For a given flow-rate, the efficiency of PHE do not lessen or grow with nano-fluids.[14].

Not much literature is available on the impact of angle on thermal, physical, and flow variables like heat transfer rate(Q), Nusselt No, Peclet No, and pressure drop. Experiments are done to find the outcome of Q(Watts) and Pressure drop (Pa) due to the angle of the plate. The angles considered are flat plate(0°),30°,40°,50°,60°. The ideal conditions for achieving the highest heat transfer rate and the lowest pressure drop have been identified

2. Materials and Methods

HRTEM, TEM images of MWCNT are in Figures 1, and 2. To thwart corrosive effects, SS material is utilised for the construction of the experimental rig. Corrugated Plate Heat Exchanger (CPHE) with corrugation angles 0,30,40,50,60 degrees is designed and manufactured with three SS plates welded to form 2 contiguous channels. The upper conduit (nano-fluid) is 5 millimetres, and the lower conduit for hot water is 15mm. The system is supported by a test-fluid repository and a hot water repository, as shown in Figure 3.

Thermocouples are fixed at the in and out of each conduit, measuring bulk in and out temperatures. The thermocouples are linked to a digital temperature indicator. Counter-current pattern of flow is used. Dimensions of the CWPHE are: Length of each plate 30 cm, Width of each plate 10 cm, Plate spacing 0.5cm (cold or nanofluid), 1.5 cm for hot fluid, and 0.5 cm for nanofluid. Corrugation angles – 0°, 30°, 40°, 50°,60°. Figure 4 conveys the corrugated angle of the plate.

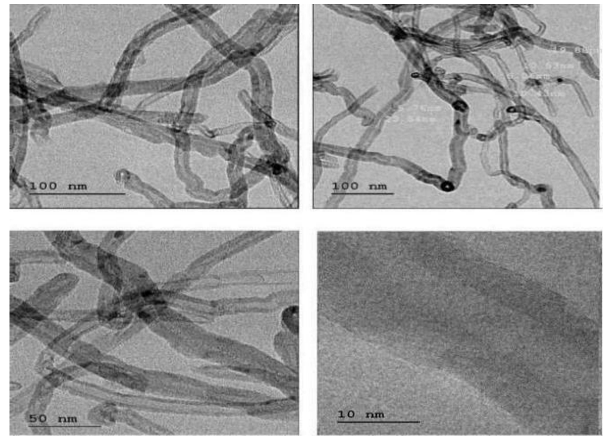

Fig. 1 HRTEM images of 'MWCNT'
Courtesy: ADNANO Private Ltd.

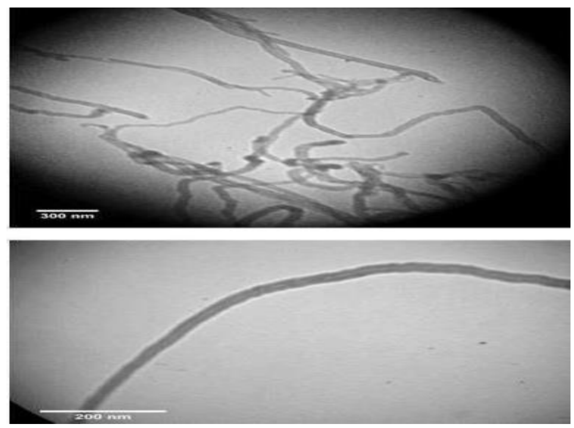

Fig. 2 TEM images of 'MWCNT'
Courtesy: ADNANO Private Ltd

Fig. 3 Experimental rig
Courtesy: International Journal of Engineering and Technology Innovation, vol. 5, no. 2, 2015, pp. 99-107

Hot water at 70 °C – 75 °C, at a constant flow rate of 3lpm, has been used for heating the test(nano) fluids. For each Hot water at 70°C – 75°C, at constant flow rate of 3lpm has been used to heat test-fluid(nano-fluid) For each experimental measurement, the in and out temperatures of the fluids by means of thermos couples, difference in height of mercury in robust manometer are noted, The test-fluids are pumped into the upper conduit through the quantified rotameter from 2lpm to 4lpm. A digital temperature indicator with an accuracy of

±0.1ºC is attached to thermocouples. Multi-Walled Carbon Nanotubes (MWCNTs) are chosen due to their superior thermal conductivity and stability. A precise amount of MWCNTs (as per the desired concentration) is measured using a digital weighing scale. According to the density of MWCNTs, to achieve a 0.01% concentration of fluid, 22grams of nano powder should be added. Similarly, to get a 0.02% concentration, 44 grams are to be added. The mixture is swirled vigorously with a magnetic stirrer to get a uniform distribution. And surfactant SDBS (Sodium Dodecylbenzene Sulfonate), 0.1 % of nanoparticle concentration for uniform dispersion and stability improvement, is added.

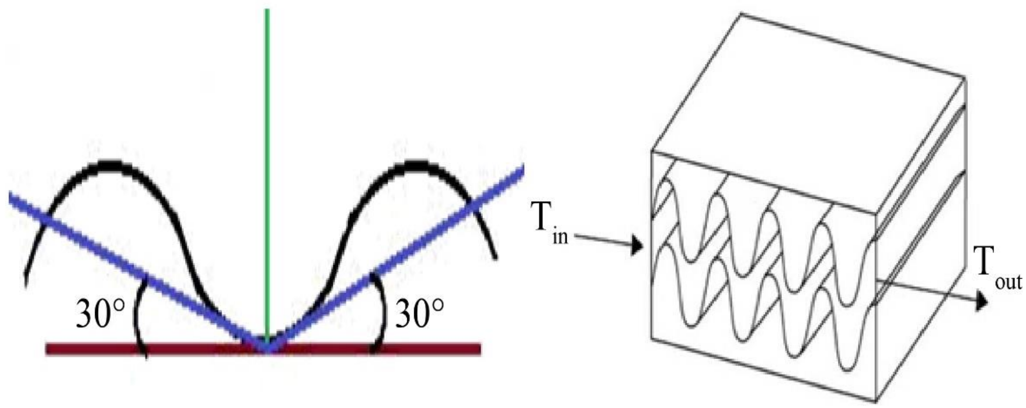

Fig. 4 Corrugated angle, plate

courtesy:https://doi.org/10.1016/j.matpr.2019.06.307)

Density, thermal-conductivity, and specific heat-capacity of MWCNT are 40Kg/m^3,2000W/mK,733J/J/kg K, respectively. Experimentation was done using 0.01%, 0.03%, 0.05%, 0.07%, and 0.09% volume fraction of MWCNT in water (ϕ). The rate of heat transfer for hot fluid (Q_h), test fluid (Q_c), and the average rate of heat transfer is calculated by equations 1,2,3. Pressure drop by Equation 4.

$$Q_h = m_h C_h dt_h \tag{1}$$

$$Q_c = m_c\, C_c\, dt_c \tag{2}$$

$$Q_{avg} = \frac{Q_h + Q_c}{2} \tag{3}$$

$$\text{Pressure drop} = \Delta h\rho g \tag{4}$$

m_c is the mass flow rate of hot fluid,

m_h is the mass flow rate of cold fluid. Mass flow rate is volume flow rate multiplied by density.

C_h, C_c are specific heat capacity of hot and cold(nano)fluid, dt_h,dt_c are in-let and out-let temperature differences of hot-fluid and cold (test)-fluid Δh is the difference in height of mercury in the manometer,ρ is the density of test fluid, g is the acceleration due to gravity. The thermo-physical properties of both fluids are calculated at bulk temperature. Viscosity, thermal conductivity, density, and specific heat capacity of cold(nano)fluid are calculated by Equations (5),6,7,8.

$$\mu_{nf} = (1 + 2.5)\emptyset\mu_w \tag{5}$$

Φ is the percentage concentration of the nanoparticle

$$K_{nf} = \frac{k_{p+2k_w+2\emptyset(k_p-k_w)(1+2.5\emptyset)}}{k_p+2k_w-\emptyset(k_p-k_w)} K_w \tag{6}$$

$$\rho_{nf} = \emptyset\rho_p + (1-\emptyset)\rho_w \tag{7}$$

$$C_{nf} = \frac{[\emptyset(\rho_{np}c_{np})+(1-\emptyset)(\rho c_w)]}{\rho_{nf}} \tag{8}$$

μ_w is the viscosity of water

K_p, K_w are thermal conductivities of nanoparticle (MWCNT), water, and ρ_p,ρ_w are densities of MWCNT and water.

3. Results and Discussion

Figure 5 details the effect of CPHE angle on heat transfer rate and pressure drop. Maximum HTR is observed at 40 ˚ corrugation angle. Minimum pressure drop is observed for the flat plate and maximum for 40 ˚ cphe. Figure 6 reflects the effect of phi on responses. As phi increases, HTR and pressure drop increase. Except for 0 to 0.01, there is a decline in pressure drop. Figure 7 explains the effect of volume flow rate on responses. As nanoparticle concentration increases, both responses increase. Figures 8, 9, and 10 are interaction plots which reveal the effect of cphe angle, nanoparticle ratio(Φ) on heat transfer rate at 2,3,4 lpm, respectively. HTR is maximum at 40-50,0.05% of nanoparticle concentration and at 4lpm.

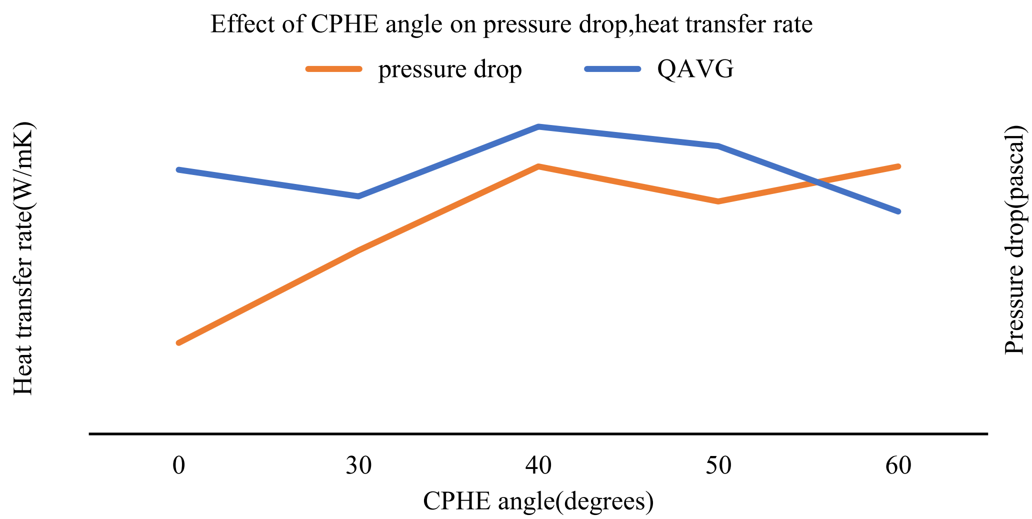

Fig. 5 Effect of CPHE angle on heat transfer rate and pressure drop

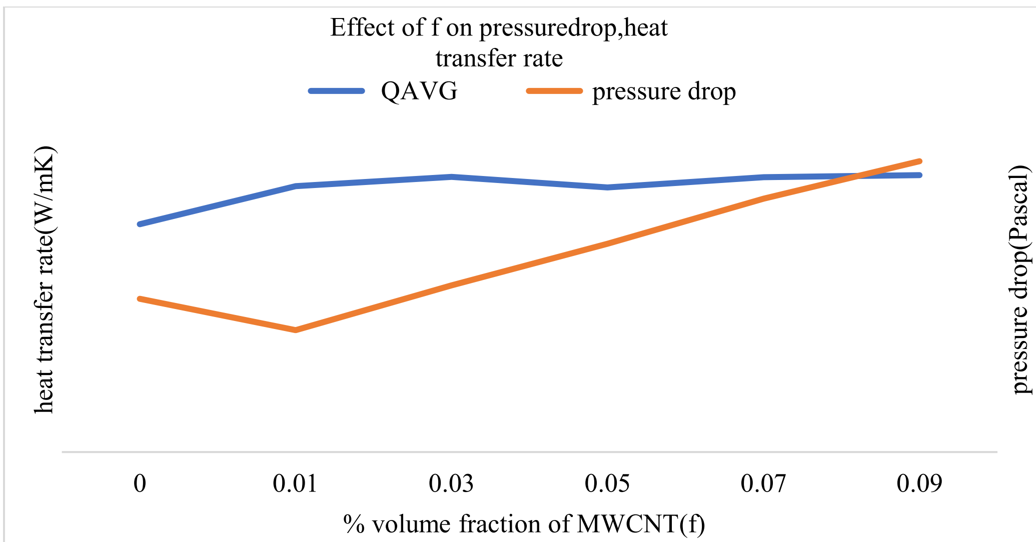

Fig. 6 Effect of phi on responses

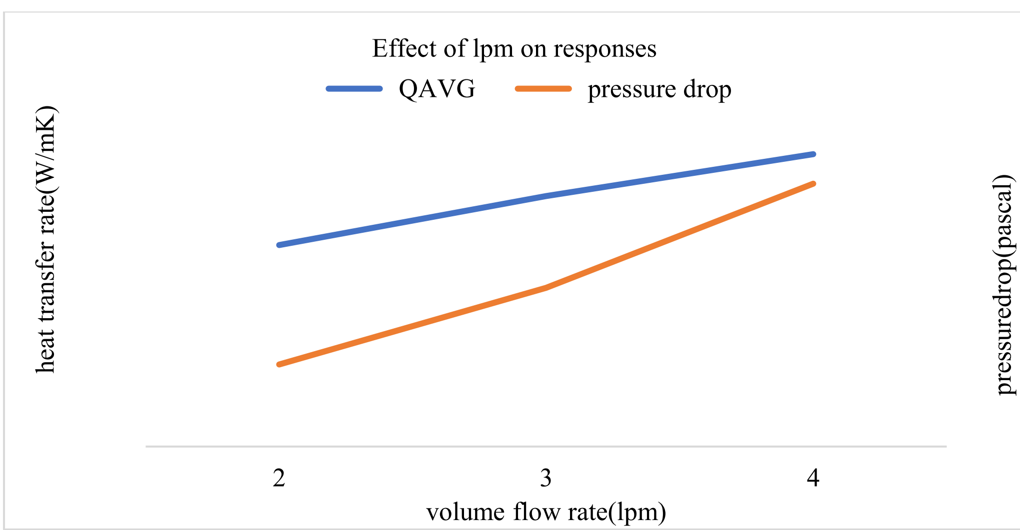

Fig. 7 Effect of lpm on responses

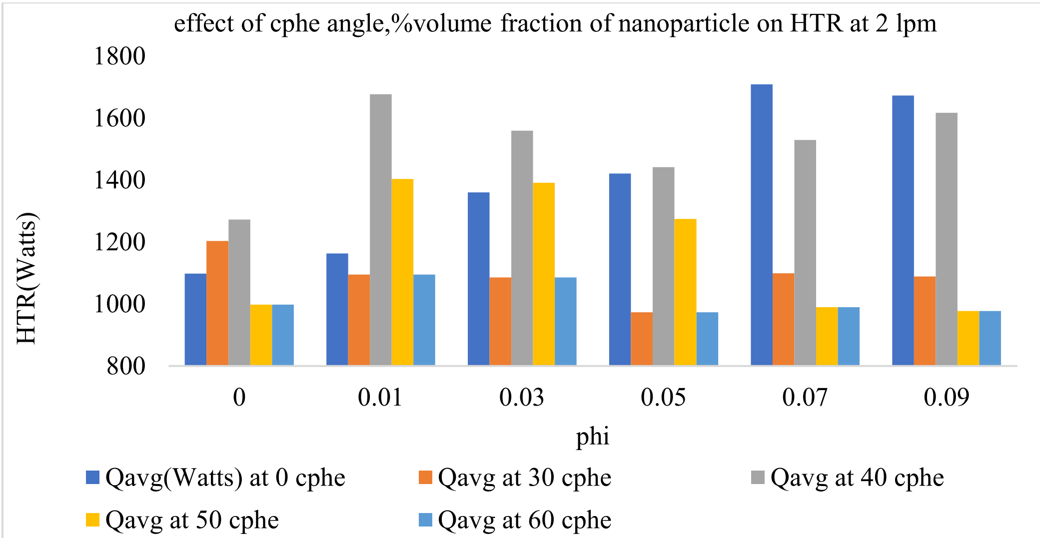

Fig. 8 Effect of cphe angle, Φ on HTR at 2lpm

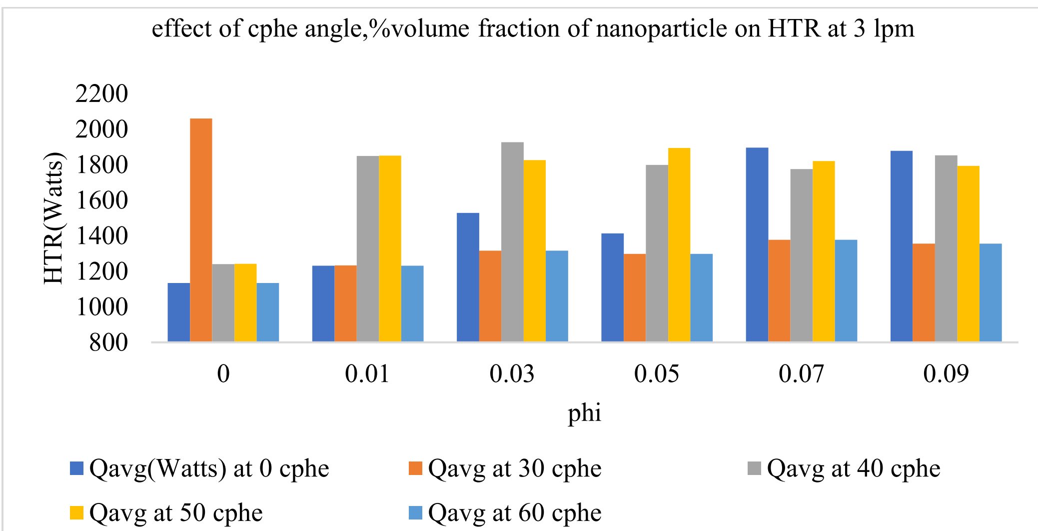

Fig. 9 Effect of cphe angle, Φ on HTR at 3lpm

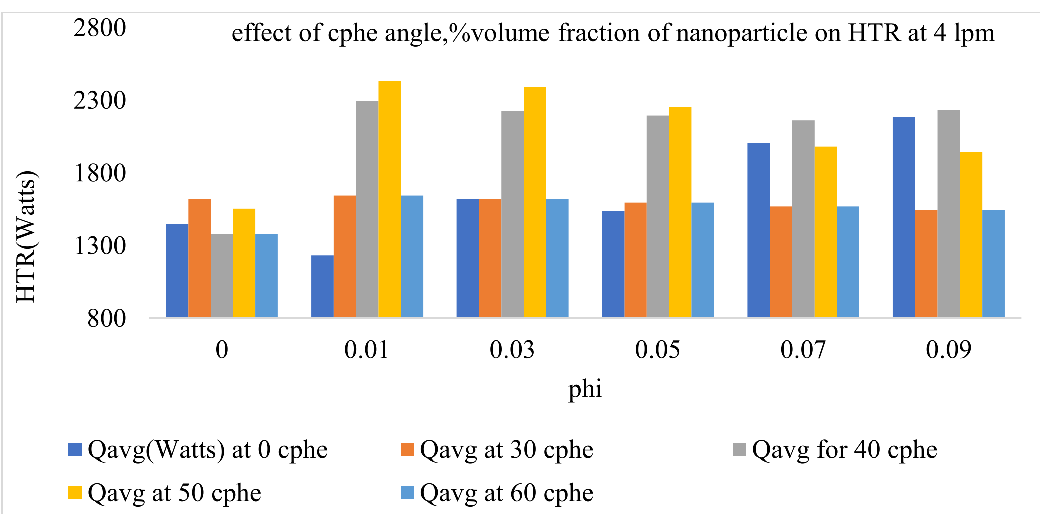

Fig. 10 Effect of cphe angle, Φ on HTR at 4lpm

Figures 11, 12, 13 are interaction plots which reveal the effect of cphe angle, nanoparticle ratio(Φ) on pressure drop at 2,3,4 lpm, respectively. Pressure drop increased due to an increase in angle, phi, and lpm, which in turn increases pumping power. A tradeoff between HTR and pumping power is required to design an effective heat exchanger.

Optimum turbulence and Brownian movement are at 40°-50º °, which enhances convection and heat transfer rate. Due to viscous impact and flow resistance, HTR declined at higher nanoparticle concentration, though the fluid has improved thermal conductivity. Optimum concentration is 0.05%. lpm is directly proportional to the Reynolds number, which in turn enhances HTR. As lpm increases, HTR increases.

As lpm increases, pressure drop(pumping power) increases due to an increase in velocity, which results in a rise in pressure drop in accordance with the Darcy-Weisbach equation. As nanoparticle concentration increases, the pressure drop rises due to a rise in viscosity and density of the nanofluid. CPHE angle surges flow resistance and turbulence surges energy losses, which causes a rise in pressure drop. Minimum (optimum) pumping power at 0° corrugated angle. Design tradeoff between HTR and pumping power.

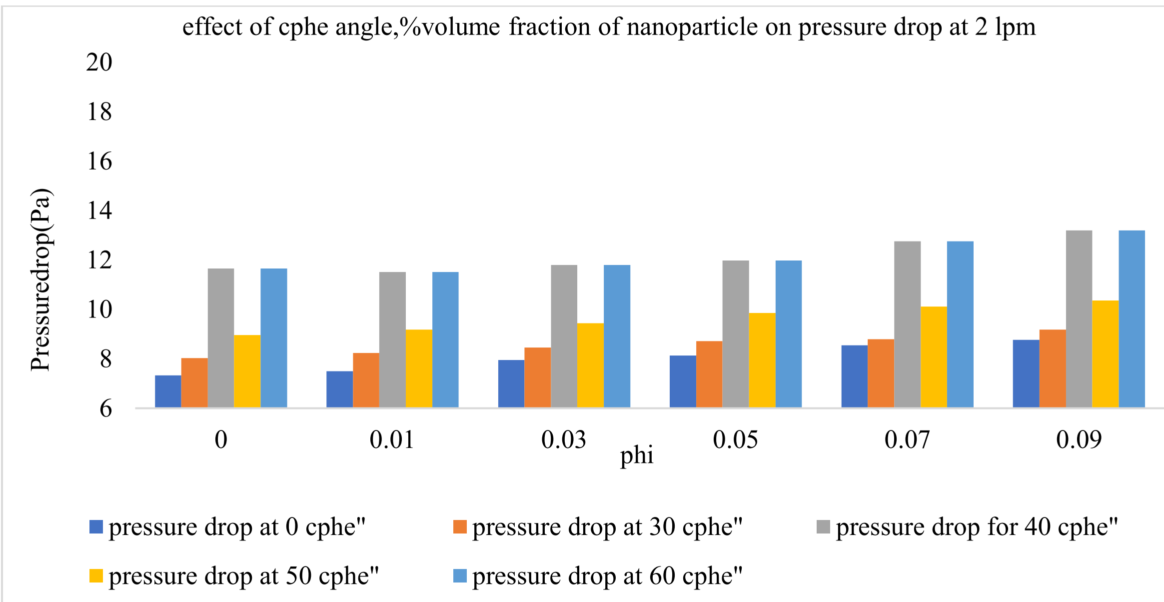

Fig. 11 Effect of cphe angle,ϕ on pressure drop at 2lpm

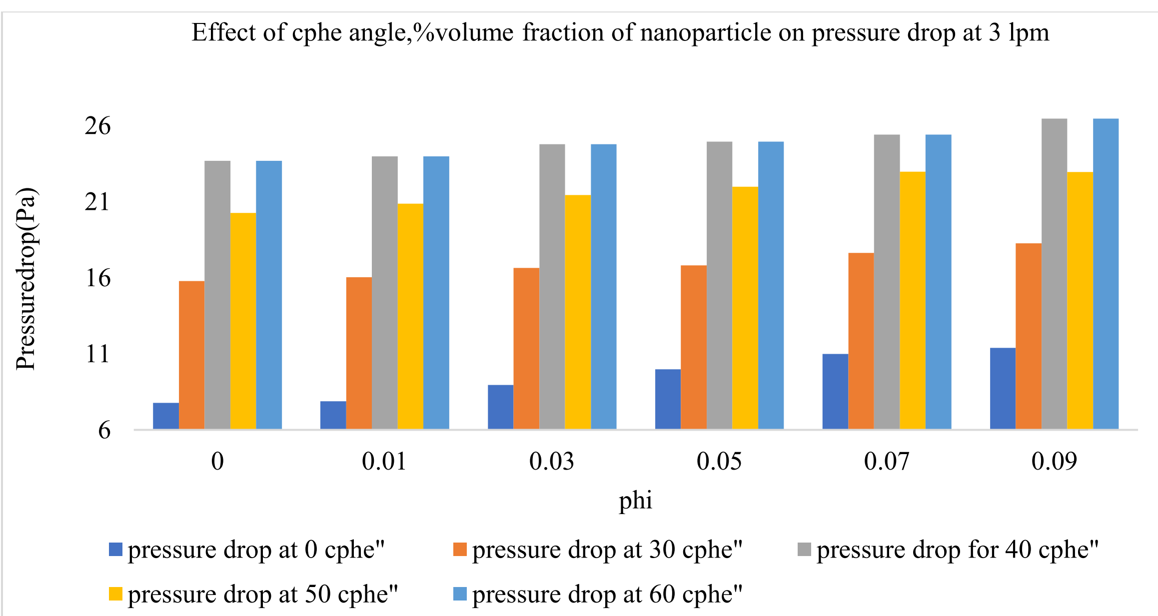

Fig. 12 Effect of cphe angle,ϕ on pressure drop at 3lpm

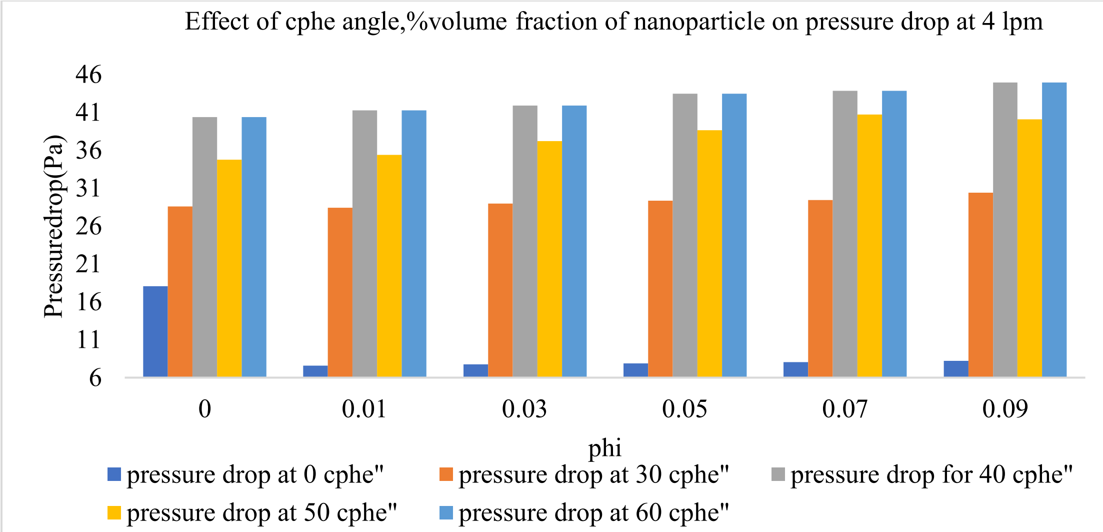

Fig. 13 Effect of cphe angle ϕ on pressure drop at 4 lpm

4. Conclusion

With water as test fluid, maximum HTR is 2060.847W/mK at 30 ° CPE angle, at 3lpm. For MWCNT nanofluid as test fluid, max HTR is 2431.613W/mK at 50° cphe angle,4lpm. An 18% increase in HTR is observed. Minimum pressure drop is 7.328871pascal at 0°,2 lpm with water as test fluid, and 7.49995 pascal at 0.01% phi,2lpm at 0 ° corrugated angle with nanofluid as test fluid. Pressure drop almost remained constant for water and 0.01% nanofluid. 0.01% MWCNT nanofluid, 50 ° Cophe angle,4 lpm is the optimum design. Nanofluids improve HTR due to Brownian motion of nanoparticles, improved thermal conductivity, and interruption of the boundary layer. At low cphe angles, flow is laminar, HTR declines, and the pressure drop plummets. At temperatures of 40 to 50 degrees, the flow is turbulent, and the pressure drop is high. As nanoparticle concentration increases, density and viscosity increase, and the pressure drop rises, although the thermal conductivity of the nanofluid rises with phi. Table 1 reveals the input variables and responses (Q, pressure drop) in the designXpert software. Table 2 depicts the optimum value and desirability.

Table 1. Input parameters

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:cphe angle	is in range	0	60	1	1	3
B:lpm	is in range	2	4	1	1	3
C:%nanoparticle concentration	is in range	0	0.09	1	1	3
rate of heat transfer	maximize	973.451	2293.775	1	1	3
pressuredrop	minimize	7.329	44.963	1	1	3

Table 2. Optimum values of responses

	cphe angle	lpm	%nanoparticle concentration	pressuredrop	Heat transfer rate	Overall Desirability
	50	4	0.01	7.5	2431.6	
Overall Desirability	1.000	1.000	1.000	0.927	0.536	0.705

4.1. Limitations and Future Scope

Increasing the Nanoparticle concentration beyond the optimal value increases the pressure drop. Prevention of agglomeration requires surfactant or ultrasonication. Efficiency depends on the regime of flow and temperature. MWCNTs are costlier, need meticulous handling, and disposal. Uncertainties in experimentation can lead to variation in results. Surface modifications and nanoparticle functionalization can reduce agglomeration. Experimental validation can be done using CFD. Machine learning techniques can be applied to find heat transfer and pressure drop. Twisted tape, helical or multi-wavy plates can increase effectiveness.

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