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ORIGINAL ARTICLE

Investigation and optimization of heat transfer coefficient of MWCNTs-Water nanofluids in a plate heat exchanger

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Abstract

This article reports an experimental study of heat transfer characteristics of multi-walled carbon nanotubes (MWCNTs). These nanofluids, consisting of water with different weight concentrations of nanofluid (0.0.1–0.145% wt.), were flown in counter flow plate heat exchanger under turbulent conditions ($2500 < Re < 6500$) for cooling applications. The nanofluid was prepared by dispersing MWCNT nanoparticles in the presence of sodium dodecyl sulfate (SDS) and water as base fluid. The results showed that the convective heat transfer coefficient (HTC) of nanofluid was higher than that of the base fluid at an equal mass flow rate and inlet temperature. The heat transfer coefficient of nanofluid increased by mass flow rate and temperature rising. Also, the heat transfer coefficient and the concentration of MWCNTs nanofluid showed a positive association at the same temperature. At a constant weight concentration, the heat transfer coefficient increased when the Reynolds number increased. The slope weight concentration tends to rise as the heat transfer coefficient grows. The increase in Reynolds numbers (or mass flow) was less than the increase in the concentration of carbon nanotubes. According to the performed experiments and software analysis (QUALITEK 4), the heat transfer coefficient and concentration are both manifolded at the same time. But there was an inverse correlation between the heat transfer coefficient and flow rate.

Keywords: *Heat Transfer Coefficient; Multi-Walled Carbon Nanotubes; QUALITEK 4 Software; Surfactant; Plate Heat Exchanger.*

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INTRODUCTION

The different types of heat exchangers like shell and tube [1-2], double pipe [3-4], plate types[5-7], or solar heat exchangers [8-9] are used extensively in various engineering applications such as oil and gas, power generation, and metallurgy, marine, food processing, waste heat recovery, chemical, mechanical industry, nuclear reactors, refrigeration, electronics, air conditioning, and ventilation [10-11]. The plate heat exchanger consists of a series of parallel metal plates corrugated and stacked together to form channels for the passage of fluid to be exposed to a bigger surface heat transfer. Each plate contains a gasket (endplate has a different gasket in u-type), which seals the channels formed when the plate pack is compressed and mounted on a frame. Thus, they commonly have flow ports in all four corners and are clamped together in a frame. The hot and cold fluids flow in intermittent channels and the heat transfer takes place between adjacent channels [12-14]. In recent decades, many researchers have studied different ways to enhance the heat transfer or increase the thermal capacity of working fluid by using nanometre-sized particles for dispersing in base liquids, known as nanofluids. One method is to add nanoparticles of highly thermally conductive materials like carbon [15], metal [16], and metal oxides [17] into base fluids to improve the overall thermal conductivity. Compared with metal or metal oxide materials, carbon nanotube (CNTs) have a higher thermal conductivity [18-20].

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Shanbedi et al. [21] experimentally investigated the influence of different surfactants including gum arabic (GA), cetyltrimethylammonium bromide (CTAB), and sodium dodecyl sulfate (SDS) on the stability and thermophysical properties of multi-walled carbon nanotubes (MWCNTs) in aqueous media. The results indicated an increase in electrical conductivity, density, viscosity, shear stress, and a decrease in surface tension (except in GA) of suspensions in all concentrations compared to pure water in constant temperature. As the temperature increased, the electrical conductivity increased significantly, while the viscosity, shear stress, density, and surface tension decreased more or less for all concentrations. Sunder et al. [22] performed an experimental investigation of forced convection heat transfer and friction factor in a tube with Fe3O4 magnetic nanofluid. The nanofluid used was a stable colloidal suspension of magnetite (Fe3O4) nanoparticles of 36 nm average diameter. The convective heat transfer coefficient and friction factor characteristics of Fe3O4 nanofluid for flow in a circular tube were evaluated experimentally in the range of $3000 < Re < 22{,}000$ with the volume concentration range of $0 < u < 0.6\%$. They found that nanofluid heat transfer was higher compared to water by volume concentration increasing. For flow in a tube, correlations were developed for the estimation of Nusselt number and friction factor of water and nanofluid. The heat transfer coefficient was enhanced by 30.96% and the friction factor by 10.01% at 0.6% volume concentration compared to the flow of water at similar operating conditions. Shanbedi et al. [23] reported a measurement on thermophysical properties such as electrical and thermal conductivity, viscosity, and density at the temperatures range of 20°C to 80°C. The result indicated that any increase in the temperature led to a decrease in the viscosity and density. This paper aimed to improve the heat transfer enhancement and flow characteristics of MWCNTs–water nanofluids at different concentrations and temperature flowing in a plate heat exchanger under a turbulent flow condition. The results were also analyzed using Qualitek-4 software.

MATERIALS AND METHODS

Material

Multiwalled Carbon Nanotube (MWCNTs), Distilled water (DW) as base fluid, and Sodium Dodecyl Sulfate (SDS surfactants to stabilize the nanofluid) were used to prepare the nanofluid. MWCNT (purity 95%) was obtained from VCN Materials Company. Also, sodium dodecyl sulfate was obtained from Sigma–Aldrich Company as a surfactant. Distilled water, Nitric Acid (HNO_3, M_w = 63.9gr mol^{-1}, density = 1.40 kg lit^{-1}, purity 65%), 1-ethyl-3-dimethyl carbodiimide (EDC), N-hydroxy succinimide (NHS), Sulfuric Acid (H_2So_4, M_w = 98 gr mol^{-1}, density = 84.1 kg lit^{-1}, purity 98%) were obtained from my country. All aqueous solutions were prepared with distilled water and all experiments were performed at room temperature, approximately 25°C.

Synthesis of CNT

To synthesize carboxylated MWCNTs, a solution of sulfuric acid and nitric acid (1:3) was mixed and sonicated with MWCNTs for 4h. To remove all unreacted acids, the resulting sample was then diluted with distilled water, centrifugation 5000, and washed with distilled water. Then a mixture of 1: 1 (v/v), mixture 1-ethyl-3-dimethyl carbodiimide, and of N-hydroxy succinimide was prepared. It was rinsed with distilled water, using centrifugation to attach the aromatic loop to the nanotubes. At this point, the CNT was ready for stabilization. Fig. 1 shows the morphology of MWCNT using a Transmission electron microscope (TEM).

Preparation of nanofluids

First, the amount of SDS surfactant was slowly dissolved in distilled water for 45 minutes by a sonicator at room temperature. The same amount of MWCNTs were slowly added to the solution and mixed by a centrifuge for 45 minutes. In the current study, the weight concentrations were 0.01%, 0.055%, 0.1% and 0.145% wt·

In this study, non-covalent functionalization with SDS surfactant in water was used. Surfactants were added to water after CNT-nanopowder preparation. The CNT and SDS were added to both at a ratio of 1:1 to make a non-covalent bond in the structure of the nanofluid, stabilizing the nanoparticles in water. The water and nanoparticles do not dissolve and settle immediately as they do not have the same polarities. Eventually, to improve the bonding between water, SDS, and nanoparticles and provide better stability, the nanofluid got shaken for 45min at the ultrasonic bath (800watts). For more stability, the other mentioned ratios were also tested.

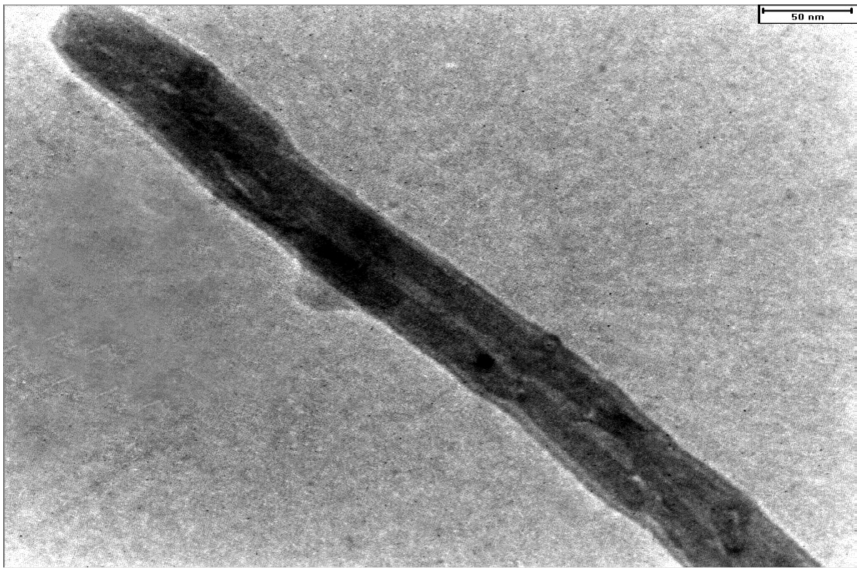


Fig. 1. TEM photograph of MWCNTs nanoparticles.

Experimental apparatus

The experimental setup consisted of a test section containing a U-type plate heat exchanger (M3 Alfa Laval model-21 plate- Stainless Steel AISI 316 with Chevron angle as 60). To study the heat transfer coefficient, two counter-flowing for measuring the flow rates of the fluids, three tanks for storage, heating or cooling of fluids (Stainless Steel AISI 304 with a capacity of 125 L), two pumps (1.8 HP) for circulation of fluid through the plate heat exchanger at different flow rates, five thermometers (Pakkens type 0-120C and accuracy of 1 C) for measuring the temperatures, two electric heaters with thermostat (2KW), and four pressure gauge (Pakkens Type 0-160 mBar) placed inside their path to measure the pressure of hot and cold water at inlet and outlet of the heat exchanger. Two U-shaped manometers were used to measure the pressure drop. A compressor, condenser, expansion valve, and evaporator (coil), relevant refrigeration system, were also used. The experimental system had two main loops of cold (nanofluids) and hot (base fluid). In the hot loop, water was heated in a reservoir by embedded electric heaters fixed at the bottom of the reservoir tank. The heated fluid was pumped from the tank. Then it passed through a valve, entered a counter flow, thermometers, and pressure gauges. After passing through the plate heat exchanger, it turned down to the tank.

For the cold loop, nanofluid entered through the pump from the cold tank, passed a valve, entered the counter flow, thermometer, and pressure gauges. After leaving the plate heat exchanger, it entered the thermometer and pressure gauge entering refrigeration system. In the cooling cycle, R-404A was used. The gas exited from the compressor discharger. After passing through the condenser, which was cooled by a fan, it entered the coil, which was located in the cold storage tank, through the expansion valve. Pressure drop in the inlet and outlet of the plate heat exchanger were measured by U-shaped manometers. Inlet and outlet pipe diameter was 32mm. The inlet temperature of the hot fluid was maintained at 40-60oC by an electric heater and thermostat. For each test condition, measurements were recorded 3 times, and the results were averaged (Fig. 2). The advances in the technology of corrugated plate type heat exchanger enhanced the overall heat transfer coefficient and supported the system to improve the energy-efficiency.

Calculation

The experimental data have been obtained under steady conditions. To evaluate the accuracy of measurements, the experimental system has been tested with distilled water before measuring the heat transfer characteristics of different weight concentration of MWCNTs/water. The mass flow and temperature of the cold and hot sides were recorded at the inlet and outlet of the

Fig. 2. Experimental setup.

heat exchanger. Thermophysical properties of fluids at mean temperatures were calculated from the Mixing theory (for Density), Xuan and Roetzel equation (for specific heat capacity), modified Maxwell's equation (for thermal conductivity-taking β = 0.1 and n=6), and Brinkman equation (for viscosity) [6, 11, 24-25]. Equations in different sources were used to calculate the heat transfer coefficient of carbon nanotube-water nanofluids compared to distilled water. The heat transfer rate for the hot and cold side can be defined as equation 1:

$$Q_h = m_h c_p (T_{h_{in}} - T_{hout}) \, , \, Q_c = m_c c_p (T_{c_{out}} - T_{cin})$$

and $Q = (Q_c + Q_h)/2$ (1)

Q is the average heat transfer rate. The logarithmic mean temperature difference (LMTD) is to determine by the following equation (equation 2).

$$\Delta T_{LMTD} = \frac{\Delta T_1 - \Delta T_2}{\ln (\Delta T_1 / \Delta T_2)} \tag{2}$$

ΔT_1 and ΔT_2 are inlet temperature difference and outlet temperature difference, respectively. The overall heat transfer coefficient is represented as equation 3:

$$Q = UA\Delta T_{LMTD} \tag{3}$$

U is the overall heat transfer coefficient and A is the surface temperature. Hydraulic diameter and the average flow velocity as length scale and velocity scale are used to defined Reynolds and Prandtl number as equation 4-6:

$$\mathrm{Re} = \frac{G_C D_h}{\mu} \tag{4}$$

$$\mathrm{Pr} = \frac{C_P \mu}{K} \tag{5}$$

that

$$G_C = \frac{m}{N_{cp} b L_W} \tag{6}$$

Where Ncp, b, Lw, and Gc are the number of channels per pass, mean mass channel gap, Plate width inside gasket, and mass velocity, respectively. Nusselt number for single-phase flow is calculated from equation 7:

$$NU = C_n \mathrm{Re}^n \mathrm{Pr}^{1/3} (\mu_{nf} / \mu_b)^{0.17} \tag{7}$$

Table 1. Denote factors and levels in design of experimental orthogonal array.

Parameters		Levels			
		1	2	3	4
A	C(wt.)	0.01	0.055	0.1	0.145
B	T(ºC)	40	50	55	60
C	Level m	L1	L2	L3	L4

Table 2. Experimental layout using L16 array.

Experiment number	Parameters and their levels			Thermal conductivity (w/m*k)		
	A	B	C			
1	1	1	1	7557.3	7558.2	7559.9
2	1	2	2	7248.3	7243.2	7247.3
3	1	3	3	6871.1	6339	6870.4
4	1	4	4	6334.2	6339	6336.8
5	2	1	2	7806.5	7808.4	7812
6	2	2	1	8356.5	8358.5	8355.5
7	2	3	4	6789.7	6800	6798.3
8	2	4	3	7497.3	7490.2	7487.9
9	3	1	3	7965.6	7959.2	7972.4
10	3	2	4	7465.3	7464.3	7461.1
11	3	3	1	9334.1	9344	9333.1
12	3	4	2	8825.2	8832.1	8828.2
13	4	1	4	8132.7	8134	8136.5
14	4	2	3	9009.7	9003.7	9010.2
15	4	3	2	9655.5	9658.9	9665
16	4	4	1	10339	10332	10338

Table 3. ANOVA results.

parameters	DOF(f)	Sum. Of Sqrs. (s)	Variance(v)	F-Ratio(f)	Pure Sum(s’)	Percent P (%)
A	3	35147679.1	11715893.04	4958.8	35140591.2	63.001
B	3	1018659.3	339553.1	143.7	1011571.3	1.813
C	3	19520847.7	6506949.2	2754.1	19513759.8	34.985
Other/error	38	89780.2	2362.6			0.201
Total	47	55776966.4				100%

For the turbulent flow, the constants C_n and n, which depends on the Chevron angle (º60), and the Reynolds number are equal to 0.306 and 0.529, respectively [26]. Therefore, the heat transfer coefficient (h) can be calculated as following (Equation 8).

$$h = \frac{Nu}{kD_h} \tag{8}$$

Design of experiments

Qualitek-4 software for the design of experiments was used in the present paper using the Taguchi approach. Taguchi approach has established 0rthogonal arrays (OA) to describe a large number of experimental situations, mainly to reduce experimental errors and to enhance the efficiency and reproducibility of laboratory experiments. The software uses L16 orthogonal arrays, with the selection of three factors of C, T, and m (flow rate) at four levels per factor that has been chosen based on the number of factors and levels mentioned in Table 1 (nominal the best). Due to the experiment number, the test results are recorded in Table 2.

The average effect of facts for factors and interactions are observed in the main effects (Table 2). In this Table, P% is the percentage contribution of each factor. Other parameters in this table include the degree of freedom for each factor (DOF), Sum of Sqrs. (S), Variance (V), F-ratio (F), Pure Sum of the numbers for each that reveals the same results. Percent (P %) at the ANOVA table (Table 3), found that changes in concentration and level m are more effective than the changes

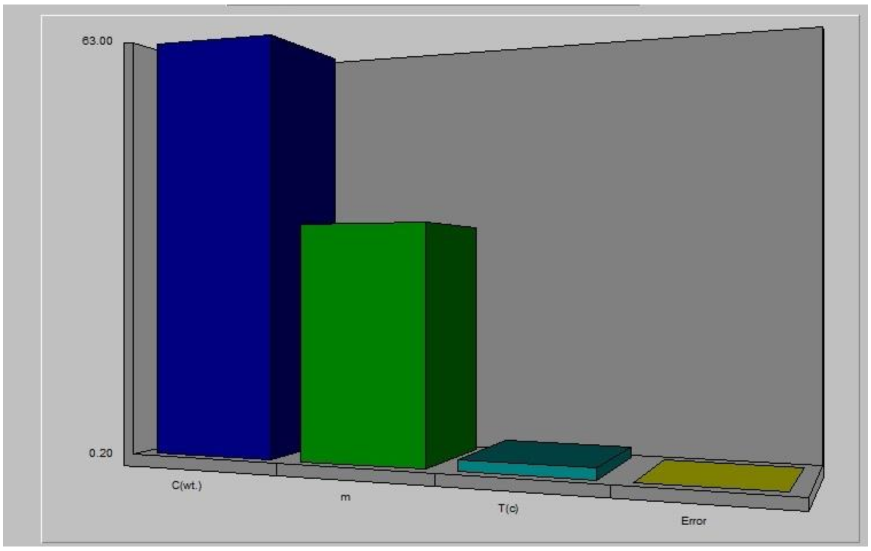
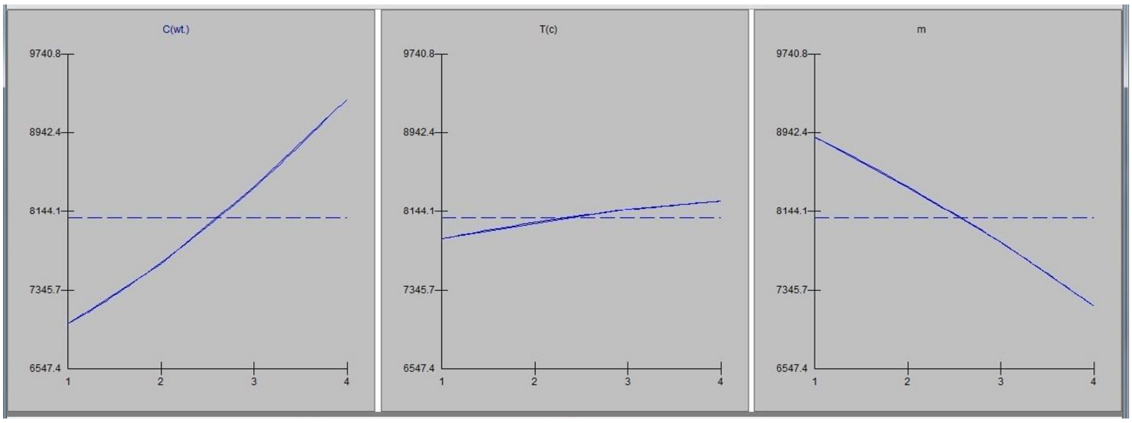


Fig. 3. Relative influence of factors and interactions.



a b c

Fig. 4. Multiple graphs of main effects (average value). Effect of concentration (6-a), temperature (6-b), and the mass (6-c).

in temperature (Fig. 3). It is also known that the concentration (Fig. 4-a) and temperature (Fig. 4-b) are increasing, while the mass flow is decreasing with closure in the valve (Fig. 4-c). Finally, the software estimates the best conditions for the experimentally. Also observed that the obtained error rate is 0.21, which is less than 15%. Thus it can be concluded that the experimental design is acceptable [27, 1].

RESULTS AND DISCUSSIONS

In the present study, MWCNT-water nanofluid was used as a working fluid. The weight concentrations used in this study were 0.01%, 0.055%, 0.1% and 0.145%. Changes in the coefficient of heat transfer of water and nanofluids of carbon nanotubes-water at constant temperature (T=60 ºC) are shown in Fig. 5. The experiments were performed in the range of Reynolds numbers between 2500-6500. Fig. 5 shows that stabilizing a small number of MWCNTs in water significantly increased the heat transfer coefficient compared to the water-based fluid. The heat transfer coefficient and particle concentration also tended to multiply at the same time. Increasing the temperature also affected the increase in heat transfer (Fig. 6). From the diagram, it can be concluded that the heat transfer coefficients increase significantly as the Reynolds number (increase in flow) increased. Figs. 5 and

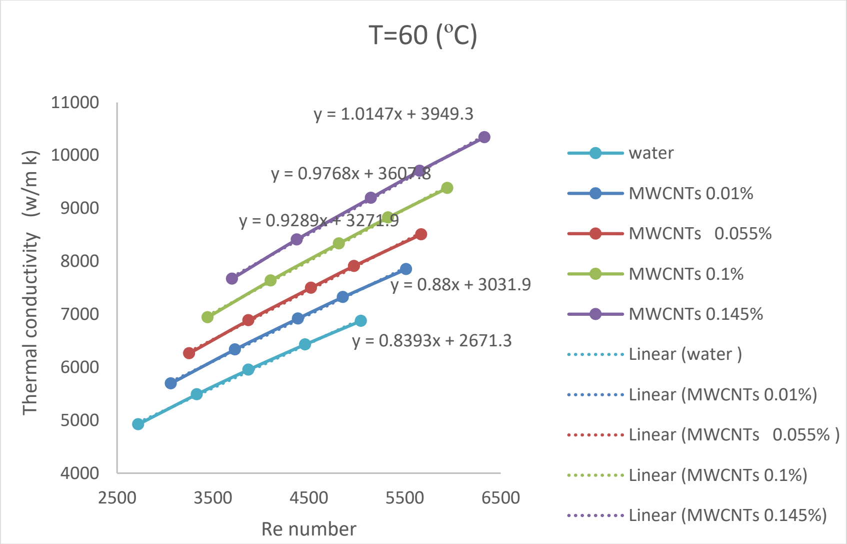


Fig. 5. Thermal conductivity of MWCNTs nanofluid at various Reynolds number for different concentrations.

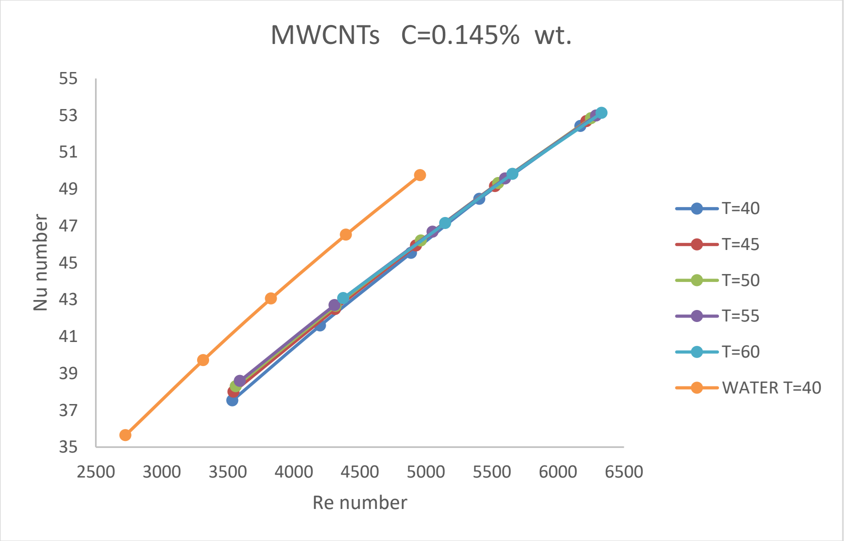


Fig. 6. Nusselt number of MWCNTs nanofluid at various Reynolds number for different temperature.

6 show that at a constant Reynolds number, the heat transfer coefficient and carbon nanotubes concentration had a positive relationship. At a constant weight concentration, the heat transfer coefficient increased by a rise in the Reynolds number. The slope weight concentration-effect and the heat transfer coefficient have grown at the same time. From the results, it can be concluded that the increase in Reynolds number (mass flow) was less than the increase in the concentration of carbon nanotubes. For example, when the Reynolds number increased from 3500 to 5000 in the weight concentration of 0.1%, the heat transfer coefficient of nanofluid increased from 11% to 19.9%. However, in constant Reynolds number of 5000 and weight concentration changing from 0.01% to 0.145%, this ratio grew from 10.2% to 38%. The increase in the heat transfer coefficient of the nanofluid of CNT-water can be regarded as the increase in the thermal conductivity of the fluid, and as a result of irregular and accidental movements increase within the fluid flow. Rising the concentration of nanoparticles made the collision between the particles become more, which in turn

increased the thermal conductivity and turbulence of the nanoparticles led to increasing the heat transfer rate. The fact of increasing heat transfer in the presence of nanoparticle was confirmed by various studies, thus it can be concluded that the experimental analysis is valid and the results are acceptable.

Laboratory results were attained for the relevant levels and factors, and the best conditions were determined in terms of temperature, flow, and concentration (Figs. 5 and 6). To validate the results, the optimal conditions, which are the maximum heat transfer coefficient for the plate heat exchanger, were investigated using Taguchi software. This software also helped to reduce the number of repetitions of the experiments and to repeat only the effective experiments, thus not consuming time. The results of Taguchi software confirmed the test results (Table 2). In this way, the optimal conditions (the best converter conditions in terms of flow rate, temperature and concentration of nanotubes) were determined that were low flow and high concentration and temperature of nanofluid.

The results were analyzed using Qualitek-4 software. It was found that by increasing the concentration (cold side), and closing the valve (decrease flow rate in the cold side) in the laboratory setup, the heat transfer was increased. Therefore, these were well-matched with the laboratory results.

CONCLUSION

By recording the flow rate of cold and hot fluid, the inlet and outlet temperatures and pressure of them, the amount of heat transfer were tested and determined. At a constant weight concentration, the heat transfer coefficient and temperature of the hot side showed a positive relationship. Adding a small amount of multi-walled carbon nanotubes in water, the heat transfer coefficient significantly increased compared to the water-based fluid. Also, the heat transfer coefficient became larger by growing flow rate (Reynolds number) of carbon nanotubes. The slope weight concentration and the heat transfer coefficient tended to grow at the same time. Moreover, the heat transfer coefficient increased when increasing Reynolds number of carbon nanotubes-water nanofluids more than water-water. On the heat transfer coefficient and Nu number, increasing the concentration was more effective than temperature increasing. And, by using the Taguchi method (Qualitek-4 software), optimal conditions were well-matched with laboratory results, and it was found that changes in concentration and level m were much than changes in temperature.

CONFLICT OF INTEREST

Authors have no conflict of interest.

NOMENCLATURE

$MWCNTs$	multi walled carbon nanotubes
PHE	Plate heat exchanger
Cp	Specific heat capacity (kj/ kg*k)
$Cm\,(C)$	weight concentrations
D_h	hydraulic diameter (m)
k	Thermal conductivity (w/m*k)
n	coefficient of shape nanoparticles
d	nanoparticle diameter (m)
h	heat transfer coefficient, W/ m^2*K
Nu	Nusselt number
Re	Reynolds number
Pr	Prandtl number
Q	heat transfer rate (W)

Greek Symbols

ρ	Density (kg/m^3)
μ	viscosity (m^2/s)
ϕ	Volume fraction
β	The ratio of nanoparticle thickness to initial radius

Subscripts

b	Base fluids
np	nanoparticles
nf	nanofluids
w	water
C	cold
h	hot

i	inlet
0	Outlet

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