Heat and Mass Transfer (2023) 59:1167–1183
https://doi.org/10.1007/s00231-022-03326-8

ORIGINAL ARTICLE

Investigation of the effect of nanofluids on heat transfer enhancement by using parallel and vertical springs in a plate heat exchanger

Gökçe Peker[1] · Cengiz Yıldız[1] · Gülşah Çakmak[1] · Ahmet Yıldız[2]

Received: 23 June 2022 / Accepted: 21 November 2022 / Published online: 5 December 2022

Abstract
IThis research presents an experimental study on the thermal performances of a counterflow plate heat exchanger using Al_2O_3/water and CuO/water nanofluids at different weight ratios. Springs were placed vertical and parallel to the plate to create turbulence in the flow. Al_2O_3/water and CuO/water nanofluids were produced using the two-step method with three nanoparticle weight fractions (0.1%, 0.5% and 1%). Within the ranges studied, the Al_2O_3-water nanofluid provides maximum improvement in heat transfer coefficient of about 76.1% in the parallel spring plate heat exchanger compared to the base fluid. For the same mass ratio and spring arrangement, this increase rate is 69.9% in the CuO-water nanofluid. The highest performance factor was determined when Al_2O_3-water nanofluid was used in the spring arrangement, whose springs were placed parallel to the channel at a flow rate of 5.5 lt/min, and this value was found to be 1.51.

Abbreviations

A	Heat transfer area (m2)
c	Specific heat (j/kgK)
Dh	Hydraulic diameter (m)
F	Fanning friction factor
G	Mass velocity (kg/ m2s)
h	Heat transfer coefficient (W /m2 K)
j	Colburn factor
JF	Thermal–hydraulic performance factor
k	Thermal conductivity(W/mK)
m	Mass flow rate (kg/s)
N	Number of channels
Pr	Prandtl number
Re	Reynolds number
T	Temperature (K)
μ	Dynamic viscosity (Pa s)

Subscripts

a	Average
c	cold
h	hot
i	inlet
n	nanofluid
o	outlet
p	plate
w	water

✉ Gülşah Çakmak
gulcak@gmail.com

1 Mechanical Engineering Department, Firat University, 23100 Elazığ, Turkey

2 Mechatronics Engineering Department, Firat University, 23100 Elaziğ, Turkey

1 Introduction

The energy crisis experienced all over the world proves the necessity of efficient use of energy. For this reason, intensive studies are carried out on the design of plate heat exchangers, which are widely used in many processes such as energy production, electronic devices and waste heat recovery, and the development of working fluids. It provides positive results such as improving heat transfer in the heat exchanger, efficient use of energy and prolonging the working life of the system. Efforts to improve heat transfer have focused on methods such as enlarged surfaces, vibration and increasing the thermal conductivity of the working fluid. As is known, the thermal conductivity of common fluids such as water used in the system is lower than the thermal conductivity of metals. To take advantage of this property of solids, nanofluids with higher thermal conductivity have been developed by mixing small solid particles into liquids. The hydrodynamic performance of nanofluids depends on fundamental properties such as density and viscosity.

One of the methods used to provide high efficiency in heat exchangers is to design a heat exchanger with high turbulence density. As the turbulence density increases, the overall heat transfer coefficient and thus the efficiency of the heat exchanger increases and the dimensions decrease.

One of the methods used to increase the efficiency in heat exchangers is the circulation of fluid with good heat transfer properties in the system. For this purpose, the use of nanofluids in heat exchangers can give an effective result.

Ajeeb et al. [1] tested the Al_2O_3 nanofluid in a compact heat exchanger. They determined the performance of the heat exchanger with the nanofluid they used with distilled water at concentrations of 0.01, 0.05, 0.10, 0.15 and 0.20 by volume. In the experiments performed at flow rates of 0.03–0.093 l/s and mixing ethylene glycol, they achieved a maximum increase of 27% in heat transfer at a concentration of 0.2 by volume. They reported the corresponding increase in pressure drop as 8%.

Çuhadaroğlu and Hacisalihoğlu [2] experimentally investigated CuO nanofluid in a plate heat exchanger used for heating at 0.27, 0.56, 0.81 and 1.1 volume fractions and three different flow rates. They calculated hydrodynamic and thermal performance values using the data they obtained. According to the results of the nanofluid used in the heating circuit, the highest efficiency value in the plate heat exchanger they tested was 96% at 0.81 volume fraction.

Sokhal et al. [3] tested a hybrid application of Al_2O_3 and CuO nanofluids in a plate heat exchanger. In the study where heat transfer and pressure drops were investigated, nanofluids with concentrations between 0.1% and 0.5% were experimentally investigated at temperatures between 60 °C and 80 °C. When they determined the highest heat transfer improvement relative to the base fluid, they achieved 21%.

Singh and Ghosh [4] investigated the performance of 30° and 60° strip plate geometries experimentally and numerically by using multi-walled carbon nanotubes (MWCNT) nanofluid in the heat exchanger. Heat transfer increased by 9.25% for 60° plates compared to 30° using distilled water. However, using 1% nanofluid by volume, maximum heat transfer of 13.64% and 17.27% was found for 30° and 60° plates, respectively.

Göltaş et al. [5] designed the plate surface of a plate heat exchanger as fish gill troughs. They also compared this heat exchanger they designed with the traditional Chevron type plate heat exchanger in terms of performance. The nanofluids they add to the working fluid, the water, are CuO and Al_2O_3 at 0.5% and 1% volume fractions. They reported that they achieved a 19.9% improvement in heat transfer and a 24.5% increase in efficiency when they used 0.5% CuO by volume in the heat exchanger where they used a gutter.

Jassim and Ahmed [6] used two types of metallic oxide nanoparticles to increase the heat transfer and efficiency of the plate heat exchanger. In the study where they compared the performance of TiO_2 and Al_2O_3, which they used at various volume concentrations, they reported that Aluminum Oxide behaved better than Titanium oxide in terms of performance at higher speeds. While they determined the efficiency of Titanium oxide they used in 3% volume fraction as 13%, they obtained this value as 23% for Aluminum oxide in the same fraction.

Zheng et al. [7] used four different nanofluids in a corrugated plate heat exchanger. The nanofluids used in the study where they examined the heat transfer and flow properties are Al_2O_3, SiC, CuO and Fe_3O_4, which are 0.05%, 0.1%, 0.5% and 1% by weight. As a result of their experimental study at flow rates of 3–9 L/min, they reported that 1.0% by weight Fe_3O_4 increased the heat transfer coefficient by 21.9% compared to the heat exchanger in which they used distilled water. They obtained the result that the pressure drop corresponding to the highest heat transfer increase they obtained was 10.1%.

In addition, Table 1 summarizes the studies of many other researchers on the use of nanofluids in plate heat exchangers.

In this study, it is aimed to increase the thermal performance of the heat exchanger with the designed new type plate type heat exchangers and the prepared nanofluids. When the studies in the literature are examined, it has been seen that generally classical type chevron type plate heat exchangers are used. In this study, springs at different angles were placed in the new type heat exchanger, which was designed differently from the literature, in order to improve the performance coefficient, that is, the increase in heat transfer in plate type heat exchangers is higher than the additional pressure loss. Springs were placed vertical and parallel to the plate to create turbulence in the flow and Al_2O_3 and CuO nanofluids were selected as working fluids in three different mass ratios. The effects of the design and nanofluids on heat transfer and pressure drop were examined at 6 different flow rates and compared with a plain channel heat exchanger. Optimum conditions were determined by calculating thermal performances.

2 Experimental investigation

The three-dimensional view of the experimental setup is shown in Fig. 1. In this study, a new type of plate heat exchanger was designed. There are 1 plate and 2 covers in the heat exchanger. The newly designed heat exchanger has dimensions of 120 × 500 mm. The channel gap is 7 mm, the gasket thickness is 2 mm and the port diameter is 15 mm. The plate thickness used in the heat exchanger is 2 mm (Fig. 2).

The plate material is St 37 structural steel and the plate is galvanized against corrosion. Hot nanofluid was used in one channel of the heat exchanger consisting of 2 channels and cold water was used in the other channel. The wire thickness of the springs placed between the plates is 1 mm, the spring diameter is 6 mm and the spring pitch is 5 mm. The springs are placed parallel and vertically to the plate. The 3D drawing of the plate is shown in Fig. 3, and the photograph of the manufactured plates is shown in Fig. 4.

Table 1 Studies using nanofluids in plate heat exchangers and their properties

Performer of the study	Plate heat exchanger features (dimensions, port diameter, plate thickness etc.)	Nano fluid Type/diameter/percentage/flow Water flows Nano fluid and water inlet temperatures	Notes
Elias et al. [8]	**Port to port** 126×394 mm **Port diameter** 50 mm **Sheet thickness** 0.5 mm	**Nano fluid type** Al_2O_3/water **Nano fluid percentage** 0.1–0.3–0.5% **Nano particle size** 30 nm **Re Number for nanofluid** between 200–350 **Hot water flow** 3lt/min	For 60 degree chevron angle at 0.5% concentration ratio, 15.14% increase in maximum heat transfer coefficient, 7.8% increase in total heat transfer coefficient and 15.4% increase in heat transfer were observed.
Bhattad et al. [9]	**Port to port** 60×355 mm **Outside width** 100 mm **Port diameter** 30 mm **Sheet thickness** 0.5 mm **Sheet spacing** 2.4 mm **One sheet heat transfer area** 0.3m^2	**Nano fluid type** Al_2O_3+MWCNT/ water **Nanofluid flow rate** 2, 2.5, 3, 3.5, 4 lt/min **Nanofluid inlet temperatures** 15,20,25,30 °C	The heat transfer coefficient increased by 39.16% and the pumping power by 1.23%.
Sarafraz et al. [10]	**Port to port** 75×400 mm **Outside width** 125×450 mm **Port diameter** 12.5 mm **One sheet heat transfer area** 0.095 m^2 **Total heat transfer area** 3.23 m^2 **Sheet thickness** 4 mm	**Nano fluid type** CuO/ water nanofluid %0.1/0.2/0.3/0.4 **Nano particle size** 50 nm **Nanofluid inlet temperatures** 50,70 °C	An optimum point was found for 0.3%, when the amplitude of the vibration given at this point increased to 5 mm, the thermal performance increased to 1.5.
Ünverdi et al. [11]	**Port to port** 50×298 mm **Outside width** 102×350 mm **Port diameter** 20 mm **Sheet thickness** 0.5 mm **Sheet spacing** 2.5 mm **Chevron angle** 30 **Number of sheets** 3	**Nano fluid type** Al_2O_3/ water **Nanofluid flow rate** 1.5–5 lt/min **Water flow** 1.5 lt/min **Nano particle size and percentage** 40 nm %0.25%0.50%0.75%1 **Nanofluid inlet temperatures** 40 oC **Water inlet temperature** 17.5 oC	The researchers observed an average of 22% improvement in the heat transfer coefficient with nanofluids compared to distilled water, while an increase of 20% in pressure drop at the maximum concentration ratio and the maximum Reynolds number.
Sun et al. [12]	**Sheet thickness** 0.5 mm **Sheet spacing** 2 mm **Number of sheets and material** Stainless steel AISI304 **Heat transfer area** 0.7 m^2	**Nanofluid type, percentage and size** Cu, Fe_2O_3 ve $A1_2O_3$/ water % 0.1, % 0.3 ve % 0.5 50 nm **Nanofluid Reynolds Number** 1000,1200,1400,…2800	The highest increase in convective heat transfer occurred with 0.5% volumetric Cu/water nanofluid. The rate of increase was found to be 34.55% compared to water.
Kumar et al. [13]	**Plate width between gaskets** 180 mm **Port to port** 60×357 mm **Port diameter** 35 mm **Chevron angle** 30°/30° ¯30°/60° ¯60°/60° **Sheet thickness** 0.5 mm **Sheet spacing** 2.4 mm	**Nano fluid type** ZnO / water nanofluid **Volume concentration ratio** % 0.5–2.0 **Nano fluid flow** 3lpm **Water flow** 3 lpm **Nanofluid inlet temperatures** 20 °C **Water inlet temperature** 50 °C	Experimental observations have shown that there is an optimum increase in heat transfer coefficient and an optimum decrease in exergy loss at 1% particle volume ratio with 60°/60° chevron angle.
Ahmad et al. [14]	**Outside width** 457×127 mm **Number of sheets** 25 **Total heat transfer area** 0.3m^2 **Sheet thickness** 0.5 mm	**Nano fluid type, percentage and flow rate** CuO/ water 50 nm %0.1, 0.3, 0.5 in volumetric ratio 8, 9, 10, 11 lt/min	The researchers observed a 52% improvement in the heat transfer capacity of the copper oxide/water nanofluid at a concentration ratio of 0.3% compared to distilled water, when compared to distilled water.

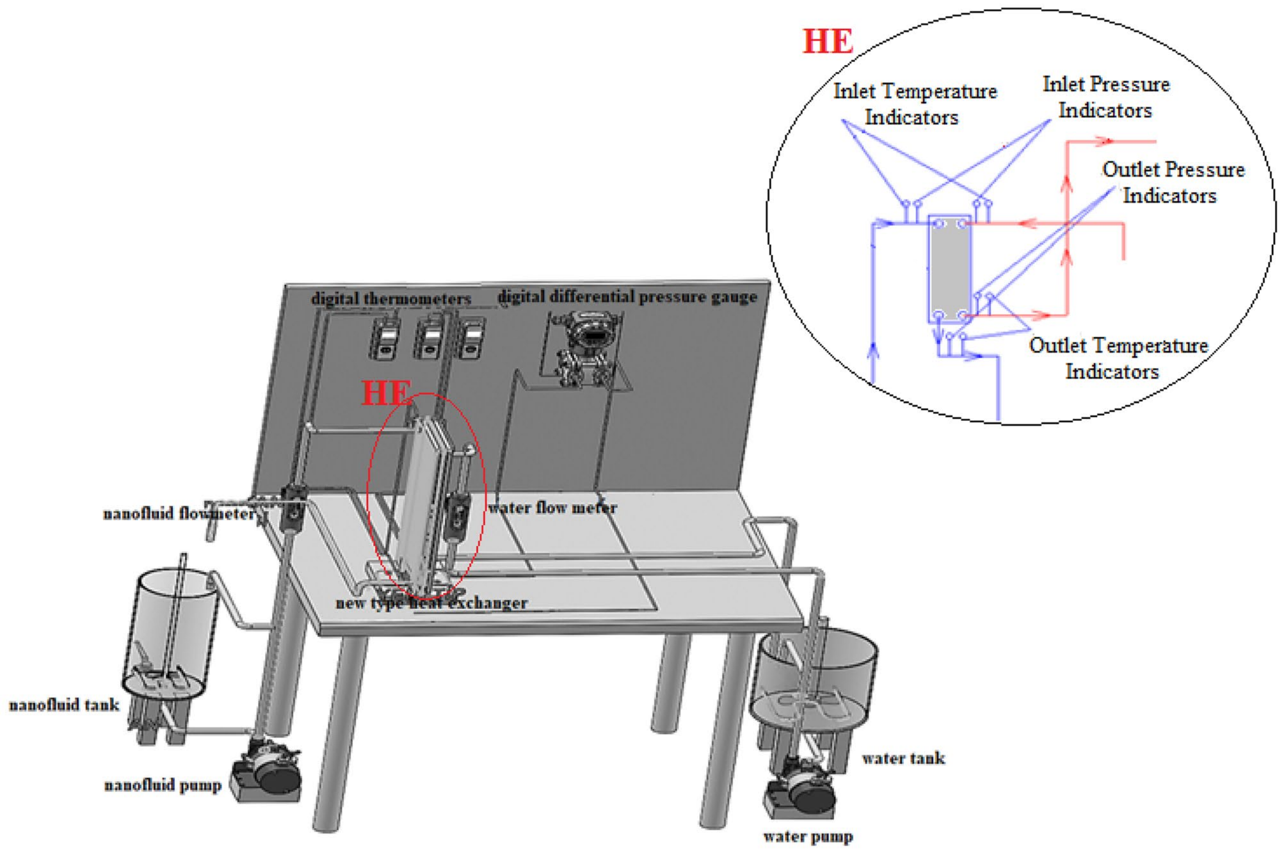


Fig. 1 Three-dimensional view of the experimental set and measuring points

As seen in Fig. 3, springs were placed between the plates in order to create a turbulent effect in the fluid in the heat exchanger and 6 flow rates were tested in each spring arrangement [15].

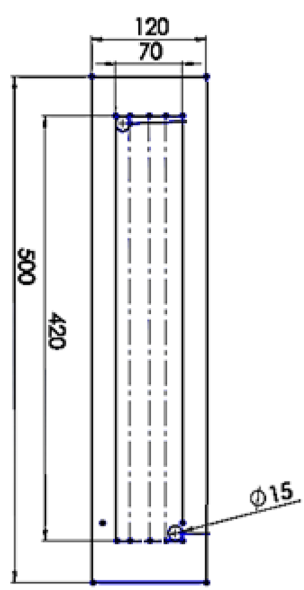


Fig. 2 Dimensions of the plate heat exchanger

In the experimental setup, distilled water and nanofluids were used as the hot fluid with an inlet temperature of 60 °C, and tap water as a cold fluid with an inlet temperature of 25 °C. During the experiments, the temperatures were kept constant and the measured temperature, flow and differential pressure values were recorded. Temperature data taken with K type thermocouples with an error of ± 0.15% were

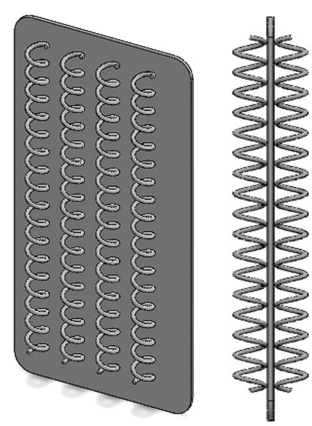


Fig. 3 Arrangement of springs in the designed new type plate heat exchanger

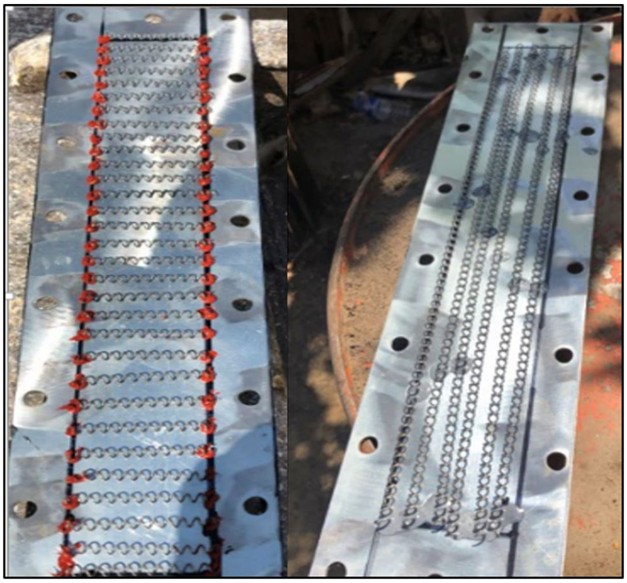


Fig. 4 Production photos of the designed new plate heat exchanger (vertical springs- parallel springs)

recorded with a 4-channel CEM brand digital recorder thermometer. The water flow was measured with a TEKSENS brand rotameter type flowmeter with an accuracy of 3%. The nanofluid flow rate was measured with TEKSENS brand electromagnetic flowmeter with an accuracy of ± 0.5%. LEEG brand differential pressure gauge with 0.075% sensitivity was used to measure the pressure drop between the inlet and outlet in the heat exchanger.

After the distilled water and nanofluids are heated in the hot water tank using a 1 kW resistance, and the cold mains water is heated to the appropriate temperature in the cold water tank using a 6 kW resistance, they are pumped to the heat exchanger. GRP 15–60/130 (U35/15–130) three-speed gear circulation pump is used as nano fluid and water pump. System pipelines are PVC selected and PVC pipes in the hot line are insulated to prevent heat loss. As seen in Fig. 1, K type thermocouples are placed on the inlet and outlet of the hot fluid and cold fluid and on the inner surface of the heat exchanger for temperature measurements. In order to determine the pressure drops, pressure sockets were placed at the hot fluid inlet and outlet points and cold fluid inlet and outlet points of the heat exchanger.

In order to increase the turbulence intensity of the fluid in the heat exchanger, it was tried to increase the heat transfer by placing springs between the plates. For this purpose, the springs are mounted on the surface with $\alpha = 0°$ and 90° angles.

In this study, Al_2O_3 and CuO nanoparticles smaller than 50 nm were purchased from Sigma Aldrich. For each nanoparticle, 0.1%, 0.5% and 1% concentration ratios by mass of nanofluid and 10 L of solution were prepared. Laboratory type Weightlab brand precision balance with 1 mg sensitivity was used for weight measurements. The mixture was stabilized by passing it through a Bandelin Sonopuls brand ultrasonic mixer and keeping it in an Alex brand ultrasonic bath of 8 L.

The "two-step" method was used in the preparation of the solutions. The nanoparticles obtained from the market are stabilized by passing them through an ultrasonic homogenizer mixed with pure water, ethanol and glycerin in desired proportions and kept in an ultrasonic bath.

Nanofluids prepared and stabilized with different particles at concentrations of 0.1%, 0.5% and 1% by mass were tested in heat exchangers whose tests were completed with water.

After the experimental system was set up, water and nanofluid in different volumetric ratios were used as the working fluid in the newly designed plate type heat exchanger, and experiments were carried out to examine their effects on heat transfer and pressure drop. Different geometries, flow rates, concentration ratios, different nanofluids are the parameters studied.

In order to control the stable working condition of the experimental setup, the test of the plain plate heat exchanger, on which no changes were made, was carried out. The data obtained at this stage were used as a reference value to determine the effect of the parameters to be modified on the heat transfer. Then, the base fluid tests of the other 3-plate heat exchanger were carried out under the same conditions. All data were recorded and used as reference values for working with nanofluids.

2.1 Nanofluid properties

The technical specifications of the purchased CuO and Al_2O_3 nanoparticles are shown in Table 2. And SEM images of Al_2O_3 and CuO particles are shown in Figs. 5 and 6, respectively.

2.2 Data reduction and error analysis

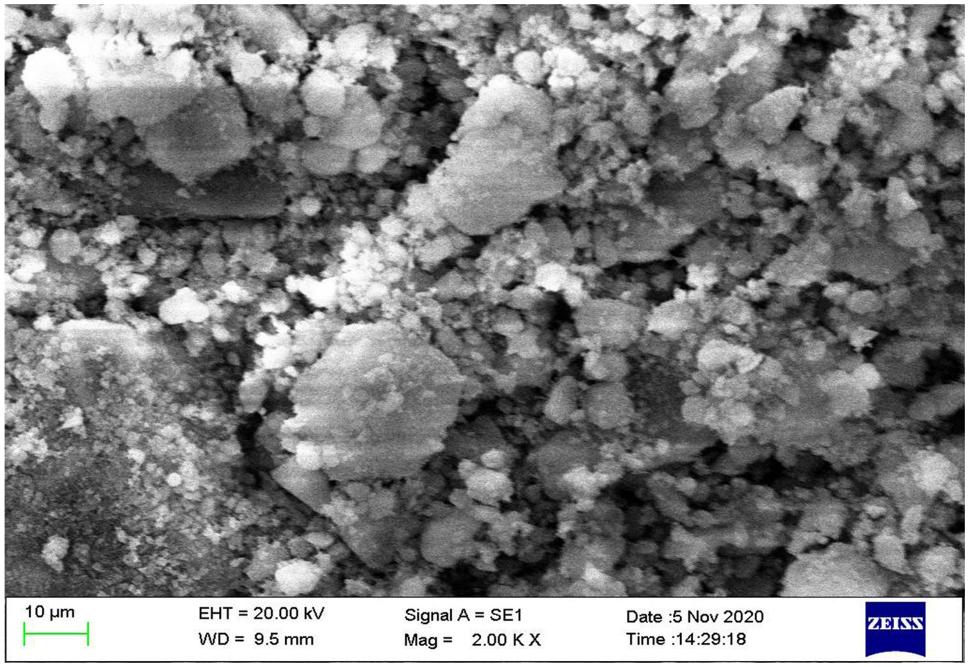
The equations used for thermal analysis are given below, respectively [16–18].

The heat given by the nanofluid to the water,

Table 2 Technical properties of CuO and Al_2O_3 nanoparticles

CuO Nanoparticles	Al_2O_3 Nanoparticles
Particle Size < 50 nm	Particle Size < 50 nm
Surface Area: 29m^2/g	Surface Area > 40m^2/g
Density: 6.4 g/cm^3	Density: 2.7 g/cm^3
Color: Close to dark brown	Color: Black
Format: Near spherical	Format: Near spherical

Fig. 5 Scanning Electron Microscope images of Al_2O_3 (2.0 KX)



$$\dot{Q}_n = \dot{m}_n C_n (T_{n,i} - T_{n,o}) \quad (1)$$

Here, m_n(kg/s) is the mass flow rate of the nanofluid, C_n (j/kgK) is the specific heat of the nanofluid, and $T_{n,i}$ and $T_{n,o}$ (K) are the inlet and outlet temperatures of the nanofluid, respectively.

The heat of the water,

$$\dot{Q}_w = \dot{m}_w C_w (T_{w,o} - T_{w,i}) \quad (2)$$

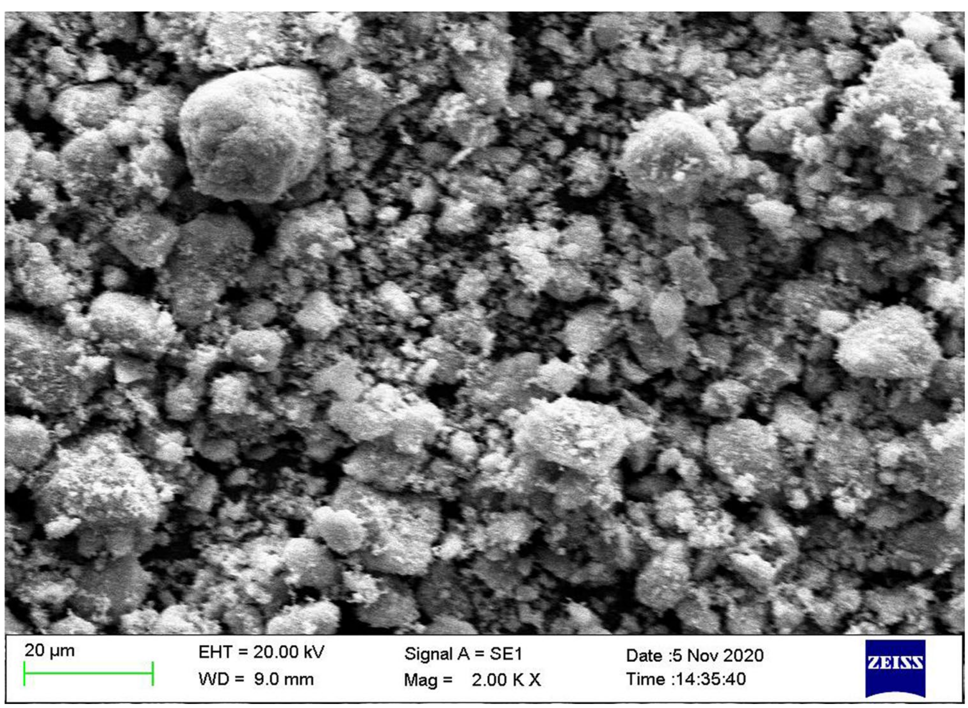
Here, m_w is the mass flow rate of water, C_w is the specific heat of water, and $T_{w,i}$ and $T_{w,o}$ are the inlet and outlet temperatures of the water, respectively.

Average heat transfer,

$$\dot{Q}_a = \frac{\dot{Q}_n + \dot{Q}_w}{2} \quad (3)$$

Reynolds number,

Fig. 6 Scanning Electron Microscope images of CuO particles (2.0 KX)



$$Re_n = \frac{G_n D_h}{\mu_n} \quad (4)$$

$$Re_w = \frac{G_w D_h}{\mu_w} \quad (5)$$

G_n and G_w (kg/sm^2)in the equations are the mass velocity of the nanofluid and water, Dh(m) is the channel hydraulic diameter, μ_n and μ_w (m Pa s)are the viscosity of the nanofluid and water.

Mass flow rates,

$$G_n = \frac{\dot{m}_n}{N_{nc} * b * L_{en}} \quad (6)$$

$$G_c = \frac{\dot{m}_c}{N_{cc} * b * L_{en}} \quad (7)$$

calculated with formulas. Here N is the number of channels, b is the channel height, L_{en}(m) is the channel width.

The logarithmic temperature difference(LMTD) method was used to find the total heat transfer coefficient in the heat exchanger.

$$U = \frac{Q_a}{A * LMTD} \quad (8)$$

$$LMTD = \frac{(T_{n,i} - T_{c,o}) - (T_{n,o} - T_{c,i})}{\ln(\frac{(T_{n,i} - T_{c,o})}{(T_{n,o} - T_{c,i})})} \quad (9)$$

The friction factor in the heat exchanger channels is calculated as follows.

$$f = \frac{\Delta P}{\left(\frac{L_{eff}}{D_h}\right)\left(\frac{2G^2}{\rho}\right)} \quad (10)$$

Here, L_{eff} is the effective channel length, D_h is the hydraulic diameter, and G is the mass flow.

The thermal–hydraulic performance (jF_i) is calculated with the following equation. where J is the Coulbourn (thermal performance) factor and plain indicates the flat plate heat exchanger, on which no changes[16].

$$jF_i = \frac{J_i / J_{plain}}{(\frac{f_i}{f_{plain}})^{1/3}} \quad (11)$$

In the experiments, temperatures, flow rates and pressure drops were measured with precision measuring instruments. The independent variable error rates of the measurements are shown as x_n and the total error rate of the dependent variables is calculated with the following formula.

Table 3 Uncertainties during the measurement of independent variables

Independent variable	Uncertainty value (%)
Nanofluid inlet temperature, T_{ni}	±0.15
Nanofluid outlet temperature, T_{no}	±0.15
Water inlet temperature, T_{wi}	±0.15
Water outlet temperature, T_{wo}	±0.15
Ambient temperature, T_a	±0.15
Nano fluid flow m_n	±2
Water flow m_w	±2.8
Hydraulic diameter, D_h	±2.0
Nanofluid differential pressure difference, Δp_n	±2.5
Water differential pressure difference, Δp_w	±2.5
Nanofluid thermal conductivity measurement, k_n	±5
Nanofluid viscosity measurement, μ_n	±1
Nanofluid density measurement, ρ_n	±5

$$W = \left[{x_1}^2 + {x_2}^2 + {x_3}^2 + \cdots + {x_n}^2\right]^{1/2} \quad (12)$$

The error rates of measuring the independent variables are given in Table 3, and the total error rates of the dependent variables are given in Table 4.

3 Experimental results and discussion

In the study, first of all, the heat transfers in the plate heat exchangers were found with the measured temperature and flow values, and the total heat transfer coefficients were calculated with these values. Then, the friction factors were calculated with the measured pressure drops, and the heat exchanger with the highest performance factor was determined.

3.1 Heat transfer coefficient results

Figure 7 shows a comparison between plate heat exchanger with parallel springs and plain for Al_2O_3-water. The highest total heat transfer coefficient was obtained for the 1% Al_2O_3-water nanofluid by mass. At the highest flow rate, this increase was observed as 76.1%. For 1% Al_2O_3-water nanofluid by mass, there was a 10% increase in the heat

Table 4 Total uncertainty results

Independent variable	Uncertainty value (%)
Reynolds Number, Re	±5.6
Heat transfer rate, Q	±5.2
Total heat transfer coefficient, U	±5.7
Friction Factor, f	±5.9

transfer coefficient compared to base fluid for a flow rate of 6.3 lt/min in the parallel spring plate heat exchanger. As the flow rate increased, the spring turbulators created more turbulence, increasing the heat transfer and the overall heat transfer coefficient.

A study with the same heat exchanger and the same dependent and independent variables has not been found in the literature. Similar to the working conditions, Zheng et al. [7] tested Al_2O_3, SiC-40, CuO and Fe_3O_4 at 0.05 wt.%, 0.1 wt.%, 0.5 wt.% and 1.0 wt.% by weight in a corrugated plate heat exchanger. In their experiments with flow rates of 3 lt/min, 6 lt/min and 9 lt/min, they found an increase in heat transfer coefficient as 5.1% for 6lt/min flow rate and 1% concentration Al_2O_3 and 9.4% for 3 lt/min flow rate. These increase rates were obtained as 10% and 12%, respectively, for our study. The difference between this reference study and our study was determined as 15% for the flat heat exchanger using only basic fluid. This difference is due to the different boundary conditions in the experimental study.

Figure 8 shows a comparison between plate heat exchanger with parallel springs and plain for CuO-water. The increase in the total heat transfer coefficient for the highest flow rate was determined as 69.9%. For 1% CuO -water nanofluid by mass, there was a 6.1% increase in the heat transfer coefficient compared to base fluid for a flow rate of 6.3 lt/min in the parallel spring plate heat exchanger.

In the (1%) nanofluid flowing plate heat exchanger, the difference between the heat transfer coefficients is more pronounced than in other mass ratio nanofluids. With the placement of the springs and the use of nanofluids, the boundary layer was fragmented during the flow, and the heat transfer coefficient increased with the continuous change in the direction of movement of the particles and the decrease in viscosity on the plate surface. While the total heat transfer coefficient curves of CuO-water nanofluid and base fluid were almost coincident, the total heat transfer coefficient curve for Al_2O_3-water nanofluid went above them. The viscosity of CuO-water nanofluid was higher than Al_2O_3-water nanofluid, which slowed down the CuO-water nanofluid. Although the heat transfer coefficient of CuO-water nanofluid increased as much as that of Al_2O_3-water nanofluid, CuO-water nanofluid could not provide as good heat transfer as Al_2O_3-water nanofluid.

Figure 9 shows a comparison between plate heat exchanger with vertical springs and plain for Al_2O_3-water The highest total heat transfer coefficient was obtained for the 1% Al_2O_3-water nanofluid by mass. At the highest flow rate, this increase was observed as 40.3%. When the obtained data were examined, it was seen that higher heat transfer coefficients were achieved in the springs placed in parallel. This increase rate was determined as 20.34% for the highest flow rate and Al_2O_3-water nanofluid density used.

Figure 10 shows a comparison between plate heat exchanger with vertical springs and plain for CuO-water. There was a 7% increase in the total heat transfer coefficient compared to base fluid in the plate heat exchanger, whose springs were placed vertically, for CuO-water nanofluid with highest flow rate and highest density. With the increase of the flow rate, the nanofluid particles dispersed all over the plate, resulting in an increase in heat transfer compared to pure water. Turbulence increased even more than pure water with the better distribution of nanoparticles and the increase in their chaotic movements.

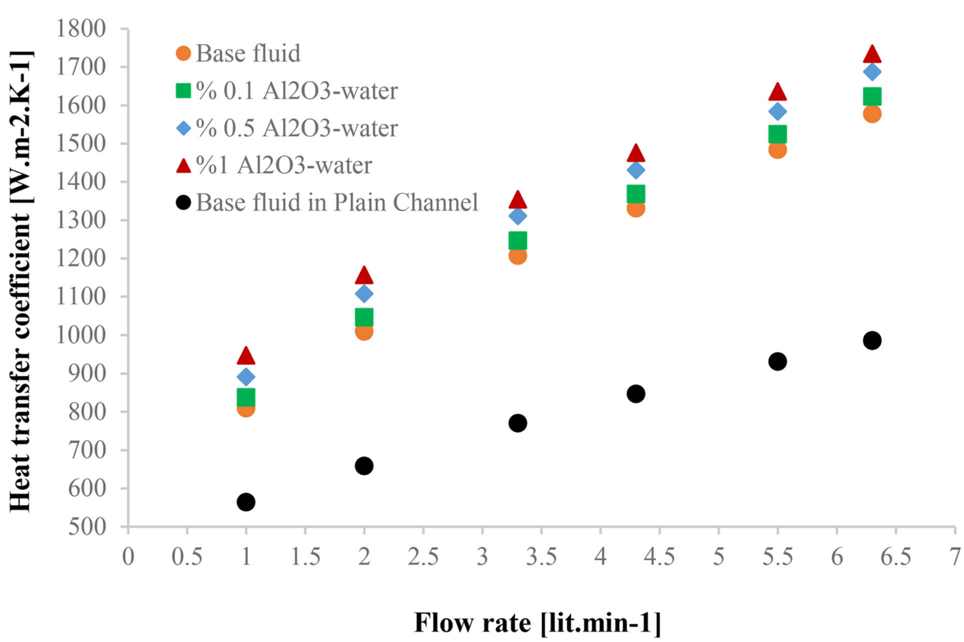


Fig. 7 Comparison between plate heat exchanger with parallel springs and plain for Al_2O_3-water

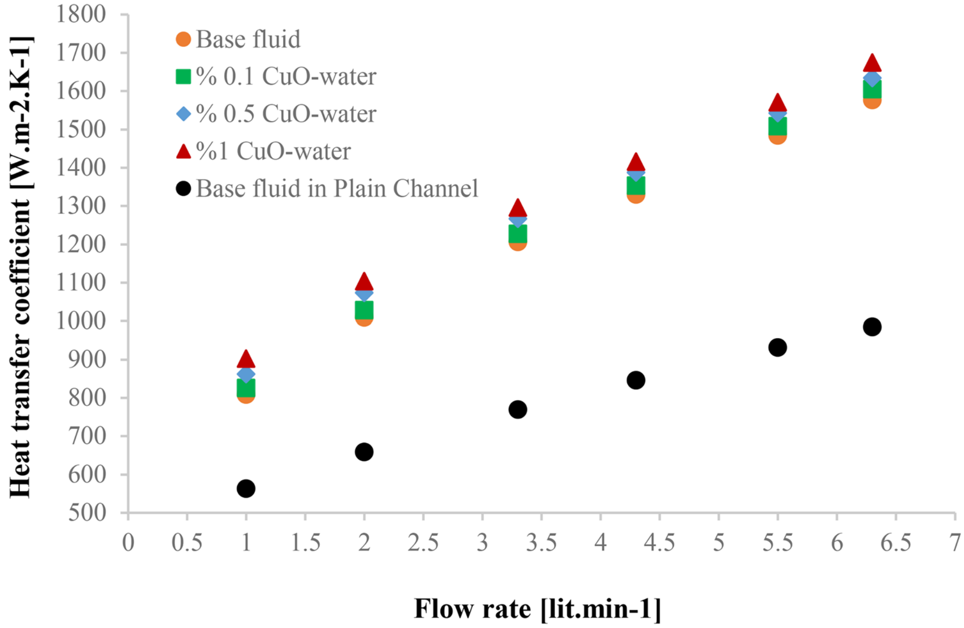


Fig. 8 Comparison between plate heat exchanger with parallel springs and plain for CuO-water

When the data for 1% density by mass are examined, there is a difference between Al_2O_3-water nanofluid and CuO-Water nanofluid in the total heat transfer coefficient curves. When Al_2O_3-water nanofluid is used at the highest flow rate, the total heat transfer coefficient obtained is 3% higher than the CuO-water nanofluid. These curves are quite high compared to base fluid.

Eddy currents were formed when pure water hit the springs, thus the turbulence intensity increased and the heat transfer coefficient increased compared to the empty plate heat exchanger. When nanofluids are used, the collision of particles increased with the use of springs, which reduced the viscosity on the plate walls and increased heat transfer.

The heat transfer provided by the nanofluids in the vertical spring plate heat exchanger is decreased because the nanofluids cannot produce as much rotational and chaotic current as in the parallel spring plate heat exchangers. This situation caused the total heat transfer coefficient to be lower in the vertical spring plate heat exchanger.

Since the surface area of the nanoparticles is larger than the other millimetric parts, their interaction with the base fluid is more and this interaction increased the heat transfer

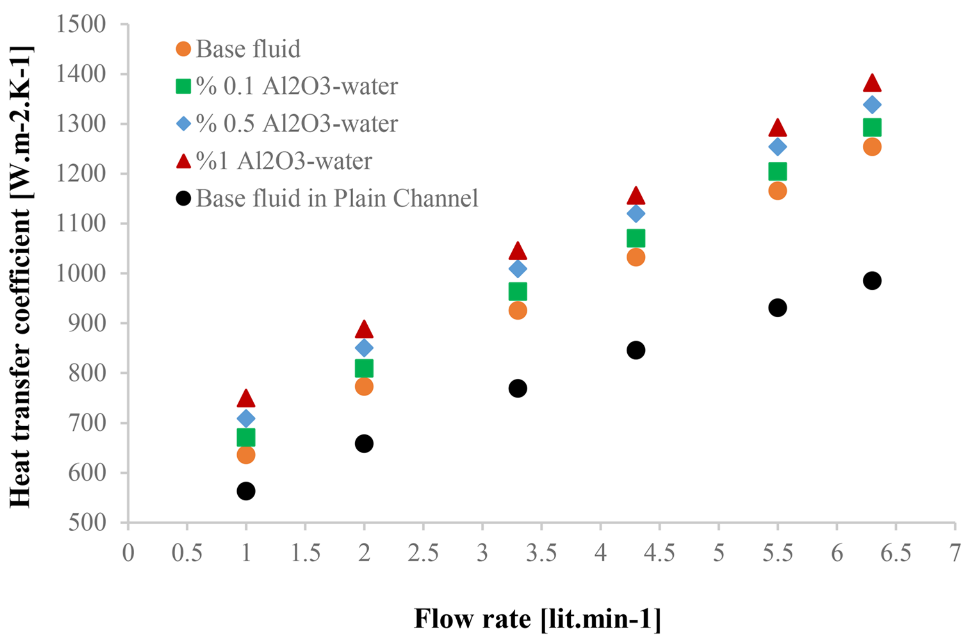


Fig. 9 Comparison between plate heat exchanger with vertical springs and plain for Al_2O_3-water

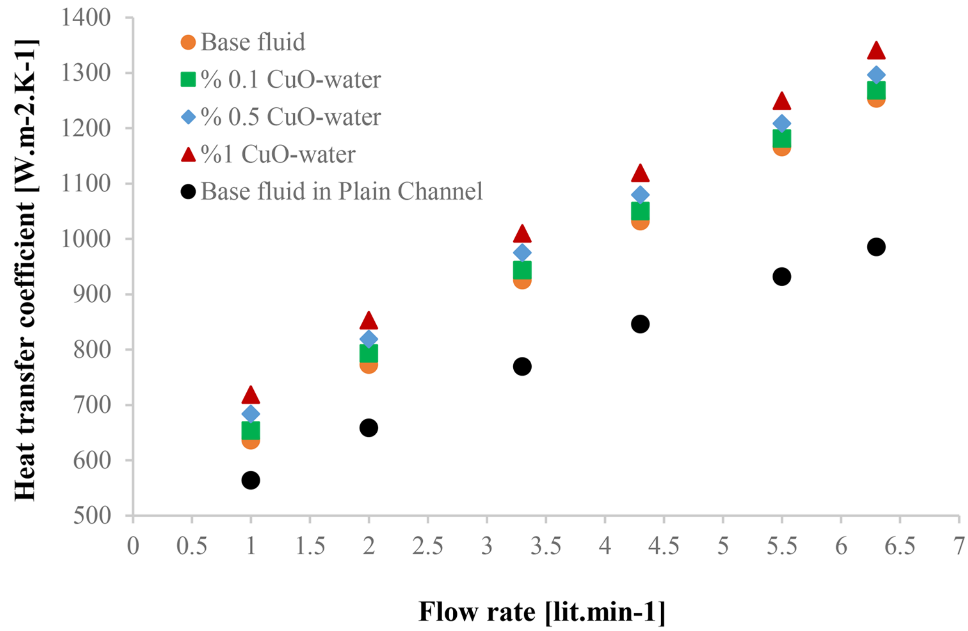


Fig. 10 Comparison between plate heat exchanger with vertical springs and plain for CuO-water

coefficient of the nanofluid. For this reason, the heat transfer coefficient in nanofluids increased compared to pure water and increased heat transfer had a significant effect. Accordingly, the changing thermophysical properties of the nanofluid doped main fluid cause it to act like a new fluid and behave accordingly.

3.2 Pressure drops results

Pressure drops are used to calculate friction coefficients and thermal performances of plate heat exchangers. Comparison of pressure drop data between plate heat exchanger with parallel springs and plain for Al_2O_3-water is presented in Fig. 11. The highest pressure drop occurred in nanofluids with the highest density used by mass, and this drop amount increased by 14% for the highest flow rate compared to the base fluid.

Comparison of pressure drop data between plate heat exchanger with parallel springs and plain for CuO-water is presented in Fig. 12. When these data are examined, it is seen that the pressure drops are higher than the pressure drops of Al_2O_3-water nanofluids. The difference between the CuO-water nanofluid percentages and the pressure drop curves for base fluid became more pronounced than for Al_2O_3-water nanofluids.

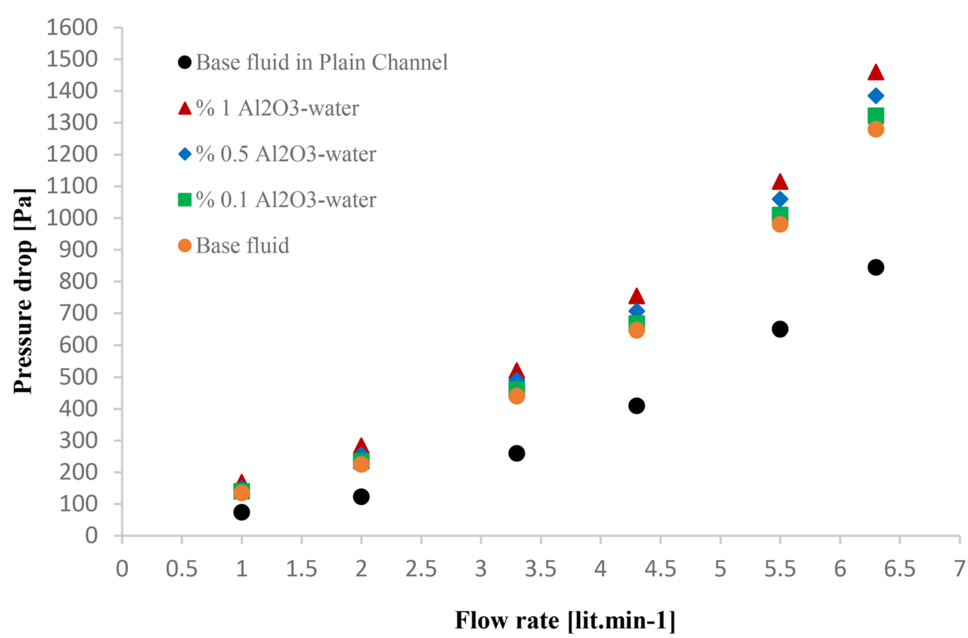


Fig. 11 Comparison between plate heat exchanger with parallel springs and plain for Al_2O_3-water

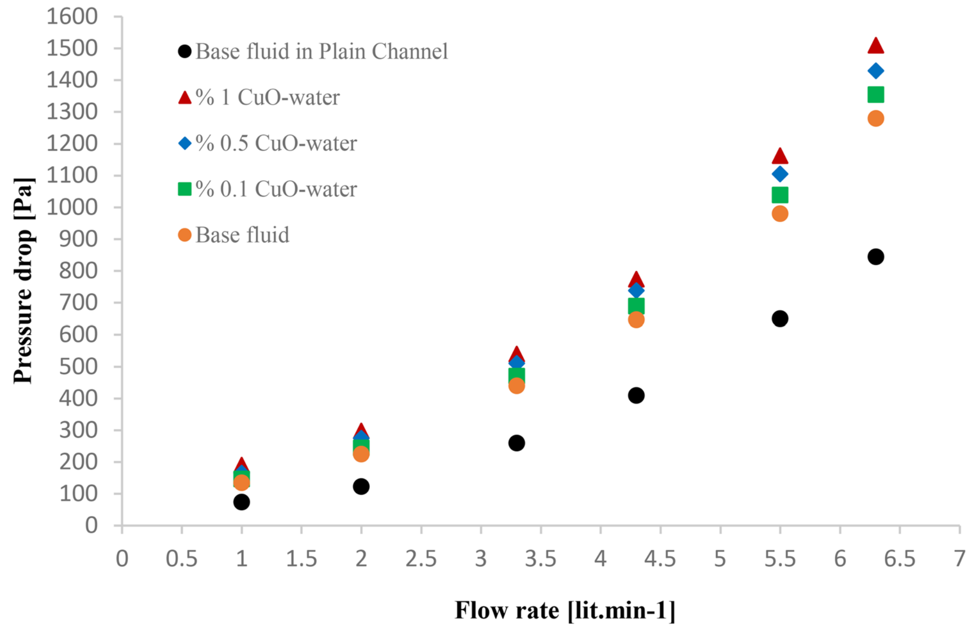


Fig. 12 Comparison between plate heat exchanger with parallel springs and plain for CuO-water

The highest pressure drop occurred in the heat exchanger whose springs were placed vertically, and this caused the performance of the heat exchanger to be lower than other types of heat exchangers.

In Figs. 13 and 14, pressure drops were investigated in plate heat exchangers with vertically placed springs in which Al_2O_3-water and CuO-water nanofluids flowed. The heat exchanger with the highest pressure drop occurred in the heat exchanger where the most dense CuO-water nanofluids were used and the springs were placed vertically, and this caused the performance of the heat exchanger to be lower than other types of heat exchangers. Since there is no obstacle that creates the turbulence effect in the plain plate heat exchanger, the increase in pressure drop is the least compared to the others. Because the viscosity of the CuO-water nanofluid was higher, the pressure drop curves were above the pressure drop curves of the Al_2O_3-water nanofluid.

With the addition of springs as a turbulator, heat transfer increased while pressure drops increased. The highest pressure drops were found as the flow rate increased and the springs were placed vertically. At a flow rate of 6.3 lt/min,

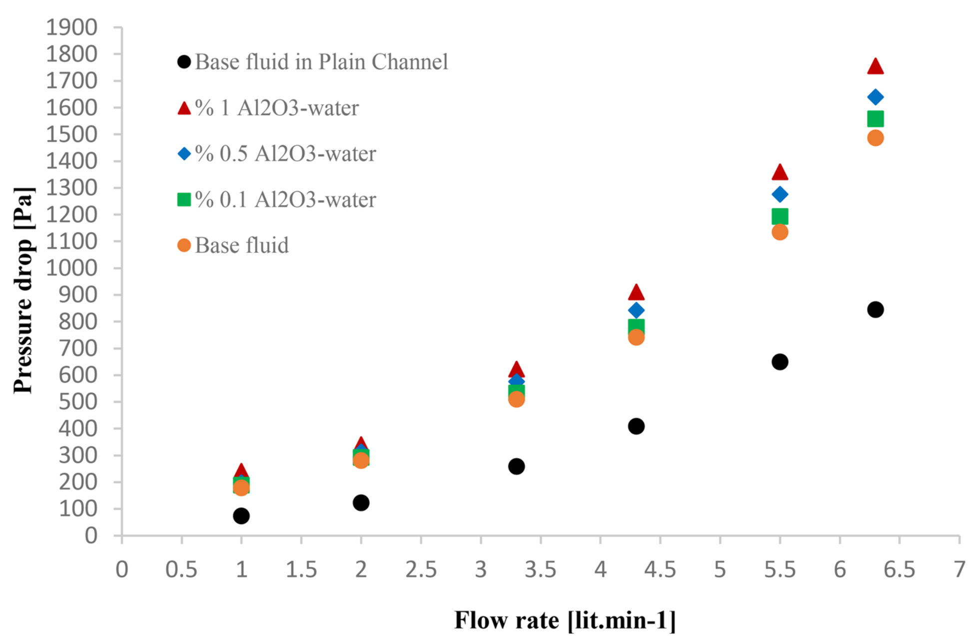


Fig. 13 Comparison between plate heat exchanger with vertical springs and plain for Al_2O_3-water

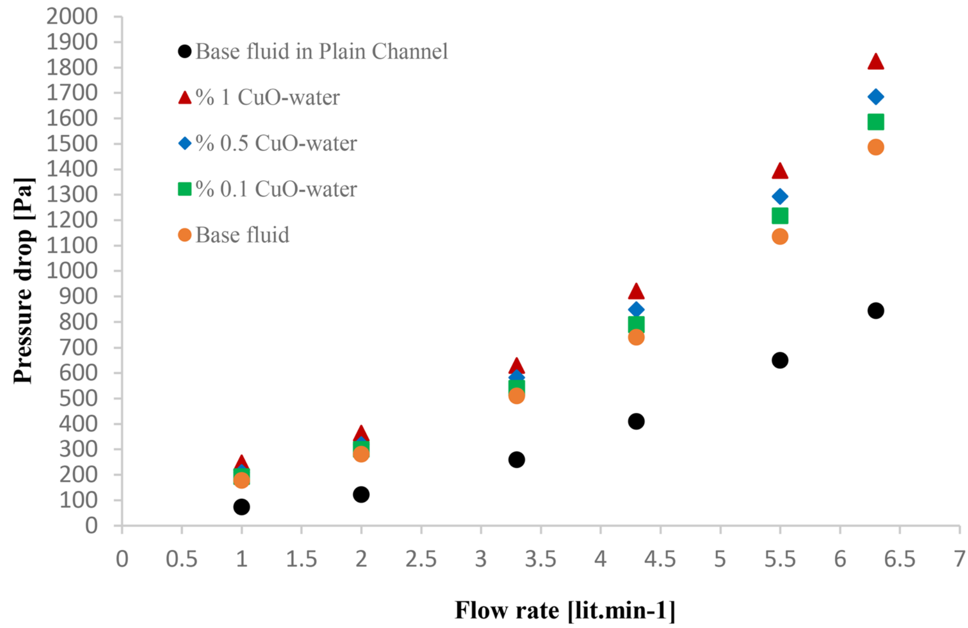


Fig. 14 Comparison between plate heat exchanger with vertical springs and plain for CuO-water

the pressure drop in the plate heat exchanger with vertically placed springs increased by 76% compared to the plain plate heat exchanger, while this rate was 51% for the plate heat exchanger with the springs placed in parallel.

The pressure drops increased with the increase in viscosity. Pressure drop in vertical spring plate heat exchanger flowing with 1% Al_2O_3-water by mass increased by 18% for 6.3 l/min flow rate, compared to operating with base liquid. This increase was determined as 14% in the parallel spring heat exchanger. Due to the increased viscosity in the CuO-water nanofluid, the pressure drop in the vertical spring heat exchanger for the highest flow rate and density increased by 3% compared to the Al_2O_3-water nanofluid.

While improving heat transfer in heat exchangers, the significant pressure drops that come with it are one of the most important factors to be examined. As a result of the pressure drop examinations, it is seen that the pressure drops increase with increasing viscosity and flow rate. At this point, while calculating the net pressure drops, losses in the pipes and local losses are subtracted from the values read in the experiments. Pressure drops are used to calculate the friction coefficients and thermal/hydraulic performances of plate heat exchangers, as will be seen in the following sections.

3.3 Friction factors results

Friction factors vary according to pressure, flow, density, plate length and hydraulic diameter. Graphs were created according to the factors calculated according to Eq. 10.

Figure 15 shows the variation of the friction factor in plate heat exchangers with distilled water flowing. Friction factors were higher in plate heat exchangers with high pressure drop. Friction factors were higher in plate heat exchangers with vertically placed springs. As can be seen in Figs. 16 and 17, the friction factors increased with the use of 1% mass nanofluids, and friction factors in CuO-water flowing plate heat exchangers were higher than in plate heat exchangers flowing with Al_2O_3-water nanofluids.

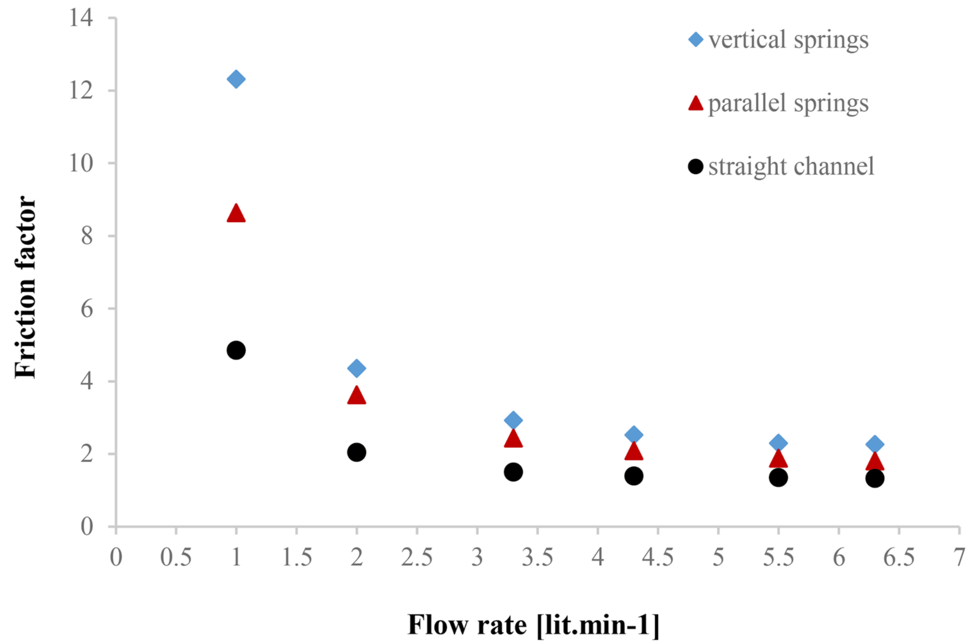
3.4 Performance factors results

In Fig. 18, the values of the performance factors calculated in parallel spring heat exchanger to which Al_2O_3-water nanofluids are flowing is seen. For the heat exchanger using Al_2O_3-water nanofluid, the maximum performance factors were obtained as 1.42, 1.46 and 1.51 for three different mass ratios, respectively. Pressure drops increased with increasing flow rates. After 5.5 lt/min, the pressure drop increased more compared to heat transfer, and the 5.5 lt/min value was the maximum performance factor.

In Fig. 19, the values of the performance factors calculated in parallel spring heat exchanger to which CuO-water nanofluids flow is seen. For the heat exchanger using CuO -water nanofluid, the maximum performance factors were obtained as 1.39, 1.40 and 1.43 for three different mass ratios, respectively. It was observed that the performance curves of CuO-water nanofluids were lower than those of Al_2O_3-water nanofluids.

In Fig. 20 and Fig. 21, the values of the performance factors calculated in vertical spring heat exchanger, flowing Al_2O_3-water nanofluids and CuO-water nanofluids can be seen. The performance factors of this type of plate heat exchanger could not exceed 1.12 due to both the increase in

Fig. 15 Variation of friction factors for base fluid flow



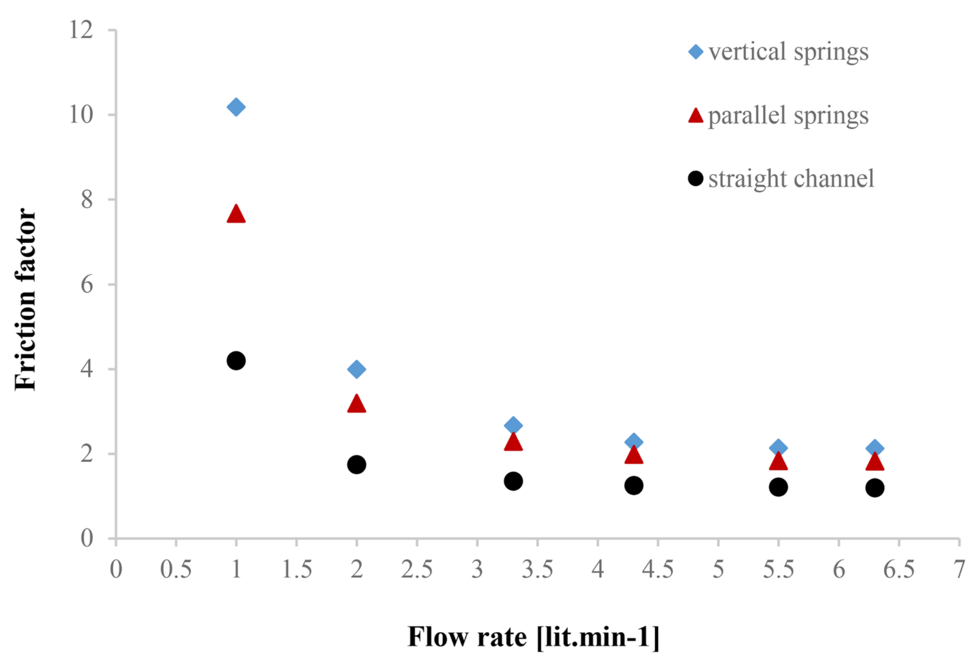
pressure drops and the insufficient heat transfer. This type of plate heat exchanger is not suitable for use in other studies.

Aliabadi [19] investigated the thermal–hydraulic properties of the wavy channel with variable wave lengths using Al_2O_3-water nanofluid. In his study, the highest performance factor obtained at 0–9% volumetric ratio of Al_2O_3-water nanofluid was found to be 1.2. The volumetric ratios calculated in our study are 0.26% and 0.15% for Al_2O_3-water and CuO-water nanofluids, respectively.

4 Practical importance / usefulness

The performance of the heat exchanger is directly proportional to their design. Various designs have been tried to improve the heat transfer between the fluids. Production of new designs has been limited, as these designs are often difficult and costly to manufacture. In the plate heat exchanger used in this study, the channel spacing is 7 mm, the wire thickness of the springs used is 1 mm and the spring diameter is 6 mm. This presented design approach

Fig. 16 Variation of friction factors for Al_2O_3-water nanofluid (1%)



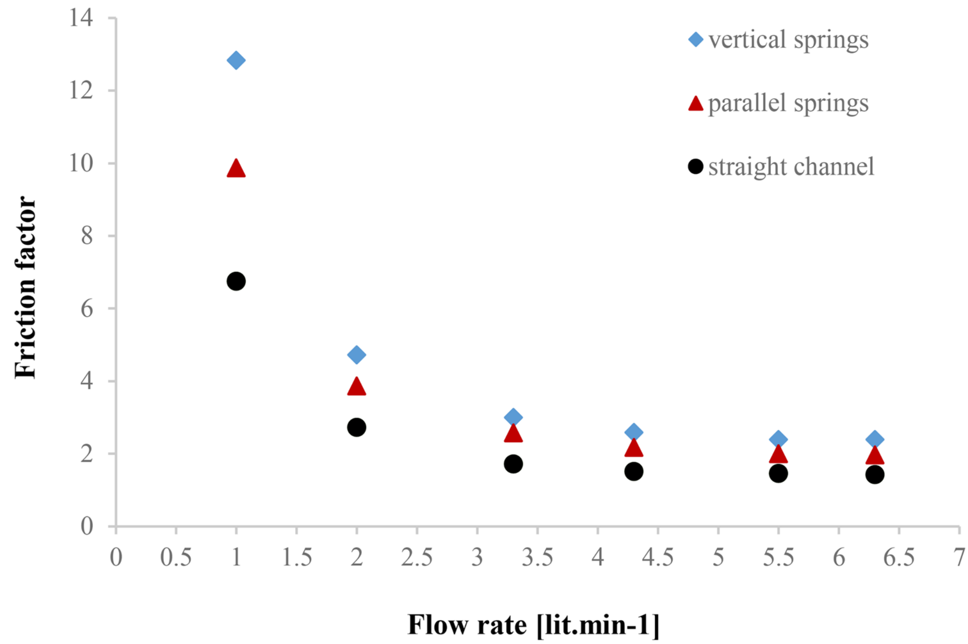


Fig. 17 Variation of friction factors for CuO-water nanofluid (1%)

can be used to design heat exchangers for a wide variety of operating conditions. For low flow rate, low pressure drop, high efficiency applications, this heat exchanger configuration provides a very flexible design.

It has been seen that the thermal performance values of the plate type heat exchanger developed in line with the results obtained are higher than the existing ones, and it has been shown that this type of heat exchanger can be used more efficiently in practical applications. From the present results, it has been seen that the use of springs in the plate type heat exchanger increases the heat transfer and the pressure loss is lower than the gain in the heat transfer. Therefore, it has been shown to contribute to the design of smaller sized heat exchangers and is an important design for better design of efficient heat exchangers for use in heat transfer applications, especially in vehicle and spacecraft applications, due to the reduction in size and weight.

In the plate heat exchanger, different spring fin arrangements had a more significant effect on the turbulence than the flow rate and pressure, and this will help to provide significant gains in terms of energy and system economy in heat exchanger applications.

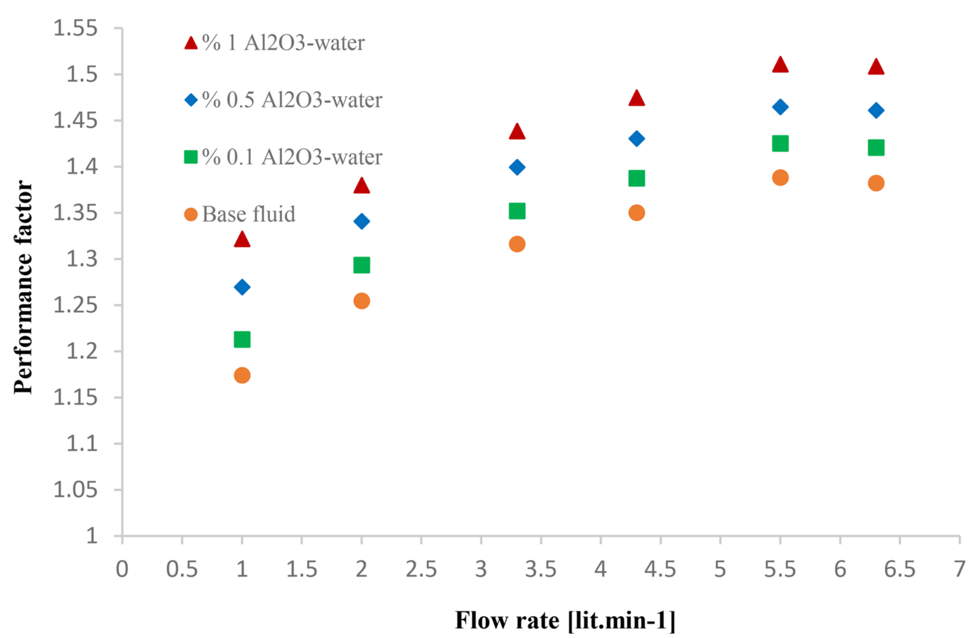


Fig. 18 Calculated performance factors for Al_2O_3-water nanofluid (parallel springs)

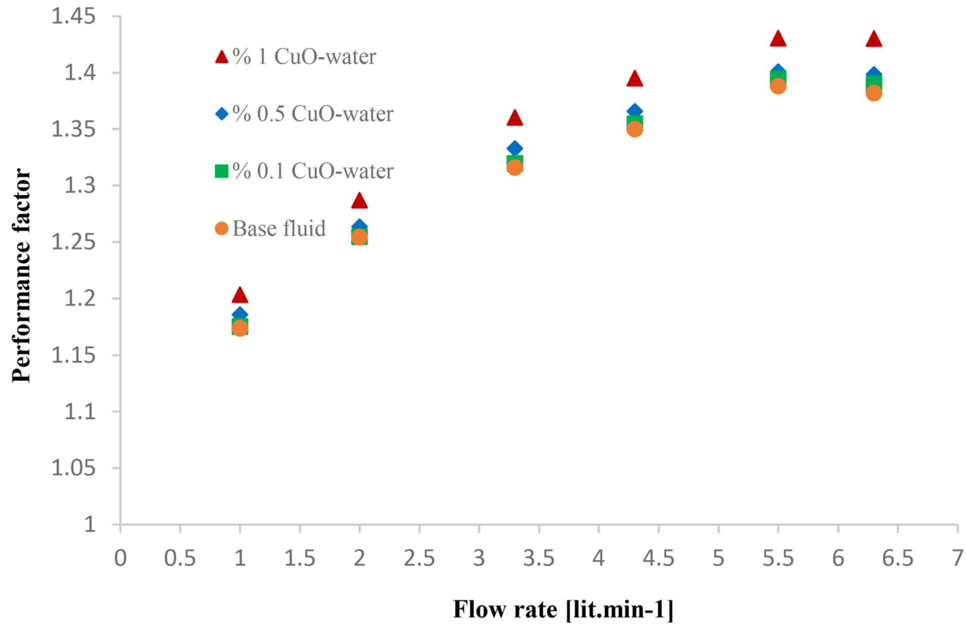


Fig. 19 Calculated performance factors for CuO-water nanofluid (parallel springs)

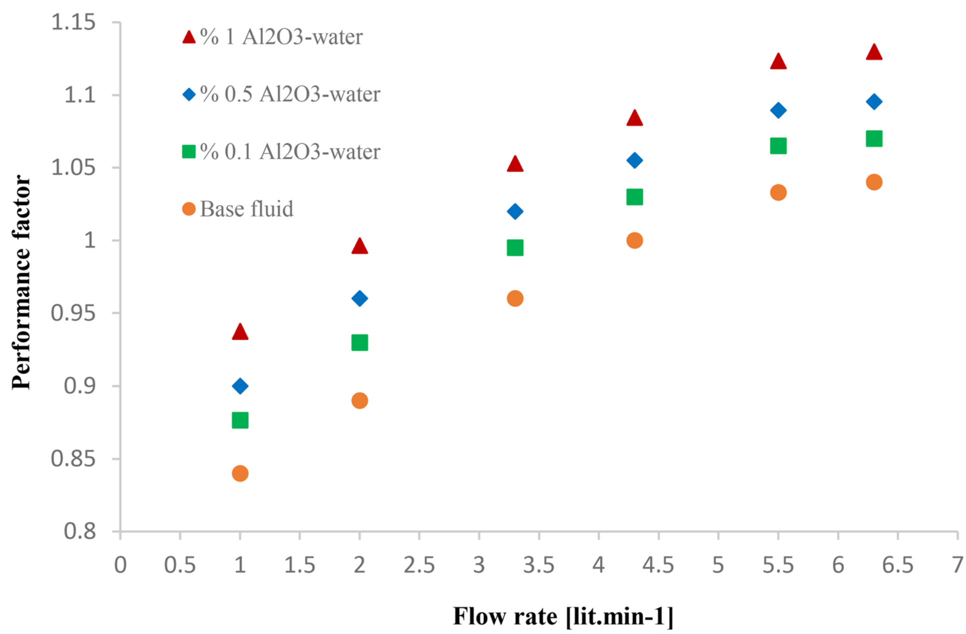


Fig. 20 Calculated performance factors for Al_2O_3-water nanofluid (vertical springs)

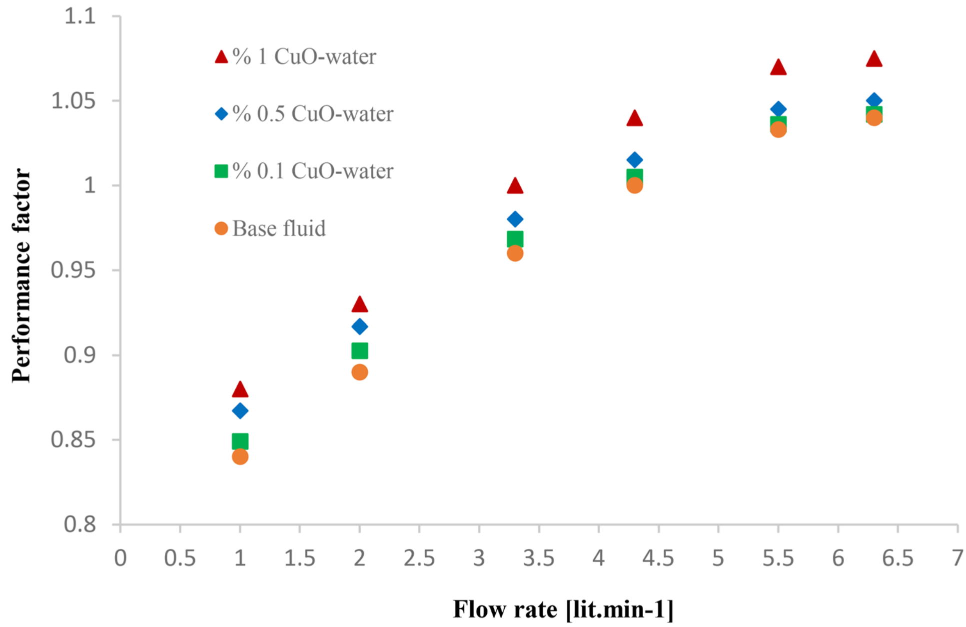


Fig. 21 Calculated performance factors for CuO-water nanofluid (vertical springs)

5 Conclusions

In the study, unlike the plate type heat exchangers manufactured by the mold method, flat plates were used and springs were mounted between the plates at different angles. Different geometries, flow rates, concentration ratios, different nanofluids are the parameters studied. The obtained heat transfer and pressure drop results were compared with each other and the results were interpreted, and the geometry, nanofluid concentration ratio and flow rate were determined to ensure efficient heat transfer.

By placing the springs in parallel, an improvement of 76.1% was observed in the heat transfer coefficient in the highest density Al_2O_3-water nanofluid used. The maximum performance factor was obtained when working with base fluid at a flow rate of 5.5 lt/min in the plate heat exchanger, the springs of which were placed in parallel, and it was found to be 1.51. At the same conditions, the performance factors for Al_2O_3-water nanofluids at 0.1%, 0.5% and 1% by mass were found to be 1.42, 1.46 and 1.51 and 1.39, 1.40 and 1.43 for CuO nanofluids, respectively. When the 1% mass ratio Al_2O_3-water nanofluid was operated at a flow rate of 5.5 lt/min in a plate heat exchanger with vertical springs, an increase of 9.6% in heat transfer, 10% in total heat transfer coefficient, and 13.8% in pressure drop was found compared to base fluid. For the CuO-water nanofluid studied under the same conditions, an increase of 4.9% in heat transfer, 6% in total heat transfer coefficient and 18.7% in pressure drop was found compared to base fluid. The results show that the heat transfer coefficient increases with the increase in flow rate and density of nanoparticles. As the density decreases, the pressure drop in nanofluids behaves similarly to the pure base fluid, but the pressure drop increases as the density increases. Both parameters are lower in smooth channels without turbulence.

The low level of heat transfer in traditional heat exchangers causes problems such as energy gain, economy, environmental pollution, and enlargement of device dimensions. In addition, precipitation problems arise when nanofluids are used in heat exchangers. As can be seen from the results, springs and nanofluids had significant effects on increasing the heat transfer coefficient in the new type of plate heat exchanger developed. Thus, by increasing the targeted heat transfer coefficient, the volume of the heat exchanger will be reduced and it will contribute positively to the cost. With the use of nanofluids and springs, a lower flow rate is given to the system, which means less pumping power and less electricity cost than a conventional heat exchanger.

In the study, a turbulent flow was provided with the heat exchanger geometry, which is easy to manufacture, and this increased the heat transfer coefficient. In addition, turbulent and eddy flow helped to avoid the problem of precipitation of nanofluids.

In future studies, experiments can be carried out to increase the performance factor by increasing the mass ratio of nanofluids. At the same time, the optimum angle and number of steps can be determined by placing the springs used at different angles and number of steps. Using a spring material with a higher thermal conductivity coefficient can also increase performance. It will be possible to increase the heat transfer by using hybrid nanoparticles in the developed heat exchanger.

The work developed and the reported results provide an important step forward for further research on the use of $Al_2O_3$and CuO nanofluids in different applications for enhancing thermophysical properties, heat transfer, and other operating conditions where energy conservation may be of particular interest.

However, besides the heat transfer improvement studies in the focused system, the environmental effects of nanofluids used in heat exchangers should also be taken into consideration. For this reason, the degradation determined at the end of the use of nanofluids in such systems should be handled from an environmental perspective and an optimization study should be carried out.

Acknowledgements This study was funded by the Scientific and Technological Research Council of Turkey (TUBITAK ARDEB 1002 Project Number: 218M931). The authors would like to express their thanks to TUBITAK for their financial supports the set-up, fabrication and research implementation. Additionally, This article was produced from the doctoral thesis named "The Effect of Nanofluid on Heat Transfer in a New Type Plate Heat Exchanger".

References

1. Ajeeb W, da Silva RR, Murshed SS (2023) Experimental investigation of heat transfer performance of Al_2O_3 nanofluids in a compact plate heat exchanger. Appl Thermal Eng 218. https://doi.org/10.1016/j.applthermaleng.2022.119321
2. Çuhadaroğlu B, Hacisaalioğlu MS (2022) An experimental study on the performance of water-based CuO nanofluids in a plate heat exchanger. Int Commun Heat Mass Transfer 137:106255. https://doi.org/10.1016/j.icheatmasstransfer.2022.106255
3. Sokhal GS, Dhindsa GS, Jakhar A, Malhi GS, Tonk R (2022) Role of hybrid nanofluids on the performance of the plate heat exchanger: Experimental study. Materials Today: Proceedings. https://doi.org/10.1016/j.matpr.2022.07.376
4. Singh S, Ghosh SK (2022) Influence of chevron angle and MWCNT/distilled water nanofluid on the thermo-hydraulic performance of compact plate heat exchanger: An experimental and numerical study. Powder Technol 405:117515. https://doi.org/10.1016/j.powtec.2022.117515pp.75-86
5. Göltaş M, Gürel B, Keçebaş A, Akkaya VR, Güler OV, Kurtuluş K, Gürbüz EY (2022) Thermo-hydraulic performance improvement with nanofluids of a fish-gill-inspired plate heat exchanger. Energy 253:124207. https://doi.org/10.1016/j.energy.2022.124207
6. Jassim EI, Ahmed F (2021) Assessment of nanofluid on the performance and energy-environment interaction of Plate-Type-Heat exchanger. Thermal Science and Engineering Progress 25:100988. https://doi.org/10.1016/j.tsep.2021.100988
7. Zheng D, Wang J, Chen Z, Baleta J, Sundén B (2020) Performance analysis of a plate heat exchanger using various nanofluids. Int J Heat Mass Transf 158:119993. https://doi.org/10.1016/j.ijheatmasstransfer.2020.119993
8. Elias MM, Rahman S, Ben-Mansour R, Hepbasli A, Rahim NA, Jesbains K (2018) Heat transfer and pressure drop characteristics of a plate heat exchanger using water based Al_2O_3 nanofluid for 30° and 60° chevron angles. Heat Mass Transf 54(1):2907–2916. https://doi.org/10.1007/s00231-018-2335-1
9. 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 Transfer 91:262–273. https://doi.org/10.1016/j.icheatmasstransfer.2017.12.020
10. Sarafraz MM, Nikkhah V, Madani SA, Jafarian M, Hormozi F (2017) Low-frequency vibration for fouling mitigation and intensification of thermal performance of a plate heat exchanger working with CuO/water nanofluid. Appl Therm Eng 121:388–399. https://doi.org/10.1016/j.applthermaleng.2017.04.083
11. Unverdi M, Islamoglu Y (2017) Characteristics of heat transfer and pressure drop in a chevron-type plate heat exchanger with Al_2O_3-water nanofluids. Therm Sci 21(6A):2379–2391. https://doi.org/10.2298/TSCI151110097U
12. Sun B, Peng C, Zuo R, Yang D, Li H (2016) Investigation on the flow and convective heat transfer characteristics of nanofluids in the plate heat exchanger. Exp Thermal Fluid Sci 76:75–86. https://doi.org/10.1016/j.expthermflusci.2016.03.005
13. Kumar V, Tiwari AK, Ghosh SK (2016) Effect of chevron angle on heat transfer performance in plate heat exchanger using ZnO/water nanofluid. Energy Convers Manage 118:142–154. https://doi.org/10.1016/j.enconman.2016.03.086
14. Ahmad SA, Javed MN, Saeed MZ, Syed H, Aslam MA (2016) Experimental investigation of plate heat exchanger using nanofluids. Int Res J Eng Technol 03(10):28–34. https://www.irjet.net/archives/V3/i10/IRJET-V3I1004.pdf
15. Peker G, Yildiz C, Çakmak G, Bilgiç Y, Yildiz A (2022) Thermal performance of new type plate heat exchanger with spring turbulence generator using nanofluid flow. Experimental Heat Transfer. https://doi.org/10.1080/08916152.2022.2081886
16. Huang D, Wu Z, Sunden B (2015) Pressure drop and convective heat transfer of Al_2O_3/water and MWCNT/water nanofluids in a chevron plate heat exchanger. Int J Heat Mass Transf 89:620–626. https://doi.org/10.1016/j.ijheatmasstransfer.2015.05.082
17. 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. https://doi.org/10.1016/j.ijheatmasstransfer.2015.05.118
18. Sun B, Peng C, Zuo R, Yang D, Li H (2016) Investigation on the flow and convective heat transfer characteristics of nanofluids in the plate heat exchanger. Exp Thermal Fluid Sci 76:75–86. https://doi.org/10.1016/j.expthermflusci.2016.03.005
19. Aliabadi MK (2017) Thermal–hydraulic characteristics of novel configurations ofwavy channel: nanofluid asworking fluid. Heat Transfer Engineering 38(16):1382–1395. https://doi.org/10.1080/01457632.2016.1255028