



Numerical investigation of a nanofluidic heat exchanger by employing computational fluid dynamic

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Abstract

Shell-and-tube heat exchanger is widely applied in different industrial processes and energy systems. Utilized fluid in the heat exchanger and its thermophysical properties are among the key factors that influence the thermal performance and fluid flow in heat exchangers. Employing nanofluids, with enhanced thermal properties, can improve heat transfer rate of heat exchanger. In this regard, the current article concentrates on the numerical simulation of a shell-and-tube heat exchanger with baffle, utilizing multi-walled carbon nanotube/water nanofluid. In this regard, computational fluid dynamic is used for modeling. The applied turbulence model in this study is $k-\varepsilon$ which is selected based on the literature review. Heat transfer rate comparison in cases of utilizing the nanofluid in shell side of heat exchanger revealed high potential of the nanofluid in thermal performance improvement. Moreover, it was noticed that by using higher concentration of the nanofluid, more enhancement would be obtained which is owing to higher increment in the nanofluid effective thermal conductivity. Average increment in the heat transfer rate of the HE in case of using multi-walled carbon nanotube/water with 4% concentration is around 29.5% in comparison with the condition water is used as the operating fluid.

Keywords Heat exchanger · Nanofluid · Multi-walled carbon nanotube · Computational fluid dynamic

Introduction

Improving the heat exchangers (HEs), as the mediums used for transferring thermal energy from one or more fluid streams with higher temperatures to the streams with lower temperatures, are broadly used for different purposes. In different energy systems such as geothermal power plants, solar thermal technologies and energy storage units, various types of HEs are employed as thermal mediums [1–4]. The selection of HEs' type depends on some factors including the operational conditions and design constraints. Shell and tube is the most prominently utilized type of HEs due to its several advantages such as its ability to be used in high pressure conditions, design flexibility and applicability in a wide range of temperature. This type of HEs, in simplest form, is composed of tubes that are located in cylindrical shell. In addition to the mentioned components, there are some other elements in shell-and-tube HEs such as baffles. The streams

of fluids flow through the shell and tubes and transfer thermal energy with each other. Similar to other types of HEs, the performance of shell-and-tube HE is under the effect of different factors including size, streams temperature difference, operating fluid, mass flow rate, etc.

Several studies have been performed on the fluid flow and thermal performance analysis of shell-and-tube HEs. Kallanavar et al. [5] conducted a study on a shell-and-tube HE to investigate the tube layout effect on the performance. They concluded that heat transfer is more favorable in counterflow condition in comparison with parallel flow state. Moreover, by considering four cases of tube layouts including triangular, rotated triangular, square and rotated square, it was observed that triangular configuration leads to the highest heat transfer rate. In another research [6], a HE by using different types of porous baffles was investigated. In their study, different permeability, porosity and baffle cuts were considered for utilization in a shell-and-tube HE. They found that using low baffle cuts leads to higher heat transfer rate while the pressure drop increases. Abbasi et al. [6] optimized a shell-and-tube HE by considering three geometrical variables including thickness, angle and number of baffles. They found that increment in number of baffles is beneficial

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in terms of heat transfer rate; however, the pressure drop would be increased as an unfavorable consequence. In the optimized condition, considered in their study, the heat transfer rate improved by 11.15%, while the pressure drop decreased by 61.3%, which shows remarkable potential of overall performance enhancement by performing optimization on shell-and-tube HEs. In addition to the studies focused on geometrical and design parameters effects on the performance of the HEs, several studies have concentrated on the impacts of operating fluids. Generally, using fluids with modified thermal properties such as nanofluids are preferred to be used in HEs. By using nanofluids, which have relatively higher thermal conductivity in comparison with their base fluids [7–10], it is expected to have improved heat transfer rate and efficiency. For instance, Fares et al. [11] applied graphene/water nanofluid in a shell-and-tube HE and found that by using the nanofluid with 0.2% concentration, the coefficient of heat transfer could be increased by a maximum value of 29%. Said et al. [12] assessed the performance of a shell-and-tube HE by applying CuO/water nanofluid. Their outcome highlighted the positive impact of employing the nanofluid in HE, which showed 7% enhancement in the overall heat transfer coefficient of the considered HE.

In addition to the conventional approaches, including numerical and experimental, artificial intelligence is applicable for modeling, assessing and predicting the performance of HEs. For instance, Esfe [13] employed artificial neural network to forecast the pressure drop and heat transfer of double-tube HE. It was noticed that Nusselt number in addition to relative pressure drop could be accurately predicted. In another study [14], different intelligent approaches including least square support vector machine, adaptive neuro-fuzzy inference system and artificial neural network employed for modeling of a coil HE. The outcomes of the models showed that all of the mentioned methods were accurate in predicting Nusselt number. Computational fluid dynamic (CFD) is another tool applicable for modeling HEs. CFD is a powerful tool for investigating fluid flow and heat transfer in a wide variety of applications [15–18]. By using CFD, time and cost will be saved, which makes them as attractive alternatives for experimental works. CFD is used for numerical simulation of shell-and-tube HEs in different studies to investigate the effects of different factors. For instance, Pal et al. [19] applied CFD for investigation of shell side fluid flow and heat transfer of a HE with and without baffle. Somasekhar et al. [20] used CFD for investigating heat transfer enhancement in a shell-and-tube HE in condition of applying Al_2O_3 /water nanofluid. The simulation outcomes indicated that by using the nanofluid, significant enhancement in heat transfer can be achieved. Ambekar et al. [21] used CFD for investigating the effect of configuration of the baffle segment on the heat transfer rate and pressure drop of a shell-and-tube HE. They found that

by using flower baffles instead of single segmented ones, the overall heat transfer coefficient decreased by 30–35%.

Owing to the improved thermal conductivity of fluids in case of containing dispersed solid structures in nanometer size, utilizing them in HEs would be beneficial in terms of heat transfer augmentation and size reduction. Among different types of nanomaterials, the carbonic ones have superior properties in terms of thermal properties, which makes them able to remarkably improve heat transfer rate in cases they are dispersed in heat transfer fluids [22]. Although the heat transfer augmentation in HEs by adding conductive nanomaterials in the working fluid has been investigated in several studies, some aspects such as stream of the fluid and temperature contour along the shell need further investigation. In this regard, the current study focuses on applying CFD for heat transfer assessment of a shell-and-tube HE with baffle in case of utilizing multi-walled carbon nanotube (MWCNT)/water nanofluid in the shell side. In addition to determination of heat transfer coefficient, temperature contour of the stream along the shell of the HE will be obtained in order to get better insight into the heating of the working fluid; furthermore, the stream of the fluid will be obtained to observe the effect of considered baffles on the fluid flow. The details of models, geometry of the HE and results are represented in the next sections.

Thermal characteristics of nanofluids with CNTs

Generally, dispersion of solid materials with nanometer dimensions in the fluid causes thermal conductivity increment. Utilization of solids with higher thermal conductivity results in more increment in thermal conductivity of the obtained nanofluids which makes CNTs more favorable for thermal conductivity enhancement in comparison with other conventionally used nanomaterials such as CuO and SiO_2 [23]. In this regard, CNTs as the materials with remarkably high thermal conductivity are preferred for reaching higher heat transfer. Several researches have been carried out on the nanofluids' thermal conductivity with CNTs [24–26]. Increment in the thermal conductivity of these nanofluids is dependent on various parameters such as length of solid structures, base fluid, temperature and structure of the CNTs [27]. For instance, Xie et al. [28] found that by dispersing MWCNTs in ethylene glycol, more than 25% augmentation in the thermal conductivity can be obtained. In another work, thermal conductivity of nanofluids containing different structures of CNTs was investigated by Nasiri et al. [29]. It was noticed that it is possible to reach thermal conductivity ratio of higher than 1.2 by utilizing MWCNT at 50 °C; this value was much higher in case of using single-wall CNT. Phuoc et al. [30] applied MWCNT in water in different

volume fractions in the range of 0.24–1.43% and observed 13% improvement in the thermal conductivity in condition of applying the highest concentration. Sadri et al. [31] measured MWCNT/water nanofluid’s thermal conductivity in various temperatures and observed that by increasing the temperature and sonication duration, thermal conductivity enhancement of the nanofluid increased. The highest observed improvement in the thermal conductivity was 22.31% in their experiments. Liu et al. [32] used MWCNT in synthetic engine oil and noticed 30% improvement in the thermal conductivity in condition of 2% vol concentration of solid phase. According to the mentioned studies, it can be concluded that CNTs have high potential for heat transfer enhancement of thermal devices such as HEs owing to their prominent thermal characteristics.

Methodology

In order to evaluate the effect of employing MWCNT/water nanofluid in a shell-and-tube HE, CFD is applied. This nanofluid is considered in the present paper due to its superior thermal characteristics, specially its thermal conductivity which is anticipated to noticeably increase heat transfer. The schematic of the considered HE is shown in Fig. 1. This configuration, by using water as the operating fluid, had been used by Ozden et al. [33]. The design parameters of the considered HE are similar to the mentioned reference which are summarized in Table 1. Flow governing equations are modified based on the case operating conditions. The time-dependent parameters are removed from the equations since the problem is considered in a steady condition. The obtained equations in this case are as follows:

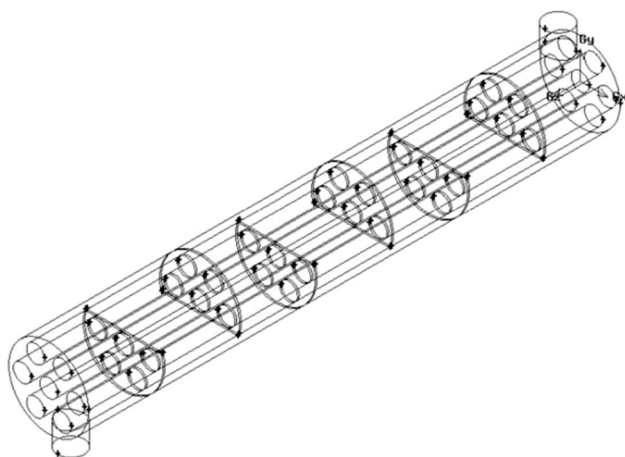


Fig. 1 Schematic of shell-and-tube heat exchanger with six baffles [33]

Table 1 Geometrical specifications of the HE [33]

Diameter of shell	90 mm
Outer diameter of tube	20 mm
Pitch and geometry of tube bundle	30 mm, triangular
Length of HE	600 mm
Baffle cut	36%
Number of baffles	6
Central baffle spacing	86 mm

Continuity equation can be expressed as:

$$\rho \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right) = 0 \tag{1}$$

In Eqs. (2)–(4), momentum equations in different directions are represented as follows [33]:

$$\nabla \cdot (\rho u \vec{V}) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} \tag{2}$$

$$\nabla \cdot (\rho v \vec{V}) = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} \tag{3}$$

$$\nabla \cdot (\rho w \vec{V}) = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} \tag{4}$$

And finally, the energy equation is defined as:

$$\rho \left(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} \right) = \frac{k}{c_p} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \tag{5}$$

As one of the boundary conditions, it is considered that outer wall of the shell is adiabatic. Moreover, at the inlet of the fluid stream, mass flow rate is used as the boundary condition, while the static pressure of the fluid, equal to atmospheric pressure, is utilized as the boundary condition at the outlet. Since the main focus of the current study is the shell-side heat transfer, the tubes are considered with a constant temperature of 60 °C. Effects of turbulence must be considered in the simulation since the flow in the HE is turbulent. Reynolds number of the flow at the inlet of the HE shell side in case of 1 kg s⁻¹ mass flow rate is around 63,000. Due to the applicability of *k*- ϵ turbulence model for high Reynolds number flow, this model is applied. The details of this model are represented in Ref. [33]. In the applied software, wall function for this turbulence model is applied.

In the present study, MWCNT/water nanofluid is used as operating fluid in order to compare the heat transfer rate with the case of employing water. In the simulation procedure, it is necessary to use appropriate thermophysical properties for the employed nanofluid in order to reach accurate results. In

Table 2 Thermophysical properties of MWCNT [35]

Property	Value
Density/kg m ⁻³	1800
Specific heat capacity/J kg ⁻¹ K ⁻¹	725
Thermal conductivity/W m ⁻¹ K ⁻¹	3000

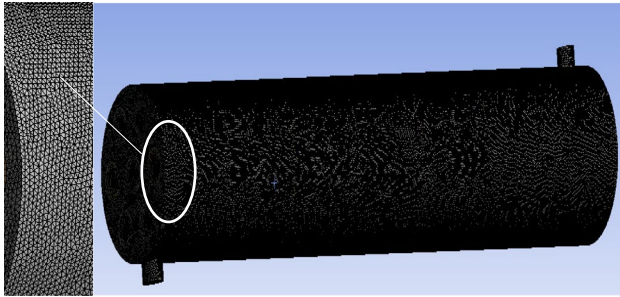


Fig. 2 Meshed geometry of the HE

Eq. (5), formulas used for the determination of thermophysical properties of the nanofluid are provided [34, 35]:

$$\frac{\mu_{nf}}{\mu_{bf}} = \frac{1}{(1 - \phi)^{2.5}} \tag{6}$$

$$\rho_{nf} = (1 - \phi)\rho_b - \phi\rho_p \tag{7}$$

$$k_{nf} = \frac{1 - \phi + 2\phi \frac{k_p}{k_p - k_{bf}} \ln \frac{k_p + k_b}{2k_b}}{1 - \phi + 2\phi \frac{k_b}{k_p - k_{bf}} \ln \frac{k_p + k_b}{2k_b}} k_b \tag{8}$$

In the above equations, subscripts p, nf and bf refer to particle (or nanotubes), nanofluid and base fluid, respectively. In addition, μ , ρ , k and ϕ are dynamic viscosity, density, thermal conductivity and volume fraction, respectively. The thermophysical properties of the MWCNT are represented in Table 2.

For meshing the domain, ANSYS MESH is used. In order to investigate the grid independency, different numbers of elements were tested in the simulation and it was found that in case of 2800000 elements, as represented in Fig. 2, the results of the simulation, which was assessed based on the fluid outlet temperature (as shown in Fig. 3), would not change with further reduction in the mesh size. For solving the mentioned equations, ANSYS CFX.17 is used.

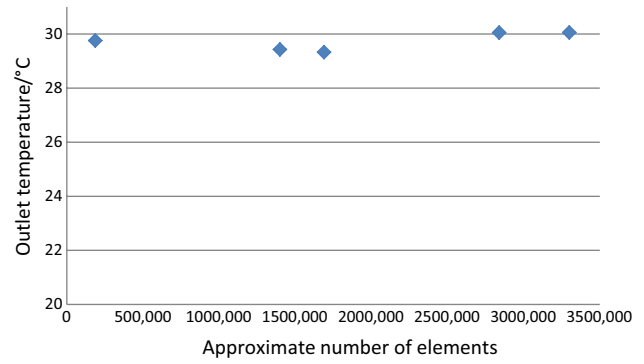


Fig. 3 Outlet temperature versus number of elements

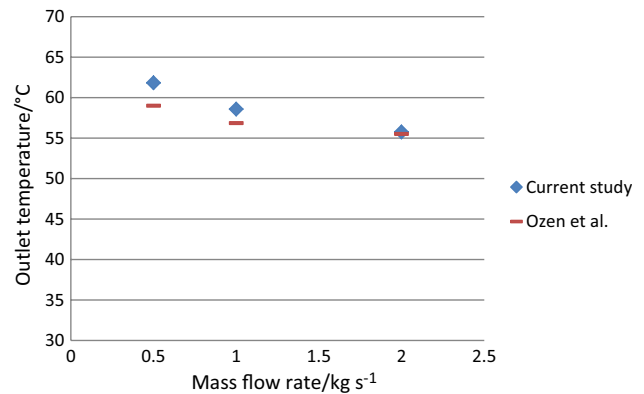


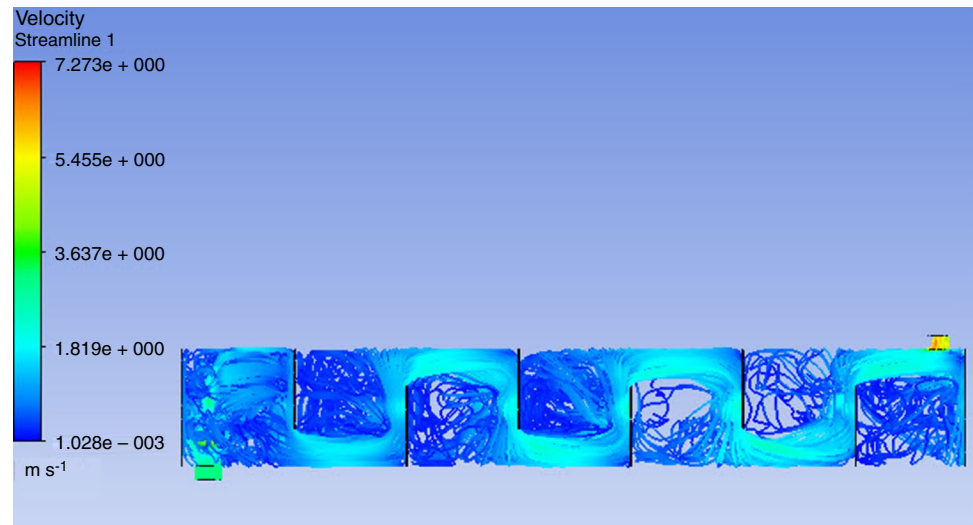
Fig. 4 Comparison between the results of the present study and Ozen et al. [33]

Results and discussion

In the first step, in order to assess the validity of the simulation, the present simulation is applied for the same conditions represented in Ref. [33]. In Fig. 4, the obtained data by the current model are compared with the ones determined in the mentioned study.

For getting insight into the fluid flow inside the HE, flow stream is obtained as shown in Fig. 5. As it is expected, the velocity of the flow in the vicinity of the baffles approaches zero since the baffles act as the wall. In addition, according to this figure, the turbulent behavior of the flow can be observed. It can be seen that in the vicinity of the baffles, the velocity of the fluid is decreased since no-slip boundary condition is considered on the wall of baffles. In addition, the highest velocity of the fluid flow exists on the inlet and outlet of the HEs which is due to lower diameter of these sections compared with the diameter of HE shell side.

Fig. 5 Flow stream inside the HE



As indicated in the previous section, the tubes of the HE are assumed in constant temperature of 60 °C, since the inlet temperature of water in the shell side is set at 20 °C, it receives heat from the tubes, and its temperature would be increased. In Fig. 6, temperature contour of the fluid, for the case of using water with 1 kg s⁻¹ mass flow rate, is shown. As it was anticipated, the temperature of working fluid increases from inlet to outlet due to higher temperature of the tube side, which is the consequence of increment in received thermal energy of the fluid in shell side. Moreover, it can be seen that in the vicinity of the baffles, the temperature of fluid is lower. Lower temperature of the fluid in these regions can be attributed to the fact that the fluid in the vicinity of baffles has lower contact with the high-temperature tubes; consequently, the received thermal energy is reduced.

The main influence of dispersing MWCNT in the base fluid is increment in the effective thermal conductivity of the working fluid. Existence of MWCNTs, as solids with relatively high thermal conductivity, in the base fluid can remarkably improve effective thermal conductivity; consequently, heat transfer rate would be increased. In the present study, two concentrations of MWCNT/water nanofluid are considered. Moreover, the mass flow rate at the inlet of HE varies from 1 to 2.5 kg s⁻¹ with 0.5 kg s⁻¹ steps. In Fig. 7, heat transfer rate in different working conditions is represented. As shown in the figure, increment in concentration of the nanofluid leads to higher heat transfer rate which is attributed to more increase in thermal conductivity and consequently the convective heat transfer coefficient. Moreover, by an increase in the mass flow rate, heat transfer rate is increased as it was anticipated due to an increase in the Nusselt number as a consequence of increment in Reynolds number of the flow. Average increase in heat transfer rate in case of using MWCNT/water nanofluid with 4%

concentration compared with water is around 29.5%, which reveals significant impact of using the nanofluid in heat transfer improvement. Furthermore, according to this figure it can be concluded that the increase in heat transfer rate is more remarkable when the volume fraction of MWCNTs increases from 0 to 2% in comparison with the case where the volume fraction increases from 2 to 4%. Although applying the nanofluid in the HE results in higher heat transfer rate, pressure drop may be increased due to higher dynamic viscosity; for instance, in case of using MWCNT with 2% concentration, pressure drop increased by around 1.6% for mass flow rate of 1.5 kg s⁻¹.

Regression model

In this section, a regression model is proposed in order to estimate the heat transfer rate of the shell side on the basis of the mass flow rate and volume fraction of the utilized nanofluid. In the applied model, dimensionless numbers of mass flow rate, volume fraction and heat transfer rate are used as follows:

$$\dot{Q} = \frac{Q}{Q_1}, \quad \dot{C} = \frac{C}{C_1} \quad \text{and} \quad \dot{m} = \frac{m}{m_1}$$

where Q_1 , C_1 and m_1 refer to minimal heat transfer rate in the shell side of HE, minimal volume fraction of the nanofluid (2%) and mass flow rate (1 kg s⁻¹), respectively. The structure of the regression is selected based on the proposed correlation by Nazari et al. [36] as follows:

$$y = a_0 + b_1x_1 + b_2x_2 + c_1x_1x_2 + f_1e^{d_1x_1} + f_2e^{d_2x_2} + \varepsilon$$

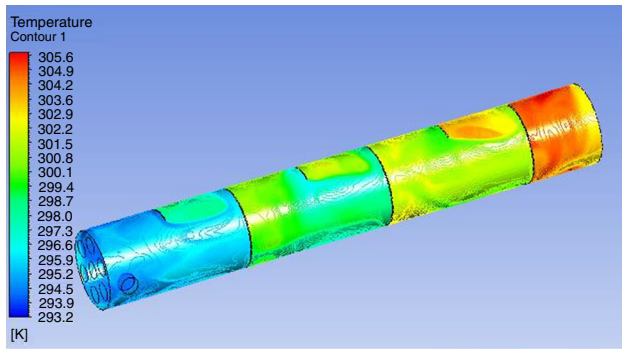


Fig. 6 Temperature contour on the outer wall of shell

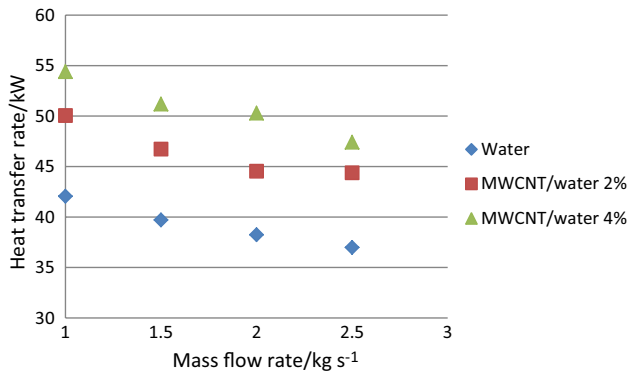


Fig. 7 Effect of adding MWCNT on heat transfer rate

where x_1 and x_2 are dimensionless volume fraction and mass flow rate, respectively. The obtained regression based on the above-mentioned structure is as follows:

$$\dot{Q} = 0.8051 + 0.1218x_1 - 0.3806x_2 - 0.01407x_1x_2 - 0.125e^{-1.493x_1} + 0.635e^{0.279x_2}$$

In Fig. 8, the obtained surface for the above correlation is represented. The black points on the surface refer to the actual data obtained by CFD. R -squared of the proposed regression is 0.9937, indicating the reliability of the model.

Conclusions

Shell-and-tube HEs are the mostly utilized HEs and applicable in various industrial processes. The performance and heat transfer rate of these HEs can be improved by applying nanofluids in them. In the present study, CFD is used for numerical simulation of heat transfer and fluid flow in a shell-and-tube HE with baffles. The applied nanofluid in the considered HE is MWCNT/water with 2% and 4% concentrations. The simulation data reveal that by employing the nanofluid with higher concentration, further enhancement in heat transfer rate can be achieved compared with water. In case of employing MWCNT/water nanofluid with 4% concentration instead of water, heat transfer rate increases by about 29.5%, indicating remarkable potential of this nanofluid in improving thermal performance. In addition to heat transfer rate, temperature contour on the outer wall of the shell is obtained which shows the trend of increment in the fluid temperature from inlet to outlet of the HE. Moreover, a regression is proposed on the basis of the outputs of CFD model and it is observed that the R -squared of the obtained model is around 0.993 that reveals high accuracy of the proposed regression.

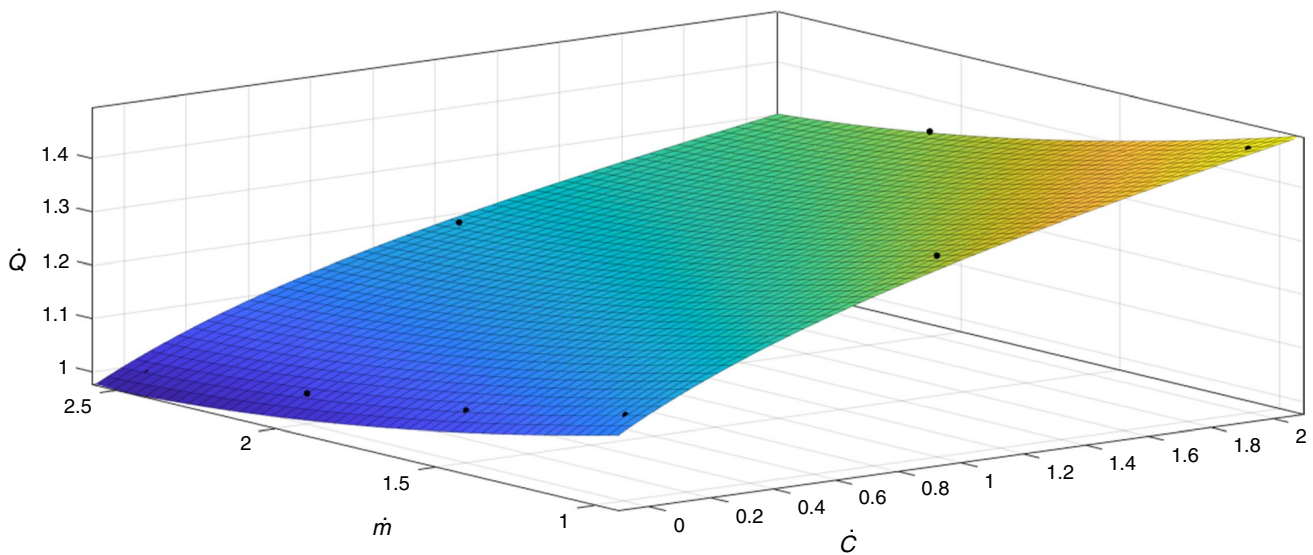


Fig. 8 Dimensionless heat transfer rate versus dimensionless volume fraction and mass flow rate

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