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| RESEARCH ARTICLE

Numerical and Experimental Performance Analysis for Different Types of Heat Exchangers

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| ABSTRACT

Heat exchangers are devices whose primary responsibility is to transfer heat, typically from one fluid to another. In such applications, the heat exchangers can be parallel flow, crossflow, or counter flow. An essential part of any heat exchanger analysis is the determination of the effectiveness of the heat exchanger. In the present work, three different types of heat exchangers are investigated. Numerical and experimental performance analyses are applied. The main objective of the present work is to compare the effectiveness of each heat exchanger at different conditions. Six experimental investigations for Plate, shell & tube, and fluidized bed heat exchangers are executed. All experimental tests are reached to steady-state conditions. The results show that the counter flow plate heat exchanger has an effectiveness of 90% compared with the parallel flow of 60% effectiveness for working experimental conditions. Also, the fouling effect in decreasing heat transfer is cleared. In the present work, fouling decreases effectiveness from about 18% to about 4%. In addition, the effectiveness of the fluidized bed heat exchanger depends on the material used for the bed. Finally, the overall heat transfer coefficient is obtained and compared for all experimental tests, and it is directly proportional to the effectiveness of the heat exchanger. The FEHT program is used to get the temperature distribution in all types of present work heat exchangers.

| KEYWORDS

Effectiveness; fluidized bed; Heat exchanger; PHE

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1. Introduction

Various industries use processes in which heat is transferred between different fluids. This transfer is carried out in the heat exchangers of various types that depend on the corresponding operating conditions and the industrial applications such as steam generation and condensation in power and cogeneration plants, automobile industry, cooling and heating in thermal processing of pharmaceutical, chemical, and agricultural products (Chorak et al., 2014). The design and performance of a heat exchanger are dependent on the total heat transfer, in turn, results in quantities such as the inlet and outlet fluid temperatures, the overall heat transfer coefficient, and the total heat transfer area (Müller-Steinhagen, Malayeri, & Watkinson, 2011). An alternate approach of heat exchanger devices lies in the notion of exchanger effectiveness. Which can be simply defined as (Fakheri, 2008; Ya, Ghajar, & Ma, 2015):

$$\varepsilon = \text{actual heat transfer} / \text{maximum possible heat transfer} \quad (1)$$

The effectiveness of the heat exchanger plays a vital role in several industries. The effectiveness is considered directly proportional to the surface area through which heat transfer takes place since the effectiveness depends on the rate of heat transfer and the heat transfer is proportional to the surface area and temperature gradient. An increase in the rate of heat transfer is done by changing the surface area of the tube in different ways, like arranging additional surfaces or using corrugation or using twisted tapes (Manideep, Rajasekhar, & Technology 2017). Heat exchangers are typically classified according to flow arrangement and type of construction. The parallel-flow heat exchanger is one for which the hot and cold fluids move in the same direction. In the parallel flow arrangement, the hot and cold fluids enter at the same end, flow in the same direction, and leave at the same end (Kim, Kim, & Byun, 2011). The parallel type is thermodynamically poor because it has a lot of thermal stress. In the counter-flow arrangement, the fluids enter at opposite ends, flow in opposite directions, and leave at opposite ends (Hasan, Rageb, Yaghoubi, & Homayoni, 2009). Alternatively, the fluids may also move in crossflow, which means perpendicular to each other and called cross-flow heat exchangers (Carluccio, Starace, Ficarella, & Laforgia, 2005; Hanson, 1989). Fouling has a great effect on heat exchanger performance. There are different types of fouling depending on the purpose of the heat exchanger and what is its application (Ajayi, Ogbonnaya, & Transfer, 2017). Increasing heat exchanger performance usually means transferring more duty or operating the exchanger at a closer temperature approach. This can be accomplished without a dramatic increase in surface area. This constraint directly translates to increasing the overall heat transfer coefficient (Lunsford, 1998). Attempts are made to clarify some hidden features of the effectiveness concept of heat exchangers and provide a critique viewpoint and comprehensive description about that (Yan et al., 2020). The main objective of the present paper is to determine the performance of different types of heat exchangers. Through different experimental investigations the performance of plate, shell& tube, and fluidized bed heat exchangers by calculating the effectiveness of each type at different conditions. In addition, using the FEHT program (Klein & Beckman, 1983) to predict the temperature distribution inside these types of heat exchangers.

2. Experimental setup

In the present work, three types of heat exchangers are investigated. These types are plate, shell & tube, and fluidized bed heat exchangers. This section discusses the different data for the experimental of present work heat exchangers.

2.1 Plate Heat Exchanger

A plate heat exchanger, as shown in figure (1) with the following technical data, is investigated and tested in different conditions:

-Type: Brazed Plate Heat Exchanger
-Max. Temperature: 225 ^oC
-Max. Operating Pressure: 1 Mpa
-Testing Pressure: 2 Mpa
-Plate Material: 304 Stainless steel
-Number of Plates: 20
-Length: 0.17 m
-Width: 0.07 m
-Area: 0.24 m^2.

The flow in the plate heat exchanger through the present experimental work is investigated between parallel and counter flow.

Figure (1): Plate heat exchanger

2.2 Shell and Tube Heat Exchanger
Figure (2) shows a shell and tube heat exchanger, which was fabricated for the purpose of investigation in the present experimental work. The main technical data for this heat exchanger are:

-Shell and Tube two pass

-Length: 0.8 m

-Width: 0.2 m

- Height: 0.2 m

-Volume: 0.032 Cubic meter

-Material: Steel

-Pass Material: Copper

The present experimental analysis for this heat exchanger is done with and without fouling.

Figure (2): Shell and Tube Heat Exchanger

2.3 Fluidized Bed Heat Exchanger
From a thermodynamical point of view, fluidised bed columns are the best type of apparatuses for carrying out mass and heat transfer processes between gas and solid phase. It is because of all types of highly effective apparatuses. They operate as near as possible to the conditions of countercurrent flow, i.e., at maximum driving force for given initial and end concentrations of the two phases and a given ratio between their flow rates. Packed beds have many applications in the chemical processing industry(Abd El-Kawi, Sarhan, & Elbakhshawangy; Peng, Moghtaderi, & Doroodchi, 2017). A specially fluidized bed heat exchanger is fabricated for the present work investigation. Figure (3) shows this heat exchanger. The main technical data of it are:

- Material: Wood
-Pass material: Copper
-Length: 0.35 m
-volume: 0.0035 cubic meter

The main experimental tests for this type are applied with sand and aluminium as bed materials.

Figure (3): Fluidized bed Heat Exchanger

2.4 Instrumentation and Measurements

There is auxiliary equipment are used in the present work to serve and measure the main parameters of the present work:

1- Two water pumps, one with a flow rate of 0.21 kg/s and the other one with a flow rate of 0.072 kg/s.

3. Insulation material type is mineral wool. Which Resistant to temperatures above 1,000 °C

4- Pipes of different diameters and lengths.

5- Temperature recording sensors with temperature range -50 to 80 °C.

6- Normal cold air Blower.

2.5 The experimental tests

Through the present work, 6 experimental investigation tests are executed. Each two experimental are for the same heat exchanger at different conditions. The different experimental tests are described in the table:

Table (1): The present work experimental tests

Experimental test no.	Description	Hot fluid	Cold fluid	$T_{c,i}$ ºC	$T_{h,i}$ ºC
1	Fluidized bed with aluminium particles as bed material.	Water	air	19	80
2	Fluidized bed with sand particles as bed material.	Water	air	19	80
3	Plate Heat exchanger with counter flow	Water	Water	25	80
4	Plate Heat exchanger with parallel flow	Water	Water	25	80
5	Shell and tube with fouling on the tubes	Water	Water	25	80
6	Shell and tube without foiling	Water	Water	25	80

3. Calculation of Overall Heat Transfer Coefficient:

One of the main purposes of this experimental work was to calculate the overall heat transfer coefficient. To calculate it, the following procedures were followed:

1- Summarize data that were given, measured, and calculated. These data include:
   i. Hot fluid flow rate.
   ii. Cold fluid flow rate.
   iii. Air properties (Density, heat capacity, viscosity, and thermal conductivity)
   iv. Water properties (Density, heat capacity, viscosity, and thermal conductivity)
   v. Input and output temperatures of air and water.
   vi. Total area of heat transfer.

2- Calculate the total heat transfer from one of the following equations:

$$Q = \dot{m}_h \; Cp_h \; \Delta T_h \quad = \dot{m}_c \; Cp_c \; \Delta T_c \qquad (2)$$

3- Calculate log mean temperature difference from the following equation:
   i. For counter flow

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{ln\frac{\Delta T_1}{\Delta T_2}} \qquad (3)$$

$$\Delta T_1 = (T_{h,i} - T_{c,o}) \qquad (4)$$

$$\Delta T_2 = (T_{h,o} - T_{c,i}) \qquad (5)$$

$$\Delta T_{lm} = \frac{(T_{h,i} - T_{c,o}) - (T_{h,o} - T_{c,i})}{ln\frac{(T_{h,i}-T_{c,o})}{(T_{h,o}-T_{c,i})}} \qquad (6)$$

   ii. For parallel flow

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{ln\frac{\Delta T_1}{\Delta T_2}} \qquad (7)$$

$$\Delta T_1 = (T_{h,i} - T_{c,i}) \qquad (8)$$

$$\Delta T_2 = (T_{h,o} - T_{c,o}) \qquad (9)$$

$$\Delta T_{lm} = \frac{(T_{h,i}-T_{c,i})-(T_{h,o}-T_{c,o})}{ln\frac{(T_{h,i}-T_{c,i})}{(T_{h,o}-T_{co})}} \qquad (10)$$

4- Calculate the overall heat transfer coefficient from the following equation:

$$Q = UA\Delta T_{lm} \qquad (11)$$

4. Calculation of Heat Exchanger Effectiveness

Calculate the effectiveness of the heat exchanger from the following equation by the substitute of the data given, measured, or calculated (Longo, Gasparella, & Sartori, 2004):

$$\varepsilon = \frac{\dot{C}_c(T_{c,o}-T_{c,i})}{\dot{C}_{min}(T_{h,i}-T_{c,i})} = \frac{\dot{C}_h(T_{h,i}-T_{h,o})}{\dot{C}_{min}(T_{h,i}-T_{c,i})} \quad (12)$$

Where:

$$\dot{C}_c = \dot{m}_c Cp_c$$

$$\dot{C}_h = \dot{m}_h Cp_h$$

5. Finite element heat transfer software (FEHT)

FEHT is an acronym for Finite Element Heat Transfer. FEHT was originally designed to facilitate the numerical solution of steady-state and transient two-dimensional heat transfer problems. However, the fundamental equations describing heat transfer, bio-heat transfer, potential flow, steady electric currents, electrostatics, and scalar magnetostatics are similar. The current version of FEHT has been designed to solve problems in all of these disciplines. Versions of FEHT have been developed for computers using the Microsoft Windows operating systems [7].

6. Results and discussion

The overall heat transfer coefficient and heat exchanger effectiveness for each of the three types of heat exchangers has been investigated. Hot fluid and cold fluid are as described in table (1) at different flow rates and temperatures. In addition, numerical analysis has been done by use of the FEHT program. The main purpose of the numerical part is to calculate the change in temperatures at different times and consequently draw the temperature distribution in each heat exchanger to predict and avoid thermal stresses. The following sections report the numerical and experimental analysis results for the present work.

6.1 Numerical results analysis

In the present work, numerical analysis is executed for the three types of heat exchangers. The main objective of the numerical analysis for the present work is to calculate temperature change with time in two dimensions and draw the temperature contours with time until reaching the steady-state conditions. In addition, it helps in investigating the thermal stresses, consequently avoiding their bad effects on the heat exchanger

For parallel flow in the plate heat exchanger, figure (4) shows the temperature distribution in each heat exchanger plate at a different time from 0 to 30 seconds. Also, parallel flow is shown in figure (5) shows the variation of temperature with time for the three diagonal nodes. It is clear steady state conditions reached approximately after 30 seconds.

For counter flow, figure (6) shows the temperature distribution in each heat exchanger plate at a different time from 0 to 30 seconds. While figure (7) shows temperature variation with time at the same conditions. It can be noticed that in the case of counter flow, steady state conditions reached approximately after 25 seconds. The explanation of reaching a steady state in a short time than parallel flow returns to the improved heat transfer mechanism between hot fluid and cold fluid. This means that counter flow is more efficient than parallel flow, as shown in the present work experimental work.

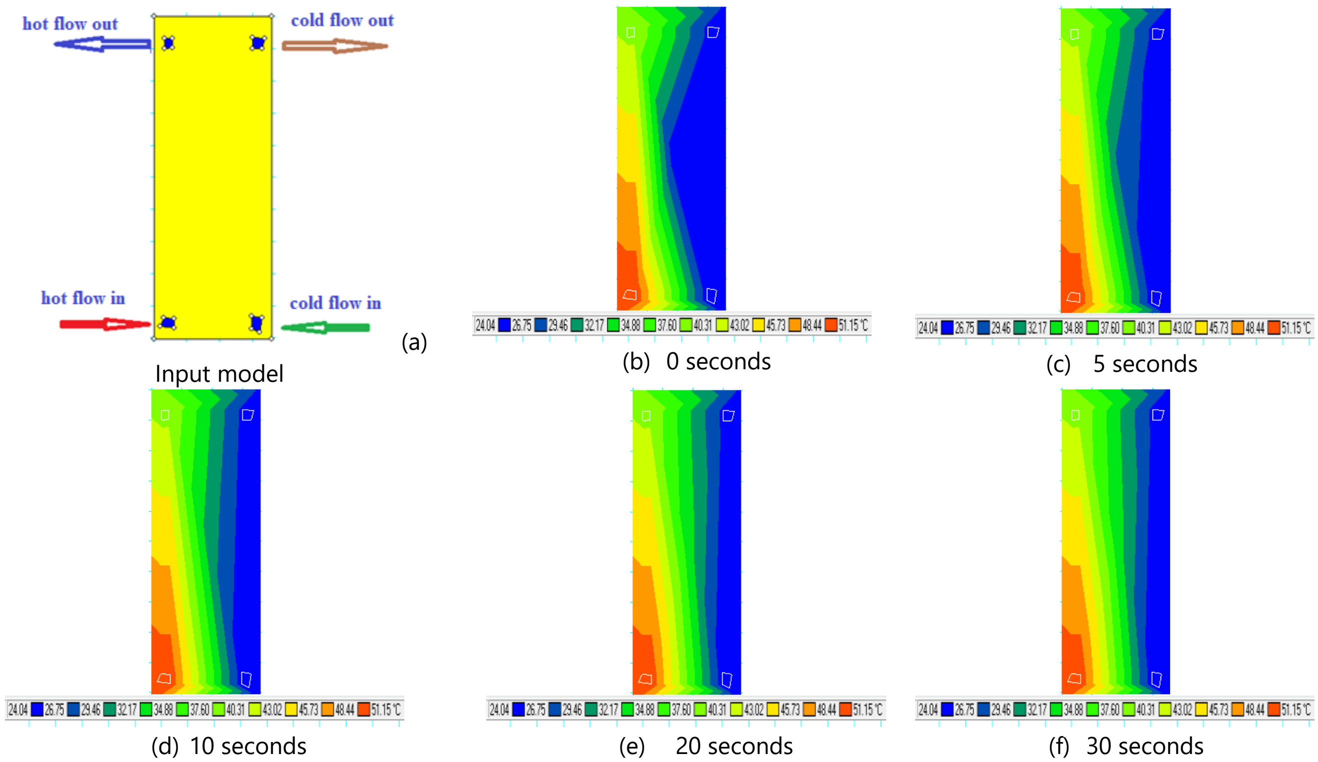


Figure (4): Temperature contours for parallel flow in a plate heat exchanger at different time

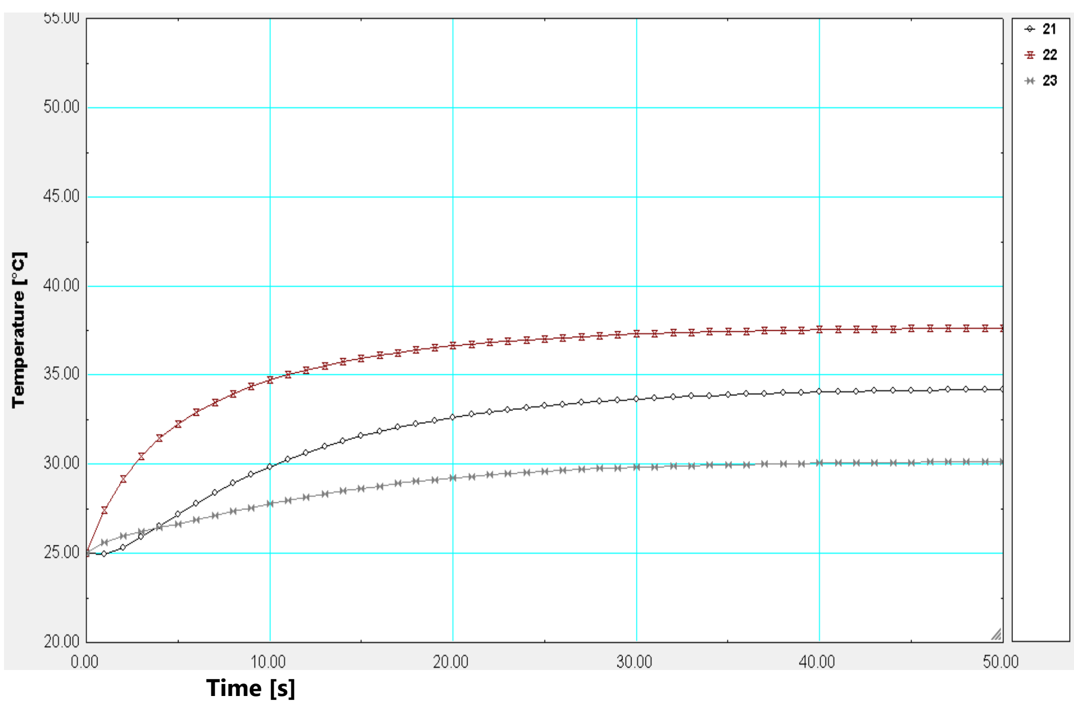
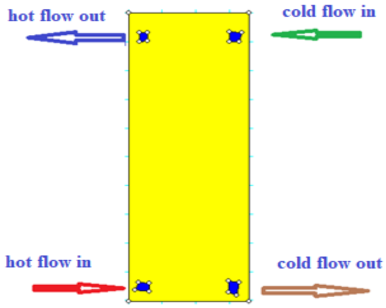
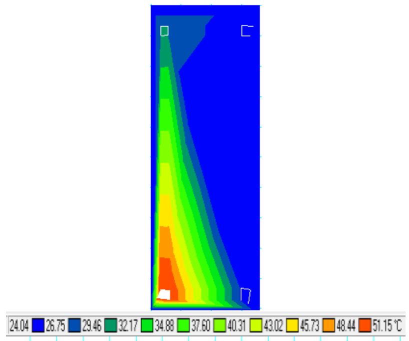


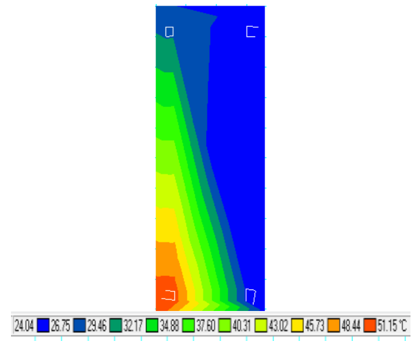
Figure (5): Temperature variation with time for three diagonal nodes for parallel flow plate heat exchanger



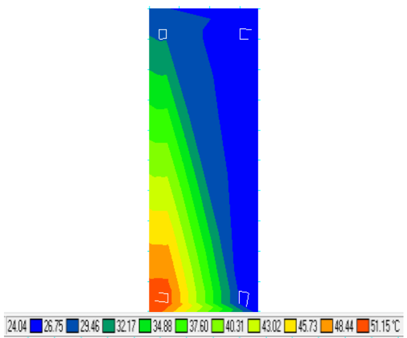
(a) Input model for counter flow



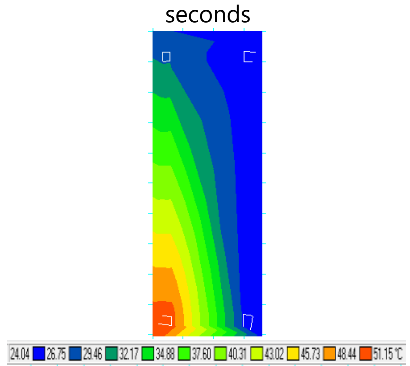
(b) Temperature contours at 0 seconds



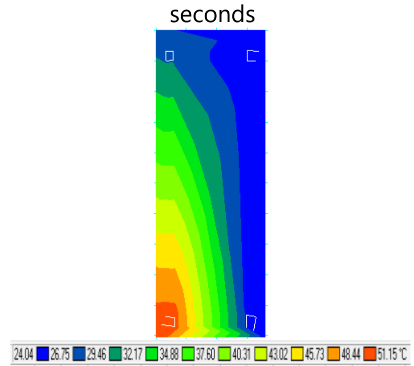
(c) Temperature contours at 5 seconds



(d) Temperature contours at 10 seconds



(e) 20 seconds



(f) 30 seconds

Figure (6): Temperature contours for counter flow in a plate heat exchanger at different time

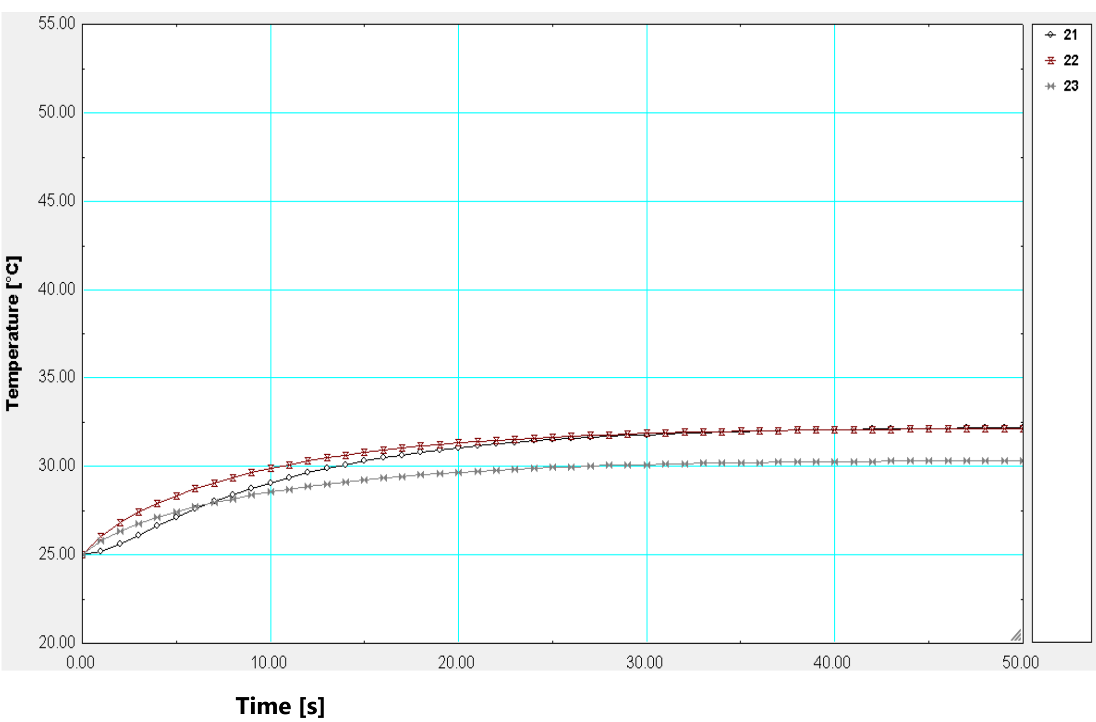
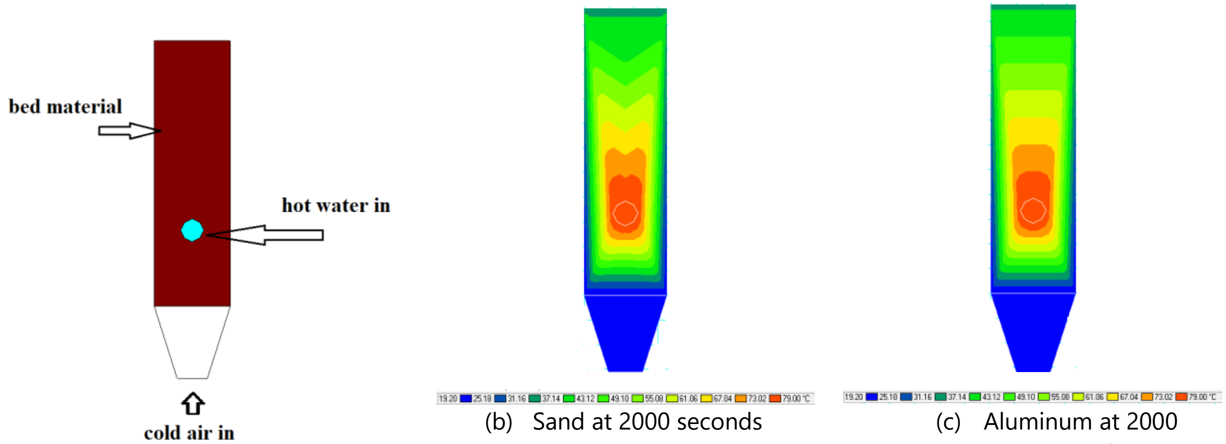


Figure (7): Temperature variation with time for three diagonal nodes for counter flow plate heat exchanger

Figures (8) shows the temperature distribution inside the fluidized bed heat exchanger with sand particles and aluminium particles as bed materials using FEHT code after 2000 seconds. While figure (9) and figure (10) show the temperature variation with time for bed material aluminium and sand, respectively. It is clear that fluidized bed with aluminium particles reaches the steady state condition faster than sand particles. This return to the high conductivity of the aluminium compared with sand.



(a) Input model (b) Sand at 2000 seconds (c) Aluminum at 2000 seconds

Figures (8): Temperature distribution inside the fluidized bed heat exchanger at different Conditions

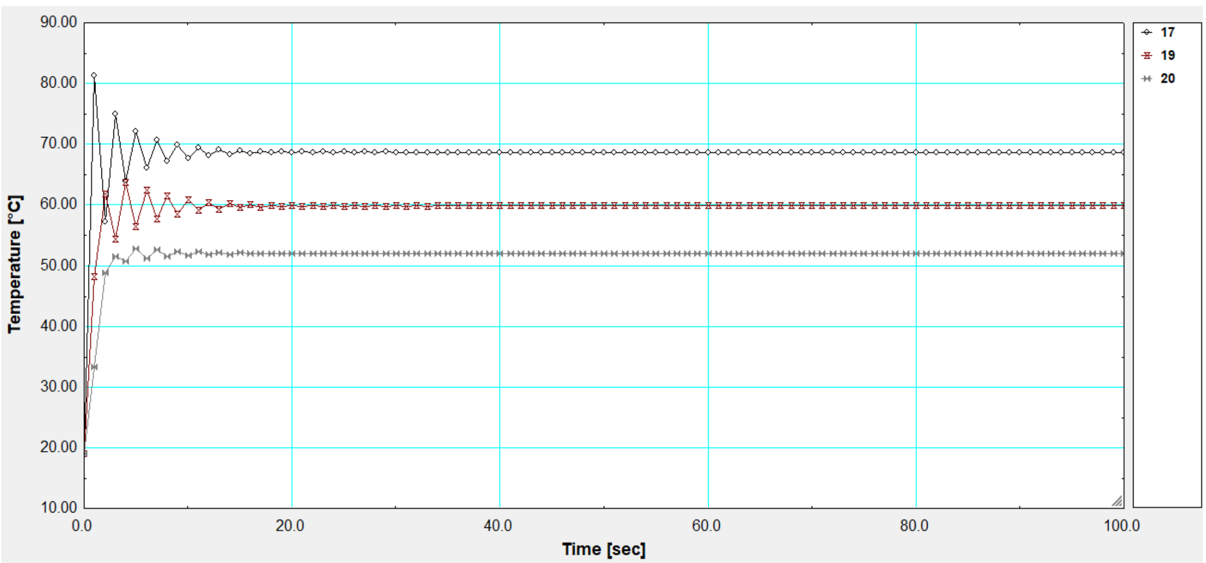


Figure (9): Temperature variation with time for three diagonal nodes for fluidized bed heat exchanger with aluminum particles

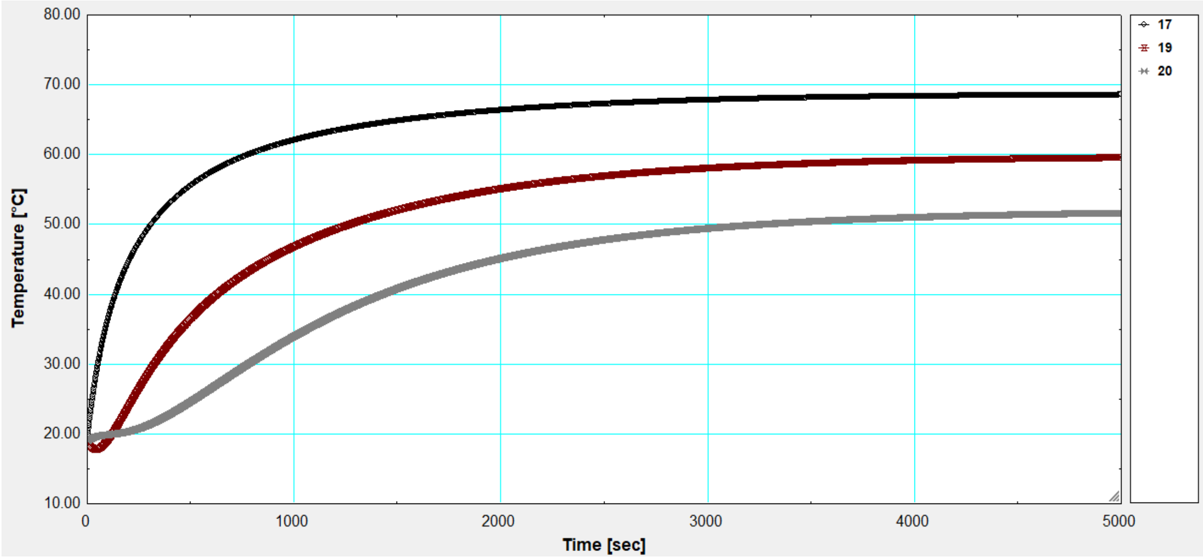


Figure (10): Temperature variation with time for three diagonal nodes for fluidized bed heat exchanger with sand particles

Figure (11) shows the temperature distribution for Shell and tube heat exchanger without fouling by using FEHT. In figure (12), the temperature variation with time for three diagonal nodes for shell and tube heat exchanger appears. The present work shell and tube heat exchanger reaches a steady state at 2400 seconds.

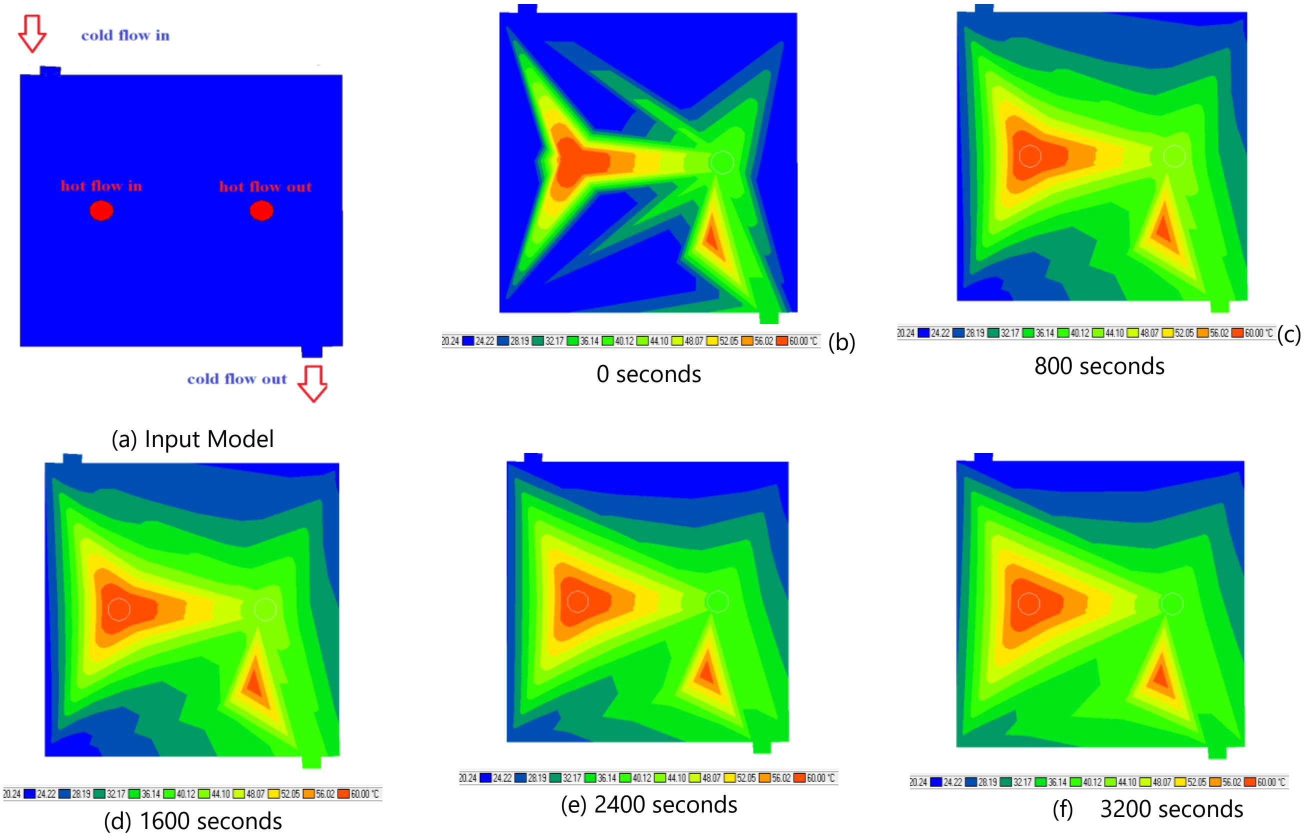


Figure (11): Temperature contours for Shell and tube heat exchanger

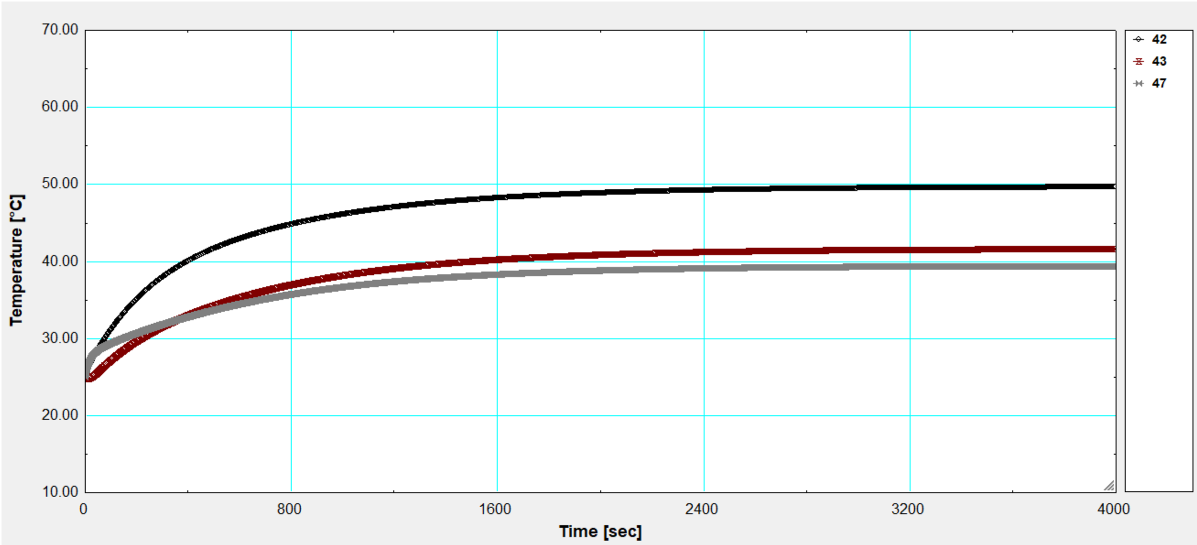


Figure (12**):** Temperature variation with time for three diagonal nodes for shell and tube heat exchanger

6.2 Experimental results analysis

To ensure that the steady state is reached, the log mean temperature difference against the different measuring points for all experimental tests is drawn in figure (13). This figure shows that for all the current tests, the steady state is reached, so all results are acceptable and ready for analysis.

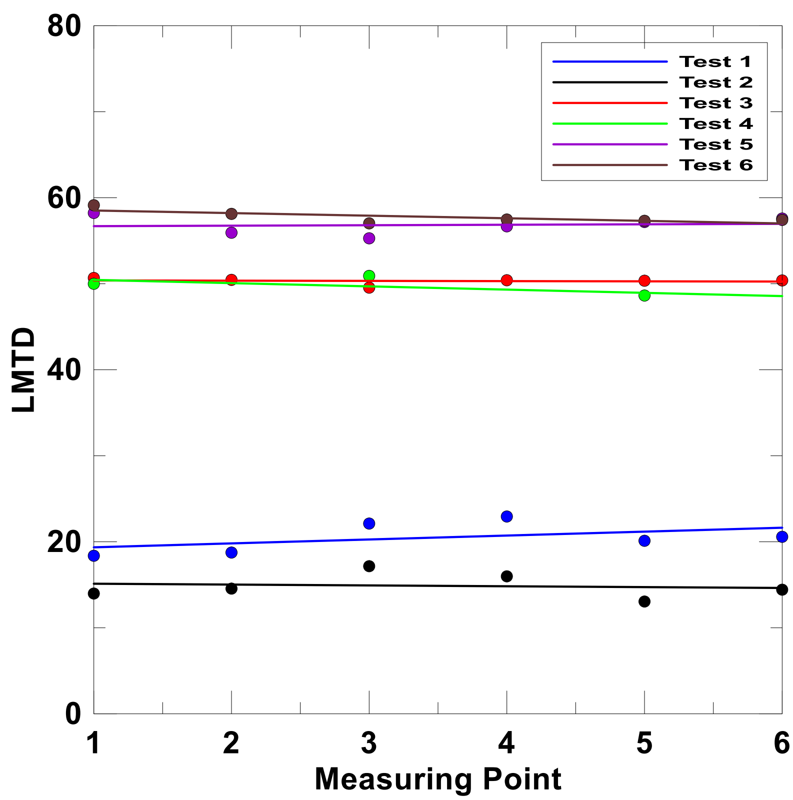


Figure (13): Log mean temperature difference variation with different measuring points

Although, the bed with aluminum particles reaches a steady state than with sand particles, as discussed before. But, in figure (14), the relation of overall heat transfer for fluidized bed with aluminum and sand bed materials is drawn, and it shows that the heat transfer mechanism for sand is better than aluminum. This returns to the thermal properties of sand as heat storage.

Figure (15) shows that the overall heat transfer coefficient in the counter flow plate heat exchanger is better than parallel flow in the same heat exchanger. This result is compatible with the general heat transfer principles because the parallel flow is poor thermodynamically.

Figure (16) shows the effect of fouling in decreasing the overall heat transfer coefficient for the same condition in shell & tube heat exchanger.

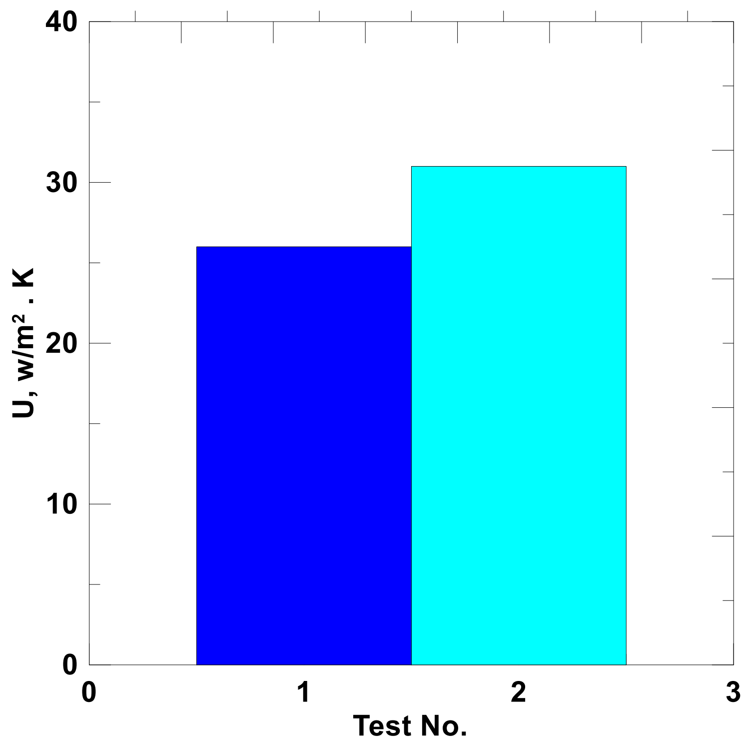


Figure (14): Comparison of overall heat transfer coefficient for different fluidized bed heat exchangers test.

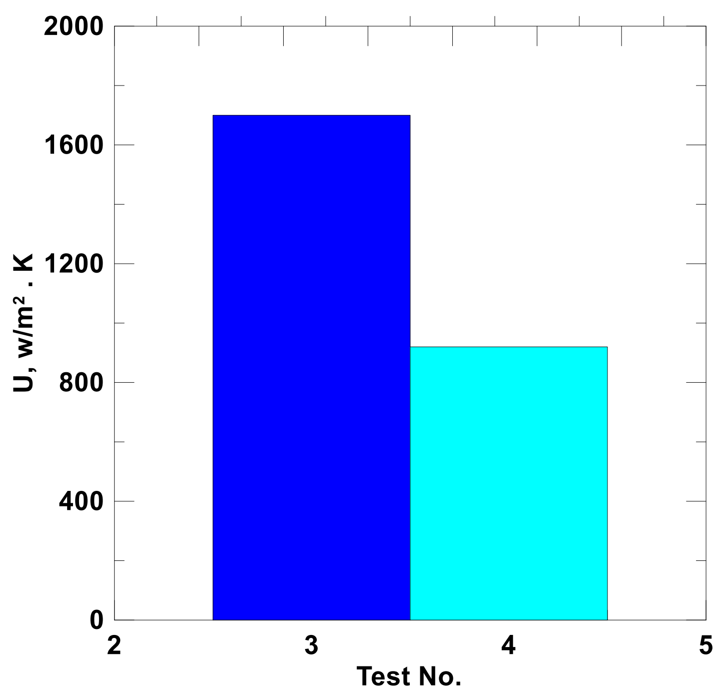


Figure (15): Comparison of overall heat transfer coefficient for different plat heat exchangers tests.

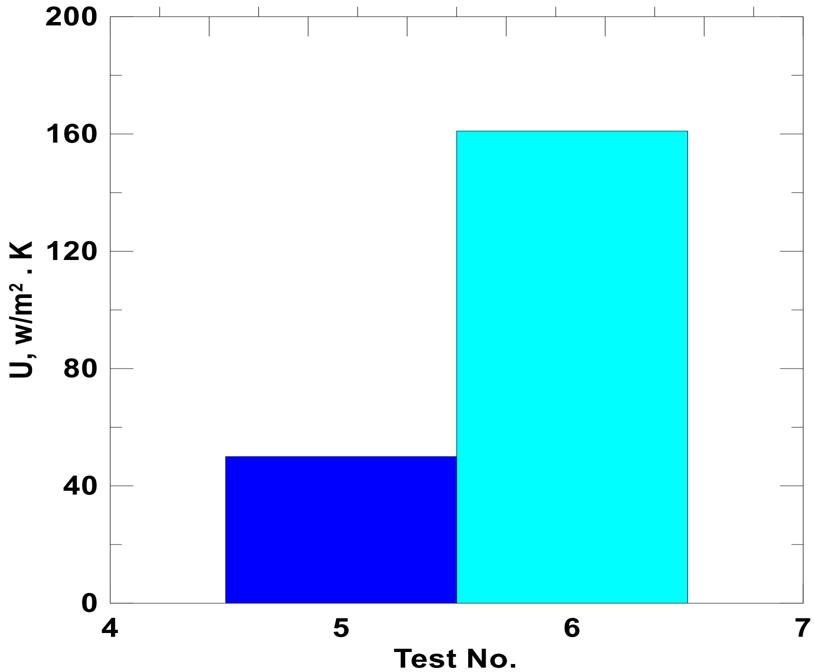


Figure (16): The effect of fouling in shell & tube heat exchanger overall heat transfer coefficient

Figure (17) is summarized one of the main objectives of the present experimental work. It shows the effectiveness of the three types of heat exchangers at the different experimental conditions. The plate type comes in the top followed by the fluidized, where shell & tube comes in the last place. This figure needs a lot of discussion to explain these differences. In general, each test conditions play the role of effect in each effectiveness of the heat exchanger. But we can compare each type of heat exchanger with its similarities. The first and second experimental tests show that the thermal effectiveness of fluidized beds with sand material is better than aluminum material. These results are compatible with the study on different materials that have been conducted in reference (Ehsani, Movahedirad, & Shahhosseini, 2016). The third and fourth experimental tests show that counter flow is better than parallel flow for plate heat exchangers. Finally, the fifth and sixth tests explain the bad effect of fouling accumulation in the heat transfer mechanism.

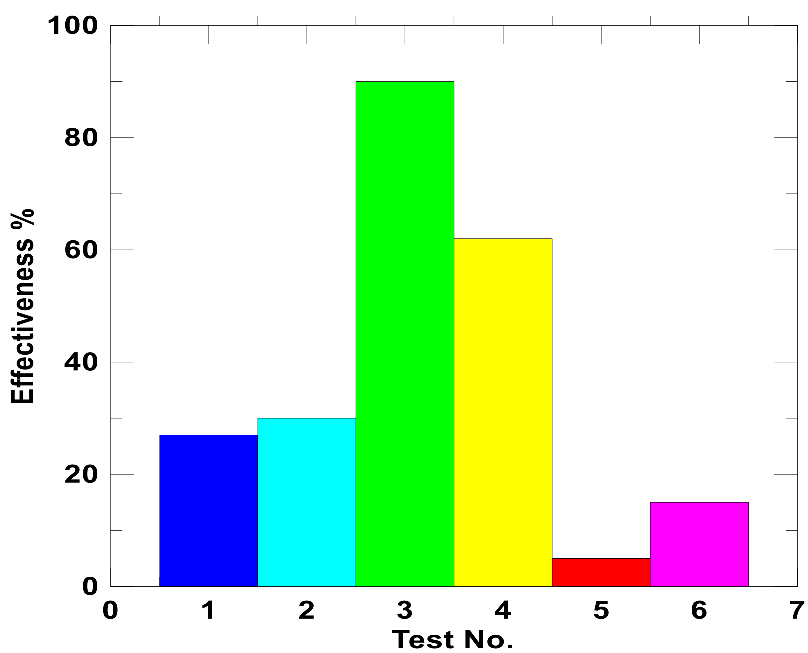


Fig. (17): Effectiveness comparison of all present work Tests

7. Conclusions

In this paper, heat transfer from different three types of heat exchangers has been studied and tested for different experimental conditions. The main conclusions which can be drawn from the results of the present work are:-

1. All experimental tests are reached to steady-state conditions.
2. Counter flow plate heat exchanger has the effectiveness of 90% compared with the parallel flow of 60% effectiveness for working experimental conditions.
3. The fouling effect in decreasing heat transfer is cleared. In the present work, fouling decreases effectiveness from about 18% to about 4%.
4. The effectiveness of a fluidized bed heat exchanger depends on the material used for the bed. In the present work, the effectiveness for the same conditions for sand material is about 30% and for aluminum is about 28%.
5. Overall heat transfer coefficient is obtained and compared for all experimental tests, and it is directly proportional to the effectiveness of the heat exchanger.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Nomenclature and abbreviations

Symbol	Definition	Dimension
$T_{c,i}$	Input temperature of cold fluid	ºC
$T_{c,o}$	Output temperature of cold fluid	ºC
$T_{h,i}$	Input temperature of hot fluid	ºC
$T_{h,o}$	Output temperature of hot fluid	ºC
ε	Effectiveness of the heat exchanger	-
$\dot{q}$	Local internal generation rate per unit volume	W/m^3
ρ	Density	Kg/m^3
C_p	Specific heat	J/kg.K
t	Time	second
k	Thermal conductivity	W/m.K
PHE	Plate heat exchanger	-
$\dot{m}_c$	Mass flow rate for cold fluid	kg/s
$\dot{m}_h$	Mass flow rate for hot fluid	kg/s