Heat Transfer and Global Energy Balance in a Plate Heat Exchanger

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Heat transfer evaluation in a plate heat exchanger (PHE) is one of the most common issue which is widely used in many engineering processes. The objective of this paper determine to formulate a global energy balance in a PHE and to study the heat losses, firstly focuses to study the heat transfer in countercurrent and parallel flow and to measure the temperature profile and to determine the number of transfer units (NTU) effectiveness of a plate heat exchanger. An addition to calculate the overall heat transfer coefficient using criteria equations, also focused to draw the temperature profile of the heat exchanger for both configurations countercurrent and parallel flow with temperature on the axial axis and thermocouple position on the horizontal axis. Furthermore discussed the behaior of temperature across the heat exchanger, compare the countercurrent and parallel flow arrangements, cpaing the experimental heat exchanger effectiveness with that estimated by the NTU method, the NTU effectiveness method application in the calculation of the output temperatures of a PHE. This concentric plate heat exchanger allows the study of heat transfer between hot water flowing through an internal sheets and cold water flowing in the ring area lying between the internal and external sheets, the plate heat exchanger allows measuring hot and cold water temperatures in different points of the heat exchanger.

Keywords: heat transfer, global energy balance, plate heat exchanger

1 Introduction

The behavior of the fluid inside the internal circulation system of a plate heat exchanger is complex due to the influence of many factors. The flow distribution has a significant influence on the performance of fluidic apparatus such as PHE. A plate heat exchanger consists of a set of corrugated metal plates confined in a shell. Each metal plate has 4 ports or holes. The plates and the ports are sealed by joints at their edge to allow hot and cold fluids flowing through narrow alternate passages formed between the plates. Heat transfers through the thin plates offering relatively low thermal resistance [1]. Heat exchangers are commonly used in energy conversion and transport processes in which heat transfers from hot fluid to cold fluid. Nowadays, the use of compact heat exchangers, for example, the plate heat exchangers, has been increasing owing to their advantages of compactness and high heat transfer efficiency [2]. Plate heat exchangers are typically categorized in three types: shell and plate, frame and plate, and brazed plate heat exchanger. The plate heat exchanger is the forerunner in heat exchanger technology; compact and manufactured to a high standard of quality and offers a durable solution that can stand high pressures and temperatures. Frame-and plate heat exchanger is commonly used for their ease of cleaning, simple adjustment of heat transfer area, compactness and excellent thermal-hydraulic performance [3]. The brazed plate heat exchanger, such plates could withstand higher pressure and later on found its increasing application as condenser and evaporator in air-conditioning and refrigeration systems [4]. Subsequent researchers have used numerical simulations to investigate plate heat exchangers: Dvořák and Vít used CFD to illustrate effects of plate pitch, material thickness and material thermal conductivity on flow and heat transfer in a heat exchanger, when non-zero material thickness was considered [5]. Giurgiu et al. in work used CFD to study the influence of geometric characteristics of the two plates on the intensification process of heat transfer [6], [7]. Jackson and Troupe and Kandlikar used numerical method to analyze the e-NTU relationship in various number of plates [8], [9]. Zhen-Xing Li and Li-Zhi Zhang investigated the flow unfavorable distribution and the consequent performance deteriorations in a cross flow and in a counter flow hollow fiber membrane module, they found that the packing fraction affects the flow unfavorable distribution substantially [10]. Najafi and Najafi performed a multi-objective optimization of PHE with pressure drop and heat transfer coefficient of a heat exchanger as objective functions [11], [12]. Brodnianska and Černecký worked experimentlly the shaped vertical heated surfaces [13], and Lee et al investigated on the heat transfer of the plate heat exchanger that has blunt sheets [14]. Plate heat exchanger is an important technology device used in the automotive industry. The increasing of PHE competition technology is increasingly required in automotive process [15]. This paper deals with the temperature field and overall heat transfer of a PHE with mathematical method calculation. With these methods it is not possible to obtain a complex view of the heat loading of the entire surface of the PHE caused by the thermal effect of cool and hot water in the surface of plates [16]. In this paper, a multi-objective is carried out such as heat transfer in countercurrent and parallel flow, overall heat transfer coefficient and minimization of the total pressure drop of PHE, (NTU) effectiveness of PHE, The PHE running under a steady state, with negligible heat loss, achieving the temperature profile for both countercurrent and parallel flow configurations. The temperature profiles were determined from the experimentally calculated data of temperature scopes, and local parameters of heat transfer were calculated.

This experimental study is thus intended to investigate the effect of the countercurrent and parallel flow conditions on the heat transfer of the Plate heat exchanger.

2 Methodology and unit description

The heat transfer of plate heat exchangers was measured in Kabul Polytechnic University. We used model of Computer Control plus Data Acquisition plus Data Management Software for Extended Plate Heat Exchanger. This Extended Plate Heat Exchanger allows the study of heat transfer between hot and cold water through alternate channels formed between parallel plates. We investigated the influence of the heat behavior between hot and cold water and automatic properties of the Plate Heat Exchanger. Automatic properties were studied through the thermocouple sensors: for hot water 5 (ST-1 to ST-5) and 5 (ST-6 to ST-10) for measuring cold water [17].

The PEH consists of a set of stainless steel plates arranged in parallel. The space between the plates forms a channel through which water flows. Hot and cold water channels alternate along the plate heat exchanger so that heat is transmitted by the thin plates. The PHE has 10 thermocouples: 5 (ST-1 to ST-5) for measuring hot water temperature (inlet, outlet and interim positions) and 5 (ST-6 to ST-10) for measuring cold water temperature (inlet, outlet and interim positions). These exchangers usually feature baffles to increase the heat transfer as shown in Figure 1.
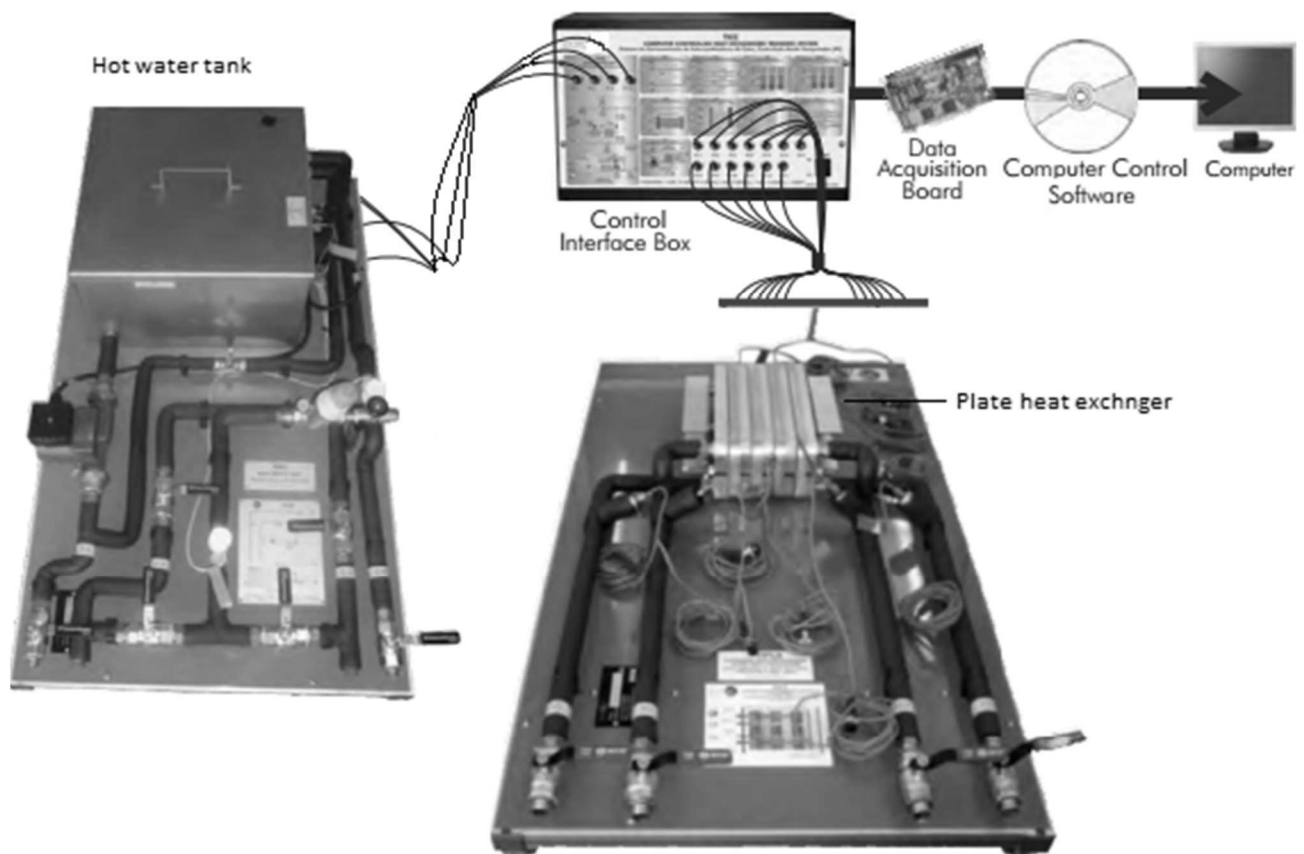

Fig. 1 Unit of plate heat exchanger [18]

The model of global flow in a plate heat exchanger may be serial flow that the whole flow passes through each plate and changes directions at the adjacent plate. This model is feasible only for small flows and it is rarely used. Or the model of global flow in a PHE may be connected flow which flow divides into sub flows that mix before leaving the exchanger. It is used for great volumes of liquid.

Hot water circuit

The working device system is started with hot water flows through a closed circuit. An electrical resistance (AR1) immersed in the tank heats the water to a certain temperature (ST-16). Water leaves the tank and is driven by a pump (AB-1) into the exchanger. Some amount of water enters the exchanger and some returns to the tank via a bypass. To facilitate this, a bypass valve (AVR-1) is included. Water is cooled along the exchanger then it flows through a flow sensor (SC-1) as it exits and then back into the heating tank and the cycle is repeated.

For drainage and control of hot water, the circuit is equipped with 4 ball valves: 2 at the base unit (AV-1 and AV-6) and 2 at the inlet and outlet of the exchanger.

Cold water circuit

Cooling water enters from the main net, goes through a flow control valve (AVR-2) then through a pressure regulator programmed at 0.5 Bar to avoid any excess pressure on the equipment. Before entering the exchanger, it goes through a flow sensor (SC-2) and then into the exchanger where it is heated. Water exits the exchanger and flows to the drainage system. Cold water can enter the

exchanger at either end. Depending on the configuration of the valves (AV-2, AV-3, AV-4 and AV-5), parallel or countercurrent flow can be set. This set-up can be experi-ential in the following scheme of the base unit. The schematics of the experimental apparatus is shown in Figure. 2.
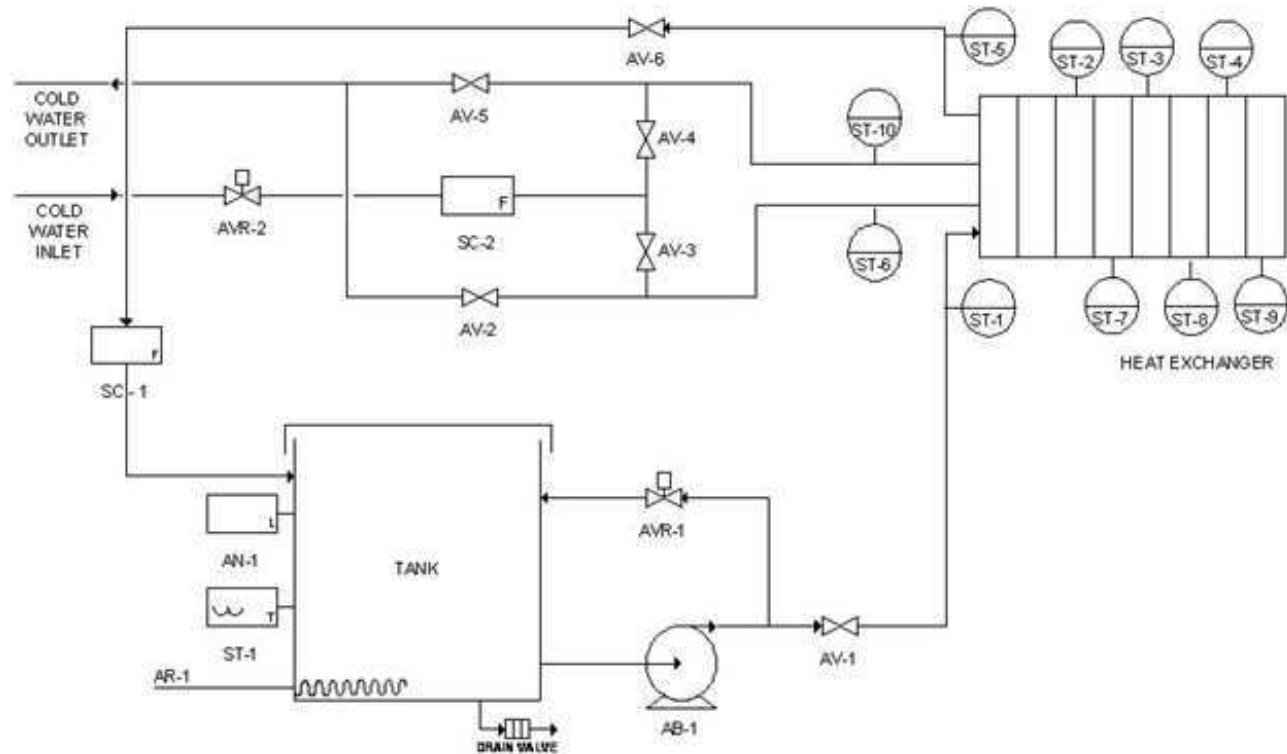

Fig. 2 *Scheme of experimental apparatus [19]*

The marking in the scheme of this experiment research apparatus are listed as follows:

- ST-16 Temperature sensor of the water in the tank
- ST-1 Hot water temperature sensor at the inlet of the exchanger
- ST-2 Hot water temperature sensor at the intermediate point of the exchanger
- ST-3 Hot water temperature sensor at the intermediate point of the exchanger
- ST-4 Hot water temperature sensor at the intermediate point of the exchanger
- ST-5 Hot water temperature sensor at the outlet of the exchanger
- ST-6 Cold water temperature sensor at the inlet/outlet of the exchanger
- ST-7 Cold water temperature sensor at the intermediate point of the exchanger
- ST-8 Cold water temperature sensor at the intermediate point of the exchanger
- ST-9 Cold water temperature sensor at the intermediate point of the exchanger
- ST-10 Cold water temperature sensor at the inlet/outlet of the exchanger
- SC-1 Hot water flow sensor

- SC-2 Cold water flow sensor
- AVR-1 Hot water flow regulation valve
- AVR-2 Cold water flow regulation valve
- AN-1 Water tank level switch
- AR-1 Electric resistance
- AB-1 Hot water flow centrifugal pump
- AV-2,AV-3, AV-4, AV-5 Cold water circuit ball valves to set the parallel / countercurrent flow
- AV-1, AV-6 Ball valves for pipe draining

3   Overall heat transfer coefficient and energy balance in a PHE

For energy balance of a PHE, if there are no changes of phases in the heat exchanger, the heat flow from the hot fluid can be calculated by the equation:

$$q_h = m_h c_{ph}(t_{h,in} - t_{h,out}), \qquad (1)$$

The heat flow to the cold fluid is:

$$q_c = m_c c_{pc}(t_{c,out} - t_{c,in}) \qquad (2)$$

Where:
m_h, m_c … the mass flows [kg s^{-1}],
c_{ph} and c_{pc} … the specific heat capacities of the hot and cold fluids [J kg^{-1}K^{-1}].

Theoretically, q_h should equal q_c, but due to environmental energy losses and also due to instrumental and observational measurement errors, they are not always equal. To represent the global phenomenon of heat transfer between fluids in a plate exchanger, thermal resistances occurring in each medium can be referred to. Heat flow on its way from the hot to the cold fluid has to overcome the resistances of the hot fluid limit layer, the separation wall and the cold fluid limit layer. These three resistances arranged in series constitute the total resistance, R_t:

$$Q = \frac{(t_h - t_c)}{R_t} = \frac{1}{\dfrac{1}{\alpha_1 A_h} + \dfrac{\delta}{kA} + \dfrac{1}{\alpha_2 A_c}} \qquad (3)$$

Where:
δ … the thickness of the separation wall.
$A = a\,N = L\,W\,N$ … heat transfer surface area in a plate heat exchanger
N … the number of thermal plates,
a … the plate surface area,
L … the plate length,
W … plate width.

In the differential form, the transferred heat, d_q, is proportional to the isothermal surface area perpendicular to the heat transfer direction, d_A, the temperature difference in the heat transfer direction,$(t_q - t_c)$, and a proportionality factor, U, called the overall local heat transfer coefficient [1].

$$dq = U(t_h - t_c)dA \qquad (4)$$

Equation (4) is solved by integration taking into account the variation of the heat transfer driving force and the overall heat transfer coefficient with the position in the heat exchanger. When constant values of the overall heat transfer coefficient and of the heat capacities of liquids in the equipment are assumed, integral form of the heat transfer rate equation is:

$$q = UA\Delta t_{lm} \qquad (5)$$

Where:

Δt_{lm} … the logarithm mean of the driving force considering its value at the beginning of the heat exchanger, Δt_1, Δt_2 … the end of heat exchanger

$$(\Delta t)_{lm} = \frac{\Delta t_1 - \Delta t_2}{\ln \dfrac{\Delta t_1}{\Delta t_2}} \qquad (6)$$

While for parallel flow $\Delta t_1 = t_{h,in} - t_{c,in}$ and $\Delta t_2 = t_{h,out} - t_{c,out}$ and $\Delta t_1 = t_{h,in} - t_{c,out}$ and $\Delta t_2 = t_{h,out} - t_{c,in}$ for countercurrent flow. The ε-NTU effectiveness method analysis of a plate heat exchanger is defined as the coefficient between the actual heat exchanged and the maximum that can be transferred in an infinite area exchanger in countercurrent flow:

$$\varepsilon_{NTU} = \frac{Q_{real}}{Q_{max}} \qquad (7)$$

where $Q_{max} = m_h c_{ph}(t_{h,in} - t_{c,in})$ if $m_h c_{ph} < m_c c_{pc}$ and $Q_{max} = m_c c_{pc}(t_{h,in} - t_{c,in})$ if $m_c c_{pc} < m_h c_{ph}$

Therefore, effectiveness equals to:

$$\varepsilon_{NTU} = \frac{(t_{h,in} - t_{h,out})}{(t_{h,in} - t_{c,in})} \text{ if } m_h c_{ph} < m_c c_{pc} \qquad (8)$$

Or to parallel flow connection:

$$\varepsilon_{NTU} = \frac{(t_{c,out} - t_{c,in})}{(t_{h,in} - t_{c,in})} \text{ if } m_c c_{pc} < m_h c_{ph} \qquad (9)$$

The number of transfer units (NTU) is a dimensionless parameter defined as:

$$NTU = \frac{U\,A}{(mc_p)_{min}} \qquad (10)$$

Also, the capacity coefficient (CR) can be defined as:

$$C_R = \frac{(mc_p)_{min}}{(mc_p)_{max}} \qquad (11)$$

4 Procedure of experiment

To evaluate the energy balance, heat losses study and overall heat transfer coefficient the following procedures completed: using the software, the tank temperature is sited to a value between 40–60 [°C], the resistor and the hot water circuit pump are turn on. The hot water flow fixed at about 3 [l min-1]. Via the valves of AV-2, AV-3, AV-4 and AV-5, and choosing of the counter current flow, the cold water flow set 1.8[l min-1]. The air should be removed from the shell side of the heat exchanger using. Whenever the system reaching to stationary operating conditions we write down the temperatures indicated by all sensors and the flow of hot and cold water, the procedure will repeat until five measurements as shown in Table 1.

Tab. 1 *Recording of measured data during experiment*

Connections	Countercurrent Flow					Parallel Flow				
Numbers	1	2	3	4	5	1	2	3	4	5
Q_h [l min^{-1}]	2.8	2.4	2	1.5	1.1	2.9	2.5	2	1.6	1.2
Q_c [l min^{-1}]	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
ST16 [ºC]	45	40	40	40	40	40	40	40	40	40
ST 1 [ºC]	36.3	36.4	36.3	36.2	36.1	36.3	37.1	37.2	37.3	37.3
ST2 [ºC]	35.1	35	34.6	34.2	33.1	31.2	31.4	31	30.6	29.5
ST3 [ºC]	34.5	34.2	33.4	32.5	33.8	31.1	31.3	30.9	30.4	29.3
ST4 [ºC]	32.2	31.7	30.5	29	27.1	30.6	30.8	30.4	29.7	28.8
ST5 [ºC]	29.9	28.1	27	25.2	23.5	30.2	30.5	30.2	29.7	28.9
ST6 [ºC]	35.5	35.6	35.3	34.9	34.2	21	20.1	20.2	20.3	20.5
ST7 [ºC]	34.2	34	33.2	32.2	30.5	29	29.1	28.7	28	27.1
ST8 [ºC]	32.7	32.2	31.1	29.7	27.7	30.2	30.4	30	29.2	28.2
ST9 [ºC]	28.7	28	26.9	25.6	24	30.3	30.6	30.2	29.5	28.7
ST10 [ºC]	19.8	19.6	19.5	19.3	19.3	30	30.5	30.1	29.5	27.5

5 Results

In a countercurrent flow the outlet temperature of the cold fluid can exceed then the outlet temperature of the hot fluid but this cannot happen in a parallel flow system as shown Figure 4 and Figure 6. In fact, the hot and cold water temperatures change continuously along the length of the heat exchanger too, as shown Figure 3 and Figure 5. Measuring hot and cold water temperatures in countercurrent and parallel flow at different points in five step along the length of heat exchanger are shown in Table 1. The calculated results for a total energy balance, the overall heat transfer coefficient heat transfer in countercurrent and parallel flow, overall heat transfer coefficient, (NTU) effectiveness of PHE, the effective of average temperature difference between the two heat transfer fluids over the length of the heat exchanger and though derived for countercurrent and parallel flow, are presented in Table 2 and Table 3. The calculation of mentioned objectives are

as follows: from the work documentation, we write all necessary information on the dimensions of the heat exchanger in top part of Table 2, and Table 3, such as the average temperature, density, dynamic viscosity, specific heat capacity and thermal conductivity of hot and cold water. For each column of countercurrent flow from Table 1, calculated the heat flow from the hot fluid q_h = 1247.8 [W], from the cold fluid q_c = 1116.06 [W] and for parallel connection configuration the heat flow from the hot and cold fluid q_h = 1231.81 [W], q_c = 815.1 [W] using Equation (1) and Equation (2), individually. The estimation of the heat losses for both countercurrent and parallel connection streams are calculated in Table 2 and Table 3 individually. As well for countercurrent and parallel connection streams calculated the hot logarithmic mean of the driving force $\Delta t_{lm,h}$ = 5.83 [°C], $\Delta t_{lm,h}$ = 7.26 [°C] using Equation (6) one-by-one. The value of the heat transfer surface aria, A = 0.32 [m^2], is available in the laboratory work documentation.

Tab. 2 *Measured data processing for countercurrent connection configuration*

$t_{av, h}$ =41.15 [ºC] $t_{av, c}$ = 23.95 [ºC] A = 0.32 [m^2]					
$Cp_{,h}$ = 4179 [Jkg^{-1}K^{-1}] $Cp_{,c}$ = 4180 [Jkg^{-1}K^{-1}] ρ_h = 992 [kg m^{-3}] ρ_c = 997.2 [kg m^{-3}]					
μ_h = 0.652 10^{-3} [Pa s] μ_c = 0.932 10^{-3} [Pa.s] k_h = 0.631 [Wm^{-1}K^{-1}] kc = 0.616 [Wm^{-1}K^{-1}]					
Number	1	2	3	4	5
Q_h [m^3 s^{-1}]	4.67E-05	4.0E-05	3.3E-05	0.25E-05	1.8E-05
Q_c [m^3 s^{-1}]	3.0E-05	3.0E-05	3.0E-05	3.0E-05	3.0E-05
m_h [kg^3 s^{-1}]	0.046	0.04	0.033	0.025	0.018
m_c [kg^3 s^{-1}]	0.03	0.03	0.03	0.03	0.03
q_h [W]	1247.829	1069.568	891.306	668.48	490.218
q_c [W]	1116.06	1116.06	1116.06	1116.06	1116.06
$\Delta t_{lm,h}$ [ºC]	5.83	5.83	5.83	5.83	5.83
$\Delta t_{lm,c}$ [ºC]	8.79	8.79	8.79	8.79	8.79
Uh [W m^{-2} K^{-1}]	890.6	763.4	636.2	477.15	349.9
Uc [W m^{-2} K^{-1}]	528.9	528.98	528.98	528.98	528.988
mh $Cp_{,h}$ [J K^{-1}]	194.9	167.12	139.26	104.45	76.59
mc $Cp_{,c}$ [J K^{-1}]	125.4	125.4	125.4	125.4	125.4
NTU$_h$	1.096	1.096	1.096	1.096	1.096
NTU$_c$	1.01	1.01	1.01	1.012	1.012
C_R	0.64	0.75	0.90	1.20	1.63
ε_{NTU}	0.53	0.53	0.54	0.54	0.54

To countercurrent and parallel hot streams configuration calculated the theoretical values of the overall heat transfer coefficient $U_h = 890.68$ [W m^{-2} K^{-1}], $U_h = 706.58$ [W m^{-2} K^{-1}], using criteria equations equation (5). Furthermore the number of transfer units NTU for hot fluid in countercurrent and parallel flow are calculated NTU$_h$ = 1.09, NTU$_h$ = 0,83 respectively, the number of transfer units for cold fluid NTU$_c$ = 1.01, NTU$_c$ = 0,72 available in Table 2 and Table 3 using Equation (10). The capacity coefficient of hot fluid for both countercurrent $C_R = 0.64$, and for parallel $C_R = 0.62$ calculated using Equation (11). The effectiveness $\varepsilon_{\text{-NTU}}$ of PHE in an infinite area exchanger in countercurrent flow $\varepsilon_{\text{-NTU}} = 0.54$ and in parallel $\varepsilon_{\text{-NTU}} = 0.42$ accessible in Table 2 and Table 3 using Equations (8, 9). For countercurrent flow the calculation processing experiment data are shown in Table 2.

The scope of temperature is defined as a distribution of temperatures in individual points of the heat exchanger in a certain time [20]. By plotting the graphs of temperature according to the length or flow in/of devices with different flows configuration (countercurrent or parallel), it is possible to give a basic idea of heat transfer between hot and cold streams. The Figure 3 represents the temperature change in cross length of PHE.
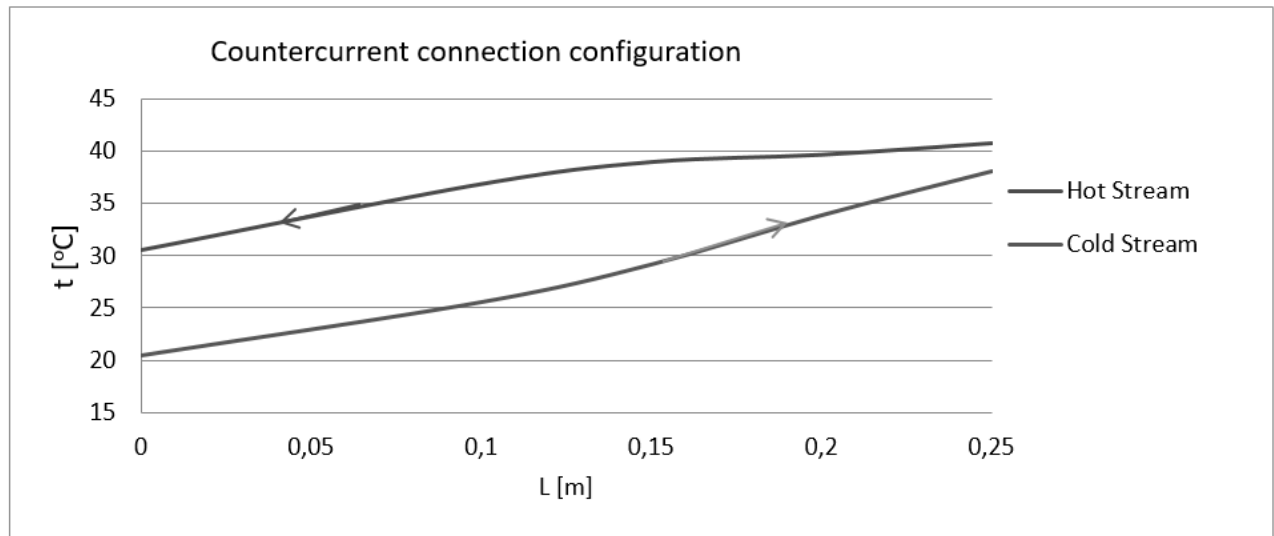

Fig. 3 *Countercurrent flow connection in a PHE*

To demonstrate the temperature change as function of flow a plate heat exchanger, which have done during experimental research in the laboratory of Kabul polytechnic University, the Figure 4, shows the countercurrent flow connection in PHE that the heat transfer processing is sufficient if there are a huge different between hot and cold flow of water in a PHE.
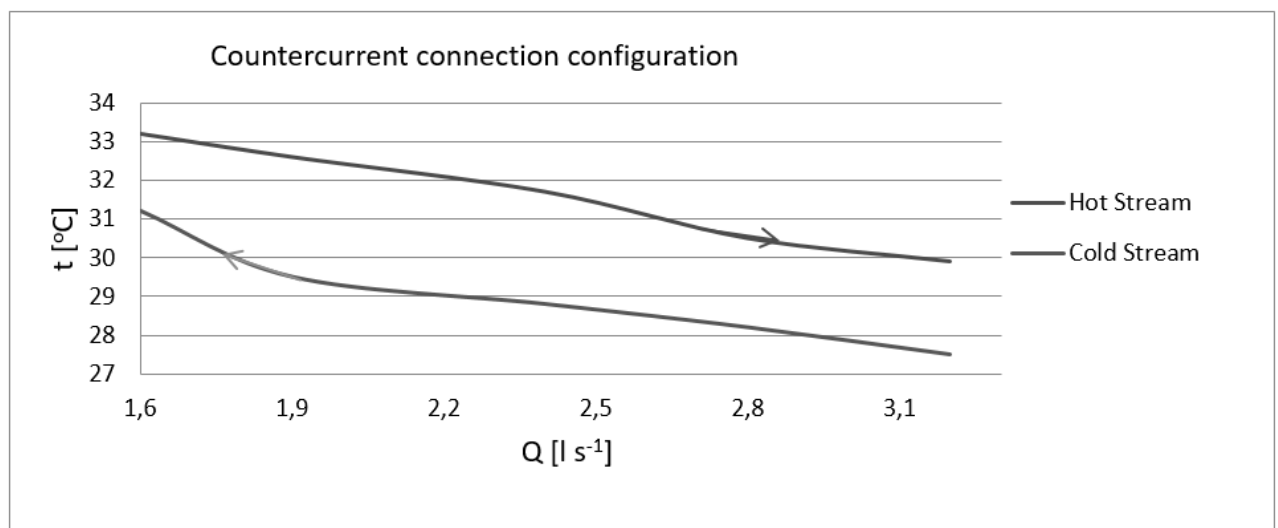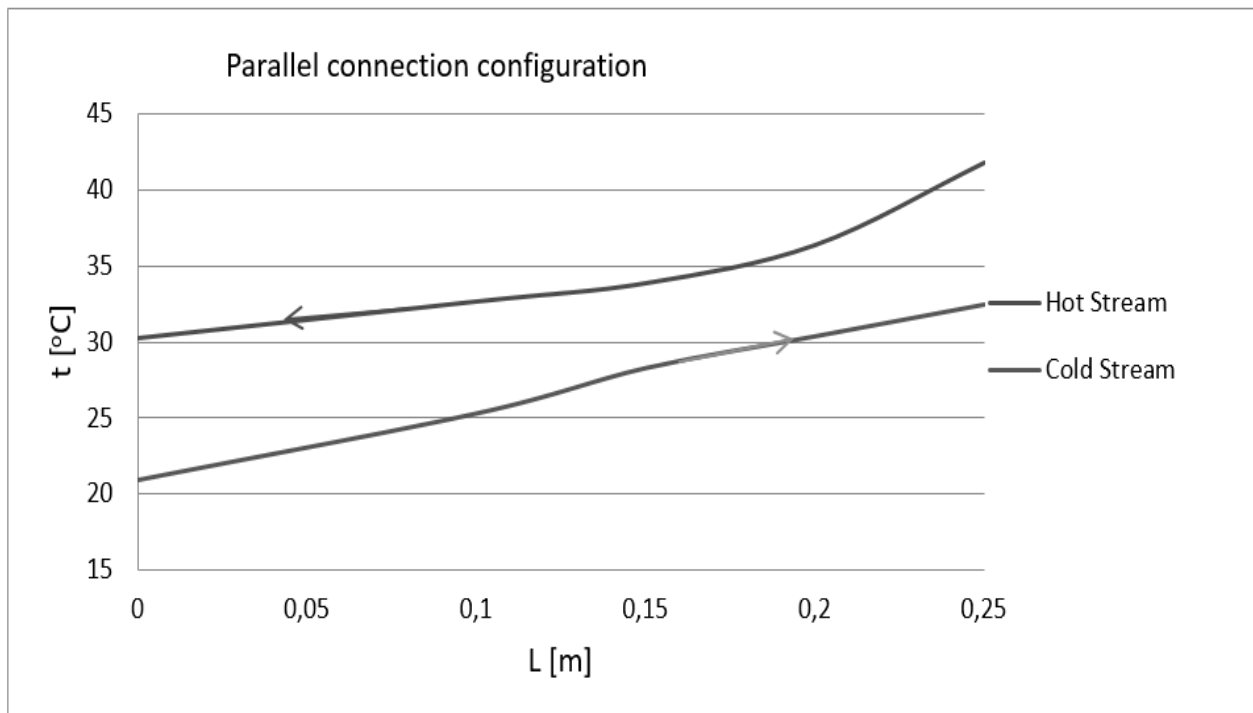

Fig. 4 *Changing of temperature in a countercurrent flow of hot and cold streams*

As well for parallel flow by calculation of the average temperature of hot and cold water in the system we find the density, dynamic viscosity, specific heat capacity and thermal conductivity of water in properties table of water.

For parallel flow the measured data processing according to measured data during experiment in Table 1, the calculation result are shown in Table 3.

Tab. 3 *Measured data processing for parallel connection configuration*

	$t_{av, h}$ =41.15 [°C]	$t_{av, c}$ = 23.95 [°C]		A = 0.32 [m²]	
	$Cp_{,h}$ = 4179 [Jkg⁻¹K⁻¹] $Cp_{,c}$ = 4180 [Jkg⁻¹K⁻¹] ρ_h = 992 [kg m⁻³] ρ_c = 997.2 [kg m⁻³]				
	μ_h = 0.652 10⁻³ [Pa s] μ_c = 0.932 10⁻³ [Pa s] k_h = 0.631 [Wm⁻¹K⁻¹] kc = 0.616 [Wm⁻¹K⁻¹]				
Number	1	2	3	4	5
Q_h [m³ s⁻¹]	4.8E-05	4.17E-05	3.3E-05	2.67E-05	2.0E-05
Q_c [m³ s⁻¹]	3.0E-05	3.0E-05	3.0E-05	3.0E-05	3.0E-05
m_h [kg³ s⁻¹]	0.048	0.041	0.033	0.026	0.02
m_c [kg³ s⁻¹]	0.03	0.03	0.03	0.03	0.03
q_h [W]	1231.81	1061.91	849.52	679.62	509.71
q_c [W]	815.1	815.1	815.1	815.1	815.1
$\Delta t_{lm,h}$ [°C]	7.26	7.263	7.263	7.263	7.264
$\Delta t_{lm,c}$ [°C]	8.998	8.998	8.998	8.998	8.998
Uh [W m⁻² K⁻¹]	706.58	609.12	487.29	389.83	292.37
Uc [W m⁻² K⁻¹]	377.4	377.42	377.42	377.42	377.42
mh $Cp_{,h}$ [J K⁻¹]	201.93	174.08	139.26	111.41	83.56
mc $Cp_{,c}$ [J K⁻¹]	125.4	125.4	125.4	125.4	125.4
NTUh	0.83	0.83	0.83	0.83	0.839
NTUc	0.72	0.72	0.722	0.722	0.722
C_R	0.62	0.72	0.90	1.12	1.50
ε_{NTU}	0.42	0.424	0.42	0.424	0.42

Fig. 5 *Temperature changing in a parallel flow connection in a PHE*

According to the separation process, the flow rate should be variable in one side and fixed in the other side (to keep constant thermal resistance) in a single test [21]. The Figure 5, represents the temperature change for parallel flows connection system in a PHE, which shows a huge difference between the cold and hot flow streams.

Anyway, the difference between the amount of hot and cold flow streams in a parallel flow connection system in a PHE shows the change of temperature in various amount of hot and cold flow which is indicated in Figure 6.
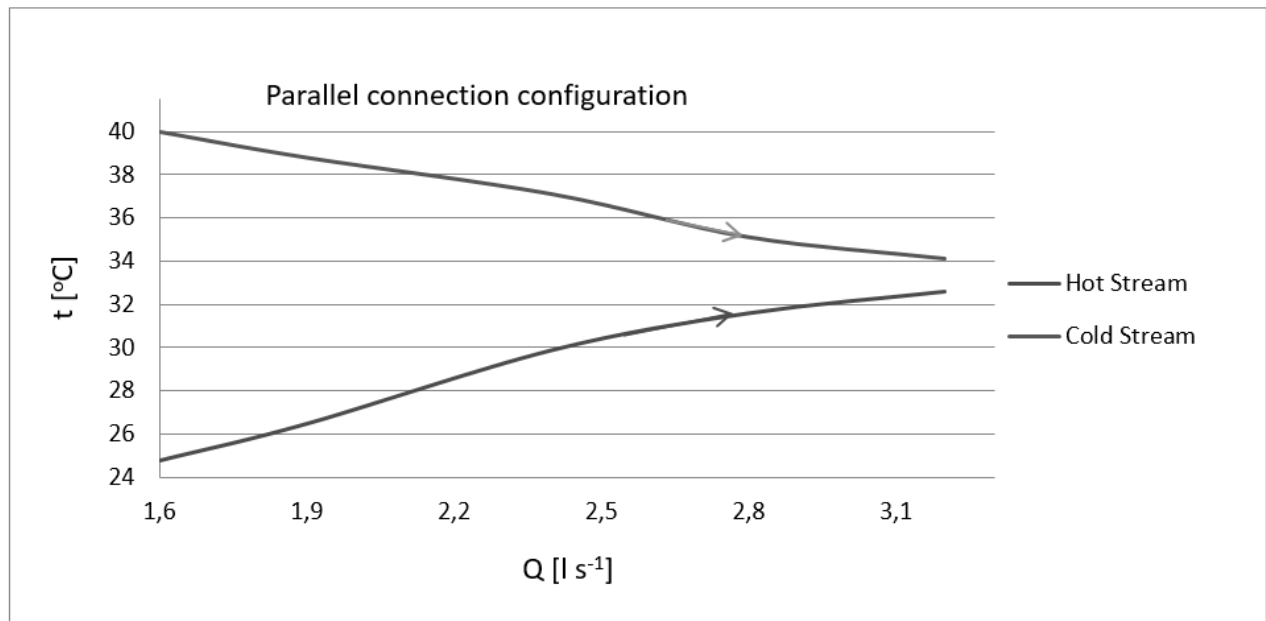
Fig. 6 *Temperature change of hot and cold streams in a parallel flow connection*

6 Conclusion

The examined plate heat exchanger type is designed supervisory control and data acquisition software. The validate and correct results of different researches, and the performance of PHE in industrial processes has always a major goal for engineers and designers. As well the PHE allows to study global energy balance, the study of losses, and the flow influence in the heat transfer, Study of the heat transfer in crosscurrent and parallel flow conditions and determination of the NTU effectiveness. The aim of the present study is to investigate application of heat transfer between hot and cold water to evaluate the influence of the flow in the heat transfer The PHE allows the heat transfer study between hot water that circulates through an internal area and cold water that flows through the annular zone between the internal and the external area. This exchanger permit to measure cold water and hot water temperatures in different points of the exchanger. This research has compared against experimental data in terms of accuracy and simulation time. The mentioned graphs and tables which are summarized above indicated the main conclusions from this study. Current work includes inspecting the real system in order to the effects of countercurrent and parallel flow on the heat exchanger plates for a better thermo-hydraulic performance. Results shows in a countercurrent flow the outlet temperature of the cold water can exceed then the outlet temperature of the hot fluid but this temperature increasing cannot happen in a parallel flow configuration.

Acknowledgements

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