A SYSTEMATIC STUDY OF THE INFLUENCE OF PROCESS VARIABLES ON THE OVERALL HEAT TRANSFER COEFFICIENT IN A SHELL AND TUBE HEAT EXCHANGER

Naveed ul Hasan Syed*[1], Qurat-ul-Ain[1], Muddasar Habib[1], Naseer Ahmed Khan[1], Sultan Ali[1]

ABSTRACT

A systematic experimental study was carried out on a shell and tube heat exchanger (STHx) to examine the influence of process variables such as hot and cold water flow rate, and the hot water inlet temperature on the overall heat transfer coefficient (U). The results show that the U increased with increasing the hot water and cold water flow rates. Similarly, the increase in hot water inlet temperature, improved heat transfer rate. It was observed that the increase in the U by increasing the cold water flow rate was significantly higher than with increasing the hot water flow rate. Under similar process conditions, at 36 oC hot water inlet temperature, the U increased from 709.96 to 1045.50 W/(m^2.^{o}C) with the increasing cold water flow rate from 0.75 to 2.5 L/min. While for the hot water case, the U increased from 709.96 to 940.43 W/(m^2.^{o}C) for the corresponding hot water flow rate. An empirical model correlating the outlet temperature of the STHx fluids with the inlet conditions has also been proposed. The proposed model was used to calculate the outlet temperatures of the hot and cold water and the heat flux. The model predictions were compared with the experimental results and a good agreement was found.

KEYWORDS: *Energy conservation, Heat flux, Modeling, Segmental baffles, Thermal boundary layer.*

INTRODUCTION

Efficient utilization of energy resources and improving the overall heat transfer coefficient (U) in energy intensive equipment such as heat exchangers, evaporators and distillation columns are the areas of significant importance at present (Du *et al.,* 2018; Andrzejczyk and Muszynski, 2018; Parikshit *et al.,* 2015). Several types of heat exchangers are used in process industries, among which shell and tube heat exchangers (STHxs) are one of the most important heat transfer equipment. The STHxs are used in a wide range of process industries that include petrochemicals, refineries, fertilizer, chemical plants, nuclear technologies and waste heat recovery units (Kapale and Chand, 2006; Thirumarimurugan and Kannadasan, 2008; Wang *et al.,* 2009; Parikshit *et al.,* 2015; Du *et al.,* 2018).

A large amount of experimental and theoretical works has been carried out to investigate the influence of different process variables such as the Reynolds number, inlet and outlet fluid temperatures, and the number of tube and shell passes on the improvement of U in STHxs (Yanik and, 2004; Wang *et al.,* 2009). The experimental studies have emphasized primarily investigating and enhancing the U in a shell and tube heat exchanger (STHx) by studying the effect of different process variables and bringing changes to the designs. Similarly, the theoretical studies are performed to develop generalized models and empirical correlations of U as a function of process variables studied (Aghareed *et al.,* 1991; Miranda and Simpson, 2005; Kapale and Chand, 2006; Wang *et al.,* 2009; Ren *et al.,* 2018).

The U depends on process variables such as mass flow rate, inlet temperatures, heat flux, temperature difference, pressure and viscosity knowing, which could improve process efficiency, reduce operational cost and helps in process equipment designing (Lachi *et al.,* 1996; Yanik and Webb, 2004; Kapale and Chand, 2006; Vera-Garcia *et al.,* 2010; Syed and Sultan, 2011). The literature shows that in general the U has been studied as a function of the feed flow rate, feed inlet temperature, temperature difference, viscosity and feed concentration (Kapale and Chand, 2006; Vera-Garcia *et al.,* 2010; Syed Naveed and Sultan, 2011).

An increase in the flow rate of a fluid entering a STHx increases the turbulence inside the device and causes the heat transfer rate to improve. On the other hand, a continuous increase in the flow rate may lead to high pressure drop inside the STHx and high pumping costs (Butterworth, 2002; Montgomery, 2003). Therefore, an optimum condition is needed to run a process smoothly.

1 Department of Chemical Engineering, University of Engineering & Technology Peshawar, Pakistan.
Corresponding author: Syed Naveed; Email: syednaveed@uetpeshawar.edu.pk

Similarly, the viscosity is another important variable to study its influence on the U. Liquids with high viscosities and concentrations have a low U as they don't readily transfer heat to the other phase. Techniques such as increasing feed inlet temperature are used to reduce liquid viscosity and improve heat transfer rate between the two phases (Cvengros *et al.,* 2000; Mandavgane, 2004; Kapale and Chand, 2006; Vera-Garcia *et al.,* 2010). Modeling the heat transfer related processes can help in understanding the dynamics of a process and to find the optimum process conditions without carrying out the vigorous experimental work. However, validation of model predictions with the experimental results is of equal importance (Kapale and Chand, 2006; Wang *et al.,* 2009; Parikshit *et al.,* 2015; Du *et al.,* 2018).

In this research work, systematic sets of experimental runs were carried out to study the effect of hot and cold water flow rate, and hot water inlet temperature on the U in a lab scale STHx. An empirical model has also been proposed to correlate the outlet temperature of cold and hot water with the feed flow rate and inlet temperature. A comparison of the model predictions and the experimental results provided a good agreement. The study has valuable importance as it provides a comparison of the effect of feed flow rate in the tube side and the shell side on the U. Moreover, the proposed model helps in understanding the relationship between the output and input process conditions.

MATERIAL AND METHOD

Experimental Set up

Figure 1 shows the diagram of the lab scale unit (HT-33X with a service unit HT-30X, Armfield) used during this study. The unit consisted of a 1-1 STHx, two peristaltic pumps for cold and hot water transportation and circulation, valves, water tanks, priming vessel and a control panel. The STHx consisted of seven stainless steel tubes with an outer diameter and wall thickness of 6.35 mm and 0.60 mm, respectively. The length of the tube bundle was 144 mm. The annulus (shell side) was made up of an acrylic tube with an inside diameter of 39 mm and the wall thickness of 3.0 mm. The unit comprised of two 25% cut acrylic sheet baffles and the combined heat transfer area was 20000 mm2.

The unit was provided with four temperature sensors named T1, T2, T3 and T4 at the inlet and outlet conditions of hot and cold water. The temperatures were displayed on the panel meter by setting the knob between T1 to T4. T1 and T2 displayed the temperatures at the inlet and outlet conditions of hot water, while T3 and T4 showed the inlet and outlet temperature conditions of cold water. The flow rate of hot and cold water was controlled through a flow control vale available within the unit and the flow rate varied between 0.75 to 2.5 L/min. Similarly, the effect of hot water inlet temperature studied in this work ranged from 27 to 51 ^{o}C

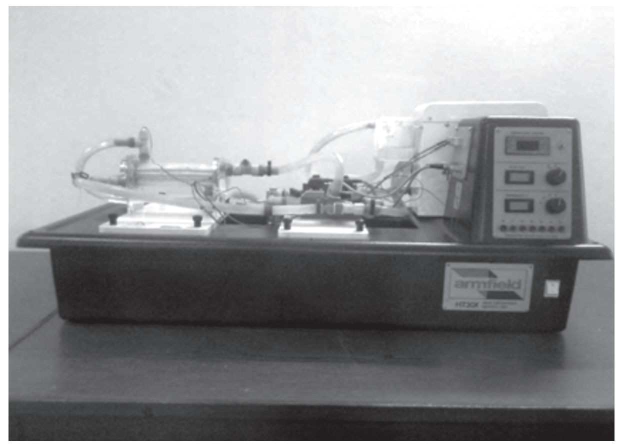

Fig. 1 1-1 Shell and Tube Heat exchanger (HT-33X – service unit HT-30X)

Figure 2 shows the schematic diagram of the full unit comprising a STHx, cold and hot water tanks, valves and pumps. Experiments were carried out under counter-current flow conditions in which hot water was passed through the tubes while cold water was kept on the shell side of the STHx. Both fluids after passing through the STHx and exchanging heat inside the equipment moved out and were discarded.

RESULTS AND DISCUSSIONS

Effect of hot water flow rate on the overall heat transfer coefficient

Figure 3, shows the overall heat transfer coefficient (U) versus the hot water flow rate. Three sets of experimental runs were carried out keeping the hot water inlet temperatures at 27, 36 and 45 oC. In these runs, the cold water flow rate was kept constant at 0.75 L/min, while the hot water flow rate was increased from 0.75

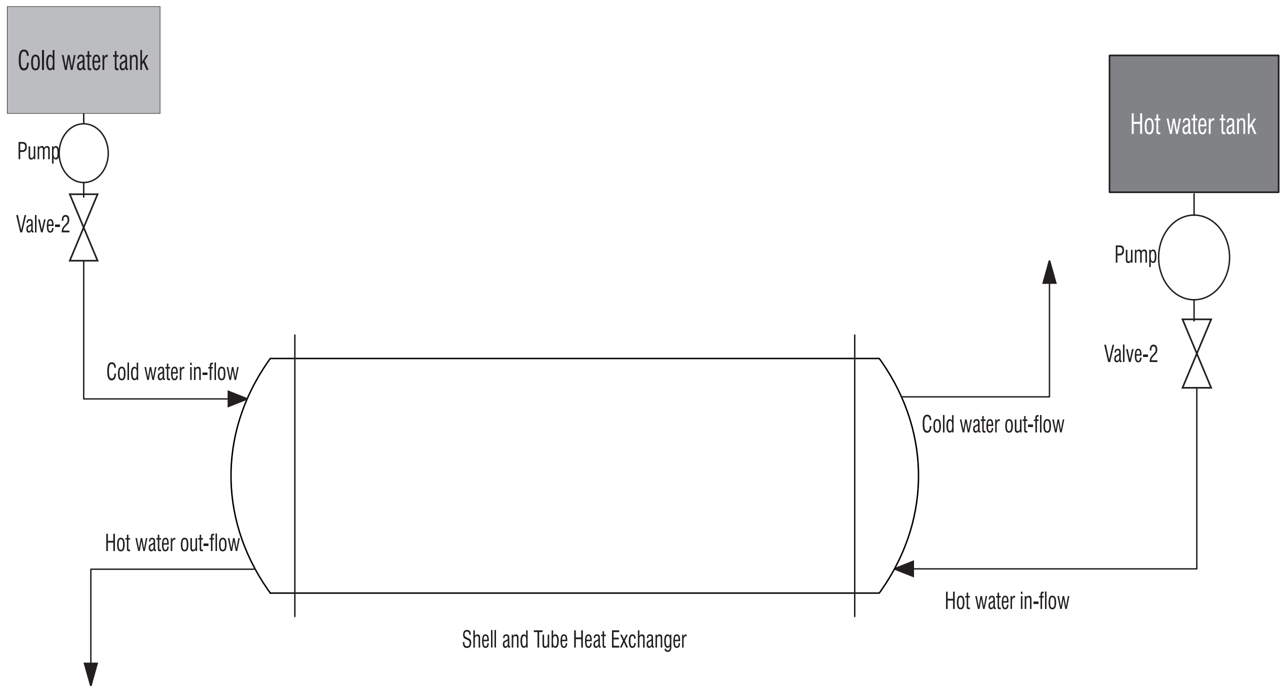

Fig. 2 Schematic representation of the shell and tube heat exchanger.

to 2.5 L/min. The results showed that the U increased monotonically with increasing hot water flow rate. In the experimental run at 27 ^{o}C, the U increased from a value of 685.65 to 931.35 W/(m^{2}.^{o}C) (blue curve), whereas at temperatures 36 and 45 ^{o}C the U increased from 709.95 to 940.15 W/(m^{2}.^{o}C) and 728.54 to 945.43 W/(m^{2}.^{o}C), respectively. The turbulence inside the tubes increased due to increase in the flow rate and caused a reduction in the thermal boundary layer. Hence the resistance to the heat transfer rate decreased.

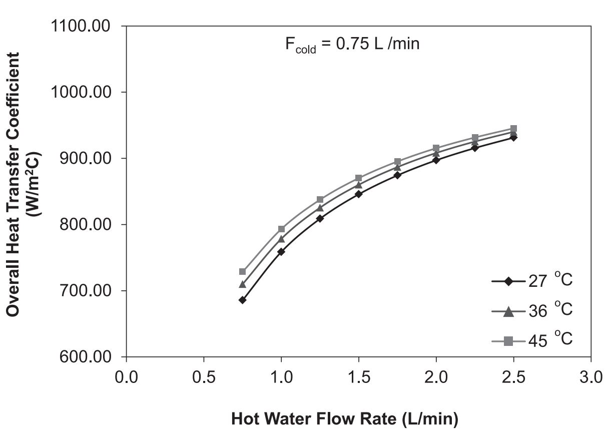

Fig. 3 Overall heat transfer Coefficient versus hot water flow rate.

3.2. Effect of cold water flow rate on the overall heat transfer coefficient

Figure 4, shows the effect of the cold water flow rate on the overall heat transfer coefficient (U). The results were taken at three different inlet temperatures 27, 36 and 45 ^{o}C of hot water. In these runs, the hot water flow rate was kept a constant value of 0.75 L/min, whereas the flow rate of cold water was increased from 0.75 to 2.5 L/min. The results showed a uniform increased in the heat transfer coefficient as expected. In this case, the U increased from 686.5 to 994.5 W/(m^{2}.^{o}C) at the hot water temperature of 27 ^{o}C. Similarly, at temperatures 36 and 45 ^{o}C, the U increased from 710.5 to 1045.5 W/(m^{2}.^{o}C) and 729.5 to 1087.5 W/(m^{2}.^{o}C).

Figure 5 illustrates a comparison of the increase in the U with increasing cold and hot water flow rates for the case when the inlet temperature of the hot water was kept at 36 oC. It was observed that the increase in the U was significantly higher in the case of cold water flow rate compared to the hot water flow rate case under the same process conditions. On the shell side of the STHx, 25% cut baffles were present due to which cold water had to flow through small cross-sectional areas on the shell side. Therefore, an increase in the flow rate of

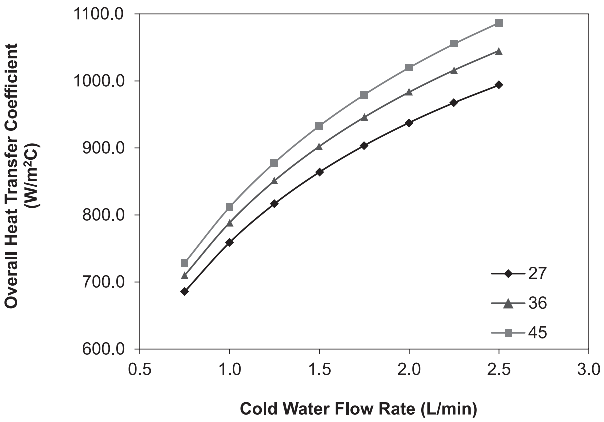

Fig. 4 Overall heat transfer Coefficient versus cold water flow rate.

the cold water caused high turbulence inside the shell and hence an improved heat transfer rate was observed.

The figure demonstrates that at 2.5 L/min of hot water flow rate, the value of U was 940.43 W/(m^2.^{o}C), whereas, for the same volumetric flow rate of cold water, the heat transfer coefficient increased to a value of 1045.50 W/(m^2.^{o}C), showing an increase of approximately 11%.

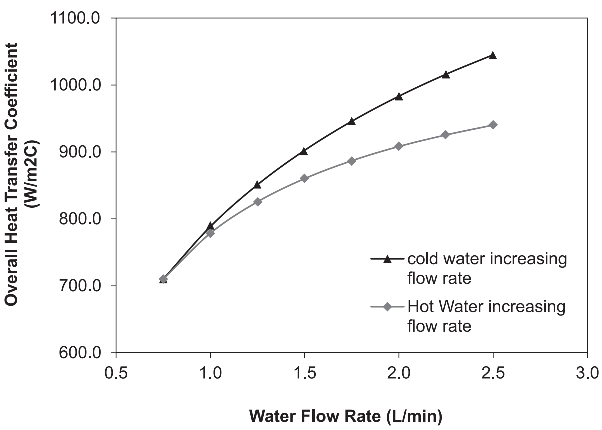

Fig. 5 Comparison of increase in the overall heat transfer Coefficient with increasing cold and hot water flow rates.

3.3. Effect of hot water inlet temperature on the overall heat transfer coefficient

Figure 6 illustrates the effect of the hot water inlet temperature on the overall heat transfer coefficient (U) for the three different sets of experimental runs. The first set of experimental runs was carried out keeping the flow rates of cold and hot water constant at 0.75 L/min, whereas the inlet temperature of hot water was altered from 27 to 51 oC. It was observed that the U increased linearly with increasing hot water inlet temperature. Similarly, two other sets of experimental runs were carried out in which the flow rates of cold and hot water were kept at 1.25 and 0.75 L/min, and 0.75 and 1.25 L/min, respectively. The increase in hot water inlet temperature increased the temperature gradient between the two fluids and hence an improved the heat transfer rate was observed. However, the increase in the U was found more in the third case when the hot water flow rate was kept at 0.75 and cold water flow rate was increased from 0.75 to 1.25 L/min. In this case, the value of U improved from 816.69 to 892.37 W/(m^2.^{o}C) when the temperature was increased from 27 to 51 oC, respectively.

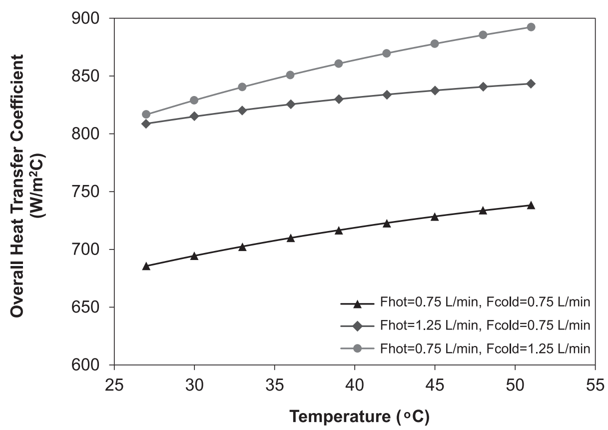

Fig. 6 Overall Heat transfer Coefficient versus hot water inlet temperature at different cold and hot water flow rates.

Overall, it was observed from the experimental runs that the cold water flow rate had a greater impact on the U compared to the hot water flow rate and the hot water inlet temperature.

Empirical model

The date generated from the experimental runs were used to develop an empirical model for predicting the outlet temperatures of hot and cold water in the STHx. For this purpose, Matlab SFTOOL was utilized to fit the experimental data. Numerous nonlinear single order equations were considered and the best fit model was selected. The model is based on the operational characteristics of the STHx. The outlet temperatures of hot water, T_{hot_o}, and cold water, T_{cold_o}, are the function of hot water inlet temperature T_{hot_i}, hot water flow rate, F_{hot}, and cold water flow rate, F_{cold}, given as,

$$\left[T_{hot\_o},\ T_{cold\_o}\right] = f\ \left[\ T_{hot\_i},\ F_{cold},\ F_{hot}\right]$$

The proposed empirical model is given as,

$$\left[T_{hot\_o}\ ,\ T_{cold\_o}\right] = \frac{a + b\left(T_{hot\_i}\right) + c\left(\frac{F_{hot}}{F_{cold}}\right) + d\left(T_{hot\_i}\right)\left(\frac{F_{hot}}{F_{cold}}\right)}{a + b\left(T_{hot\_i}\right) + c\left(\frac{F_{hot}}{F_{cold}}\right) + d\left(T_{hot\_i}\right)\left(\frac{F_{hot}}{F_{cold}}\right)}$$

The influence of T_{hot_i} on T_{hot_o} and T_{cold_o} is represented by a 2nd term in the nominator and denominator of the model, i.e. Eq. (2). Similarly, the effect of hot and cold water flow rates on T_{hot_o} and T_{cold_o} is shown in the form of ratio of hot water flow rate to the cold water flow rate. The ratio of flow rates of the fluid, Fhot/Fcold, is represented as a 3rd term in the nominator and denominator of the model. The 4th terms in the model represents the combine effect of hot water inlet temperature, hot water flow rate and cold water flow rate. The coefficients presented in the model and the statistical data are tabulated in Table 1.

The outlet temperatures calculated from the model predictions were utilized to find the heat flux through the heat exchanger. Table 2 shows the values of outlet temperatures and heat flux predicted by the model and a comparison with the experimental results.

Table 1: Model Coefficients.

Model Coefficients	T_{hot_o} Model	T_{cold_o} Model
a	8.667	15.060
b	0.510	0.009
c	2.004	3.779
d	2.967	0.163
f	0.0017	-0.0027
g	3.116	0.404
h	-0.00067	-0.00038
R2	0.998	0.971
R2 adjusted	0.998	0.971
RMSE	0.288	0.308

Table 2: Model predictions and the experimental results.

Fhot	F cold	Th,i	Th,o Exper-imental	Th,o mod-eled	% Error Th, o	Tc,i	Tc,o Exper-imental	Tc,o Mod-eled	% Error Tc,o	Heat Flux exper-imental	Heat Flux mod-eled	% Error Heat Flux
0.75	0.75	27	24.88	25.23	1.39	16	18.15	17.80	1.93	6.079	6.317	-3.927
0.75	0.75	39	34.4	35.19	2.26	16	20.74	19.93	3.87	13.140	13.707	-4.313
0.75	0.75	51	43.85	45.09	2.83	16	23.51	22.20	5.60	20.423	21.369	-4.633
1	1	27	25	25.23	0.89	16	18.03	17.80	1.25	7.636	7.827	-2.500
1	1	39	34.70	35.19	1.40	16	20.44	19.93	2.47	16.414	16.852	-2.671
1	1	51	44.32	45.09	1.72	16	23.02	22.20	3.56	25.406	26.122	-2.819
1.25	1.25	27	25.10	25.23	0.50	16	17.93	17.80	0.70	9.071	9.195	-1.376
1.25	1.25	39	34.93	35.19	0.74	16	20.21	19.93	1.35	19.431	19.706	-1.416
1.25	1.25	51	44.69	45.09	0.88	16	22.63	22.20	1.92	29.993	30.431	-1.458
1.5	1.5	27	25.18	25.23	0.17	16	17.84	17.80	0.24	10.414	10.462	-0.463
1.5	1.5	39	35.11	35.19	0.21	16	20.02	19.93	0.41	22.252	22.343	-0.413
1.5	1.5	51	44.99	45.09	0.20	16	22.32	22.20	0.55	34.281	34.413	-0.383
1.75	1.75	27	25.25	25.23	-0.11	16	17.77	17.80	-0.16	11.684	11.649	0.298
1.75	1.75	39	35.27	35.19	-0.23	16	19.86	19.93	-0.40	24.918	24.815	0.413
1.75	1.75	51	45.24	45.09	-0.35	16	22.06	22.20	-0.62	38.332	38.142	0.496
2	2	27	25.31	25.23	-0.34	16	17.71	17.80	-0.50	12.894	12.772	0.945
2	2	39	35.40	35.19	-0.61	16	19.72	19.93	-1.10	27.457	27.153	1.110
2	2	51	45.46	45.09	-0.81	16	21.84	22.20	-1.64	42.187	41.667	1.234

2.25	2.25	27	25.37	25.23	-0.55	16	17.66	17.80	-0.80	14.054	13.843	1.504
2.25	2.25	39	35.52	35.19	-0.94	16	19.60	19.93	-1.71	29.891	29.380	1.710
2.25	2.25	51	45.64	45.09	-1.22	16	21.65	22.20	-2.54	45.877	45.022	1.866
2.5	2.5	27	25.41	25.23	-0.73	16	17.61	17.80	-1.07	15.170	14.867	1.996
2.5	2.5	39	35.62	35.19	-1.22	16	19.49	19.93	-2.26	32.229	31.509	2.234
2.5	2.5	51	45.80	45.09	-1.57	16	21.48	22.20	-3.36	49.423	48.229	2.417

Figure 7 represents a comparison of the heat flux predicted by the model and the experimental results. The comparison showed that the model predictions were in good agreement with the experimental results, and the difference in their values fall within ±10%.

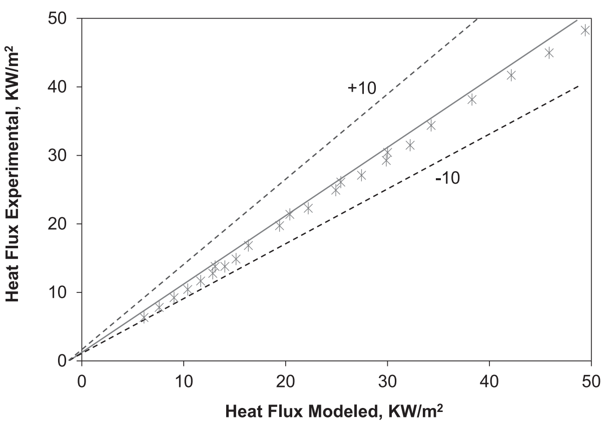

Fig. 7 Model predicted heat flux versus the experimental heat flux.

CONCLUSIONS

An experimental study was carried out on a lab scale 1-1 pass shell and tube heat exchanger (STHx) to investigate the effect of process variables such as hot and cold water flow rate, and the hot water inlet temperature on the overall heat transfer coefficient (U). The unit consisted of seven stainless steel tubes and a shell. Three different sets of experimental runs at temperature 27, 36 and 45 oC were performed. The results showed an increase in the U by increasing the hot water and cold water flow rates. Likewise, the U increased with the improvement in the heat transfer rate that occurred due to an increase in hot water inlet temperature. It was found that the heat transfer rate enhanced significantly when the cold water flow rate was increased as compared to the increase in the hot water flow rate. In the experimental runs, when the inlet temperature of the hot water was kept at 36 oC, the U increased from 709.96 to 1045.50 W/(m^2.^{o}C) with an increase in the cold water flow rate from 0.75 to 2.5 L/min. Whereas, the U increased from 709.96 to 940.43 W/(m^2.^{o}C) for the corresponding hot water flow rate. The increase in the U happened due to the presence of baffles on the shell side that caused more turbulence to create on the shell side and thus improved the heat transfer rate. Moreover, an empirical model relating the outlet temperature of the fluids in the STHx with the inlet conditions was also proposed. The proposed model was used to calculate the cold and hot water outlet temperatures and the heat flux. The model predictions were compared with the experimental results and provided a good agreement. It is also important to mention here that the proposed model is not a generalized model for all STHxs, however, provides suitable results for the process conditions under which the study was carried out.

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Nomenclature

Fcold	Cold water flow rate	L/min
Fhot	Hot water flow rate	L/min
Thot_i	Hot water inlet temperature	^{o}C
Thot_o	Hot water outlet temperature	^{o}C
Tcold_i	Cold water inlet temperature	^{o}C
Tcold_o	Cold water outlet temperature	^{o}C
A	Area	m^2
m*	Mass flow rate	kg/sec
U	Overall Heat Transfer coefficient	W/m^2 ^{o}C
STHx	Shell and Tube Heat Exchanger	

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