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Performance Analysis of Shell and Tube Heat Exchanger Using Miscible System

[1]M. Thirumarimurugan, [2]T.Kannadasan and [3]E.Ramasamy
Department of Chemical Engineering, Coimbatore Institute of Technology, Coimbatore-641 014

Abstract: An experimental investigation on comparative heat transfer study on a solvent and solution were made using 1-1 Shell and Tube Heat Exchanger. Steam is the hot fluid, whereas Water and Acetic acid-Water miscible solution serves as cold fluid. A series of runs were made between steam and water, steam and Acetic acid solution. In addition to, the volume fraction of Acetic acid was varied and the experiment was held. The flow rate of the cold fluid is maintained from 120 to 720 lph and the volume fraction of Acetic acid is varied from 10-50%. Experimental results such as exchanger effectiveness, overall heat transfer coefficients were calculated. A mathematical model was developed for the outlet temperatures of both the Shell and Tube side fluids and was simulated using MATLAB program. The model was compared with the experimental findings and found to be valid.

Key words: Heat exchanger design, simulated annealing, overall heat transfer coefficient

INTRODUCTION

A heat exchanger is a device in which energy is transferred from one fluid to another across a solid surface. Exchanger analysis and design therefore involve both convection and conduction. Two important problems in heat exchanger analysis are (1) rating existing heat exchangers and (ii) sizing heat exchangers for a particular application. Rating involves determination of the rate of heat transfer, the change in temperature of the two fluids and the pressure drop across the heat exchanger. Sizing involves selection of a specific heat exchanger from those currently available or determining the dimensions for the design of a new heat exchanger, given the required rate of heat transfer and allowable pressure drop. The LMTD method can be readily used when the inlet and outlet temperatures of both the hot and cold fluids are known. When the outlet temperatures are not known, the LMTD can only be used in an iterative scheme. In this case the effectiveness-NTU method can be used to simplify the analysis. The choice of heat exchanger type directly affects the process performance and also influences plant size, plant layout, length of pipe runs and the strength and size of supporting structures. The most commonly used type of heat exchanger is the shell-and-tube heat exchanger, the optimal design of which is the main objective of this study. Computer software marketed by companies such as HTRI and HTFS are used extensively in the thermal design and rating of HEs. These packages incorporate various design options for the heat exchangers including the variations in the tube diameter, tube pitch, shell type, number of tube passes, baffle spacing, baffle cut, etc. A primary objective in the Heat Exchanger Design (HED) is the estimation of the minimum heat transfer area required for a given heat duty, as it governs the overall cost of the HE. But there is no concrete objective function that can be expressed explicitly as a function of the design variables and in fact many numbers of discrete combinations of the design variables are possible as is elaborated below. The tube diameter, tube length, shell types etc. are all standardized and are available only in certain sizes and geometry. And so the design of a shell-and-tube heat exchanger usually involves a trial and error procedure where for a certain combination of the design variables the heat transfer area is calculated and then another combination is tried to check if there is any possibility of reducing the heat transfer area. Since several discrete combinations of the design configurations are possible, the designer needs an efficient strategy to quickly locate the design configuration having the minimum heat exchanger cost. Thus the optimal design of heat exchanger can be posed as a large scale, discrete, combinatorial optimization problem[13]. Most of the traditional optimization techniques based on gradient methods have the possibility of getting trapped at local optimum depending upon the degree of non-linearity and initial guess. Hence, these traditional optimization techniques do not ensure global optimum and also have limited applications. In the recent past, some experts studied on

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Corresponding Author: M. Thirumarimurugan, Department of Chemical Engineering, Coimbatore Institute of Technology, Coimbatore-641 014 Tel: 91-9943549700

the design, performance analysis and simulation studies on heat exchangers[12,13,15,16,18]. Modeling and Simulation of Shell and Tube Heat Exchangers Under Milk Fouling was carried out[15]. Dynamic Model for Shell and Tube Heat Exchangers was discussed[12]. Shell and Tube heat exchangers are applied where high temperature and pressure demands are significant and can be employed for a process requiring large quantities of fluid to be heated or cooled. Due to their design, these exchangers offer a large heat transfer area and provide high heat transfer efficiency in comparison with others. Modeling is a representation of physical or chemical process by a set of mathematical relationships that adequately describe the significant process behavior. Improving or understanding chemical process operation is a major objective for developing a process model. These models are often used for Process design, Safety system analysis and Process control. The simulation of an industrial system on a computer involves mathematical representation of the physical process undergone by the various components of the system, by a set of equations, which are in turn solved. Simulation is much cheaper than setting up big experiments or building prototypes of physical system and variables on the behavior of the system. A steady state model for the outlet temperature of both the cold and hot fluid of a shell and tube heat exchanger will be developed and simulated, which will be verified with the experiments conducted. Based on these observations correlations to find film heat transfer coefficients will be developed.

MATERIALS AND METHODS

Experimental Studies

Experimental Set up: Experiments were conducted on a 1-1 Shell and Tube Heat Exchanger. The Fig. 1 shows the schematic diagram of the heat exchanger.

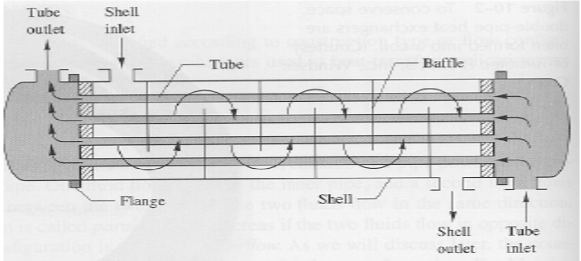

Fig. 1: 1-1 Shell and Tube Heat Exchanger

Table 1: Hot water-water system

Volumetric flow rate of cold fluid (lpm)	Volumetric flow rate of hot fluid (lpm)	Fluid Temperatures (ºC)			
		Cold fluid inlet	Cold fluid outlet	Hot fluid inlet	Hot fluid outlet
2	0.88	29	59	100	76
3	0.88	29	56	100	72
4	0.88	29	52	100	70
5	0.88	29	49	100	68
6	0.88	29	47	100	65
7	0.88	29	45	100	62
8	0.88	29	41	100	59
9	0.88	29	38	100	56
10	0.88	29	36	100	53
11	0.88	29	33	100	50

Table 2: 10% Acetic acid-water solution

Volumetric flow rate of cold fluid (lpm)	Volumetric flow rate of hot fluid (lpm)	Fluid Temperatures (ºC)			
		Cold fluid inlet	Cold fluid outlet	Hot fluid inlet	Hot fluid outlet
2	1.68	29	45.0	100	71.0
3	1.68	29	42.0	100	70.0
4	1.68	29	40.0	100	69.0
5	1.68	29	39.0	100	67.5
6	1.68	29	38.0	100	66.0
7	1.68	29	36.0	100	65.0
8	1.68	29	34.0	100	64.0
9	1.68	29	32.0	100	63.5
10	1.68	29	31.5	100	62.0
11	1.68	29	31.0	100	61.5

Experimental procedure: The overhead tank was filled with water. The heater was switched on and temperature was set to 100°C. It was waited until the set temperature was reached. The pump was switched on and water was allowed into heating tank and the hot inlet valve to the Heat exchanger was opened. The cold fluid inlet valve was opened. It was waited until the steady state has been reached. At steady state, all the four temperatures and flow rates of cold and hot fluid do not change. The Rota meter reading and the flow rate of hot fluid using collection tank was noted down. The flow rate of cold fluid was changed and waited for new steady state to be reached. The above step can be repeated

Experimental observations: The Observations made for the Hot Water-Water system and the varying composition of Hot Water -10% Acetic acid solution system are given in the following Table 1 and 2. The composition was taken based on volume.

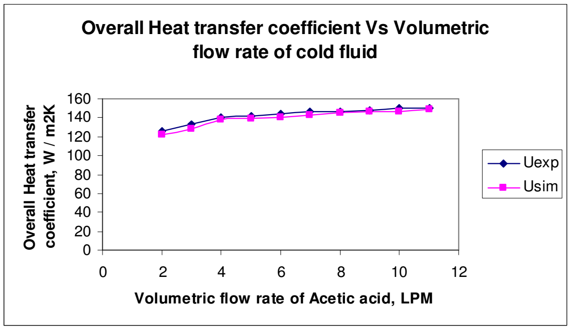

Fig. 2: Overall Heat Transfer Coefficient Vs Vol. flow rate of Cold fluid and composition of cold fluid

Modeling and simulation

Physical modeling: The physical model equation was developed using dimensional analysis followed by least square curve fitting experimental data as follows:

$$Nu = 0.4232(Re)^{0.339} (Pr)^{0.3412} (x)^{0.003}$$

Simulation: The models derived above are simulated using MATLAB. Simulation is done for various flow rates and for 10% Acetic acid and plotted in Fig. 2 along with the experimental values.

RESULTS AND DISCUSSIONS

The effect of different input variables on output variable are discussed in detail in the following sections. Heat exchanger effectiveness, the film coefficients for both hot and cold fluids and overall heat transfer coefficient calculations for the above observed readings are presented in the Table 3 and 4.

Effect of flow rate of the cold fluid: Increase in the flow rate of cold fluid results in increase in the overall heat transfer coefficient as can be seen from tables. This is because increase in the flow rate increases the Reynolds number, which in turn increases the Stanton number and thereby the film heat transfer coefficient. The increase in film heat transfer coefficient will increase the overall heat transfer coefficient. This will also cause a decrease in the tube outlet temperature, as can be observed form tables. This is because increase in the volumetric flow rate increases the mass flow rate in a much faster rate than over all heat transfer coefficient or the heat energy transferred. Since the specific heat remains almost constant, tube outlet temperature should decrease to comply with law of conservation of energy. As the flow rate of tube side fluid is increased, the tube side heat transfer coefficient increases, which in turn decreases fin effectiveness and surface effectiveness. The variation of fin effectiveness, surface effectiveness and exchanger effectiveness with flow rate for different compositions is shown in figures. Also the overall heat transfer coefficient increases, thereby NTU also increases and so exchanger effectiveness comes down.

Effect of composition of the cold fluid: A decrease in composition of Acetic acid will increase the overall heat transfer coefficient as can be seen from tables. This is because increase in the concentration of water increases the heat capacity of the tube side fluid and hence the heat transferred. Decrease in composition decreases the tube outlet temperature because decrease in the concentration increases the specific heat value, which leads to decrease in tube outlet temperature. A decrease in composition of Acetic acid will increase the overall effectiveness and will decrease the surface and fin effectiveness. Fin effectiveness and surface effectiveness of hot side remains almost constant since the variation in composition of cold side fluid does not affect the hot side fluid. Fin effectiveness and surface effectiveness of cold side shows a slight increase with decrease in volume percentage of Acetic acid as evident from tables. This may be because of the slight decrease in film heat transfer coefficient with increase in composition of water. Surface effectiveness depends on film effectiveness and hence this also will increase. Overall effectiveness increase with decrease in composition of Acetic acid

Overall heat transfer coefficient for S and T HE: As the volumetric flow rate of the tube side fluid is increased from 120 to 720 lph, the overall heat transfer coefficient increased from 126.167 to 150.15 W/(m^2 K). For the same volumetric flow rates, the simulated values varies from 121.805 to 148.605 W/m^2K respectively, i.e., almost same as experimental values.

Shell outlet temperature for S and T HE: For the flow rate increments from 120 to 720 lph, the outlet temperature of the shell side fluid varied from 45 to 31ºC, whereas the simulated values were 42 to 30ºC, respectively.

Tube outlet temperature for S and T HE: For the flow rate increments from 120 lph to 720 lph, the outlet temperature of tube side fluid varied from 71 to 61.5ºC, whereas the simulated values were 68 to 60ºC respectively.

Table 3: Water-water system

Cold fluid (Water)			Hot fluid (water)								
Fluid Temperature (ºC)		Mass flow rate (Kg h^{-1})	Fluid Temperature (ºC)		Mass flow rate (Kg h^{-1})	Heat transfer coefficient (W/m^2K)					Effectiveness (%)
						Tube side	Shell side	Overall			
t_i	t_o	m_c	T_i	T_o	m_h	h_i	h_o	U	C*	NTU	ε
29	59	118.764	100	76	51.012	178.579	478.810	110.742	0.432	1.772	74.8
29	56	178.272	100	72	51.084	178.468	664.850	118.343	0.288	1.892	80.0
29	52	237.960	100	70	51.109	178.314	710.663	119.617	0.216	1.912	81.0
29	49	297.648	100	68	51.141	178.194	786.183	121.067	0.172	1.934	81.5
29	47	357.336	100	65	51.185	178.027	849.143	122.850	0.144	1.961	83.2
29	45	416.880	100	62	51.228	177.833	930.835	124.378	0.123	1.984	84.5
29	41	477.000	100	59	51.264	177.672	1029.525	125.786	0.108	2.005	85.5
29	38	536.976	100	56	51.300	177.492	1091.340	126.582	0.096	2.017	86.7
29	36	596.880	100	53	51.336	177.295	1114.810	126.903	0.086	2.021	87.0
29	33	656.892	100	50	51.372	177.130	1166.408	127.388	0.078	2.028	87.6

Table 4: 10% Acetic acid-Water solution

Cold fluid (Water)			Hot fluid (water)								
Fluid Temperature (ºC)		Mass flow rate (Kg h^{-1})	Fluid Temperature (ºC)		Mass flow rate (Kg h^{-1})	Heat transfer coefficient (W/m^2K)					Effectiveness (%)
						Tube side	Shell side	Overall			
t_i	t_o	m_c	T_i	T_o	m_h	h_i	h_o	U	R_c	NTU	ε
29	45.0	120.179	100	71.0	97.548	222.070	460.254	126.167	0.862	1.056	53.00
29	42.0	180.482	100	70.0	97.577	221.995	578.965	133.689	0.574	1.120	58.50
29	40.0	240.832	100	69.0	97.606	221.969	734.423	140.647	0.430	1.177	63.00
29	39.0	301.158	100	37.5	97.648	221.870	766.641	141.643	0.344	1.205	66.00
29	38.0	361.461	100	66.0	97.690	221.768	847.226	144.092	0.287	1.222	65.30
29	36.0	422.199	100	65.0	97.718	221.679	920.641	146.198	0.245	1.228	67.50
29	34.0	482.408	100	64.0	97.745	221.587	952.571	146.843	0.215	1.233	68.20
29	32.0	543.182	100	63.5	97.759	221.567	985.977	147.493	0.191	1.251	69.00
29	31.5	603.675	100	62.0	97.799	221.451	1086.990	149.701	0.172	1.252	72.50
29	31.0	664.114	100	61.5	97.812	221.438	1116.180	150.150	0.156	1.254	74.08

The results for the other compositions were similar to that obtained from the one considered here as the reference. From the above comparisons it can be said that the mathematical model developed for the system is very close.

CONCLUSION

Experiments were conducted on a 1-1 Shell and Tube heat exchanger with different cold side flow rates and different compositions of cold fluid. The effect of these parameters on the shell outlet temperature, tube outlet temperature and overall heat transfer coefficients were studied. It was found that cold fluid outlet temperature decreases and the overall heat transfer coefficient increases with increase in flow rate of cold fluid. Also the outlet temperature of cold fluid decreases and overall heat transfer coefficient increases with increase in composition of water. The overall effectiveness of heat exchanger was found to increase with decrease in composition of water. It was found that the Cross Flow Heat Exchanger is the most effective compared with the Shell and Tube Heat Exchanger. A mathematical model of this system is developed, simulated using MATLAB and compared with the experimental values. Finally a correlation for the calculation of film heat transfer coefficient is developed using dimensional analysis for tube side.

NOMENCLATURE

T_i = Inlet temperature of hot fluid (ºC)
T_o = Outlet temperature of hot fluid (ºC)
t_i = Inlet temperature of cold fluid (ºC)
t_o = Outlet temperature of cold fluid (ºC)
Re = Reynolds No.
Pr = Prandtl No.
Nu = Nusselt No.
St = Stanton No.
NTU = No. of heat transfer units of an exchanger
lpm = Litres per minute

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