Performance Analysis of Shell and Tube Heat Exchanger Using Miscible System

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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. 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...
the design, performance analysis and simulation studies on heat exchangers. Modeling and Simulation of Shell and Tube Heat Exchangers Under Milk Fouling was carried out. Dynamic Model for Shell and Tube Heat Exchangers was discussed. 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.

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:

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

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 from 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 increases from 126.167 to 150.15 W/(m² K). For the same volumetric flow rates, the simulated values varies from 121.805 to 148.605 W/m²K 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 31°C, whereas the simulated values were 42 to 30°C, 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 61.5°C, whereas the simulated values were 68 to 60°C respectively.
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 (°C)
- $T_o$ = Outlet temperature of hot fluid (°C)
- $t_i$ = Inlet temperature of cold fluid (°C)
- $t_o$ = Outlet temperature of cold fluid (°C)
- $Re$ = Reynolds No.
- $Pr$ = Prandtl No.
- $Nu$ = Nusselt No.
- $St$ = Stanton No.
- $NTU$ = No. of heat transfer units of an exchanger
- $lpm$ = Litres per minute
REFERENCES

1. Hesselgreaves, J.E., 2002. An approach to fouling allowances in the design of compact heat exchangers. Applied Therm. Eng., 22.
2. Holman, J.P., 1997. Heat Transfer. 8th Edn., McGraw-Hill Book Company, New York.
3. Zealsing, P., 2004. Heat exchanger design for good process performance. Chemical product finder
4. Robert, H.P. and D.W. Green, 1997. Perry's Chemical Engineering Hand Book, 7th Edn., McGraw-Hill Company, New York
5. Rohsenow, W.M., J.P. Hartnett and E.N. Ganic, 1985. Hand Book of Heat transfer Applications, 2nd Edn., McGraw-Hill Company, New York.
6. Donald, Q.K., 2000. Process Heat Transfer, Tata Mc Graw Hill Edition.
7. Warren, L. McCabe, J.C. Smith and P. Harriott, Unit Operations of Chemical Engineering. 5th Edn., Mc Graw Hill International Edition.
8. Babu, B.V., 2004. Process Plant Simulation, Oxford University Press.
9. Kothandaraman, C.P. and S. Subramanyan, 2000. Heat and Mass Transfer Data Book, Tata McGraw Hill Edition.
10. William, L.L., 1990. Process Modeling, Simulation And Control for Chemical Engineers, 2nd Edi., McGraw Hill International Edition.
11. Rudra, P., Getting Started with MATLAB(Version 6.0.7.0), Oxford University Press.
12. Aghareed, M.T., M.A. El-Rifai, Y.A. El-Tawil and R.M. Abdel-Monen, 1991. A New Dynamic Model for Shell and Tube Heat Exchangers. Energy Conservat. Manage., 32: 439-446.
13. David, B., 2002. Design of Shell and Tube Heat Exchangers When the Fouling Depends on Local Temperature and Velocity, Applied Thermal Eng., 22: 789-801.
14. Sparrow, E.M. and L.G. Reischneider, 1986. Effect of Inner Baffle Spacing on Heat Transfer and Pressure Drop in Shell and Tube Heat Exchanger. Int. J. Heat Mass Transfer, 29: 1617-1628
15. Michael, C.G., G.E. Rotstein and S. Miccheietto, 1998. Modeling and simulation of shell and tube heat exchangers under milk fouling. AIChE J., 44: 959-971.
16. Mandavgane, S.A., M.A. Siddique, A. Dubey and S.I. Pandharipande, 2004. Modeling of Heat Exchangers Using Artificial Neural Net Work. Chem. Eng. World, pp: 75-80.
17. Anantharaman, S., 1997. Design and construction of shell and tube heat exchangers. Chem. Ind. Dev. Incorporat. Chem. Process. Eng., 11: 15-21.
18. Yusuf, A.K. and O. Guraras, 2004. A computer program for designing of shell and tube heat exchangers. Applied Therm. Eng., 24: 1797-1805.