HEAT TRANSFER AND PRESSURE DROP CHARACTERISTICS OF INTENSIFIED TUBULAR GLASS REACTOR

ARJUN GOPAL*, VIVEK RANADE#
*Department of Chemical Engineering
Institute of Chemical Technology, Mumbai, India
#Department of Chemical Engineering and Process Development,
National Chemical Laboratory, Pune, India.

Received on December 18, 2013; Revised Manuscript accepted on September 25, 2014

Abstract: The construction of the tubular reactor is similar to a shell and tube heat exchanger, with a single tube with 73 passes. The tube side will be used for carrying out the reaction and the shell side is used for passing the coolant. The shell & tube geometry offer large surface area in combination with efficient heat transfer and compactness. The advantage of using glass as a material of construction is universal corrosion resistance. The specific surface area of the intensified reactor is 448 m^2/m^3. Large scale reactors used in industries have very low specific surface area leading to poor heat transfer characteristics. These kinds of mid-range reactors can handle better throughput than micro-reactors which offer surface areas more than 10000 m^2/m^3. The objective of my project was to determine the heat transfer coefficient and pressure drop for these mid-range tubular reactors and try to characterize the values of heat transfer and pressure drop by comparing the values with established correlations available in literature. For the shell side calculations, the Kern method [1] and Bell-Delaware method [2] were used for determining the pressure drop and heat transfer coefficient in the various regimes, to correlate with the experimental results. The tube side heat transfer coefficients were determined using the various correlations stated in [1] and [3] for different flow regimes. Two correlations namely, Sieder-tate and Gnielinski were used to calculate the process side film coefficients. The process side pressure drop was found using a manometer and the friction factors were compared with established correlations, such as cole-brook white [4]. Experimentally, the heat transfer coefficient is determined by the Wilson Plot method [5] by varying the tube side flow rates keeping shell side flow rate fixed for three different temperatures. The results of the experiments seemed logical and matched the established correlations in most cases. Future work in characterizing such reactors such as RTD has been proposed.

Keywords: Heat transfer, Shell and tube heat exchanger, intensified reactors

Introduction

Shell-and-tube heat exchangers are used widely in the chemical process industries, especially in refineries, because of the numerous advantages they offer
over other types of heat exchangers.

The tube side is used for the fluid that is more likely to foul the walls, or more corrosive, or for the fluid with the higher pressure (less costly). Cleaning of the inside of the tubes is easier than cleaning the outside. When a gas or vapour is used as a heat exchange fluid, it is typically introduced on the shell side. Also, high viscosity liquids, for which the pressure drop for flow through the tubes might be prohibitively large, can be introduced on the shell side. In our case as the MOC of the heat exchanger is glass, fouling is minimized greatly, leading to lower costs as regards to pumping, as fouling greatly increases pressure drop across the tube side.

In these heat exchangers, one fluid flows through tubes while the other fluid flows in the shell across the tube bundle. The design of a heat exchanger requires a balanced approach between the thermal design and pressure drop. The pressure drop results in the increase of the operating cost of fluid moving devices such as pumps and fans. This shows that along with the design for the capacity for heat transfer, the pressure drop determinations across the heat exchanger are equally important. The estimations for pressure loss for the fluids flowing inside the tubes are relatively simple, but complex in the shell-side flow. The pressure drop also is affected by baffle spacing and shape of baffles and the proper utilization of shell side pressure drop, in not forming of dead zones, is essential in improving the film transfer coefficients outside of tube. [13] [16]
The calculation of convection coefficients constitutes a crucial issue in designing and sizing any type of heat exchange device. The Wilson plot method [5] [6] and its different modifications provide an outstanding tool for the analysis and design of convection heat transfer processes in research laboratories. The Wilson plot method deals with the determination of convection coefficients based on measured experimental data and the subsequent construction of appropriate correlation equations.

Insight into heat transfer coefficient determination in various flow regimes

Pipe flow is always laminar if the Reynolds number is less than Re < 2300, and is said to be turbulent at higher values. There is no doubt that turbulent flow sets in at $Re > 10^4$. In the transition region of $2300 < Re < 10^4$, the type of flow is influenced by the nature of the inlet stream and the form of the pipe inlet.

The average heat transfer coefficient U over a length l of a pipe is defined by [8], [9]:

$$\dot{Q} = \dot{m} * C_p * \Delta T = U * F * LMTD$$

The variable LMTD is the logarithmic mean temperature difference and is given by:

$$LMTD = \frac{(T_w - T_i) - (T_w - T_o)}{ln\left(\frac{(T_w - T_i)}{(T_w - T_o)}\right)}$$

Where T_i and T_o are the inlet and outlet temperatures of the flowing medium and T_w is the constant pipe wall temperature. F is defined as the LMTD correction factor and is taken to be around 0.8 to 0.9 for cross flow shell and tube heat exchangers [14].

Heat Transfer in Laminar flow for constant wall temperature

Hydrodynamically Developed Laminar Flow

Many authors have proposed numerical methods for determining heat transfer in thermally and hydrodynamically developed laminar flow (in long pipes) and in thermally developing and hydrodynamically developed laminar flow (the Nusselt Graetz problem).

The asymptotes for the local Nusselt number at a point x, as measured from the point at which heating or cooling commences, are given by:

Nu=3.66 [7] [11] [15]

For small values of graetz number and for larger values of graetz numbers:

$$Nu_2 = 1.077 * Gz^{1/3}$$

$$Graetz\ Number(Gz) = Re * Pr * \frac{d}{x}$$

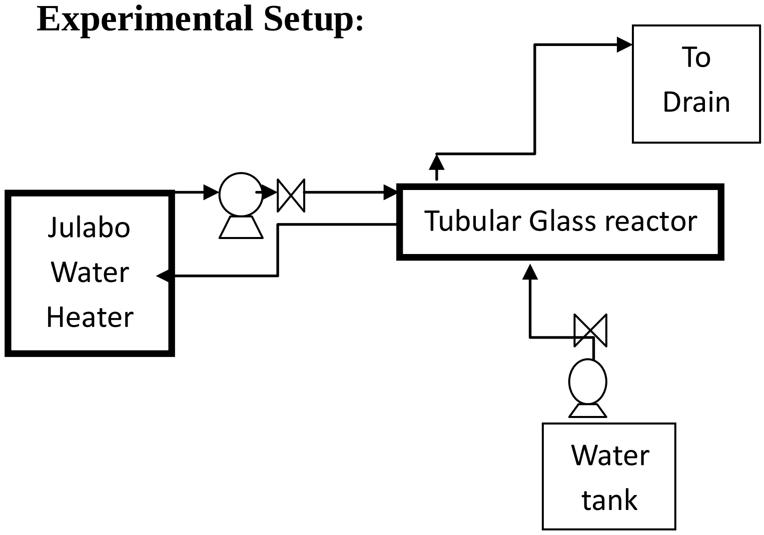
Local Nusselt numbers in the entire 0 < Gz <∞ range, with a deviation that attains a maximum at 6% at 10 < Gz< 100 and is otherwise much smaller, can be obtained from:

$$Nu = \{3.66^3 + 0.7^3 + [Nu_2 - 0.7]^3\}^{1/3}$$

Simultaneous thermal and hydrodynamically developing flows

As a result of friction between the fluid and the pipe wall, a velocity profile gradually develops at the pipe inlet. If, at the same time, heat is transferred, a temperature profile also sets in. Boundary layers are thus formed, and heat transfer in this zone is calculated in the light of the boundary layer theory.

Experimental Setup:



Reactor Setup:

Experimental Procedure:

Heat Transfer experiments

To determine the heat transfer coefficients on the shell and tube side, Wilson plot method is used. The general heat resistance equation written for the shell and tube heat exchanger is as follows:

$$\frac{1}{U} = \frac{1}{h_o} + \frac{1}{h_i} + \frac{ln\left(\frac{d_o}{d_i}\right) * d_o}{2 * \pi * k}$$

Where U is the overall heat transfer coefficient, h_i and h_o are the inner and outer heat transfer coefficients respectively. The outer and inner diameters of the tube are denoted by d_o and d_i respectively and k is the thermal conductivity of the glass wall.

The Wilson plot method is used for turbulent flow through pipes, in which case the inner heat transfer coefficient is directly proportional to Reynold's number raised to a certain power. In our case, as the heat exchanger is modified to be used as a reactor, we desire longer residences times in the tube side, where reactions take place; hence the flow through tubes is laminar. The range of our study is shown below:

- Temperature(°C)- 45-65
- Residence time(min)-2-7
- Process side Reynold's Number-800-2400

Thus two approaches were attempted, one was to use the Wilson plot method to obtain heat transfer coefficient in laminar region by fitting a correlation similar to Sieder-Tate equation. This method yielded better results in form of improved Nusselt numbers and the deviation from the established correlation was found to be small in most of the readings (within 10%-15%).

The second method attempted to modify the Wilson plot method and fit a correlation for Nusselt number similar to the Gnielinski correlation stated in [3] [7]. This method yielded poorer Nusselt numbers and the data when compared to the original correlation gave large errors, thus experimental data points were validated with the Sieder-Tate equation and the relevant plots were made.

Experiments were carried out by keeping the shell side flow rate fixed and varying the tube side flow rate for a particular temperature. For one shell side flow rate at 4 tube side flow rates, the experiment was performed. These experiments were repeated for three temperatures, 45°C, 55°C and 65°C.

Pressure Drop Experiments

Pressure drop experiments were conducted specifically on the process side as operating expenditures are directly proportional to the pressure drop across the process side, as increased pressure drops translate to increased pumping costs. The experiments were carried out by varying the tube side flow rates and determining the pressure drop using a standard manometer. The pressure drop was plotted as a function of the Reynold's number and a standard parabolic type of fit was obtained. The pressure drop was compared with the standard Darcy-weisbach equation [1] [10] and the experimental values were found to be higher than the theoretically predicted pressure drop values. This is expected as exactly taking into account the several losses due to fittings is practically impossible.

Theoretical Calculations and Results:

Theoretical Nusselt numbers in laminar flow for the tube side are calculated using the Sieder-Tate correlation [1] which is given by the following expression:

$$Nu = 1.86 * \left(Re * Pr * {}^{d}/_{L}\right)^{1/3}$$

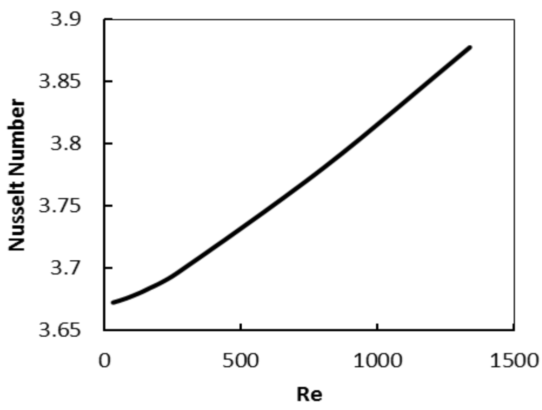


Fig: Theoretical Nusselt number v/s Reynold's number

Experimental Results and Plots:

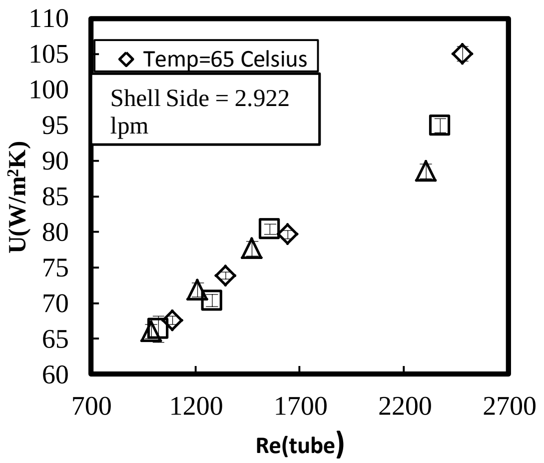


Fig: Overall Heat transfer coefficient vs Process side Reynold's number for a fixed shell side flow-rate

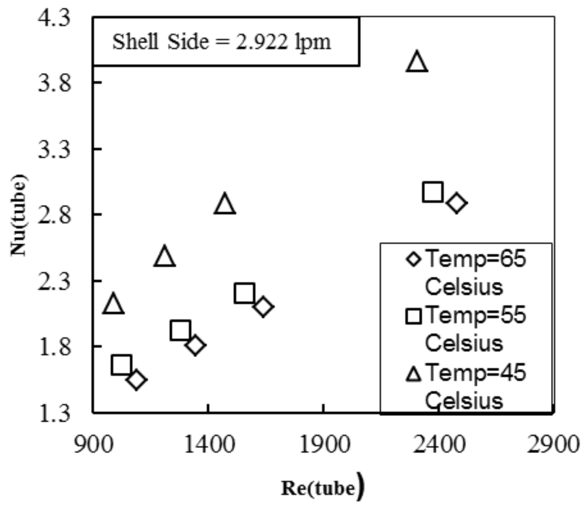


Fig: Nusselt Number vs Process side Reynold's number for a fixed shell side flow-rate

Conclusions:

The below graph shows the deviation of experimentally derived Nusselt numbers from the Sieder-Tate correlation.

$$Nu = 1.86 * (\mathrm{Re} * \mathrm{Pr})^{1/3}$$

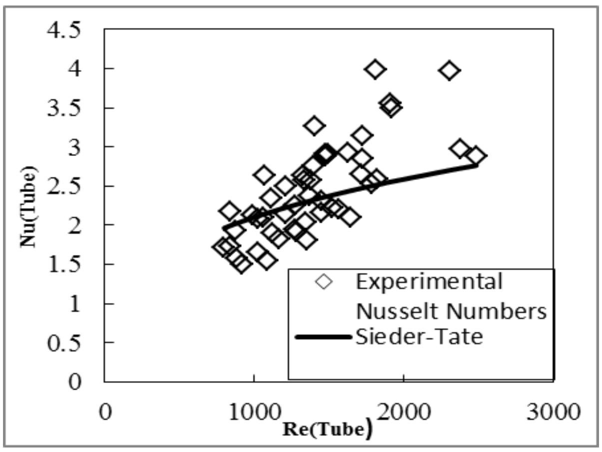


Fig: Nu (tube) vs Re (tube)

The Nusselt numbers for heat transfer in the glass reactor were found to be poor, indicating further improvements have to be done in planning of experiments, in optimizing the residence time v/s flow rate curve to achieve best heat transfer.

Future Work:

The heat transfer and pressure drop characteristics of a reactor are essential in characterizing the kind of reactions that take place in it. The Residence Time Distribution (RTD) is also an indispensable tool in determining the deviation of the reactor from plug flow behaviour and thus provides complete information about the degree of mixing in the reactor. There is immense scope for conducting RTD experiments and determining RTD of mid-range reactors such as the shell and tube glass reactor as conducting experiments on large scale reactors is difficult.

The validation of the experimental data was done by comparing the results with the sieder-tate correlation; a better correlation for laminar flow was obtained in [3]. Due to the complicated nature of the correlation in [3], fitting the data even using MATLAB was not possible and thus producing a correlation of that form was not possible. However most of the experimental points, matched the form of correlation, with different constants as a function of temperature.

Validation of these experimental data through Computational Fluid Dynamics (CFD) will also give insights into how to improve the design and further modifications which will enhance heat transfer coefficients.

Acknowledgements:

I would sincerely like to thank Dr. V.V Ranade of NCL, Pune to allow me to experience the research facilities during my summer internship. I would also like to thank INSA-NASI-IASc for providing me the SRFP2013 to work in NCL, Pune.

References:

1. Process heat transfer, D.Q Kern

2. Heat transfer equipment design, R.K Shah, E.C Subbarao, R.A Mashelkar

3. V.Gnielinski-"On heat transfer in tubes"-International Journal of Heat and Mass Transfer 63 (2013) 134–140

4. Colebrook, C.F. and White, C.M- "Experiments with Fluid friction roughened pipes."Proc. R.Soc.(A), 161,1937.

5. Jose´ Ferna´ndez-Seara, Francisco J. Uhı´a , Jaime Sieres, Antonio Campo-"A general review of the Wilson plot method and its modifications to determine convection coefficients in heat exchange devices"- Applied Thermal Engineering 27 (2007) 2745–2757.

6. "A general review of the Wilson plot method and its modifications to determine convection coefficients in heat exchange devices"- Applied Thermal Engineering 27 (2007) 2745–2757.

7. V. Gnielinski, Heat transfer in laminar flow, in: VDI Heat Atlas,

second ed., Springer Verlag, 2010 (Chapter G1, Section 3).

8. Fundamentals of Heat Exchanger Design. Ramesh K. Shah and Dušan P. Sekulic, John Wiley and Sons
9. Heat Exchangers Selection Rating and Thermal Design Second Edition, sadic Kakac and Hongtan Liu

10. J. Taborek, Design method for tube-side laminar and transition flow regime with effects of natural convection, in: Open Forum Session Forum of the Ninth Int. Heat Transfer Conference, Jerusalem, Israel, 1990.

11. Brodkey, R. S. and Hershey, H. C. - Transport Phenomena - A Unified Approach

12. "Modeling for shell-side pressure drop for liquid flow in shell-and-tube heat exchanger "-Uday C. Kapale, Satish Chand - International Journal of Heat and Mass Transfer 49 (2006) 601–610

13. Pressure drop on the shell side of shell-and-tube heat exchangers with segmental baffles- Edward S. Gaddis , Volker Gnielinski - Chemical Engineering and Processing 36 (1997) 149-159.

14. Coulson & Richardson's Chemical Engineering Volume 1 Fluid Flow, Heat Transfer and Mass Transfer.

15. Heat transfer and pressure drop characteristics of smooth tubes at a constant heat flux in the transitional flow regime- Melissa Hallquist

16. H. Li, V. Kottke, Effect of baffle spacing on pressure drop and local heat transfer in shell-and-tube heat exchangers for staggered tube arrangement, Int. J. Heat Mass Transfer 41 (10) (1998) 1303–1311.