Design and fabrication of an experimental setup to develop empirical heat transfer and pressure drop correlations for single phase flow in plate heat exchanger

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ABSTRACT

The objective of the present work is to investigate the heat transfer characteristics and thermal performance of plate heat exchangers. An experimental setup was designed and fabricated to develop empirical heat transfer and pressure drop correlation for plate heat exchangers for various commercially available chevron plates. This paper focuses on the design of various parameters in order to select the components of the setup. The apparatus thus designed and fabricated will be used to conduct single phase experiments using 30% ethylene glycol with flow rates and temperatures corresponding to a maximum Reynolds number of 2500 and Prandtl number in the range of 6 to 25. The setup was later tested to conform to these ranges.

Keywords: Plate heat exchangers, Heat transfer correlation, Pressure drop correlation, Nusselt number correlation, Single phase flow

INTRODUCTION

Plate heat exchangers are widely used in dairy, pharmaceuticals and paper/pulp industry as well as in HVAC applications. They transfer heat by placing thin, corrugated metal sheets side by side and connecting them by gaskets. Flow of the substances to be heated and cooled takes place between alternating sheets allowing heat to transfer through the metal sheets. In the majority of the industrial applications, the plate heat exchanger is the design of choice because of its distinguishing and attractive features (easy-to-maintain, compact design, light weight) and because of the many advantages it offers. A number of analytical and experimental studies have been conducted to study the heat transfer and fluid flow characteristics of tubular heat exchangers. However a very limited work is found in open literature regarding the heat transfer through plate heat exchangers. Computerized design software has been developed by the manufacturers of plate heat exchangers but not a lot of data is available for research purposes about the design of these heat exchangers. Therefore, there is an urgent need for comprehensive and systematic research in this field.

In the present study, to investigate the heat transfer and pressure drop characteristics of plate heat exchangers, an experimental setup was designed and fabricated. The objective of this paper is to present the selection of equipment for the experimental setup. These include chiller, heaters, pumps, instrumentation and piping. The setup will be used to conduct single phase experiments in order to develop empirical heat transfer and pressure drop correlation for plate heat exchangers with chevron plates of various chevron angles. 30% ethylene glycol is the working fluid with flow rates and temperatures corresponding to a maximum Reynolds number (Re) of 2500 and Prandtl number (Pr) in the range of 6 to 25. These ranges are verified by means of test experiments conducted using the setup.

LITREATURE REVIEW

Since not a lot of data about the plate heat exchangers is available in the open literature, some of the available literature was surveyed to look for the general form of heat transfer and pressure drop correlation for the plate heat exchangers. These general forms of correlations are vital in determining the system parameters and variables involved in the experimentation. Once these parameters and variables are known, the experimental setup can then be designed.

Due to the proprietary nature of the plate heat exchanger business, there is a lack of design information in the open literature. The correlations reviewed are specific in nature as it relates to a specific geometry, fluid, and experimental range of operation. General correlations were reported by Troupe et al. [1] and Muley and Manglik [2]. Nearly all of them are in the form of a power law curve fit, with some of the latest correlations using a leading coefficient and exponent as a function of chevron angle. The augmented heat transfer performance of a PHE is due to several enhancement mechanisms presumed to be a direct consequence of plate surface characteristics. They include disruption and reattachment of boundary layers, vortex flows, swirl flows, and secondary circulations. Some of the correlations reported in open literature could be used for plates of different manufacturers as long as the geometric parameters are incorporated as defined in the specific correlation; for quick calculations, the correlations by Kumar [3], Jackson et al. [5], Marriot [6], Roetzel et al. [7] are recommended; for more elaborate calculations, Heavner et al. [4], and Muley and Manglik [2] would be appropriate.

From the literature surveyed the general form of heat transfer and pressure drop correlation was established and it was concluded that heat transfer is a function of Reynolds number (Re), Prandtl number (Pr) and geometry of the plates (Chevron Angle β) while pressure drop depends upon Reynolds number (Re) and plate geometrical characteristics. Moreover, from the literature surveyed it was observed that most correlations for the heat transfer are determined focusing heavily on one variable and using a very modest range for the other. Thus the experimental setup is designed so as to provide with moderate ranges of both Reynolds and Prandtl numbers to make the correlations more useful to the scientific community.

EXPERIMENTAL SETUP

A schematic of the experimental apparatus is shown in Fig. 1. The setup consists of a plate heat exchanger, a hot fluid loop and a cold fluid loop. The hot fluid loop consists of a hot fluid tank and a pump that is pumping hot fluid from the tank to the heat exchanger. The hot fluid tank has the capacity of 150 US gallons and is equipped with 8 electric immersion heaters. The cold fluid loop consists of a cold fluid tank and a pump that is pumping cold fluid from the cold fluid tank to the heat exchanger.

The cold fluid tank has the capacity of 35 US gallons and is equipped with 2 heaters. These heaters are used to fine tune the temperature to the desired level. Temperatures are measured at the inlet and exit of the plate heat exchangers for both the hot and cold streams using the Resistance temperature device (RTDs). Pressure differential is used to measure the pressure drop across the hot and cold streams. Flow rates are measured by using graduated cylinder and stop watch. The fluid is cooled by a 2 TR Packaged Air Cooled Water Chiller with R22 as the refrigerant. One heater in each of the tank is connected to a temperature controller via magnetic contactor to maintain the desired temperature of the fluids in both the tanks. Bypass loops with bypass valves are also provided for both the tanks to control the flow through the plate heat exchanger.

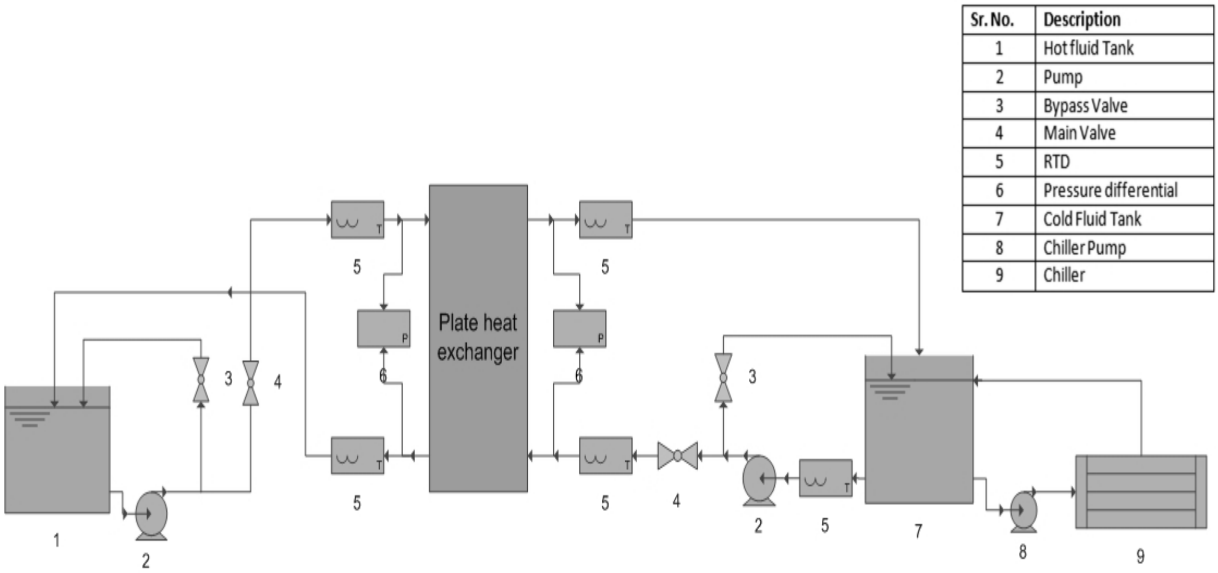

Fig 1. Schematic Diagram of Experimental Setup

After the desired temperatures of the cold and hot fluids are achieved, the fluids of both the loops are pumped in to the plate heat exchanger where they exchange heat. The flow rate of the hot fluid is controlled by using a variable frequency drive. The cold fluid flow rate will be controlled by the bypass valve. Flexible piping is used to connect both the loops with the inlet and outlet ports of the plate heat exchanger. Parallel and Counter flow configurations can be achieved by reversing the pipe connections to the exchanger ports. RTDs are installed at various locations to measure the bulk fluid temperatures. The pressure drop across the plate heat exchanger will be measured by using pressure differentials.

Since the heat transfer is a function of Reynolds number, Prandtl number and plate geometry and pressure drop in plate heat exchangers depends upon Reynolds number and the geometrical characteristics of the plates; thus a system of varying these parameters is included in order to accurately determine their dependence. Reynolds number can be varied by changing the fluid flow rate through variable frequency drives and bypass valves. Prandtl number can be varied by changing the temperature of the fluid using chiller, heaters and temperature controllers. Plate geometry can be varied by using plates with different chevron angles (β) in the plate heat exchanger. Experiments will be conducted at various temperatures and flow rates of hot and cold fluids using plates of different chevron angles β . The system will be allowed to reach the steady state before any reading is made.

EXPERIMENTAL EQUIPMENT

Table 1 Details of the equipment

Sr.	Item	Model / Capacity	Qty.
1.	Plate heat exchanger	Thermo wave Germany	1
2.	Chiller	2TR vapor compression chiller	1
3.	Cold Fluid Tank	35 US gal	1
4.	Hot Fluid Tank	150 US gal	1
5.	Heater for cold fluid tank	500 W	2
6.	Heater for hot fluid tank	1200 W	8
7.	Pump for hot fluid	ETA 40-20 M	1
8.	Pump for cold fluid	ETA 40-20 M	1
9.	Temperature controller	DTC -234	1
10.	Magnetic Contactor	440V 50 Hz	2
11.	Pressure Differential	315T-DP-IV-140-01-01-0-23-M3-B1-02	2
12.	RTDs	(PT100) 16-1-6-3-150-CE4C-R100-B (TC UK)	5
13.	Insulation		
14.	Globe valve		4
15.	Motor	2.2 kW	2
16.	Variable frequency drive	PS-43P7B	1

EQUIPMENT DETAILS AND SELECTION

Chiller

A chiller is a compressor based cooling system that is similar to an air conditioner except it cools and controls the temperature of a liquid instead of air. The main components of this 2 TR air cooled water chiller are the evaporator, condenser, recirculating pump, expansion valve, an internal tank, and temperature control. The internal tank helps maintain cold fluid temperature and prevents temperature spikes from occurring.

As shown in the schematic (fig 1), the chilled fluid from the chiller is fed into the cold fluid tank. The larger volume of the cold fluid tank compared to the tank internal to the chiller, helps achieve the steady state and resists temperature fluctuations. The chiller provides a stable temperature, flow and pressure once it has been programmed. The chiller can be adjusted to provide flow rate in the range of 4-6 gpm.

For experiments conducted below the room temperature, the chiller will act as a driver and the load will be created by the heater. In this case the chiller capacity is calculated as:

Maximum mass flow rate = 6 gpm

Maximum ΔT (across chiller inlets and outlets) = 5 K

$$\dot{q} = \dot{m} c_p \Delta T \quad (1)$$

$\dot{q}$ = 7.194 kW = 2.05 tons

Heater

An electric heater consists of electric resistance elements (which are submerged inside the tank) and a thermostat. The hot fluid tank in the setup contains eight immersed electric heaters of 1200 watts each. Heaters are connected to controller which ensures that the fluid temperature in the tank corresponds to the desired value.

For experiments conducted above the room temperature, the heater will act as a driver and the load will be created by the chiller. In this case the heater capacity will be equal to that of the chiller i.e. 7.194 kW. However combined available wattage of all the heaters is 9.6 kW that is greater than 7.194 kW. This provision ensures the correct operation of the setup incase one or two of the heaters is non-functional.

Pumps

Before a pump can be selected for the setup, four parameters must be determined. These are: the total head or pressure against which the pump must operate, the desired flow rate, the suction lift and the characteristics of the fluid.

Channel pressure drop in PHE: In order to select the pump size and to estimate the pressure drop an already available correlation [8] was used. This estimation would also serve as a confirmation of the correlation that will be developed by our setup.

$$\Delta P_c = 4 f \frac{L_{eff} N_p}{D_h} \frac{G_C{}^2}{2\rho} \left(\frac{\mu_b}{\mu_w} \right)^{-0.17} \quad (2)$$

Putting on the values involved in the experiment the total head (in ft of water) was found to be

$$\Delta h_c = 3.56 m = 11.7\, ft \ \ of\ water$$

Pump Selection: After the pressure drop calculations were made, accounting for losses in the heat exchanger and major and minor losses, system equation was developed. This equation was used to draw system curve on the manufacturer's pump performance curves for the selection of the pump. For our case a pump with discharge nozzle 40 mm and impeller nominal diameter of 200 mm was selected. Furthermore the flow rate of hot fluid is controlled by a variable frequency drive connected to the motor of the hot fluid pump.

Storage Tanks

As shown in fig (1) the close loops of hot and cold fluid consist of the 150 US gallons and 35 US gallons storage tanks respectively in order to achieve the steady state. The cold fluid from the chiller is stored in the cold fluid tank from where it is pumped to the plate heat exchanger. This cold fluid tank acts as a moderator as it diminishes the effect of fluctuation in the fluid temperature at the outlet of the chiller on the experiment. The cold fluid tank also has the provision of a heater to fine tune the temperature to the desired level. Hot fluid tank is equipped with 8 heaters that are required to heat the fluid.

Instrumentation

Pressure Differential

To obtain accurate pressure drop across the heat exchanger, Pressure Differentials (PDs) are used. The PDs used are made of capacitive pressure sensors. These pressure transmitters are often used to measure the differential pressures in mbar scale with rather high accuracy, for differential pressure, gauge pressure and absolute pressure applications, the transmitter can measure them in very wide ranges. The total pressure drop across a PHE came out to be 11.7 feet of water. The selection of the pressure differential was made on the value of the pressure drop inside the plate heat exchanger. The pressure differential that is used has the capacity between 0 to 10 psia.

Resistance Temperature Detectors

The temperature range in which the setup will operate is 5 ^{0}C to 75 ^{0}C. The RTDs used are able to handle this range and perform accurate measurements. The RTDs used in the setup are PT100 A Class RTDs with outer diameter of 6 mm. These RTDs are able to provide stable output for long period of time with high accuracy and have ease of recalibration.

CONCLUSIONS

An experimental setup was designed and fabricated that will be used to investigate the thermal performance of plate heat exchangers by developing empirical single phase heat transfer and pressure drop correlation. The experimental setup was designed keeping in view all the parameters that influence the heat transfer and pressure drop in a plate heat exchanger. Experiments can be performed corresponding to a maximum Reynolds number (Re) of 2500 and Prandtl number (Pr) in the range of 6 to 25. These ranges were later verified by test experiments.

The experimental setup is also intended to serve as an initiative for future experimentation and research.

ACKNOWLEDGEMENT

This work was supported by Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, Pakistan and American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE), Northern Pakistan Chapter. This work has been done as part of the Mechanical Engineering undergraduate senior design project.

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