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Role of channel shape on performance of plate-fin heat exchangers: Experimental assessment

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ABSTRACT

A comparative evaluation of seven common configurations of channels used in plate-fin heat exchangers is presented. All the channels, including plain, perforated, offset strip, louvered, wavy, vortex-generator, and pin, are fabricated and tested experimentally. The working fluid is water, and Reynolds number range is from 480 to 3770. To evaluate the performance of these channels and also select an optimum plate-fin channel, three mostly used energy-based performance evaluation criteria are employed. The results are presented as plots of dimensional and non-dimensional parameters. In comparison with all of the studied channels, the vortex-generator channel shows a significant enhancement in the heat transfer coefficient and a proper reduction in the heat exchanger surface area. Therefore, it can be applied as a high quality interrupted surface in the plate-fin heat exchangers. Moreover, the wavy channel displays an optimal performance at low Reynolds numbers.

1. Introduction

1.1. Plate-fin heat exchanger specifications

Process intensification (PI) usually pertains to chemical engineering instruments and methods. The plate-fin heat exchanger (PFHE) as a multi-functional device and heat transfer augmentation techniques in this heat exchanger can be a popular issue from the PI point of view. A PFHE consists of a block with alternating layers of extended surfaces as plate-fins. These layers are separated by parting sheets and restrained by side bars. A large heat transfer area, light weight per unit volume, high thermal performance, possibility of heat exchange among several streams, and close temperature on channels are the advantages which make the PFHE one of the popular type of heat exchangers. Based on different applications, various types of plate-fin channels such as plain, perforated, offset strip, louvered, wavy, vortex-generator, and pin are used in the PFHEs. Each of these channels enhances the heat transfer with special techniques. The PFHEs are employed over a wide range of temperatures and pressures for gas–gas, gas–liquid, and multi-phase duties, such as cryogenics for separation and liquefaction of air (Coldbox system), production of petrochemicals and large refrigeration systems, and natural gas processing and liquefaction. To make the PFHEs as compact as possible in these application, the complex plate-fin channels, i.e., perforated, offset strip, louvered, wavy, vortex-generator, and pin, can be replaced instead of plain one.

1.2. Literature review

The great advantages and different applications of the PFHEs are the factors that motivate many investigators to study the performance of these heat exchangers. Therefore, numerous experimental and numerical studies have been conducted on characteristics of each plate-fin channel. The experimental and numerical thermal-hydraulic data of the PFHEs with different channels are given for perforated [1,2], offset strip [3–9], louvered [10–15], wavy [16–26], vortex-generator [27–33], and pin [33–38]. Nevertheless, studies which focus on the comparison of the thermal-hydraulic performance of different channels are very limited. A review of the prominent comparative studies [39–43] is presented here.

A comparative assessment of five different channels, namely plain with the rectangular and triangle cross sections, offset strip, louvered, and vortex-generator, to operate in compact heat exchangers was experimentally conducted by Brockmeier et al. [39], when air operated as the working fluid. They reported that the vortex-generator surface has the best performance, and it can

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reduce the heat transfer surface area up to 76% for the fixed heat duty and pumping power. A thermodynamic analysis was performed by Tagliafico and Tanda [40] to compare the performance of a number of the PFHE surfaces. The comparisons were done under constraints, including the fixed heat transfer duty, mass flow rate, and length–width of the heat exchanger. In another study, four basic channels of the PFHEs, namely the rectangular plain, strip offset, perforated, and wavy, were simulated at the laminar flow regime by Zhu and Li [41]. The major purposes of this study were the heat transfer behaviors in both the developing and the developed regions and local Nusselt number variations along the flow direction. Correlations for the thermal entry length were also obtained. In all of the previous comparative studies, the surface of one side of the heat exchanger was considered. A study on both sides of the heat exchanger surfaces was conducted by Khalil et al. [42]. Dong et al. [43] recently used of the VG-I criteria which measures the possible reduction of the surface area to compare five plate-fins. They considered the air as coolant on the gas side of a flat-tube heat exchanger.

Because of differences in geometrical parameters, working fluids, and data reduction methods which were adopted in different literature, a comprehensive assessment of the common plate-fin channels is not possible. Also, in most previous comparative studies, the air was considered as working fluid. To the best of our knowledge, no experimental study has compared the thermal-hydraulic performance of different plate-fin channels when a liquid such as the water was used in the PFHE as working fluid. Also, a detailed performance evaluation of all the channel shapes was not considered in the comparisons. Therefore, this motivates us to evaluate a PFHE performance with different plate-fin channels. Seven common channel shapes, including plain, perforated, offset strip, louvered, wavy, vortex-generator, and pin, were fabricated and tested by using a proper experimental procedure at the constant temperature boundary condition. The thermal-hydraulic specifications in these channels were obtained and presented in the dimensional and non-dimensional forms. Three extensively used energy-based performance evaluation criteria (PEC), including the $j/f^{1/3}$ ratio, JF factor, and VG-I criterion, were used for the appraisal.

2. Experiments and measurements

2.1. Experimental test loop

A schematic diagram of the designed and fabricated experimental test loop is shown in Fig. 1. The main sections of the experimental rig are; (1) transmission fluid state, (2) measurement equipment, (3) constant temperature bath system, and (4) cooling unite. The basic components along with their model are numbered and introduced in the schematic. This setup was designed to measure the heat transfer and pressure drop characteristics of the working fluid flowing over the length of different plate-fin channels.

As shown in Fig. 1, the flow rate was controlled by two adjustable ball valves; one after the pump and by-pass three-way and the other one at the by-pass line. The accurate flow adjustment was conducted by a rotameter. The main flow measuring device was a high sensitive ultrasonic flow meter. Two high precise T-type thermocouples were used to measure the inlet and outlet temperatures of the fluid by putting them into the flow line. Nine K-type thermocouples were mounted on the external and different positions of the test section surfaces to measure the wall temperature distribution and ensure the uniformity of the surface temperature along the test section. The pressure drop was found by subtracting the measured local pressure values at the inlet and outlet of the test section. To achieve a high accuracy, two very sensitive pressure transmitters were utilized. Authenticity of the estimated pressure drop was examined by using two glass pipes as differential pressure manometer.

The constant temperature bath system consists of a two-phase chamber and temperature–pressure control systems. The two-phase chamber was made of 2 mm thick stainless steel sheets. The dimensions of the chamber were 20 cm × 60 cm × 30 cm (Width × Length × Height). The temperature of the chamber was controlled by a 2 kW electrical heater as heat source, a temperature controller, a power controller, and a calibrated T-type bulk temperature sensor. This control system maintained the operating fluid at its boiling point. The pressure of the chamber was controlled by a small size-high accurate pressure control digital sensor and a steam electrical pressure valve boarded on the chamber.

The cooling unit system consists of a brazed PFHE, a flat tube-and-plate fin heat exchanger along with an air fan, a calibrated bulk K-type temperature sensor, and a temperature controller. While the working fluid was cooled circa the reservoir temperature in the brazed PFHE, the supplementary cooling to achieve the stringent temperature of the reservoir was done in the second heat exchanger by crossing the air over its flat tubes. The signal obtained from the temperature sensor located at the outlet of this heat exchanger was used in the temperature controller which commanded the on–off status of the air fan. Some detail, including model, range, and accuracy, about all the measuring instruments are presented in Table 1.

For all the experimental tests, the data were logged by a computer whenever the steady-state condition was achieved, usually within 10–15 min from the beginning of each experiment. In the present study, the steady-state condition was defined as all the measurement quantities and operation factors remained constant. Then, the working fluid flow rate was increased, and the new data were recorded. To reduce the measuring errors as much as possible, the decreasing fluid flow rate trend was also utilized. All the factors were measured six times; half for the increasing trend and half for the decreasing trend, and the most centralized four of them were chosen to calculate the average values used in the data reduction section.

2.2. Test sections

To create a physically meaningful and reliably comparative study and also to assess relative advantages of different plate-fin channels, three comparative constraints, namely comparable geometrical parameters, similar operating conditions, and equal thermo-physical properties of the working fluid, were considered here.

The geometrical constraints encompass the following cases,

- A similar frontal flow area,
- A similar channel length,
- A similar fin thickness,
- And similar values of specific geometrical parameters.

The first three constraints produce an equal external heat transfer area attaching with the saturated steam except the wavy channel due to its special geometry. The frontal flow area, channel length, and fin thickness of 3×10^{-4} m^2, 0.4 m, and 4×10^{-4} m were chosen, respectively.

The other constraint was selected from the operating conditions point of view,

- A same volumetric flow rate,
- A same inlet temperature,