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A new method to simultaneously measure local heat transfer and visualize flow boiling in plate heat exchanger

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ABSTRACT

This paper presents the development of a novel method to combine measurement of local heat transfer coefficient and flow visualization in frame-and-plate heat exchanger (FPHE) simultaneously. A heat flux plate is built using two original chevron plates and clay as thermal infills. Thermocouples are deployed on the inner surfaces of both plates. With the known thickness and thermal conductivity of the clay, the instrumented plate functions as a heat flux sensor. After initial calibration, this plate is installed to measure fluid heat transfer from one side, while leaving visual access from the other. Preliminary results of water-water single-phase heat transfer and R245fa-water flow boiling are presented. Combined with visualization, the method provides a viable solution to relate local heat transfer with flow regime within a plate channel, while preserving the real geometry and operating condition.

1. Introduction

Frame-and-plate heat exchanger (FPHE) is commonly used for their ease of cleaning, simple adjustment of heat transfer area, compactness and excellent thermal–hydraulic performance [1]. Early applications of FPHE are mainly for liquid–liquid heat transfer in the lower pressure range (usually below 1.6 MPa), including dairy, pulp and paper industries for their hygiene requirements [1]. It has also been adopted by two-phase applications such as steam generator and petrochemical boiler. With the introduction of brazed plate heat exchanger (BPHE), such plates could withstand higher pressure and later on found its increasing application as condenser and evaporator in air-conditioning and refrigeration systems. Lately plate and shell heat exchangers (PSHE) are introduced as another variation of the similar design.

Plate heat exchanger (PHE, including FPHE, PSHE and BPHE) essentially consists of multiple thin metal plates that are stamped with a wavy chevron, herringbone or similar pattern. Fluid channels are formed by pressing the plates with opposite chevron direction together. The high performance of PHE owe not only to the enlarged surface area, but also to the geometry of the plates such as the corrugation depth, wavelength and angle. The contact points between crests and troughs of two adjacent plates subdivide the fluid path into an array of interconnected unitary cells, which turbulate the flow and enhance heat transfer.

To the best of our knowledge there is no general correlation that accounts for all the effects of geometrical parameters, working fluids and operating conditions. Various corrugation designs have been developed mainly on an empirical basis. Recent development of generalized correlations, taking theoretical [1–3], semi-empirical [4] or empirical [5–7] approaches to predict single-phase heat transfer, has shown moderate success in accounting geometries such as surface enlargement factor, chevron angle and aspect ratio (wave depth/wave length) for low *Pr* number fluids. However, the understanding of two-phase flow in PHE is still far from satisfactory. Numerous studies in this topic were found as summarized in review articles [8–10]. Each study has developed different correlations based on their own experiments with various fluids and plate geometries. However, comparison of these correlations at the same condition yields drastic difference, as pointed out by Eldeeb et al. [10]. There is still no general correlation that accounts for each separate effects on two-phase flow regime, which heat transfer has been successfully correlated with in round tubes. Only a few works in literature focused on developing flow maps and studying flow regimes and their local heat transfer characteristics in PHE, as are reviewed in the next section.

2. Literature review

Convective heat transfer has shown to be greatly dependent on flow pattern, which is revealed through various visualization

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techniques. For single-phase flow, visualization provides information on the magnitude and direction of the local velocity field, the dynamic behavior of the flow, the transition to turbulence and flow recirculation zones. For two-phase flow, the respective distribution of the liquid and vapor also takes on some commonly observed structures, which the prediction of in-tube heat transfer in recent development has shown great success by phenomenologically relating to. Yet the flow visualization was rendered more difficult in PHE due to its complex geometry. Only a very limited number of visualization and local heat transfer studies have been found in literature. Their techniques and some key findings are reviewed as below. For the scope of this paper, discussion is only limited to two-phase evaporation, which is also interchangeably referred to as flow boiling.

2.1. Literature review on flow visualization

Van Carey's group [11,12] combined measurement of local heat transfer and flow visualization of methanol and n-butanol in a cross-ribbed channel that resembles the geometry of PHE. Heat was provided through conduction on one side, and measured by thermocouple placed at distances with known thermal resistance. The adiabatic side provides visual access, which showed a churn or annular flow regime for vertical upward flow and wavy or annular for horizontal flow. Virtually no nucleate boiling was observed. The authors also described a method of correlating heat transfer for annular film flow.

Lin's group [13,6] combined heat transfer and visualization with a different scheme. R134a at various mass flux and vapor quality was split into two streams, one for heat transfer measurement (3-channel) and the other for visualization (2-channel). In the visualization part the end plate was substituted with transparent acrylic plate machined and polished with the same geometry. In saturated boiling [13], liquid film was relatively thin and flow was dominated by evaporation at liquid–vapor interface. Intense nucleate boiling was observed near the inlet port. In subcooled boiling [6], bubbles were somewhat suppressed by raising the mass flux and inlet subcooling and heat flux show large effects on the bubble population, coalesce and generation frequency. Although the inlet condition was the same, the visualization only represented the flow with one side heat transfer. The difference was not investigated.

Jassim et al. [14] presented their investigation of adiabatic pressure drop and flow visualization in three different PHE geometries. The experiments were carried out with R134a in vertical upward flow arrangement. Chevron geometry was machined on a clear PVC plate and bolted together to form a PHE-similar flow passage. Light was provided by the reflection of stroboscope from a white background for uniformity. As a result, four flow regimes (bubbly, rough annular, smooth annular and mist) were clearly observed and mapped out on a mass flux versus quality basis for each geometry. Pressure drop was found to have a strong linear relationship with the kinetic energy per unit volume.

The test section presented by Grabenstein and Kabelac [15] provided a way to preserve the original geometry during visualization. The transparent part was casted by existing industrial stainless steel plate using polyurethane. Local heat transfer was measured by temperature oscillation IR thermography technique. The visualization was carried out in one channel, with R365mfc (normal boiling temperature 40.1 °C) as working fluid. Film, bubbly and slug flow were observed and heat transfer and pressure drop mechanism were developed in each flow regime.

Other than low pressure refrigerant, gas liquid mixture was also found to be a common working fluid. Bai and Newell [16] investigated the pressure drop and flow visualization of air/alkylbenzene oil mixture in chevron plate heat exchanger. Results showed that liquid tended to follow the groove under certain conditions. Tribbe and Muller-Steinhagen [17] used air/water mixture in their visualization and pressure drop study in a 1-channel setup. Three chevron angles were investigated. Regular bubbly, irregular bubbly, churn, film and partial film flow patterns were identified and flow map was constructed. Pressure drop was correlated with two-phase multiplier and Lockhart-Martinelli parameters. Vlasogiannis et al. [18] also used air/water mixture for heat transfer and visualization, which was made possible by replacing the end plate with a lithographically embossed plexiglass plate. Flow map was constructed with 5 flow patterns, each measured with heat transfer enhancement over single-phase flow at various superficial liquid velocities. Nilpueng and Wongwises [19] reported visualization with air/water mixture in asymmetric chevron plates (55° and 10°), identifying bubbly, bubble recirculation and annular-liquid bridge pattern in upward flow and slug, annular-liquid bridge and annular-liquid bridge/air-alone pattern in downward flow. Two-phase multiplier of all regimes was correlated as a function of Lockhart-Matinelli number in this study.

The aforementioned two-phase flow visualization were all carried out by using high speed camera to capture the liquid vapor interface. Nevertheless, visualization using neutron radiology was reported by Asano et al. [20] as an alternative method. It was used to investigate the flow regime and void fraction of air/water mixture in both a 1-channel and 18-channel PHE. The liquid content was shown to be proportional to the image brightness. The result suggested that liquid distribution depended on the inlet liquid flow rate, while effect of the gas flow was little. The visualization technique was later used to combine with heat transfer measurement, as reported by Baba et al. [21] in 2009. The test section had 3 channel, with HCFC-142b (CH_3CFCl_2) evaporating in the center and fluorocarbon FC3283 without hydrogen in side channels as heating medium for its low neutron attenuation. Their results showed downward boiling produced higher heat transfer coefficient, contradicting the conventional acceptance of superiority of the vertical upward flow for boiling.

2.2. Literature review on local heat transfer measurement

There were a few methods reported to measure local heat transfer coefficient in plate heat exchanger for single-phase fluid. In 1985, Focke et al. [22] used diffusion-limited current technique (DLCT) to investigate the effect of the chevron angle from 0° to 90°. The test method was based on a diffusion controlled reaction of an ion, which simulated a constant wall temperature mass transfer at high *Pr* number. The same method was adopted by Heggs et al. [23] in 1997, who found the flow to be of higher turbulence around the contact points of the plates. In 1989, Gaiser and Kottke [24] applied a molecular absorption method to study local heat transfer of PHE in a wind tunnel. The plate was coated with wet filter paper containing the first reactive component. Streaming air contained a reactive gas as the second component. The reaction gas was absorbed by the reactive liquid component and caused a chemical reaction resulting in a colored product. The locally transferred mass was determined from the light reflectance of the absorption paper samples and converted to a surface map of Nusselt number by the analogy of heat and mass transfer. In 1996, Stasiek and Ciofalo [25] reported their experiment of local heat transfer measurement using liquid crystal thermography. Heat transfer was measured between air and a sample plate under a constant temperature water bath. Liquid crystal was coated on the outer surface of the end plate on the air side. It modifies incident white light and display colors whose wavelength is a function of temperature. In 2010, Freund and Kabelac [26] applied oscillation IR thermography (TOIRT) to investigate local heat transfer in PHE. The method used a halogen spot array periodically (0.1–