2021

Two-phase Refrigerant Flow in the Inlet Header of Brazed Plate Heat Exchangers: Visualization and Its Effect on Distribution

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ABSTRACT

When used as direct expansion (DX) evaporators, brazed plate heat exchangers (BPHEs) suffer from the maldistribution of the two-phase refrigerant flow among parallel plate channels. One of the critical mechanisms of two-phase maldistribution is the phase separation in the inlet header.

This paper presents an experimental investigation of the two-phase refrigerant (R134a) flow in the inlet header of a brazed plate evaporator and its effects on the distribution. Visualization of two-phase flow is accomplished through a 3D-printed transparent window at the inlet header of the heat exchanger. The observed flow regime is periodic and three stages are identified in a cycle. The influence of the operating conditions on the two-phase flow regime is also explored. The two-phase flow distribution in the BHPE is quantified by an IR thermography-based method. The quantification results demonstrate that the two-phase flow regime in the inlet header significantly affects the distribution.

1. INTRODUCTION

Two-phase refrigerant maldistribution among different channels is one of the main issues in the heat exchangers with the "headers and multi-parallel channels" structure, like microchannel heat exchangers (MCHXs) and plate heat exchangers (PHEs) of different types: frame-type (FPHE), brazed-type (BPHE), and shell-type (SPHE). Generally, two dominant mechanisms determine the two-phase flow distribution in such a structure: 1) phase separation in the inlet header; 2) header induced pressure drop (Tuo and Hrnjak, 2013a). The phase separation in the inlet header is mainly because the liquid and vapor refrigerant differ greatly in the thermophysical properties, especially density. The significant difference in the thermal properties results in the different magnitude of forces, like inertia, gravity, etc, exerted on two phases, which leads to different behaviors of two phases in the inlet header. As for the header induced pressure drop, it is caused by the different pressure profiles along the inlet and outlet header of the heat exchanger, which leads to an uneven pressure drop across each channel, and the refrigerant flow rate through each channel is thereby not identical.

Two-phase flow visualization is a good tool to understand the mechanism behind the phase separation in the inlet header. Fei and Hrnjak (2002) experimentally visualized and quantified the two-phase flow of R134a in the inlet header of an automotive PHE with downward flow channels. The authors defined three flow regimes in the inlet header, namely "stratified flow", "liquid jet" and "mist flow" and concluded that the occurrence of dispersed droplets improved the distribution significantly. Huang et al. (2007) visualized the two-phase R410A flow in a horizontal round inlet header with 10 upward flow channels. Their observation indicated that the low momentum vapor refrigerant on the top layer was easily taken off in the branch tubes near the inlet, while the high momentum liquid refrigerant on the bottom layer travels farther toward the end of the manifold. One year later, Marchitto et al (2008) used air and water to explore the two-phase flow distribution in a horizontal round header with 8 pairs of upward flow channels. The visualization results in their work showed that a nozzle at the inlet of the distributor introduced a jet inside and significantly improved the distribution. Tuo and Hrnjak (2013b) for the first time observed the periodic reverse flow from the microchannel to the inlet header of the MCHX. The authors also confirmed through the visualization that this reverse flow moderates the maldistribution of liquid refrigerant due to vapor-liquid interface oscillations around the tube inlets. The two-phase flow of R410A in a vertical header of the MCHX was visualized by Zou and Hrnjak (2013). Two flow regimes were identified from their visualization: churn and separated flow and the authors also concluded that the churn flow is more beneficial to the distribution because the two phases are more homogeneous. Allison and Garimella (2017) observed the two-phase flow conditions in the horizontal rectangular and triangular header. In their work, flow patterns in the header were categorized into five main groups, and a flow regime map based on the inlet superficial phase velocities was developed for each geometry.

This paper presents an experimental investigation of the two-phase refrigerant (R134a) flow in the inlet header of a brazed plate heat exchanger (BPHE) and its effects on the distribution. Visualization of two-phase flow is accomplished through a 3D-printed transparent window at the inlet header of the heat exchanger. The two-flow regimes in the inlet header are identified based on the visualization. The quantification of the two-phase distribution in the BPHE is achieved by an IR thermography-based method.

2. EXPERIMENTAL FACILITY

The experimental facility is shown in Fig. 1. In the tests, distilled water is heated by two immersion electrical heaters in the tank and circulates through one side of the tested BPHE to provide heat to the refrigerant. The subcooled refrigerant, R134a, is driven by a gear pump and flows through a Coriolis type mass flow meter to measure the flow rate. An electrical heater, controlled by a variable frequency drive, is then used to adjust the vapor quality of the refrigerant. Before entering the tested BPHEs, the two-phase refrigerant becomes fully developed in a transparent developing tube (or feeding tube) where the flow condition is visualized. The two-phase refrigerant enters the BPHE through the inlet header at the bottom and then is distributed into different plate channels where the refrigerant evaporates. To observe the two-phase flow condition, the inlet header of the BPHE is cut and a 3D-printed transparent window is installed at the inlet header to provide sealing and visual access. An infrared camera is also installed to capture the temperature profile on the sidewalls, which would be used to quantify the two-phase distribution. After evaporation, the refrigerant leaves the BPHE through the outlet header at the top and flows through the condenser and subcooler to recover to the subcooled state before the pump. The pressure transducers and type T (copper-constantan) thermocouples are installed at locations indicated in Fig 1. Moreover, four probes are inserted into the headers of the tested BPHE to measure the pressure profile in the headers and the temperature change across the plate channels. Details of the probe design can be found in Li and Hrnjak (2021a). In this study, a BPHE with 50 plates is used, of which the geometric parameters are listed in Table 1.

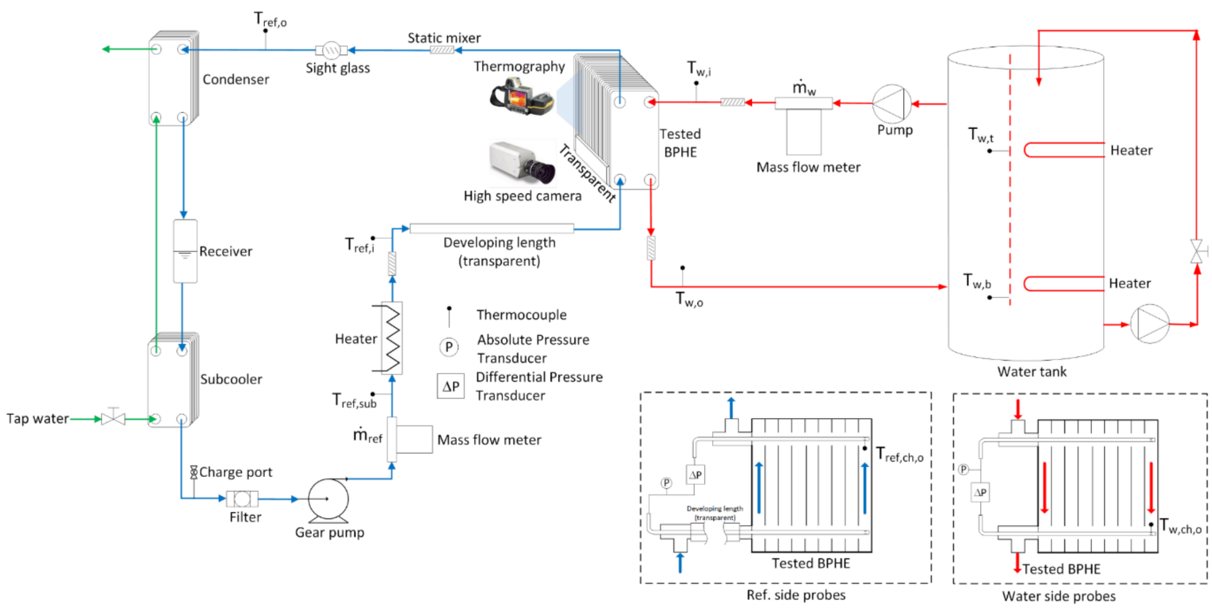

Figure 1: Experimental facility

The design of the visualization section is shown in Fig. 2. The inlet header of the BPHE has been partially cut by an inclined angle. The transparent observation window is made through 3D printing to provide sealing and visual access.

Small pieces of stainless-steel are installed into the transparent window to substitute the cut-off part of the metal plates in the BPHE so that the original header geometry is maintained. The transparent window is glued to the inlet header of the BPHE by epoxy glue. The leaking test has been conducted and this visualization section can hold the pressure up to 900 ~ 1000 kPa.

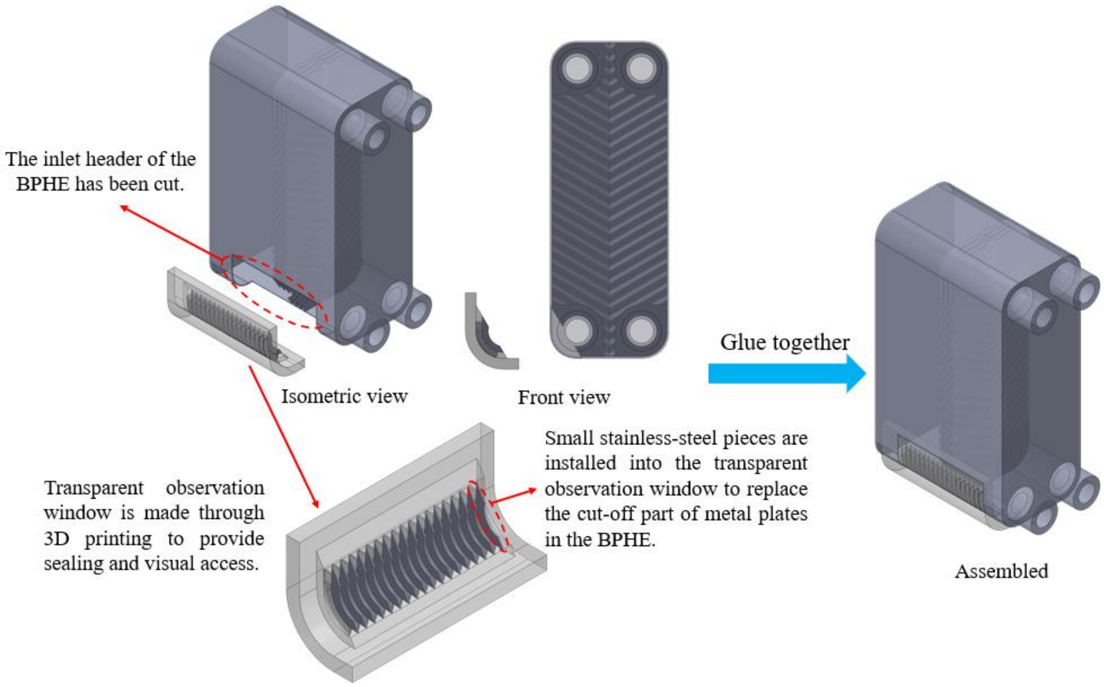

Figure 2: Design of the visualization section

Table 1: Geometric parameters of the BPHE

Parameter	Value
Chevron angle, φ, ^{o}	60
Corrugation depth, b, mm	2.0
Corrugation pitch, P_c, mm	7.0
Plate thickness, t, mm	0.30
Port length, L_p, mm	172
Total length, L_v, mm	206
Port width, L_h, mm	42
Total width, L_w, mm	76
Heat transfer area per plate, A_p, m^2	0.014
Port diameter, D_p, mm	20.0

3. VISUALIZATION OF TWO-PHASE FLOW IN THE INLET HEADER

The two-phase flow conditions in the inlet header, as well as that in the feeding tube before the heat exchanger, are visualized in the experiments. The experiments cover three different refrigerant inlet vapor quality ($x_{r,i}$ ~ 0.1, 0.2, 0.3) and three different refrigerant mass flux at the BPHE inlet ($G_{r,i}$ ~ 77, 96.3, 115.5 kg/m2s). In the tests, the saturation temperature of the refrigerant ($T_{r,sat}$) and the inlet temperature of the water ($T_{w,i}$) are maintained around 15 and 30 ^oC respectively. The water mass flux at the BPHE inlet is changing proportionally to the refrigerant mass flux. The resulting bulk exit superheat of refrigerant is ranging from 8 to 13 ^oC.

3.1 Typical flow regimes in the inlet header

Based on the visualization results, the two-phase flow regime in the inlet header is identified to be periodic and three stages are included in one cycle. A specific experimental condition (($G_{r,i}$ = 115.5 kg/m^{2}s, $x_{r,i}$ = 0.1, $T_{r,sat}$ = 15.3 ^{o}C, $T_{w,i}$ = 30.0 ^{o}C, $G_{w,i}$ = 600.9 kg/m^{2}s) is taken as an illustration.

The first stage, shown in Fig. 3, is called the **top corner vapor flow**. In this stage, the flow regime in the feeding tube is stratified or stratified-wavy flow, in which, due to the gravitational force, the vapor refrigerant flows at the top of the tube and the liquid refrigerant flows at the bottom. When the two-phase flow enters the inlet header, the lighter vapor at the top has a smaller momentum which makes it easier for the vapor refrigerant to turn 90^o and branch out through the first several channels near the entrance. The liquid refrigerant occupies the bottom of the inlet header when entering the BPHE. With the vapor refrigerant branching out through the first several channels, the liquid level rises, and eventually, the liquid refrigerant occupies the entire cross-sectional area of the inlet header. This flow regime is characterized as the vapor refrigerant only exists at the top corner of the inlet header near the entrance, and the liquid refrigerant occupies most of the volume of the inlet header. Moreover, the vapor generation, due to the heat conduction of the metal plates, is also observed in the inlet header. The bubbles generated in the inlet header flows into the different plate channels under the effect of buoyancy.

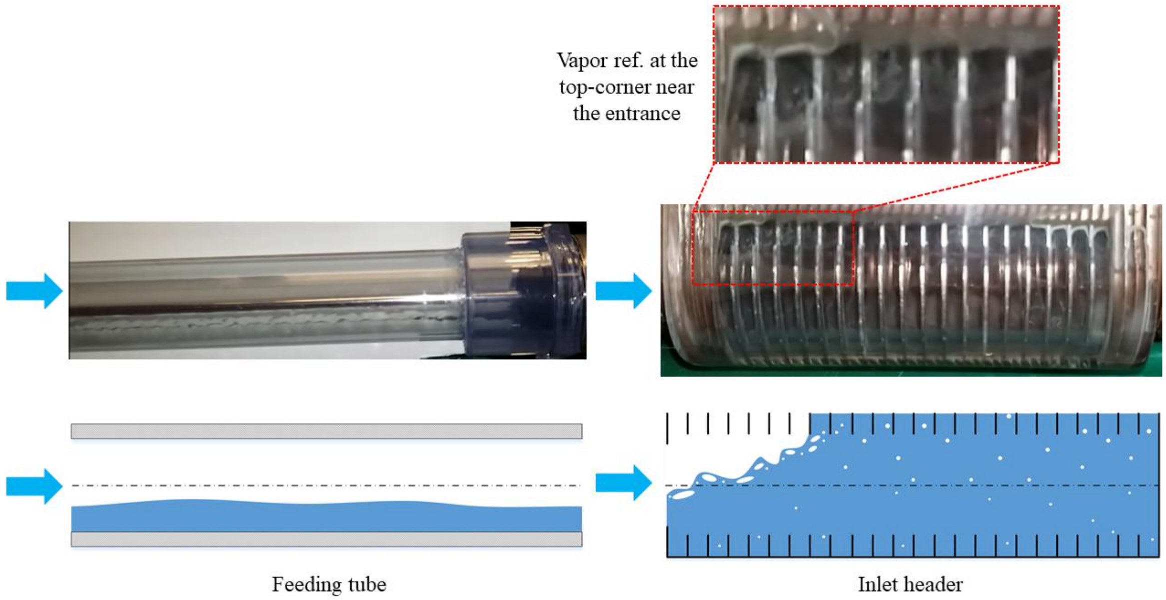

Figure 3: Two-phase flow in the inlet header, 1st stage: top corner vapor flow

The second stage demonstrated in Fig. 4, is called the **vapor jet flow**. Triggered by the Kelvin-Helmholtz instability, the rolling waves are present in the feeding tube. With the waves rolling forward and partially block the tube cross-section, the vapor refrigerant above the wave peaks accelerates and is partially mixed with the liquid refrigerant due to the interfacial shear. The high-speed, vapor-rich refrigerant mixture enters the inlet header in the form of a jet. The jet flow produces many high-speed small bubbles in the core area of the inlet header, which can reach the downstream of the header. Therefore, this jet flow helps distribute the vapor refrigerant to the downstream channels. The small bubbles are also observed to merge and form the big bubbles in the downstream of the header.

The third stage, shown in Fig. 5, happens immediately after the second stage. When the big waves in the feeding tube move to the entrance of the heat exchanger, the entrance is largely, or in some conditions, completely blocked by the liquid refrigerant. With the sequent waves reaching the heat exchanger entrance, the liquid level at the entrance is further lifted. Therefore, very little vapor can enter the heat exchanger thus the inlet header is almost occupied by the liquid refrigerant, except the bubbles generated in the header due to the heat conduction. This stage is then called the **liquid blockage flow**. With the liquid refrigerant is delivered to the heat exchanger, the liquid level near the heat exchanger entrance decreases. Then, the flow regime resumes to the first stage and the next cycle starts.

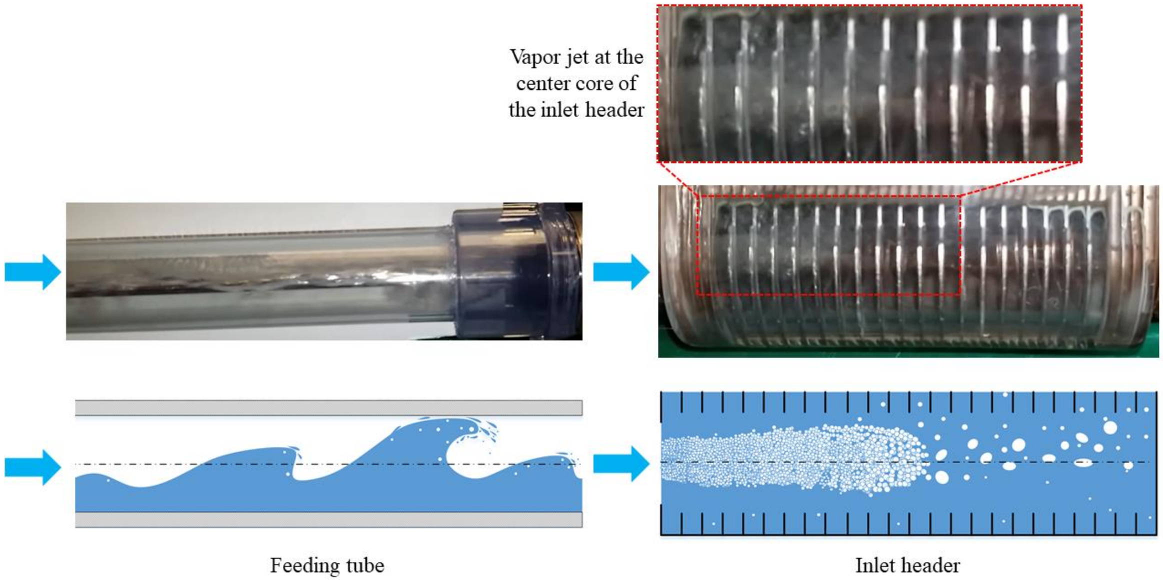

Figure 4: Two-phase flow in the inlet header, 2nd stage: vapor jet flow

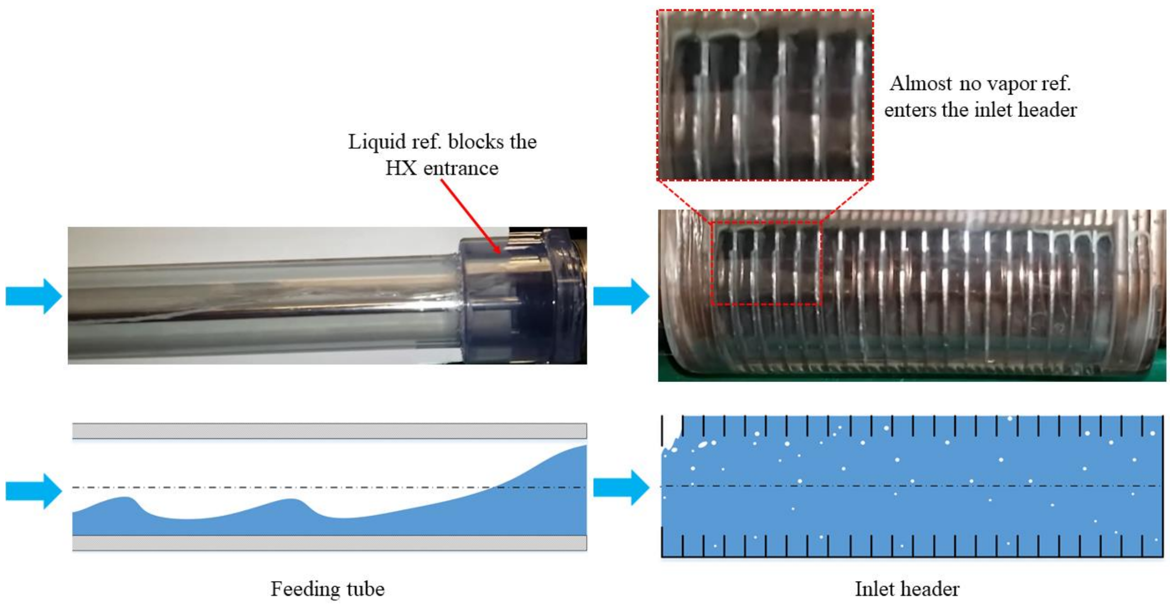

Figure 5: Two-phase flow in the inlet header, 3rd stage: liquid blockage flow

3.2 Effects of the inlet vapor quality on the flow regimes

Fig.6 gives the comparison of the two-phase flow regimes in the feeding tube and the inlet header at a fixed refrigerant mass flux ($G_{r,i}$ ~ 77kg/m^{2}s) but different vapor quality. At the 1st stage, with the inlet vapor quality increases from 0.1 to 0.3, the two-phase flow regime in the feeding tube remains stratified or stratified-wavy flow, but the liquid level decreases, and the vapor refrigerant velocity increases to satisfy the required mass flux. With a higher momentum, the vapor refrigerant could reach more downstream channels in the inlet header, indicated by the marked liquid-vapor interface in the figure. At the 2nd stage, on one hand, the velocity difference between the liquid and vapor phase in the feeding tube is increased with the inlet vapor quality, so that the waves are easier to trigger. On the other side, due to the reduced liquid level at the higher vapor quality, the height of the trigger waves is reduced, which makes it harder to push the downstream vapor refrigerant to the inlet header and form the vapor jet. Therefore, it can be seen in Fig. 6, when the inlet quality changes from 0.1 to 0.2, the vapor jet in the inlet header is more obvious. However, with the inlet quality keeps increasing to 0.3, the two-phase flow in the inlet header remains top-corner vapor flow as seen in the 1st stage, and the vapor jet can not be observed due to the low liquid level. For the last stage, at the inlet vapor quality of 0.1 and 0.2, almost no vapor is observed entering the inlet header because of the blockage of the liquid level at the entrance. But at the inlet vapor quality of 0.3, the liquid level is too low to block the vapor refrigerant, the flow regime in the inlet header remains the top corner vapor flow.

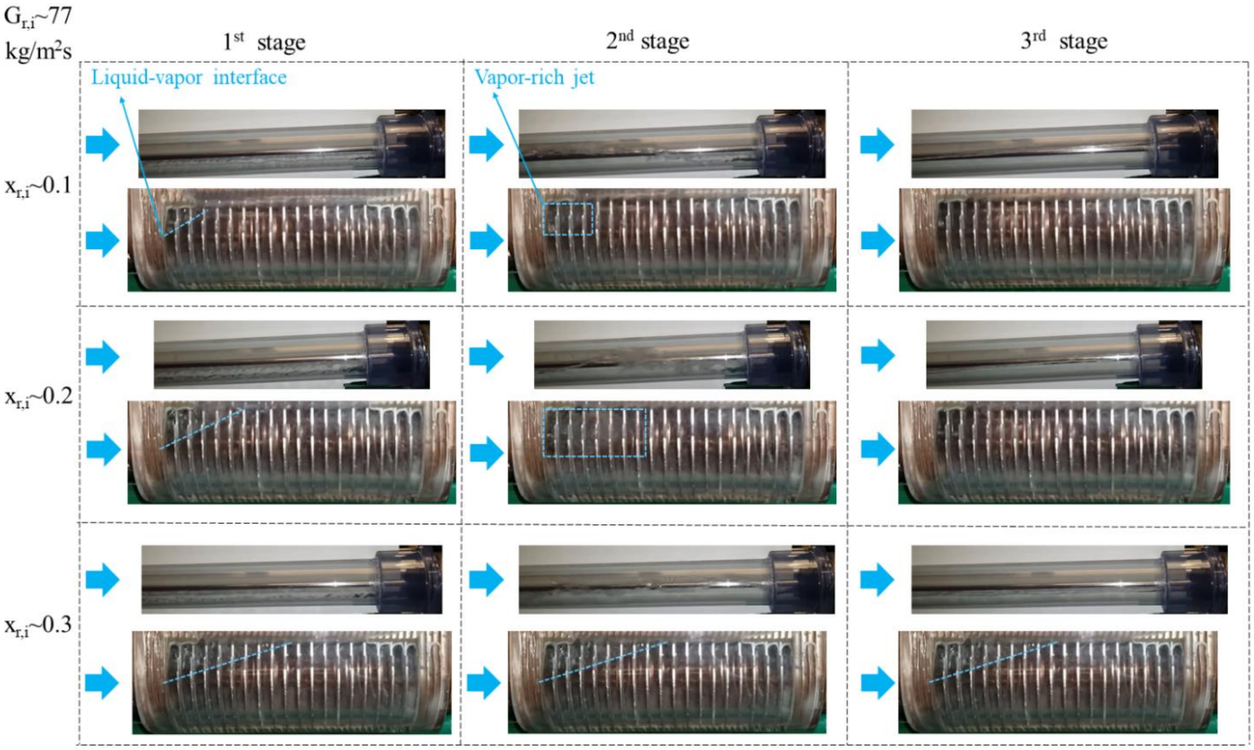

Figure 6: Effects of the inlet vapor quality on the two-phase flow regimes

3.2 Effects of the mass flux on the flow regimes

Fig. 7 shows the effects of the refrigerant mass flux on the two-phase flow regime.

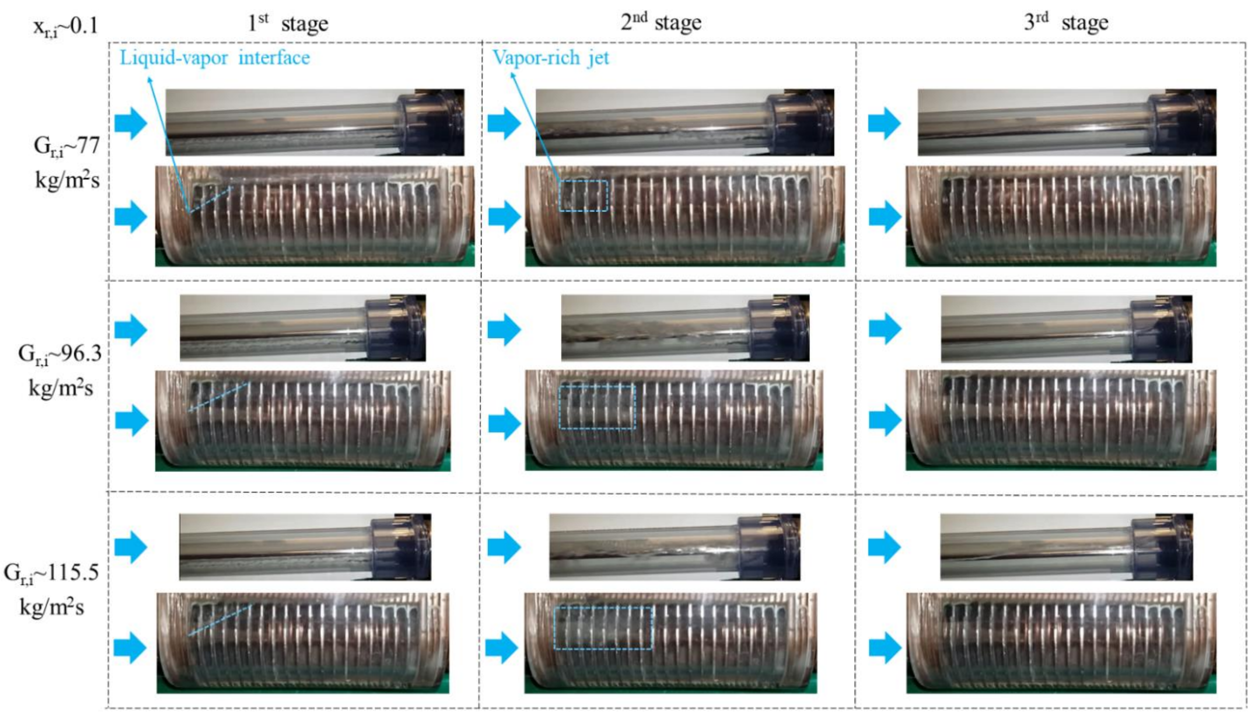

Figure 7: Effects of the mass flux on the two-phase flow regimes

The most distinguishable difference when comparing the two-phase flow regimes at different refrigerant mass fluxes is the magnitude of the vapor jet at the 2nd stage. With a higher mass flux, the velocity of both vapor and liquid phase increases, and the magnitude of the generated waves in the feeding tube also increases, which forms a stronger vapor jet flow in the inlet header. The two-phase flow regimes at the 1st and 3rd stages are quite similar at the different refrigerant mass flux.

4. EFFECTS OF TWO-PHASE FLOW REGIME IN THE INLET HEADER ON DISTRIBUTION

As discussed above, the phase separation in the inlet header is one of the dominant mechanisms behind the two-phase maldistribution and the two-phase flow regime is a crucial influence factor of the phase separation. To explore the effects of the flow regime in the inlet header, the two-phase distribution in the BPHE is experimentally quantified. An infrared thermography-based method is used in this study for quantification. The basic idea is first identifying the boundary between the two-phase and superheated region on the sidewall of the BPHE from the IR images. The identified boundary is then matched in a BPHE evaporator model by adjusting the two-phase distribution. The quantification of the two-phase distribution is thereby achieved. The details in this method can be found in Li and Hrnjak (2021b). The quantification results are given in Fig. 8.

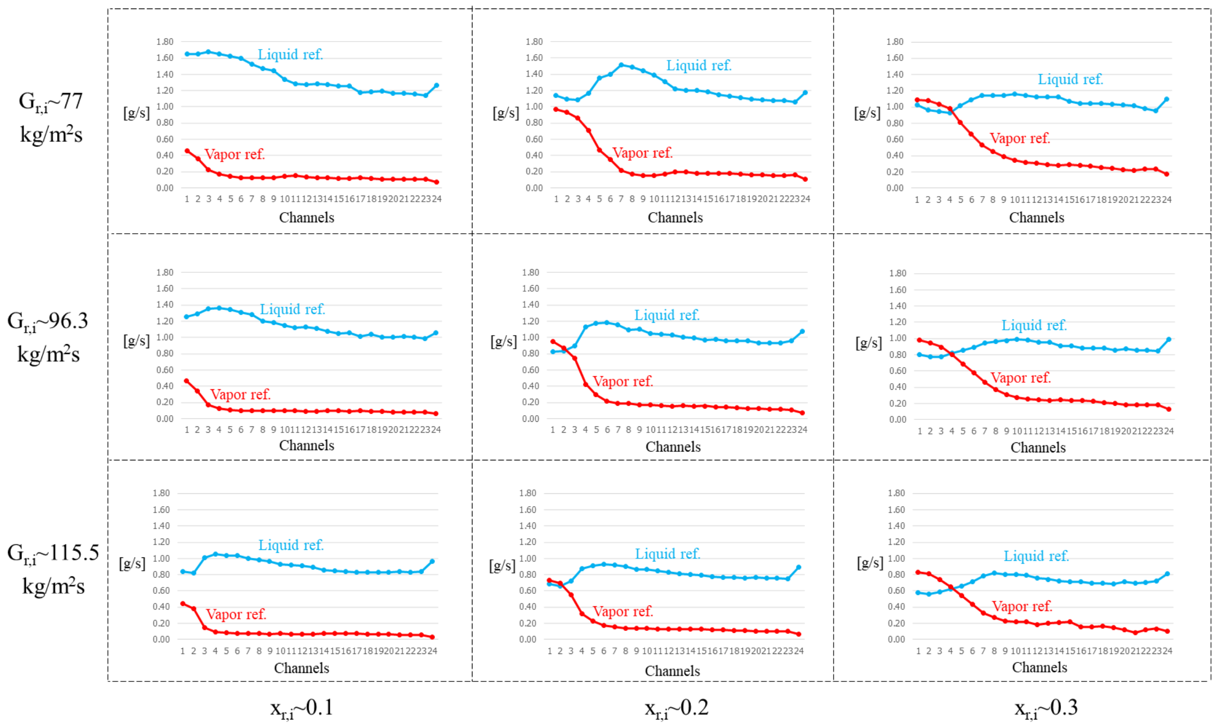

Figure 8: Quantification of two-phase flow in the BPHE

As shown in Fig. 8, the general distribution profile is that the vapor refrigerant mainly branches through the first several channels and very limited vapor refrigerant can reach the channels at the downstream of the inlet header. For the liquid refrigerant, the channel mass flow rate first increases at the first several channels, reaching the maximum, and then decreases along the flowing direction in the inlet header. This distribution profile is corresponding to the top corner vapor flow regime (1st stage) in the inlet header: the vapor refrigerant mainly presents at the top corner of the header and branches through the channels at this region; the liquid refrigerant occupies most of the volume of the inlet header, which gives the liquid refrigerant a distribution profile similar to that of the single-phase flow. The contribution of the vapor jet flow regime (2nd stage) is to deliver the vapor refrigerant to the downstream of the inlet header, which explains the presence of the vapor refrigerant, though very limited, in the channels at this region. As for the 3rd stage, the liquid blockage flow intensifies the single-phase-like distribution of the liquid refrigerant.

When comparing the distribution profile at different inlet vapor quality, one could find that with a higher inlet quality, the vapor refrigerant reaches more downstream channels, and this matches with the visualization results in Fig. 6.

With the vapor delivered to more channels, the distribution of liquid refrigerant is improved when the inlet quality increases.

The distribution of vapor refrigerant seems to maintain a similar profile when the refrigerant mass flux changes. This agrees with the observation that the vapor-liquid interface does not change too much at the 1st stage in Fig. 7. Due to the single-phase-like distribution behavior of the liquid refrigerant, with a higher mass flux, the maldistribution is more significant.

5. CONCLUSION

In this study, the two-phase refrigerant flow in the inlet header of the BPHE is visualized. The observed flow regime is periodic and three stages are identified in a cycle: top corner vapor flow, vapor jet flow, and liquid blockage flow. The influence of the operating conditions on the two-phase flow regime is explored. The visualization results show that with a higher inlet vapor quality, the top corner vapor flow is intensified; the vapor jet flow is intensified at the moderate vapor quality but weakened at the highest vapor quality; the liquid blockage flow becomes less identifiable due to a lower liquid level. An increased refrigerant mass flux generally intensifies the vapor jet flow. The two-phase flow distribution in the BHPE is quantified by an IR thermography-based method. The quantification results demonstrate that the two-phase flow regime in the inlet header significantly affects the two-phase flow distribution.

NOMENCLATURE

G	mass flux	kg m^{-2} s
x	vapor quality	-

Subscript

ch	channel
i	inlet
r	refrigerant
sat	saturation
w	water

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ACKNOWLEDGMENT

The authors thankfully acknowledge the support provided by the Air Conditioning and Refrigeration Center at the University of Illinois at Urbana-Champaign.