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X. Bai
University of Illinois at Urbana-Champaign

T. A. Newell
University of Illinois at Urbana-Champaign

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AN INVESTIGATION OF TWO-PHASE FLOW CHARACTERISTICS IN CHEVRON-STYLE FLAT PLATE HEAT EXCHANGERS

Xuan Bai* and Ty A. Newell

Air Conditioning and Refrigeration Center
Department of Mechanical and Industrial Engineering
University of Illinois at Urbana-Champaign
1206 W. Green Street, Urbana IL 61801
*(217-244-3531; xuanbai@uiuc.edu)

ABSTRACT

The purpose of this study is to investigate the two-phase flow field characteristics in flat plate heat exchangers. The main objectives are the causes of plate wetting/drying, measurement of fluid flow field characteristics, and the effects of enhanced plate passageways. Three types of passageways are being investigated: smooth-walled passageways, chevron-style passageways, and embossed (bumpy) plate passageways. Pressure drop and flow distribution data are examined over a Reynolds number range of 5,000~30,000. Different passageway orientations (horizontal, upflow, and downflow) are investigated. This paper will present flow field results for chevron-style and smooth-walled heat exchanger passageways with air and alkylbenzene oils as working fluids.

INTRODUCTION

Plate heat exchangers (PHE) have been widely used in the chemical and process industry for many years. The advantage of PHE relative to their shell-to-tube counterparts was clearly described in the reviews from Kerner et al. [1], Shah and Focke [2], and Williams [3]. PHE were originally used almost exclusively in the dairy, brewing, and food industries due to the ease with which they may be disassembled and cleaned to meet hygienic requirements. In the last 20 years, however, plate heat exchangers have been introduced to the refrigeration and air conditioning systems as evaporators and condensers for their high efficiency and compactness. With the increasing interest in PHE, it is important to know how to predict their thermal performance and the associated pressure drop.

Plate heat exchangers often consist of an array of stamped or corrugated plates clamped together in a frame. "Brazed" construction is also common where the plates are fused together into an assembly. Due to the great variety of possible corrugation patterns, it seems impossible to provide users with generalized thermal and hydraulic design equations. Most investigations on PHE have involved determining the friction factor and heat transfer coefficient experimentally by modifying correlations available for flat plate channels of the forms:

$$Nu = a * \mathrm{Re}^{b} * \mathrm{Pr}^{c}$$
$$f = d * \mathrm{Re}^{e}$$

Where a, b, c, and d are constants. A summary of published heat transfer and friction factor – pressure drop correlations can be found in the review from Talik et al. [4]. Each correlation is only valid for specific plate-type corrugations within a certain Reynolds number range.

The fluids in refrigeration heat exchangers are two-phase flow. Most studies mentioned above were conducted on single-phase liquid-to-liquid conditions using water as the working fluid. The information available for PHE at two-phase flow conditions is much more limited. Yan et al. [5, 6] investigated the performance of PHE under evaporation and condensation conditions with refrigerant R-134a as the working fluid.

Characteristics of the flow patterns in two-phase flow are recognized as one of the most significant factors affecting pressure drop, heat transfer, and refrigerant charge in refrigerant systems. Condensation research results from Dobson at al. [7] show that condensation heat transfer is strongly affected by the characteristics of the two-phase flow structure. Evaporation investigation results from Wattlet et al. [8] and Kattan et al. [9-11] very clearly illustrate the importance of flow regime characteristics on heat transfer predictions for evaporation. Once we understand the two-phase flow characteristics of the flow patterns in a PHE, heat transfer relations may be developed by modeling the thermal boundary layers in the fluids, as indicated by Martin [12].

Flow visualization provides us a direct method to visually explore the flow pattern between two parallel plates. Luo et al. [13] investigated the single-phase flow pattern in two corrugated ducts of different corrugation patterns by the dye-injection technique with water as test fluids. A transition Reynolds number for flow in the duct was 80 to 120 was found. Flow visualization was also used by Yan et al [5] to examine R-134a evaporation in a heat exchanger.

In this paper, flow visualization is used to study the characteristics of the two-phase flow patterns in PHE. Different passageway orientations (horizontal, upflow, and downflow) are investigated. The flow pattern in smooth-walled heat exchanger passageways was also investigated as a research base against which to compare to effects of enhanced plate passageways. Initial results for chevron-style passageways with oil-air are presented in this paper. Current activities are directed toward refrigerant (R123) saturation conditions and refrigerant-oil conditions.

EXPERIMENTAL APPARATUS AND PROCEDURE

Figure 1 shows a schematic of the adiabatic, near-ambient pressure, two-phase flow visualization loop used in this study. A liquid pump is used to circulate the liquid phase. A blower is used to transport vapor through 3.8cm inner diameter copper tubes to the test section. The liquid and vapor mixes together before entering the test section. The two-phase mixture from the test section is separated and returns to the liquid reservoir and vapor blower, respectively. Liquid mass flow rate is measured by a mass flow meter. Vapor mass flow is determined by measuring pressure drop through a straight tube section that is before the injection of the liquid phase. The air mass flow rate is calibrated with a commercial air mass flow meter. Vapor mass flow rate agreement between the mass flow meter and the tube pressure drop measurements is within 5 percent. The liquid/vapor mass flow rate and the mixture quality in test section can be controlled by adjusting by-pass valves and shut-off valves on the liquid/vapor lines. By changing the status of the shut-off valves, we can realize three different orientations: horizontal, vertical up, vertical down flow in the loop. Thermal couples are attached to the liquid/vapor lines and test section to measure the temperatures along the loop.

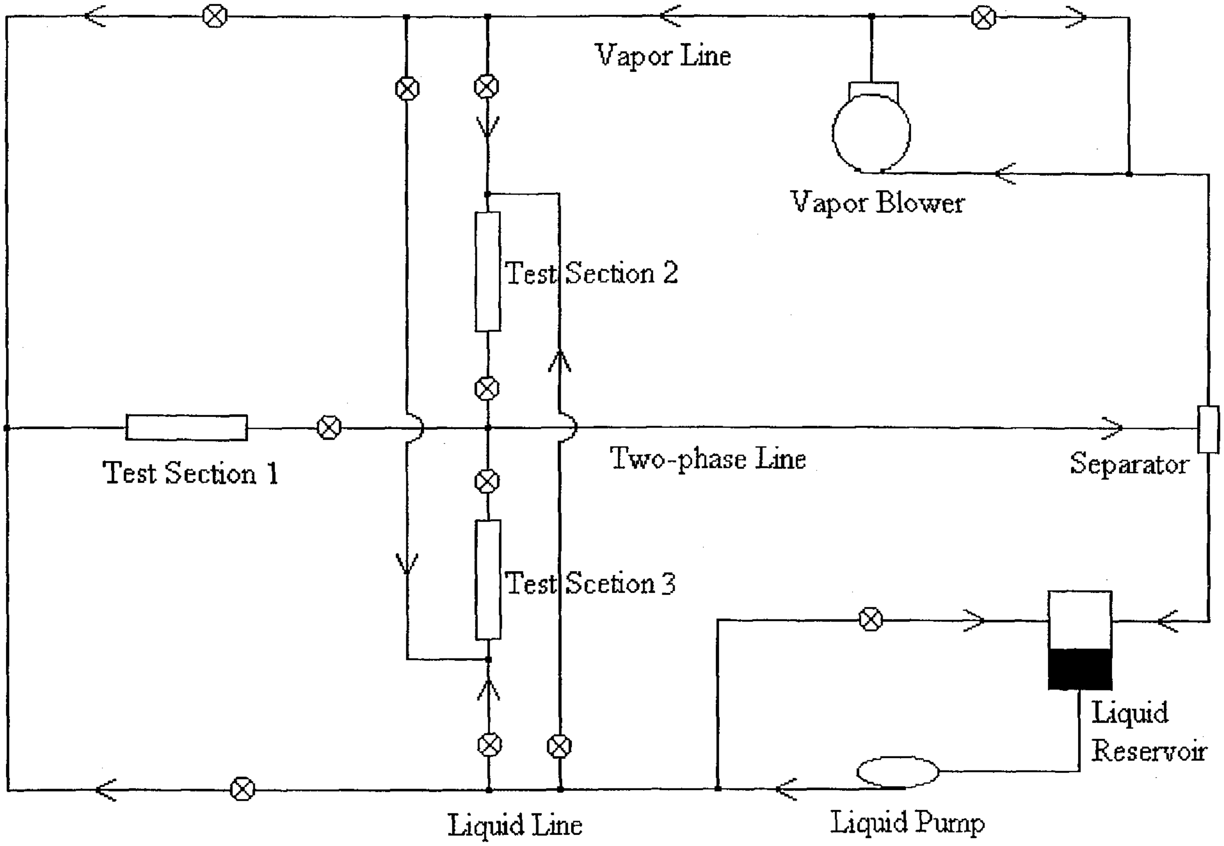

Figure 1. Schematic of Experimental Apparatus

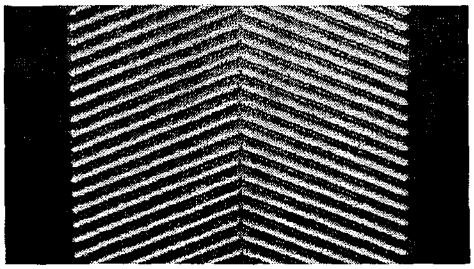

Figure 2. Photograph of Chevron-style Flat Plate Heat Exchanger Surface Made from Transparent PVC

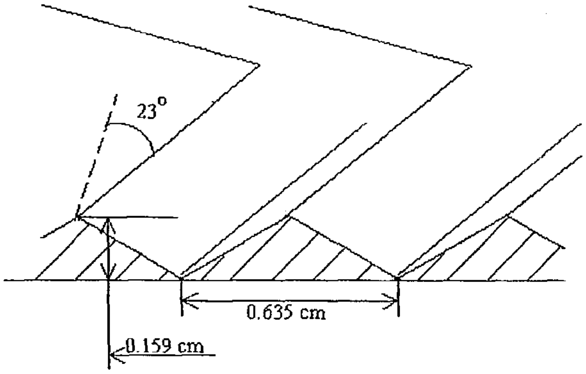

Figure 3. Geometrical Features of Chevron Structure

Test sections have been made from transparent polyvinyl chloride (PVC) sheets. The thickness of the sheets is 0.635 cm. The length of the test sections including the inlet and outlet ports is 50.8 cm and the width is 12.7 cm. Three smooth test sections with plate spacings of 1.27

cm, 0.64 cm, and 0.32 cm were built. Chevron-style surface structures were machined and polished to geometry similar to commercially available plates. Chevron test section was built with two chevron plates attached and pressed together with the V-grooves in counter directions. Figure 2 is the photograph of the PVC chevron-style flat plate. Figure 3 conatins geometrical features of the chevron structure used in the experiment. The chevron inclination angle is 23°. The chevron depth is 0.169 cm and the chevron pitch is 0.635 cm. Two pressure taps are attached to the test section to measure the pressure drop.

RESULTS AND DISCUSSION

Tests were conducted with air and alkylbenzene oils as working fluids at ambient pressure and temperature. Alkylbenzene oil is one kind of refrigeration and air conditioning compressor lubricants. The oils used here have a density of 0.977×10^3 kg/m^3 at 20°C and a kinematic viscosity of 72.3×10^{-6} m^2/sec at 40°C. Pressure drop and flow distribution data are examined over a Reynolds number range of 5,000~30,000. Different passageway orientations (horizontal, upflow, and downflow) are investigated.

Pressure Drop and Friction Factor

Experiments were first conducted in three smooth test sections with plate spacings of 1.27cm, 0.64cm, and 0.32 cm with dry air. Figure 4 shows comparison of the pressure drop in different spacing test sections. The Reynolds numbers used in this paper are calculated with the following equation: $\mathrm{Re}_{Dh} = \frac{4Q}{p\nu}$, where Q is the air volume flow rate and p is the wetted perimeter. It is very clear that the pressure drop increases significantly with the decrease of the plate spacing and the increase of Reynolds number. These results cover large range of pressure drop and flow conditions. They are the reference to complex passageways and two-phase flow.

Figures 5, 6, and 7 show pressure drop data for oil/air flows in different test sections/orientations. The tests were conducted over a quality range of 0.6~0.95, where the quality is ratio of the air mass flow rate to the total mass flow rate the test sections. Increasing oil flow rates increases pressure drop. In all test sections, the trend of oil/air pressure drop curves is almost same to that of dry air. It indicates that two-phase flow pressure drop may be predicted by using similar correlations for single-phase flow. Comparing figure 6 and 7, we found the effects of the oil flow on pressure drop in 0.32cm vertical down flow test section were much smaller than in 0.64cm vertical up flow test section. It may be due to two reasons: (1) Effect of gravity is favorable to vertical down flow; (2) The air velocity in 0.32cm test section is almost twice of the air velocity in 0.64cm test section. It brings the liquid moving faster in 0.32cm test section. At same liquid mass flow rate, the liquid film thickness is thinner in 0.32cm test section. So the effect of oil flow is weaker.

Figure 8 shows the comparison of friction factor in all test conditions. The dry condition tests data are agree with the analytical formula for turbulent flow between two parallel plates. The analytical friction factor was calculated with the following equation [14]:

$$\frac{1}{f^{0.5}} \approx 2.0\log\left(0.64\,\mathrm{Re}_{Dh}\, f^{0.5}\right) - 0.8$$

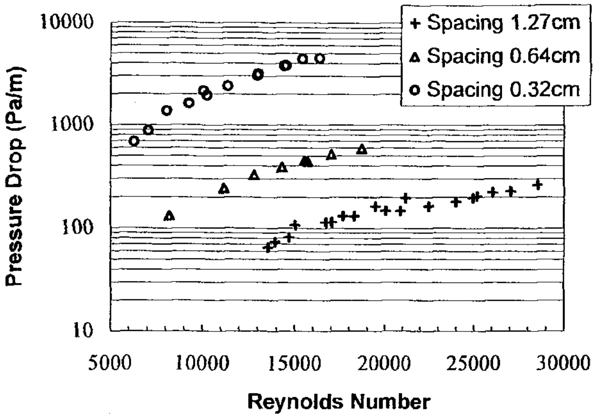

Figure 4. Pressure Drop in 1.27cm, 0.64cm and 0.32cm Plate (Dry Condition)

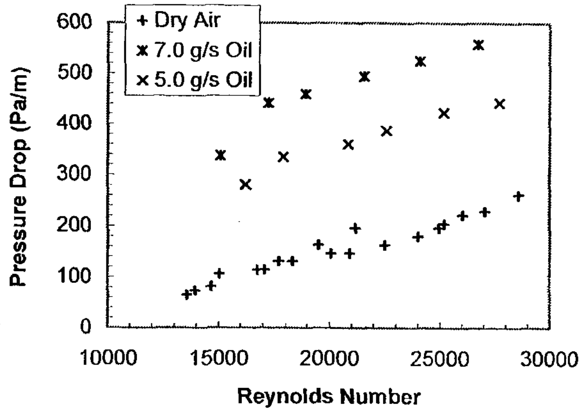

Figure 5. Pressure Drop in 1.27cm Horizontal Plate (Oil/Air Flow)

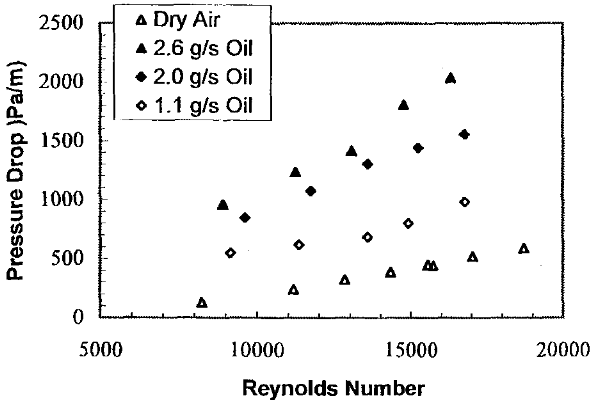

Figure 6. Pressure Drop in 0.64cm Vertical-up Plate (Oil/Air Flow)

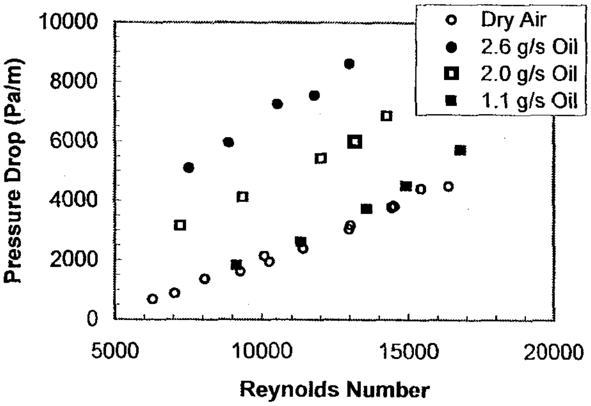

Figure 7. Pressure Drop in 0.32cm Vertical-down Plate (Oil/Air Flow)

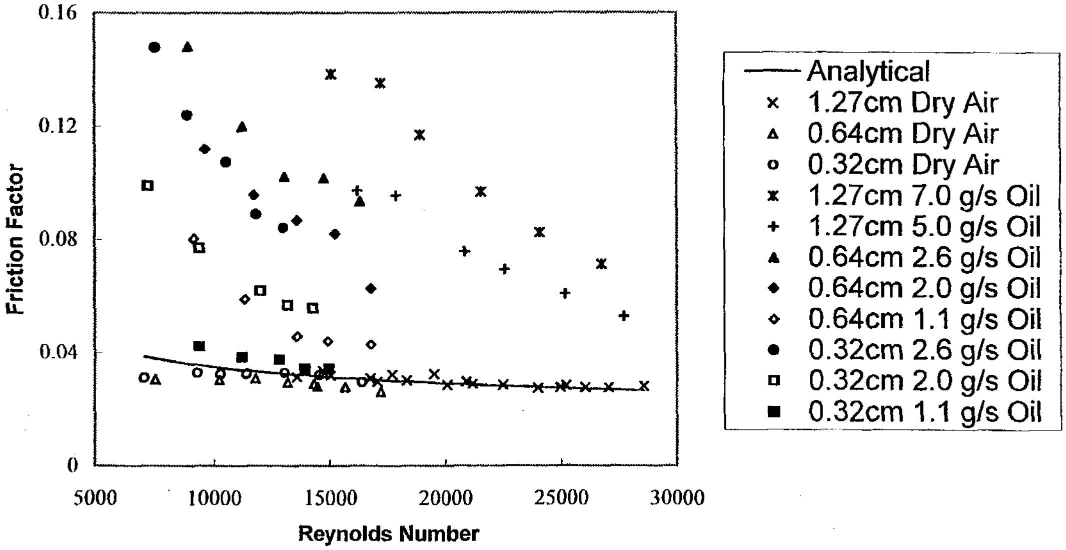

Figure 8. Comparison of Friction Factor

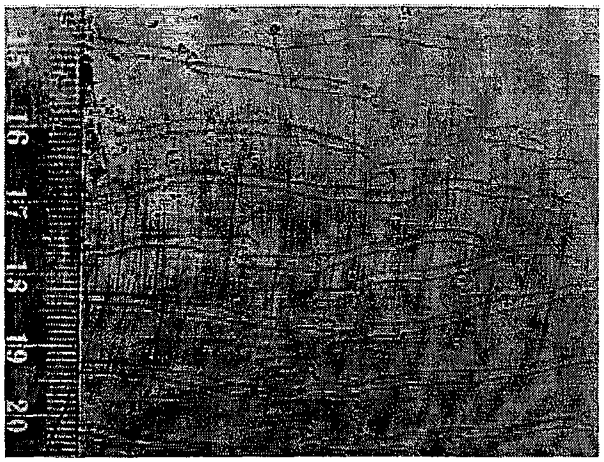

Figure 9. Photograph of Air/Oil Flow in 0.64cm Test Section

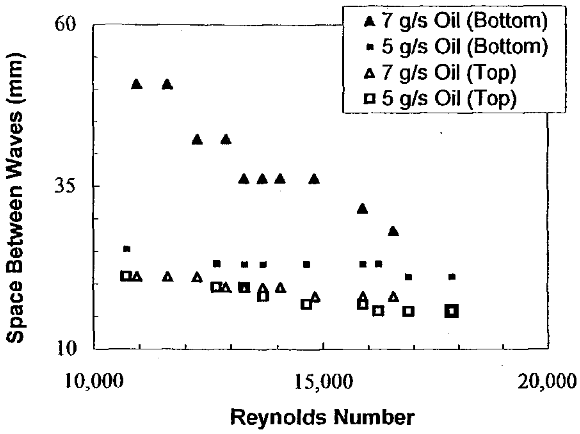

Figure 10. Wave Spacing in 1.27cm Horizontal Plate (Oil/Air Flow)

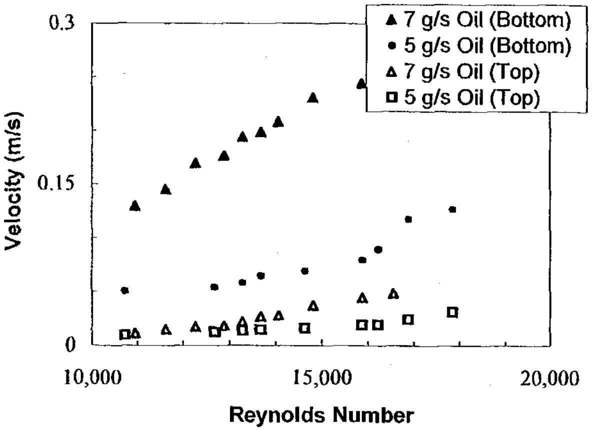

Figure 11. Wave Velocity in 1.27cm Horizontal Plate (Oil/Air Flow)

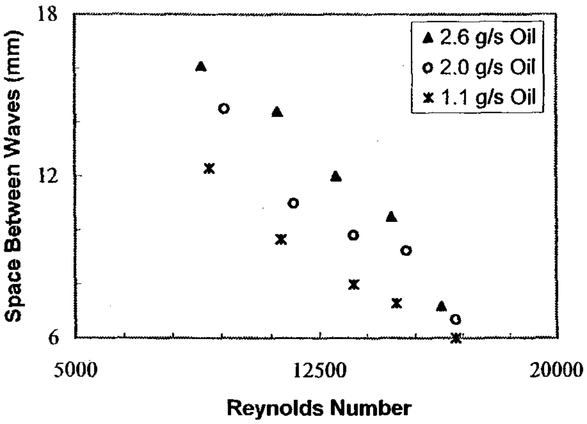

Figure 12. Wave Spacing in 0.64cm vertical-up Plate (Oil/Air Flow)

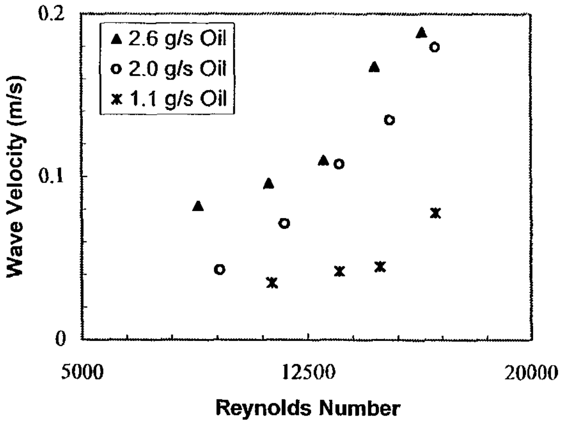

Figure 13. Wave Velocity in 0.64cm vertical-up Plate (Oil/Air Flow)

Flow Visualization Results

Videotaping was used to record the flow field characteristics in the plate test section. Wave-shape liquid along plate was observed in some smooth plate tests. Figure 9 shows the waves in 0.64cm vertical up plate with air mass rate 18.9g/s, oil mass flow rate 2.0 g/s, and Reynolds number 15255. For the horizontal 1.27cm spacing smooth test section, the liquid distributions along top and bottom plates are different. As shown in figures 10 and 11, bottom waves move faster than top waves and bottom spacing is lager than top wave spacing. It indicates that thicker liquid films have higher wave velocities. For horizontal plates, top film waves similar may be an upper limit to film thickness reached. Similar results can be observed in vertical plates. The liquid distribution is symmetrical along two vertical plates. Figures 12 and 13 show the wave distribution in 0.64cm vertical up plate.

Some very interesting flow behavior has been observed in the flat plate test section with a chevron pattern. Figure 14 is a photograph of liquid distribution in chevron-style plate, where the mean flow direction is from left to right. It indicates clearly that the liquid tends to follow a groove under certain flow conditions, on the upper plate, for instance, up to the vertex of the chevron, whence it drops to the lower plate to continue moving forward. This pattern is illustrated in Figure 15. So the actual liquid path length is much longer than the direct distance from inlet to outlet. There are also some flow merging at the vertex and moving forward form one vertex to another.

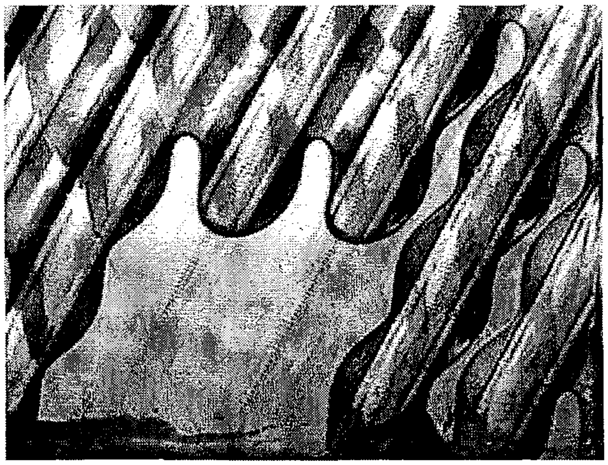

Figure 14. Photograph of Liquid Distribution in Chevron-style Test Section

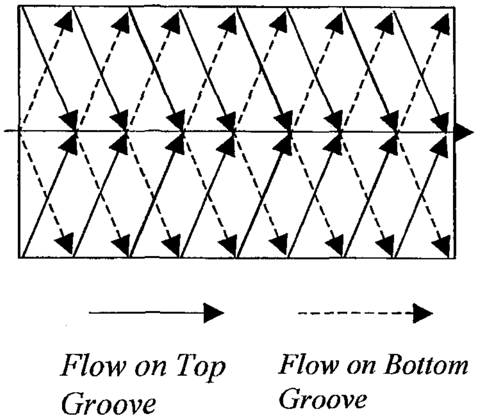

Figure 15. Illustration of Observed Flow Pattern in Chevron Test Section

CONCLUSIONS

A flow visualization loop was set up to investigate the two-phase flow field characteristics in flat plate heat exchangers. The results from the present study indicate that the two-phase flow pressure drop may be predicted with similar correlation for single-phase flow in PHE. Wave–shape liquid along smooth plate was observed. They may act like traveling bumps. Charactering shape and movement may help predict pressure drop. Two-phase flow tends to move along chevron grooves, which extends the flow passageway and introduces larger pressure drop and heat transfer coefficient to PHE. Eliminating the flow "short-circuiting" along vertexes can increase heat transfer coefficients.

ACKNOWLEDGMENTS

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