

Observation and Analysis of Two Phase Flow of Boiling Refrigerant R600a Inside Horizontal Tubes

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Abstract

This paper presents a study of one component two-phase flow inside horizontal tubes, with bends using refrigerant R600a (Isobutane) as the working fluid. Two-phase refrigerant enters the evaporator and exits as a superheated vapour. As vapour quality increases with evaporation, the vapour velocity also increases causing increased interfacial tension forces and the two-phase flow experiences different flow patterns. The phase change flow patterns that occur in the tubular evaporator, which forms part of a typical refrigeration plant, were observed recorded and discussed here. The evaporator was a 16-row trombone shaped transparent glass coil with return bends of 180 degrees and was connected to a refrigeration unit consisting of a hermetic compressor, air-cooled condenser, liquid receiver, and finally connected to a hand expansion valve. The effect of mineral oil on the flow patterns and behaviour at the transition zone together with several photographic and recording techniques were also discussed and reported here. All pressures quoted in this paper are absolute values.

1. Introduction

Elucidation of fluid behaviour in straight plain tubes provides the foundation for understanding phase changes in boiling liquid refrigerants, leading to more accurate considerations of the heat transfer process, improving the design of heat exchangers and the predictions of overall performance of refrigeration systems. Such behaviour is usually characterised mathematically, with dimensionless correlations, with no visual record of the phenomena taking place within the tube. Vohr (1), presented a literature survey of two-phase, two-component boiling in horizontal and vertical tubes. However,

one-component two-phase flow was not considered in this study. Zahn (2) studied the evaporation of refrigerant R22 inside horizontal tubes, under conditions simulating actual operation of a small air-conditioning coil. Although a sketch of the phenomena occurring in the area before and after the transition zone was presented, there were no actual photographic results reported. Also, the photographic evidence presented for the two-phase flow area does not clearly identify the flow patterns, or the change from one flow pattern to another. Worsoe-Schmidt (3) studied the characteristics of flow patterns and the effects of oil content for R12 evaporating in horizontal tubes, however, no reference to the oil ripples was found. Also, both studies made no mention of the effect of the return bends in heat transfer augmentation.

Cooper et al (4) describe the study of photographic methods and techniques at Harwell. Collier and Hewitt (5) present a review of photographic methods and experimental techniques for investigating two-phase flow. Both studies emphasise the difficulties faced when photographing round tubes and suggest that best results were obtained with planar outer surface. By producing a square transparent box with water in between the glass coil and the box causes the same effect, due to the refractive index of the water. One other suggestion was to introduce a dyestuff to the refrigerant, however, this was not possible because of the phase change. Derbyshire et al (6) and Bennett et al (7) have studied X-ray photography for flow visualisation. Although the X-ray photography shows promising results, the technique does not seem to be suitable for the present study. Hewitt (8) describes methods of illumination and improving time resolution independently. At the same time methods for studying entrainment in two-phase flow were discussed. A photograph of dispersed flow shows liquid droplets with slight tails; this is due to the drag force acting upon the liquid droplets. Cumo et al (9) presented a photographic study of two-phase, highly dispersed flows, however indications of droplet trajectories being found straight and parallel to the flow even very close to the wall do not seem to be correct, since the direction looks more random than straight.

A report containing relevant information on the photographic equipment available, including illumination factors and costs worth considering for investigations is the one presented by The Department of Scientific and Industrial Research (10).

From the literature, none of the studies covered the one component two-phase flow inside horizontal tubes, using R600a as the working fluid, or the highly turbulent film boiling in the annular flow as

discussed by Lagos et al (11) or the effect of the return flat bends in an evaporator. It was therefore proposed to examine a single component two-phase flow-boiling refrigerant visually, by constructing a flow visualisation test rig.

2. Experimental facility and Procedure

The refrigeration system rig is shown in Figure 1. It has an evaporator of the direct expansion type, with R600a (Isobutane) as the working fluid. The main components of the system were; hermetic compressor, air-cooled condenser, liquid receiver, plain transparent glass tube evaporator and a hand expansion valve. These formed interdependent system whose settings could be varied over a wide operating range. The test section was a 16-row trombone shaped transparent glass coil evaporator with bends of 180 degrees (Figure 2), immersed in water in a tank. The total length of the glass coil including the bends was 6394mm with inside diameter of 8mm and outside diameter of 12.5mm.

The water in the tank was heated using a 2 kW electrical immersion heater, placed at the bottom of the tank. The water was then circulated between the top and bottom of the tank via a small water pump calibrated to circulate water at 0.189 l/s in order to achieve equilibrium and a constant temperature in the tank. The system also incorporates a vapour bypass coming from the top of the high pressure liquid receiver injected straight to the inlet of the evaporator, which is connected immediately after the hand expansion device, in order to obtain a larger transition and mist zone for visual observation. The high pressure, high temperature liquid refrigerant was fed into the glass coil evaporator by a hand expansion device, which meters the liquid refrigerant into the evaporator at a rate such that all the liquid is vaporised before the refrigerant reaches the evaporator exit. Therefore, visual observation and photographic study of the behaviour of the refrigerant R600a flowing inside the transparent glass coil evaporator could be made.

The refrigeration plant also incorporates two standard test gauges, which are of the Bourdon type, measuring the pressure at the compressor suction and condenser discharge and two refrigerant flow meters installed in the liquid line area, just before the hand expansion device. The flow meters have been installed in parallel: one with a H-C-150 tube scaled from 0.0025 to 0.015 l/s and the other one with a G-F-150 tube scaled from 0.0006 to 0.004 l/s, both of them calibrated for Isobutane under the maximum temperature operating condition of 45°.

The pressure measuring instrument used at the suction of the compressor is a compound type, calibrated to read from 0 to 8 bar and the pressure at the outlet of the condenser is measured by a pressure gauge calibrated to read from 1 to 10 bar. The measurement of the temperature along the closed circuit was by using T-type thermocouples. The refrigeration system was charged with about 600g of R600a (Isobutane).

The operation of the system was designed for both up flow and down flow. However, since stability of flow is required, it was found from initial experiments that up flow provided better results, hence this experimental study is based on up flow only.

The system was switched on and set to run at a preliminary condition, so that it could reach the steady state condition, without the danger of the liquid refrigerant, either in bulk state or droplet form overflowing into the suction line and being drawn into the compressor. However, superheat control is also important. A low superheat setting can cause flow and temperature instability and also allow liquid to leave the evaporator in aerosol form, this adversely influences the COP. High superheat settings will increase the proportion of the evaporator which contains liquid which is not in contact with the tube walls. A compromise superheat setting maximises the capacity and the COP and this is normally about 5 K, the setting achieved.

Once stability is obtained the flow rate is readjusted again for better visual observation. The condensing temperature was set to 40.5°C, with an evaporator pressure and temperature of 2.3 bar and 11°C. The water temperature was kept constant at 28°C. The compressor suction temperature was 27.5°C measured at the compressor inlet, therefore, 16 K of superheat was obtained and hence the proportion of the evaporator is increased containing wet gas being dried and superheated.

Tests were carried out at steady state with a single refrigeration duty.

The range of parameter is given below.

Dryness Fraction at inlet	~ 0.15
System Pressure measured at evaporator exit (bar)	1.3 – 2.6
Evaporator inlet temperature (°C)	- 0.4 – 15.7
Evaporator outlet temperature (°C)	29.8 – 15.9
Mass flux (kg/m ² s)	34.80 – 79.6
Evaporator load (kW)	0.6 – 1.2

The hand expansion valve was adjusted to give a defined mixed flow and photographic records were made. These were then

interpreted to elucidate the flow regimes, plus modes of heat transfer occurring within the evaporator.

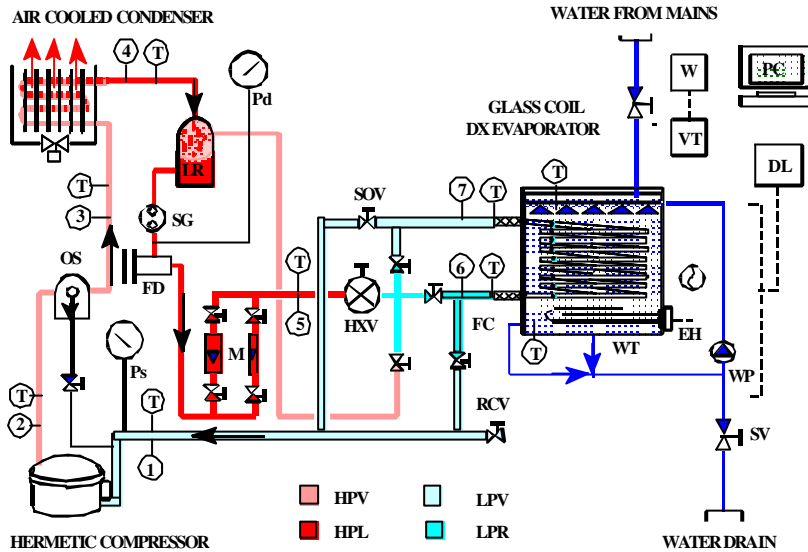


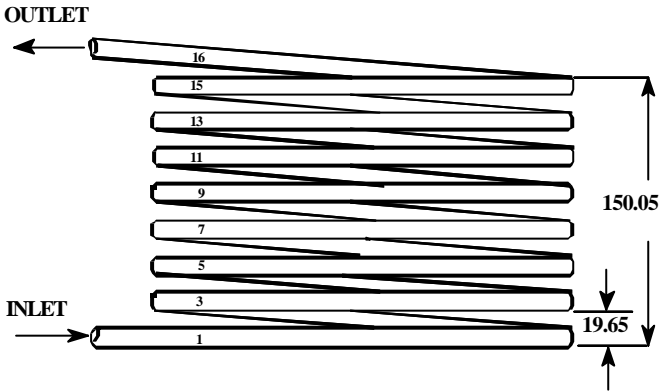
Figure 1. Schematic diagram of the experimental facility (Stage I)

Nomenclature For Figure 1

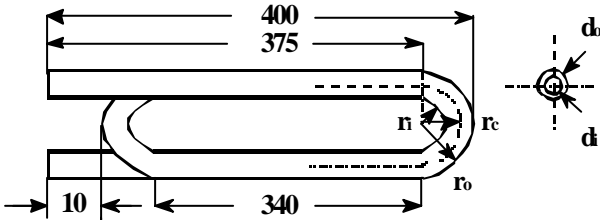
DL	data logger (RS 232)
EH	electrical immersion heater
FC	flexible connector
FD	filter drier
HXV	hand expansion valve
HPV	high pressure vapour
HPL	high pressure liquid
LR	high pressure liquid receiver
LPV	low pressure vapour
LPR	low pressure refrigerant (two-phase flow)
M	refrigerant flow meter
OS	oil separator
PC	personal computer
Ps	suction or evaporator pressure
Pd	discharge or condenser pressure
RCV	refrigerant charging valve
SG	sight glass

SOV	BM manual shut-off seat valve
SV	stop valve
T	T-type thermocouple
VT	voltage variable transformer
W	wattmeter
WP	water pump
WT	water tank

The numbers on the diagram show the inlet and outlet of the main components of the system, where the main phase-changes occur.



Front view of the transparent glass coil



Top view of the transparent glass coil

Figure 2 Transparent glass coil with 180° bend

Where:

- r_o outside radius of the 180° bend, 25mm
- r_c axial radius of the 180° bend, 18.75mm.
- r_i internal radius of the 180° bend, 12.5mm.
- d_o outside diameter of the Pyrex glass tube, 12.5mm.
- d_i internal diameter of the Pyrex glass tube, 8mm.

The numbers from 1 to 16, on the front view (Figure 2) indicate the number of the front rows looking perpendicularly onto the transparent glass coil only. Also, all dimensions are in mm.

3. Flow Visualisation and Recording Techniques

The transparent Perspex tank and glass coil provides an excellent arrangement for visual observation and photographic studies. The test section was enclosed in a dark environment in order to prevent light entering and reflection from the surroundings. Two 800W red head tungsten lights provided the illumination inside the dark space. The exact positions of the lamps were determined to maximise the clarity of the image and minimise surface reflection. The photographs were taken using a standard Minolta XG-1 photographic camera using a 50 mm diameter lens, 1:2 anastigmatic lens, a +4 close-up lens (49 mm) and a focal plane shutter of 1/1000 second was used with 200, 400 and 1000 ASA films. The distance between the lens of the photographic camera and the test section wall was 150mm.

Since it is very important in two-phase flow to distinguish the image produced between the two phases, a Glo-Stick capsule for leak detection was infused in the system, enabling flow visualisation, using an Ultraviolet-Fluorescent Leak detection equipment. Essentially this colours the oil without affecting the refrigerant.

Other equipment used in this study was a Nikon F5 photographic high-speed camera, 60-mm/ F2.8 AF M-Nikon micro-lens with 1600 ASA high-speed film. The shutter speed was set to 1/8000 sec and Illumination was provided using a Strobosun 1203B type, at 50-flashes/ sec.

A Sony video camera HVC-400P with a Sony adapter HVA-200CE power supply was used for recording. The camera was connected to an 8mm lens boroscope tube having a total length of 780 mm, an oscilloscope and a video recorder to record the two-phase flow. However, in order to film the area beyond the transition zone a high-

speed cine camera connected to a laser was used. The filming was done with and without a diffuser.

4. Analysis

The visualisation was recorded photographically and the progression is shown accordingly. While changes are continuous, visual distinct flow patterns were observed, hence, in addition to common boiling terms, several extra names for the observed phenomena have been introduced e.g. *Wavy-Stratified*, *Wavy Crest*, *Semi-Annular*, *Misty-Annular* and these are shown in the Figures and discussed as follow.

4.1. *Wavy-Stratified* This characteristic is observed at the inlet of the glass tube evaporator up to $\frac{3}{4}$ of the first row, where flow becomes disturbed due to the increase in quality hence increase in velocity. The liquid flows along the bottom of the pipe and the gas flows on the upper part of the tube.

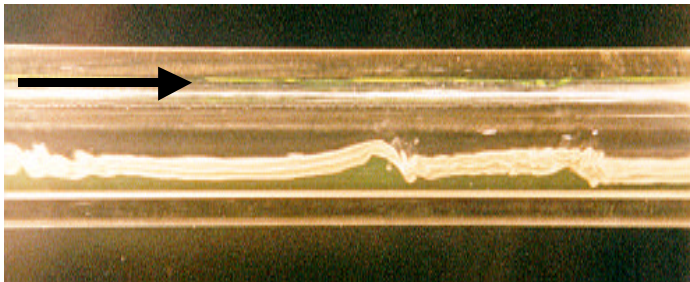


Figure 3. Wavy-Stratified

4.2. *Wavy Flow* The wavy-stratified flow is followed by a continuous distributed wavy flow changed into a rapid pulsating flow wavy flow just before the end of the first row. The uniformly along the third row due to the rigorous boiling of the liquid refrigerant. The length between the waves decreases as evaporation increase with continuous increase in velocity.

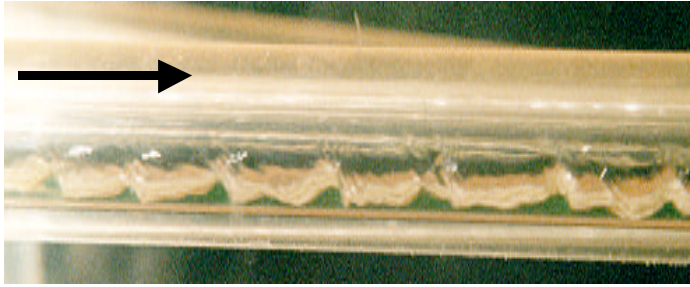


Figure 4. Wavy Flow

4.3. *Wavy Crest* As the velocity of the vapour refrigerant increases due to the evaporation of the bulk liquid boiling inside the tube, the interface of the continuous wavy flow suffers a further disturbance causing an increase in wave amplitude in the fifth row, which is identified as wavy crest flow.

The crest of the wave wets the inside top surface of the tube wall by shattering and splashing. The liquid droplets generated by this process, which are of different sizes, are then torn away from the crest by the strong vapour shear. The bigger droplets return to the bulk liquid behaving like dolphins advancing in the open sea and the smaller droplets are entrained in the vapour core.



Figure 5. Wavy Crest

4.4. *Semi-Annular* Since precipitation continued and vapour quality kept increasing with liquid evaporation, the flow became more and more turbulent and the top surface of the inside wall of the tube became intermittently wetted along the seventh tube. Although the amount of liquid droplets entrapped in the vapour core seemed to have increased, the bigger ones still do not last long before they end up back in the bulk liquid. However, the smaller droplets continue entrapped in the vapour core.

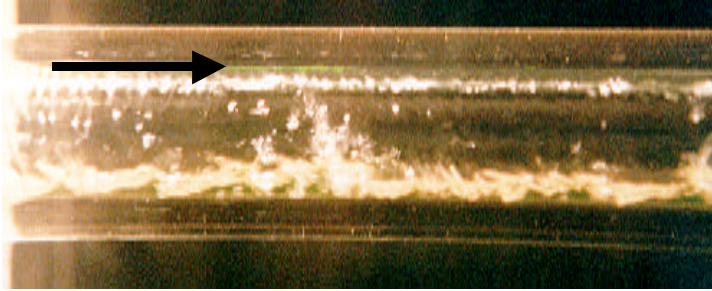


Figure 6. Semi-Annular

4.5. *Misty-Annular* Immediately after the semi-annular flow, annular flow becomes visible, this is in fact a misty annular flow as observed in Figure 7, in which a thin liquid film covers the inside surface of the tube wall and high velocity vapour flows as a central core.

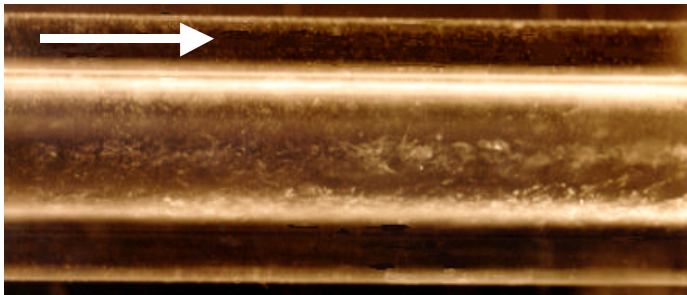


Figure 7. Misty-Annular

The velocity of the liquid film at this instance was found to be the highest, hence, it may also be stated that at this very instance the vapour velocity must be the highest. Also, since it was found that the thin liquid film boiling as highly turbulent (Figure 8), a large amount of liquid droplet (which are of the micro-droplet size) entrainment occurs from around the inside surface of the *annular liquid film*.

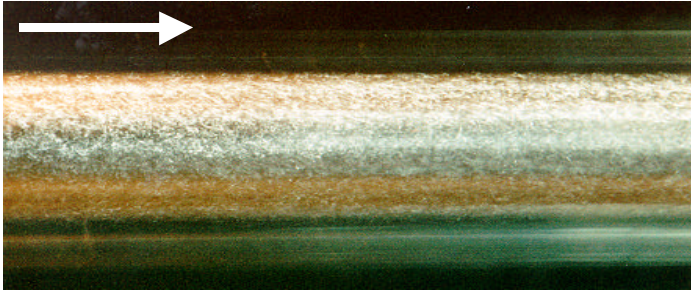


Figure 8. Annular film boiling

4.6. *Dryout* Soon after the annular flow, partial dryout is observed along the top portion of the tube wall first, before final dryout occurs. Dryout occurs due to the bigger liquid droplets being torn away by the strong vapour shear and entrapped for a period of time, until they collide with other liquid droplets and finally joining the liquid bulk on the bottom surface.

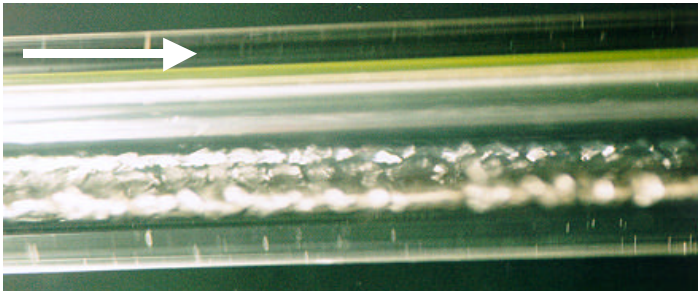


Figure 9. Semi-Annular film boiling and final dryout

This phenomenon occurs due to the gravitational body forces affecting the liquid droplets. Hence, the liquid film on the bottom surface becomes thicker, taking longer to dry out. This phenomenon may be observed in the eleventh row. However, when mineral oil is allowed to circulate, the mixture will continue to flow and *oil ripples* are observed on the top surface, falling slowly to the bottom surface and eventually covering the entire inside periphery.

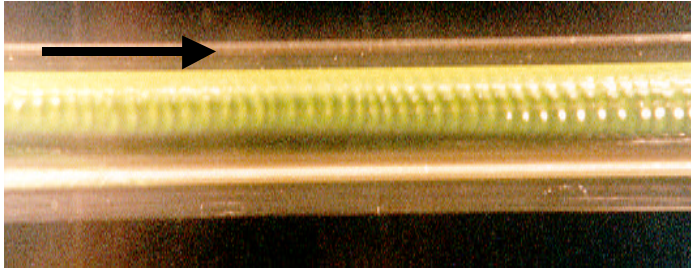


Figure 10. Oil ripples

The flow pattern observed is also *annular flow*, but, richer in mineral oil. As the liquid refrigerant finally dries out on the top surface the mineral oil eventually slides around the inner surface of the wall, ending on the bottom surface and continuing to travel towards the outlet of the evaporator and back to the compressor. This transition zone is observed in the thirteenth row and shown in Figure 11.

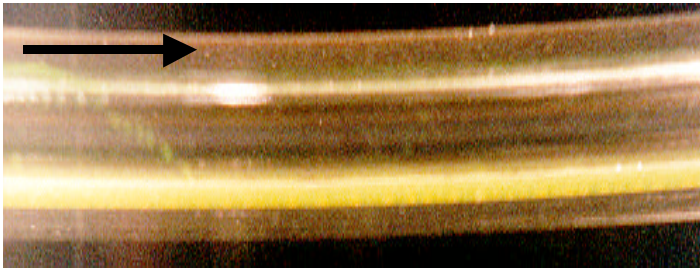


Figure 11. Transition zone

From the *transition zone* onwards, *misty flow* takes over, as observed at the end of the fifteenth tube, just before the last bend (Figure 12).

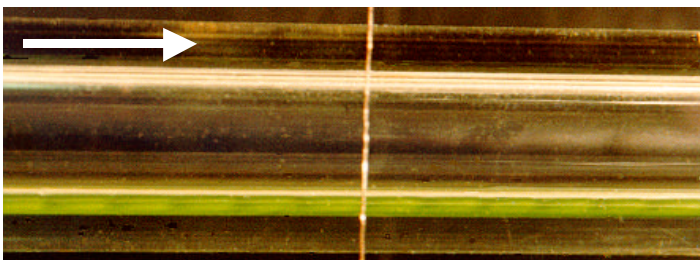


Figure 12. Misty Zone

The micro liquid droplets are dispersed in the fast moving vapour. Finally *superheated zone* is observed in the sixteenth row, where only a thin streamline of oil is observed on the bottom surface of the inside tube wall, heading to the exit of the evaporator. This is a critical section, where there is no liquid refrigerant left to help move the oil. However, it is thought that the already superheated vapour velocity 10 m/s is high enough to drag the oil back to the compressor. At lower qualities, occurring in the first to the fifth bend, along the end of the first row and the end of the fifth row. The 180 degree return bends act as wave breakers, because the flow patterns occurring at these points are disturbed from their actual patterns and forced to the top surface of the tube wall. Hence, the surface becomes wetted 1.5 times the inside diameter just before the 90 degree return bend until after the complete 180 degree curvature, where the liquid bulk was observed to continue its course on the bottom surface of the tube. At these bends the liquid wets the inside surface of the tube wall, sliding around the periphery in a swirling flow manner and flow becomes more turbulent. However as quality increases further, from the sixth to the seventh bend, the wetted area increases up to three times the inside diameter. The liquid velocity increases up to the eleventh return bend, where the flow is observed to be more annular and turbulent. Even at higher qualities the contribution to the heat transfer from the thirteenth and fifteenth return bends are still significant, due to the highly turbulent flow occurring across the return bends. In general 180 degree return bends were found to contribute to higher heat transfer.

5. Conclusions

Two-phase refrigerant enters the evaporator and exits as a superheated vapour. As vapour quality increases with evaporation, the vapour velocity also increases causing increased interfacial tension forces and the two-phase flow experiences different flow patterns. These flow patterns were identified, reported and presented in this study. Flow visualisation and the acquisition of photographic records shows evidence of the way boiling takes place inside horizontal tube evaporators, which form part of a typical refrigeration plant. Hence, the design and performance data for heat exchanger equipment could be improved.

The use of high-speed photographic technique showed the highly turbulent flow occurring in annular flow, where the entire internal periphery of the tube is covered with a thin liquid film, showing evidence of a significant amount of liquid droplets entrapped in the

vapour core. This is due to the precipitation caused by the vigorous boiling and the strong vapour shear around the inside perimeter. The suspended liquid droplets in the misty zone are of the micro-droplet size, between 25 to 150 microns. However, large numbers of droplets are identified between 45 to 100 microns, which provides the opportunities for heat transfer enhancement in this area. Due to the gravitational body forces affecting the liquid droplets, the concentration of them is just below the centre of the axial flow. The highly turbulent flow at the return bends seems to cause a slight retardation of the liquid droplets, increasing pressure drop. Hence, increasing heat transfer across the return bends. Therefore, it can be concluded that the return bends contribute to greater heat transfer in an evaporator coil.

6. Acknowledgements

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