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Experimental Measurement of Oil Hold-up During Refrigerant Condensation and Evaporation in Two Phase Flow

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ABSTRACT

This paper presents the effects of heat transfer on oil hold-up in smooth, axially finned, and 18° helically finned 8.915mm I.D. horizontal tubes under evaporation and condensation conditions with a R134a /ISO32 polyol ester refrigerant oil mixture. Heat fluxes ranging from 4000 to 6000 W/m^2 were applied through a water jacket. The tests were conducted at a saturation temperature of 25° C, at mass fluxes of 100 to 300 kg/m^2-s, and a range of average qualities from 20-95%, oil flow concentration varied from 3-5.5%. Oil hold-up is observed to reach a minimum value in the mid-range qualities, but increases at higher qualities. In general, the enhanced tubes exhibit higher oil hold-up compared to the smooth tube, but enhanced tube trends differ between condensation and evaporation based on enhancement. The addition of oil is found to decrease condensation heat transfer while increasing evaporative heat transfer at lower and mid-range qualities.

1. INTRODUCTION

Vapor compression based refrigerant systems usually contain oil for lubrication purposes that is present in evaporators and condensers where heat transfer is occurring. Oil hold-up, also referred to as oil entrainment, has been found to degrade heat transfer, increase pressure drop, and can starve the compressor of the necessary amount of lubrication required to function. Therefore, it is important to study how the oil holds up, how it is affected by heat transfer, and how it affects heat transfer, pressure drop, and void fraction, as these are important considerations in refrigeration system design. The introduction of internally enhanced tubes in refrigeration systems has created a need to study their affect on oil hold-up. These enhancements can change how the oil flows and is held up in the system. This paper investigates the effects of heat transfer on oil hold-up in smooth, axially finned, and 18° helically finned 8.915mm I.D. horizontal tubes under evaporation and condensation conditions with a R134a /ISO32 polyol ester refrigerant oil mixture. The effect of oil on heat transfer is also investigated.

2. LITERATURE REVIEW

The knowledge base on oil and refrigerant combinations has been focused mainly on the interactions of the oil with the refrigerant. Oil effects on refrigerant systems as a whole and on a component basis have also been studied. Lee (2002) provides a detailed review of the aforementioned research. Shen and Groll (2003) present a comprehensive literature review on refrigerant oil mixtures and their effects on heat transfer and pressure drop. Several studies included in their review

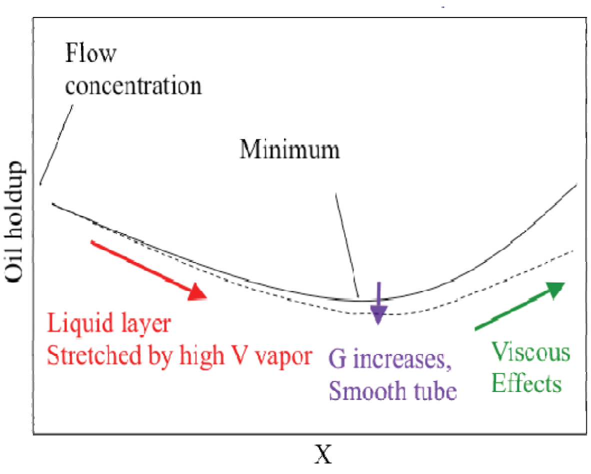

Figure 1: Summary of adiabatic oil hold-up trends.

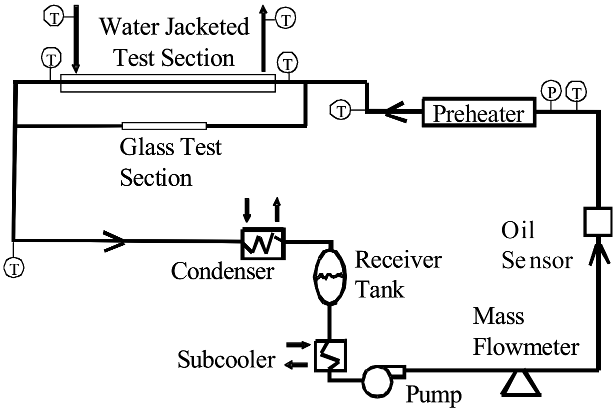

Figure 2: Experimental flow loop design.

detail the use of enhanced tubes and their effect on heat transfer and pressure drop. Typically heat transfer augmentation was observed at low mass fluxes and oil concentrations of less than 3%. Degradation was noticed for conditions outside of those ranges. It is not mentioned, however, how the oil hold-up itself has affected the heat transfer or how condensation or evaporation conditions affect how much oil is held up.

This study focuses on the future research needs outline by Crompton et al. (2004). Crompton et al. (2004) conducted oil hold-up experiments under adiabatic conditions. A model of adiabatic oil hold-up was also created. She observed how mass flux, tube enhancements, oil flow concentration, and quality affected oil hold-up. It was found that as qualities approach zero the flow concentration was the dominant factor affecting oil hold-up. Mass flux was shown to have a small effect on oil hold-up with the highest oil hold-up values occurring at low mass fluxes. A minimum oil hold-up value was also observed to occur at mid-range qualities. These results are summarized in Figure 1. Enhanced tubes were shown to affect the high quality ranges with helical tubes showing greatest oil hold-up, followed by axial and then smooth tubes.

With the addition of evaporation and condensation conditions the results will help gain insight into oil holdup in evaporators and condensers and provide direction for system optimization. Cremaschi (2004) and Cremaschi et al. (2006) have also been conducting oil hold-up experiments, referred to as oil retention, using a computer based modeling approach with experimental verification. Crompton et al. (2004) created oil hold-up models during her investigation of adiabatic oil hold-up. The simple model, given in equation 1, for low qualities uses void fraction and quality to determine the amount of oil hold-up.

$$\frac{m_{ox}}{L} = \frac{m_o}{L}\left(\frac{1-\alpha}{1-x}\right) \tag{1}$$

A complete derivation and explanation of terms can be found in Crompton (2004). Models similar to this should aid in the design of refrigerant systems in the future.

3. FLOW LOOP DESIGN

A modified version of the experimental flow loop used by Crompton et al. (2004) was used in this experiment. Most of the additions to the core system consisted of improvements in the operation of the loop by decreasing pre-heater thermal mass and replacing valves. A refractive index based oil concentration sensor was also added to continuously monitor oil concentration with an uncertainty of ±0.1% oil concentration. The sensor was placed after the refrigerant pump. The sensor was first calibrated for temperature effects using single-phase refrigerant. Then it was calibrated for the effects of oil over a range of 1 to 5% by injecting a specified amount of oil into the loop. This is done to correct for changes in the refractive index of the oil and refrigerant over changes in temperature and for variation in oil concentration. A layout diagram of the experimental flow loop can be seen in Figure 2.

The liquid refrigerant is pumped with a gear pump that is driven by a variable frequency drive from the bottom of a 2-liter receiver tank through a water cooled shell and tube style sub-cooler. The liquid refrigerant then travels through a Coriolis style mass flow meter with an uncertainty of ±0.1% followed by a pre-heater used to reach the desired quality calculated from an energy balance. The pre-heater consists of a finned tube heat exchanger with opposing electric resistance heater plates bolted on either side of the heat exchanger. The electric heaters are controlled with on/off switches and a variable autotransformer to provide fine adjustment of quality. This pre-heater design was optimized to prevent "burn out" at 100% quality and rapidly obtain steady state. The refrigerant is then directed through 90-degree bends to remove effects of heat flux from the pre-heater such as dry-out before it reaches the test section. The refrigerant then travels to one of three test sections. The operator channels the refrigerant through a smooth, axial, or helical tube. Finally, the refrigerant is condensed in a water-cooled brazed plate heat exchanger and is directed back into the receiver tank. A pressure transducer measures the inlet pressure of the pre-heater with an uncertainty of ±1.9 kPa. The temperatures before the inlet of the pre-heater and the test section are measured with type T thermocouples. These pressures and temperatures are used to determine the thermodynamic states necessary to compute the test section inlet quality. As a check on the energy balance, an experiment was performed by heating single phase flow in the pre-heater and measuring the temperature difference across it along with the flow rate to determine the uncertainty associated with the pre-heater power input of ±0.8%.

Three test sections were created to investigate the effects of heat transfer on oil hold-up in horizontal tubes under evaporation and condensation conditions. Each test section consists of either a smooth, axially finned, or 18° helically finned 8.915 mm I.D. copper tube with four stations of four thermocouples welded on the walls and a clear P.V.C water jacket as shown in Figure 3. The wall temperature is determined as the average of the 16 thermocouples welded on the tube wall. Insulation is placed on the outside of the water jacket. The test section is cooled with water supplied from a water conditioner at 15.7°C for condensation conditions and at 33.9°C for evaporation conditions with a flow rate of 1 L/s. Thermocouples are placed at the inlet and outlet of the test section in order to determine the average refrigerant temperature. The inlet and outlet temperature of the test section water jacket is also measured in order to determine the heat lost by the test section. The mixing section consists of a collapsed plastic net is placed in the water flow stream at the exit of the test section to provide an average water temperature. After the test section the refrigerant is condensed in a flat plate heat exchanger. The loop temperature is controlled by varying the flow rate of chilled water entering the flat plate condenser. All of the thermocouples in the test section and flow loop are type T and were calibrated with an RTD probe with an uncertainty of ±0.01°C and are determined to have an uncertainty of ±0.1°C.

Single-phase heat transfer tests were conducted to verify that the experimental apparatus is working properly. The single phase heat transfer coefficients for heated sub-cooled liquid R134a in 8.915 mm diameter smooth copper tube at different mass fluxes can be observed in Figure 4 along with the Dittus-Boelter heat transfer relation.

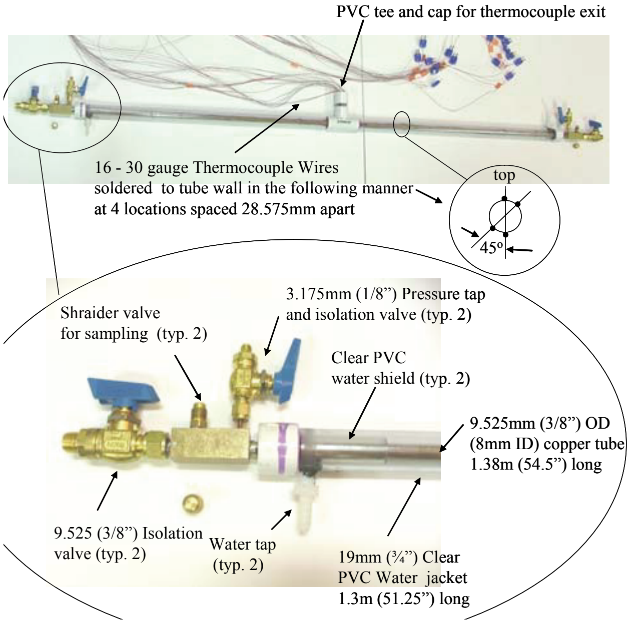

Figure 3: Test section design prior to installation

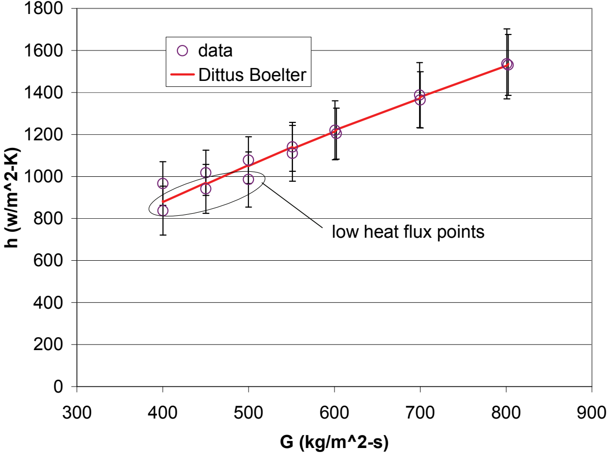

Figure 4: Sub-cooled liquid R134a heat transfer in 8.915 mm diameter smooth tube with heat addition varying from 2,600 to 5,600 W/m2-K

From Figure 4 it can be seen that the data has good agreement with the Dittus Boelter correlation with all of the predicted points within the experimental uncertainty. There is a set of low heat flux points at the same mass flux as other higher heat flux points indicated in Figure 4, which explains the scatter of the data at the low mass flux range. A waterside and refrigerant side energy balance was performed on the single-phase tests yielding a maximum error of 5%. All measurements in the present study represent the average of approximately 50 measurements taken at 3-second intervals by a data acquisition system.

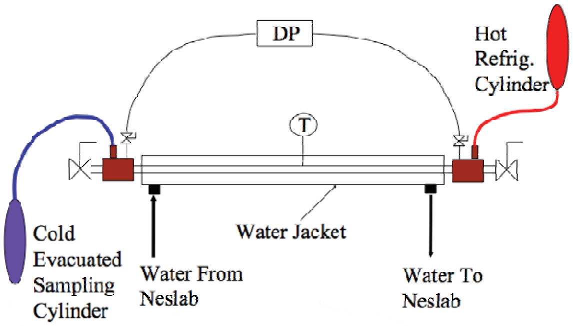

Figure 5: Oil extraction procedure.

4. OIL EXTRACTION PROCEDURE

The following oil extraction process is depicted in Figure 5. When the refrigerant loop conditions reach steady state, isolation vales are closed simultaneously and the water and refrigerant loops are bypassed to an alternate test section. An evacuated cylinder, chilled in an ice water bath, is rapidly connected to the shraider valve while remaining in the bath. A charge of approximately 110g of refrigerant heated to approximately 45^o C is then washed through the section. The refrigerant in the cold cylinder is then bled off in a recovery tank and evacuated using a recovery unit, leaving the oil. The sampling cylinder can then be weighed and compared to its empty weight in order to determine the oil hold-up. Controlled tests involving representative refrigerant-oil mixtures were conducted on a test section prototype in order to determine the accuracy of this sampling technique, and were found to measure oil hold-up to $\pm$0.01 g. All three test-sections were tested consecutively to ensure comparable loop conditions. During testing mass flux was held at $\pm$4% and quality maintained within $\pm$3% of target values.

5. RESULTS

5.1 Oil Holdup

The oil holdup data obtained for 100, 200 and 300 kg/m^2-s mass fluxes is given in Figures 6 through 8, respectively. Oil holdup is defined as the mass of oil present per meter of tube at a given mass flux and quality. Several trends can be observed from the oil holdup data in Figures 6 through 8:

1) As the quality approaches zero the oil holdup is determined by the flow concentration and there appears to be little deviation between tube types at a quality of 20% for condensation conditions. This oil holdup trend was observed for adiabatic conditions by Crompton et al. (2004) and Piggott (2001).

2) The oil holdup at 20% quality is found to be less for evaporation conditions than condensation conditions.

3) The oil holdup is seen to decrease until the mid quality range as the vapor core accelerates the liquid film. This oil holdup trend is consistent with adiabatic trends found by Crompton et al. (2004) and Piggott (2001).

- A minimum in oil holdup is observed at mid quality ranges as observed in the data for adiabatic conditions presented by Crompton et al. (2004) and Piggott (2001).
- The minimum does not appear to be a function of heat flux as the minimum under evaporation and condensation conditions is not noticeably different for a given mass flux and tube type.
- The quality at which the minimum occurs increases with increasing mass flux. This trend was not captured in the adiabatic oil holdup tests by Crompton et al. (2004) and Piggott (2001), which contain more “scatter” in the oil holdup data.
- The smooth tube oil holdup minimum occurs at higher qualities than for enhanced tubes, with the axially finned, and 18^o helically finned tubes found to exhibit minima at similar quality values.

4) After the mid quality range oil holdup is seen to increase due to the increase in viscosity of the refrigerant/oil mixture as observed in the adiabatic data of Crompton et al. (2004) and Piggott (2001).

5) Oil holdup decreases with increasing mass flux. We postulate that this reduction is due to the increase in void fraction, which is observed in Yashar (1998) and Yashar et al. (2001) as mass flux increases (liquid film is sheared thinner). This was also observed in the adiabatic tests of Crompton et al. (2004) and Piggott (2001).

6) Enhanced tube oil holdup is greater than smooth tube oil holdup and is most evident at qualities above 50% as observed for adiabatic conditions of Crompton et al. (2004) and Piggott (2001). It is postulate that this is due to oil entrapped between the microfins.

7) At 100kg/m^2-s oil holdup is greater for evaporation conditions than condensation conditions except for the 18° helically finned tube, which exhibits the opposite effect. This effect is more pronounced at qualities above 50%. The greater oil holdup under evaporation conditions may be attributed a thick oil film forming at the top of the tube as refrigerant/oil is periodically splashed on the top of the tube where the refrigerant evaporates leaving a thick oil film. According to the flow regime map developed by Jassim (2006) mainly stratified flow exists at 100kg/m^2-s for R134a at 25 degrees C in 9mm diameter smooth tube with minimal turbulence at the top of the tube. However, it is postulated that under condensation conditions "washing" of the top of the tube occurs as the pure refrigerant condenses resulting in a lower oil holdup.

8) At mass fluxes of 200kg/ m^2-s and above there is little difference between oil holdup under evaporation and condensation conditions except for smooth tube at 200kg/ m^2-s which exhibits higher oil holdup under evaporation conditions than condensation conditions. It is postulated that the lack of distinction between evaporation and condensation conditions at the higher mass fluxes may be due to the turbulent mixing of the liquid film associated with annular flow that is present which "washes" the top of the tube under both evaporation and condensation conditions. This turbulent film is not present at the top of the tube in the stratified flow that exists at the 100 kg/m^2-s mass flux as previously indicated. Enhanced tubes are known to cause a transition to annular flow at lower mass fluxes which may indicate why the smooth tube still has higher oil holdup under evaporation conditions than condensation conditions at 200 kg/ m^2-s.

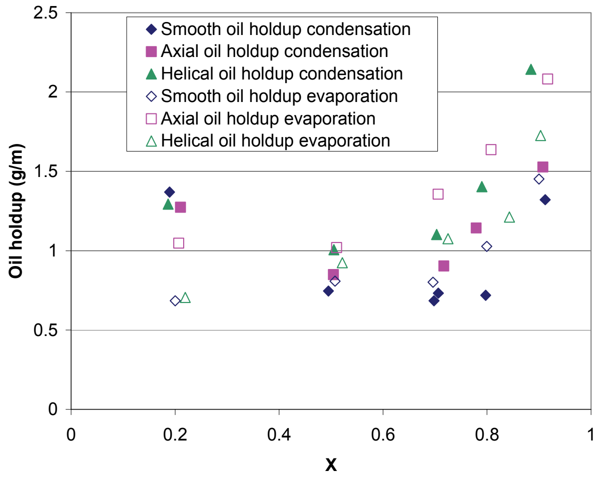

Figure 1. Average quality versus oil holdup for horizontal 9mm nominal diameter smooth, axially finned, and 18° helically finned tubes with R134a/ISO32 POE (3-5.5% by mass) at 100kg/m^2-s and 25ºC

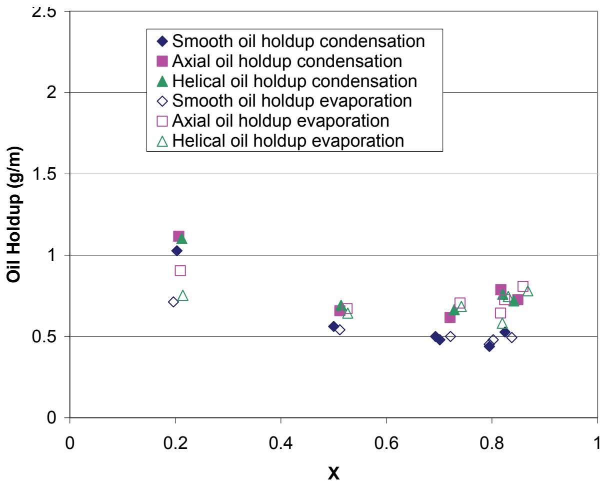

Figure 3. Average quality versus oil holdup for horizontal 9mm nominal diameter smooth, axially finned, and 18° helically finned tubes with R134a/ISO32 POE (3-5.5% by mass) at 300kg/m^2-s and 25ºC

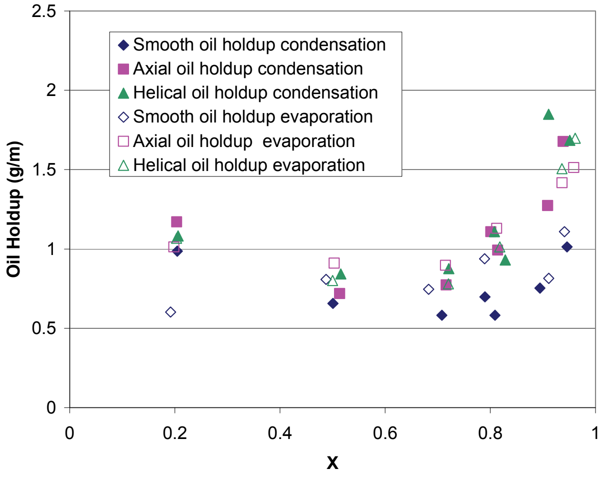

Figure 2. Average quality versus oil holdup for horizontal 9mm nominal diameter smooth, axially finned, and 18° helically finned tubes with R134a/ISO32 POE (3-5.5% by mass) at 200kg/m^2-s and 25ºC

5.2 Heat Transfer

The heat transfer data corresponding to the oil holdup data points in figures 6 through 8 are given in figures 4 through 9 with the addition of pure refrigerant data in order to illustrate the effects of oil on heat transfer in 9mm nominal diameter smooth, axially finned, and 18° helically finned tubes. Figures 4, 5, and 6 correspond to R134a condensation heat transfer at 100, 200, and 300 kg/ m^2-s, respectively, and figure 7, 8, and 9 correspond to R134a evaporation heat transfer at 100, 200, and 300 kg/ m^2-s, respectively. The following heat transfer trends can be observed from figures 4 through 9:

1) Oil reduces the condensation heat transfer coefficient for nearly all qualities and mass fluxes investigated.
  - The condensation heat transfer reduction increases dramatically for qualities above 60%.
  - The condensation heat transfer reduction is much greater for the enhanced tubes than the smooth tube, which may be a result of the higher oil holdup present in the enhanced tubes.

2) Oil enhances evaporation heat transfer at some qualities and mass fluxes
  - Oil enhances evaporation heat transfer at 100 kg/ m^2-s for:
    - -Smooth tube at qualities below ~90%
    - -Axially finned tube at qualities below ~80%
    - -Helically finned tube at qualities below ~60% (negatively effects heat transfer above x~60%)
  - There is little or no enhancement at 200 and 300 kg/ m^2-s except for smooth tube which shows slight enhancements at qualities below ~80%

3) At 200 and 300 kg/ m^2-s oil reduces the evaporation heat transfer coefficient in the microfinned tubes when compared to the pure refrigerant data at qualities above ~50%

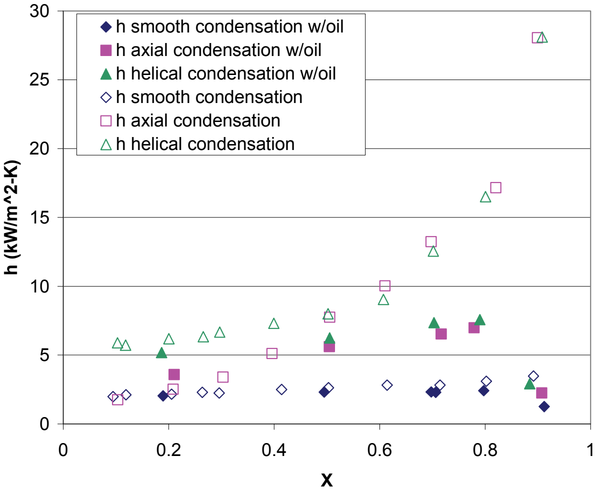

Figure 4. Average quality versus heat transfer coefficient for horizontal 9mm nominal diameter smooth, axially finned, and 18° helically finned tubes for pure R134a and with R134a/ISO32 POE (3-5.5% by mass) at 100kg/m^2-s and 25°C under condensation conditions

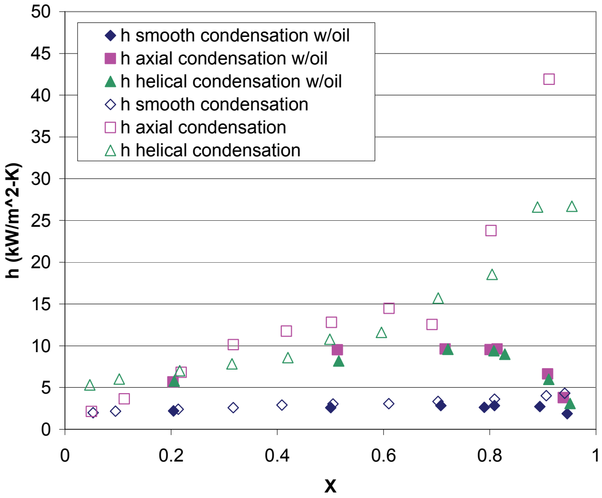

Figure 5. Average quality versus heat transfer coefficient for horizontal 9mm nominal diameter smooth, axially finned, and 18° helically finned tubes for pure R134a and with R134a/ISO32 POE (3-5.5% by mass) at 200kg/m^2-s and 25°C under condensation conditions

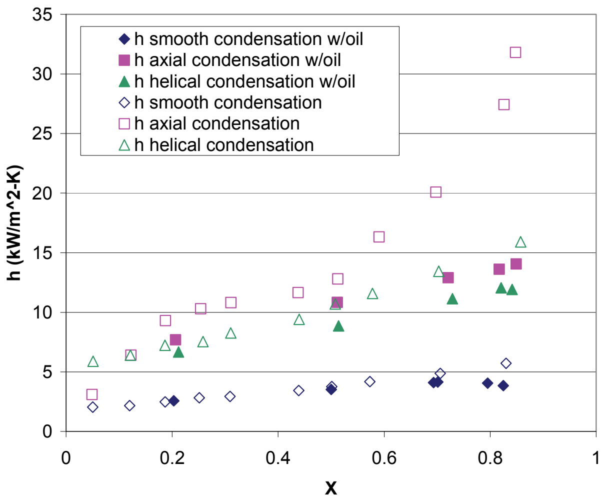

Figure 6. Average quality versus heat transfer coefficient for horizontal 9mm nominal diameter smooth, axially finned, and 18° helically finned tubes for pure R134a and with R134a/ISO32 POE (3-5.5% by mass) at 300kg/m^2-s and 25°C under condensation conditions

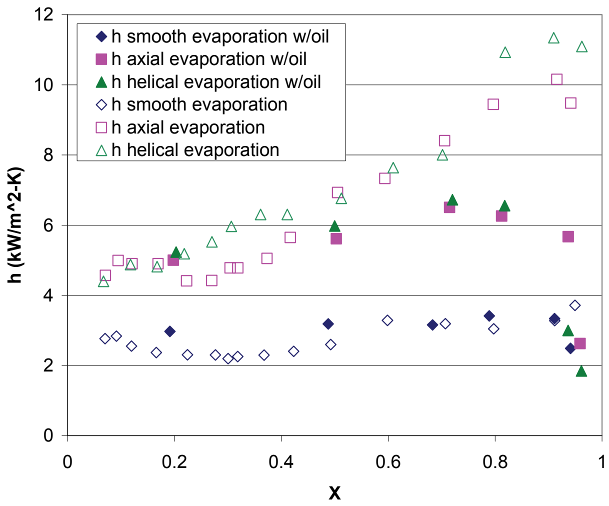

Figure 8. Average quality versus heat transfer coefficient for horizontal 9mm nominal diameter smooth, axially finned, and 18° helically finned tubes for pure R134a and with R134a/ISO32 POE (3-5.5% by mass) at 200kg/m^2-s and 25°C under evaporation conditions

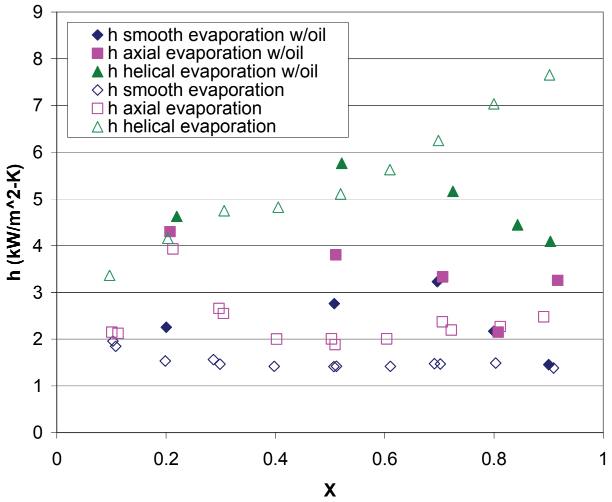

Figure 7. Average quality versus heat transfer coefficient for horizontal 9mm nominal diameter smooth, axially finned, and 18° helically finned tubes for pure R134a and with R134a/ISO32 POE (3-5.5% by mass) at 100kg/m^2-s and 25°C under evaporation conditions

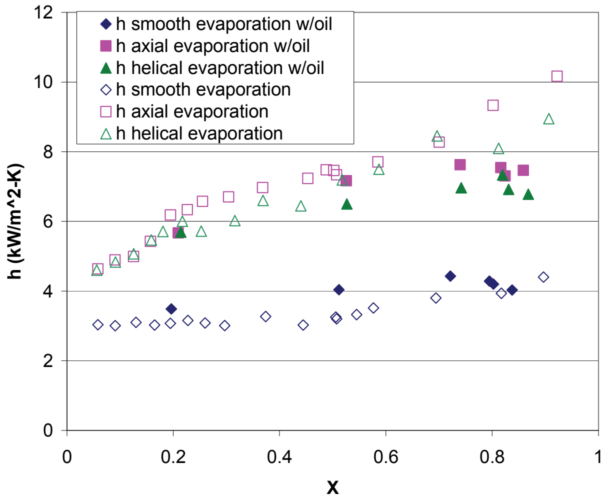

Figure 9. Average quality versus heat transfer coefficient for horizontal 9mm nominal diameter smooth, axially finned, and 18° helically finned tubes for pure R134a and with R134a/ISO32 POE (3-5.5% by mass) at 300kg/m^2-s and 25°C under evaporation conditions

6. CONCLUSIONS

Oil holdup data is obtained in the present study for R134a/ ISO32 POE (3 to 5% by mass) mixture in horizontal 9mm nominal diameter smooth, axially finned, and 18° helically finned tubes under evaporation and condensation conditions. Oil holdup under evaporation and condensation conditions is similar to that found under adiabatic conditions in Crompton et al. (2004) and Piggott (2001). However, oil holdup under condensation conditions is found to be lower than oil holdup under evaporation conditions at low mass fluxes where stratified flow exists (100kg/m^2-s), which may be attributed to "washing" of the walls by pure refrigerant during condensation conditions. There is not a significant difference between oil holdup between tests conducted under evaporation and condensation conditions at mass fluxes of 200 kg/m^2-s and greater except for the smooth tube at 200 kg/m^2-s.

Furthermore, it is found that the quality at which the minimum in oil holdup occurs generally increases with mass flux. Oil is seen to inhibit condensation heat transfer for all cases, especially for enhanced tubes at high qualities. Oil is found to enhance evaporation heat transfer at 100 kg/m^2-s for all tube types, but there is little or no enhancement at 200 and 300 kg/m^2-s where the microfinned tubes show a reduction in heat transfer at qualities above 50%. Future work should be done to develop a model that captures the oil holdup trends observed in the present study model for evaporation and condensation conditions. This model should utilize flow regime information as it is postulated to be relevant to oil holdup.

NOMENCLATURE

L	Length	(m)
x	Quality	(-)
a	Void Fraction	(-)
m_o	Oil Mass	(kg)
m_{ox}	Oil mass at a given quality	(kg)

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