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ABSTRACT

This work presents an experimental investigation of the ester oil ISO VG10-refrigerant R134a mixture flow with foam formation through a straight horizontal 3.22 mm ID diameter, 6.0 m length tube. An experimental apparatus was designed to permit the measurement of both pressure and temperature profiles along the tube as well as the visualization of the flow patterns of the two-phase flow. Tests were performed at different mass flow rates, several refrigerant mass fractions at the inlet of the flow, and inlet mixture temperatures around 28 and 39 °C. A liquid mixture flow with constant temperature and pressure gradient could be seen at the inlet of the tube. As the flow proceeded towards the exit of the tube the pressure drop produced a reduction of the refrigerant solubility in the oil yielding to formation of the first bubbles. Initially, small and few bubbles could be noticed and the flow behaved as a conventional two-phase flow. Eventually, the bubble population increased and foam flow was observed at the exit of the flow. Due to the great formation of bubbles, both the temperature and pressure gradient of the mixture were greatly reduced in this region of the flow.

1. INTRODUCTION

Regarding to the refrigeration cycle a good miscibility of the refrigerant in the lubricating oil is required in order to allow easy return of circulating oil to the compressor through the reduction of the oil viscosity. However, inside the compressor this miscibility considerably modifies the leakage of the refrigerant gas through the clearances, the lubrication of sliding parts, and the performance of journal bearings. The solubility of the refrigerant in the lubricating oil depends on the oil temperature and refrigerant vapor pressure, reducing as the temperature increases or the pressure decreases. Consequently, as the mixture flows through the several types of channels inside the compressor there will be formation of refrigerant gas bubbles (outgassing) due to the reduction of the solubility caused by the friction pressure drop. Calvert (1990) shows that the behavior of this flashing flow is much different from the conventional two-phase flows as the void fraction reaches values typically of about 0.7 (Winkler *et al*., 1994) where foam flow is generally observed. Therefore, a general understanding of the oil-refrigerant mixture flow with foam formation through small channels is crucial in order to develop a knowledge basis onto which lubrication and gas leakage models can be built.

Mainly in the 80 and 90-decade, several works related to oil-refrigerant mixture started being developed. Some of these works were directed towards the determination of the themophysical properties of the new mixtures (Martz *et al*.; 1996, Grebner and Crawford., 1993; Thomas and Pham, 1992; Baustian *et al*., 1986; Thome, 1995; and Van Gaalen *et al*., 1990, 1991a, 1991b). Other researchers concentrated their studies on the behavior of refrigerant flows contaminated with lubricating oil with the objective of analyzing the influence of the oil in the mixture flow and heat transfer dynamics in evaporators and condensers. Some examples of these researchers are Schlager *et al*. (1987), Jensen and Jackman (1984), Wallner and Dick (1975) Hambraeus (1995) and Mitrovic (1998).

Motta *et al*. (2001) provided a good literature review on oil-refrigerant mixture flashing flows. It is worthy noting that most of the works are related to mixture flows with a low oil mass fraction (less than 5%), that is, the oil is treated as the contaminant. There have been very few studies of oil-refrigerant flow in which the oil is contaminated by the refrigerant. Lacerda *et al*. (2000) presented an experimental research on oil-refrigerant two-phase flow through a long tube using mineral oil and R12 as refrigerant. They measured the pressure and temperature profiles of the flow through a 2.86 mm-diameter Bundy type tube. Furthermore, they visualized flow patterns of the same

mixture flowing through a 3.03 mm-diameter glass tube. The visualization results showed a foam flow at the end of the tube, where they measured a great reduction in both temperature and pressure. Poiate Jr. and Gasche (2002) obtained similar pressure and temperature distribution for the same mixture flowing through a 3.22 mm-diameter Bundy type tube, and visualization results for the flow through a 3.0 mm-diameter glass tube. The results are qualitatively the same.

Recently, Barbosa Jr. *et al*. (2004) presented an analysis of the available prediction methodologies for frictional pressure drop in two-phase gas-liquid flows of oil-rich refrigerant-lubricant oil mixtures in a small diameter tube. Several correlations and methods for the calculation of the frictional two-phase pressure drop were investigated by the authors, some of them being state-of-art methods developed based on data for small diameter channels. They found none of the methodologies perform satisfactorily over the range conditions covered during R12-mineral oil mixture flow tests in a 5.3 m long, 2.86 mm diameter tube.

This research was undertaken to study the behavior of the flashing flow of a mixture composed by R134a and an ester oil ISO VG10 using the same apparatus utilized by Poiate Jr. and Gasche (2002). It will be presented the results for pressure and temperature distribution along the flow through a 6 m long, 3.2 mm ID tube, and some flow pattern visualization results.

2. EXPERIMENTAL METHOD

The experimental apparatus was designed to produce steady flows of the oil-refrigerant mixture through two 6 m long tubes in such a way that three types of flow patterns could be observed along the flow: a liquid mixture flow at the entrance of the tube, an intermediary two-phase region, and a foam flow in a region near the end of the tube. One metallic Bundy type tube was instrumented with pressure transducers and thermocouples in order to measure the pressure and temperature distribution along the flow. A glass tube was used to permit the visualization of the flow patterns.

2.1 Apparatus and Instrumentation

A general view of the experimental apparatus is shown in Fig. 1. Basically, the experimental apparatus is composed by four tanks, test section, a vapor return line, an oil return line, instrumentation, and a data acquisition system. All these equipments are connected with each other in order to produce the flow through either of two 6 m long horizontal tubes, which consist the test section. The first tube is made of borosilicate glass (3.0 m ID) and allows flow visualization. The other tube is a metallic Bundy type 3.22 mm ID (±0.03) equipped with 10 pressure transducers (±2 kPa) and 15 type T thermocouples (± 0.5°C) installed along the tube surface. The experimental apparatus runs on the blow down mode.

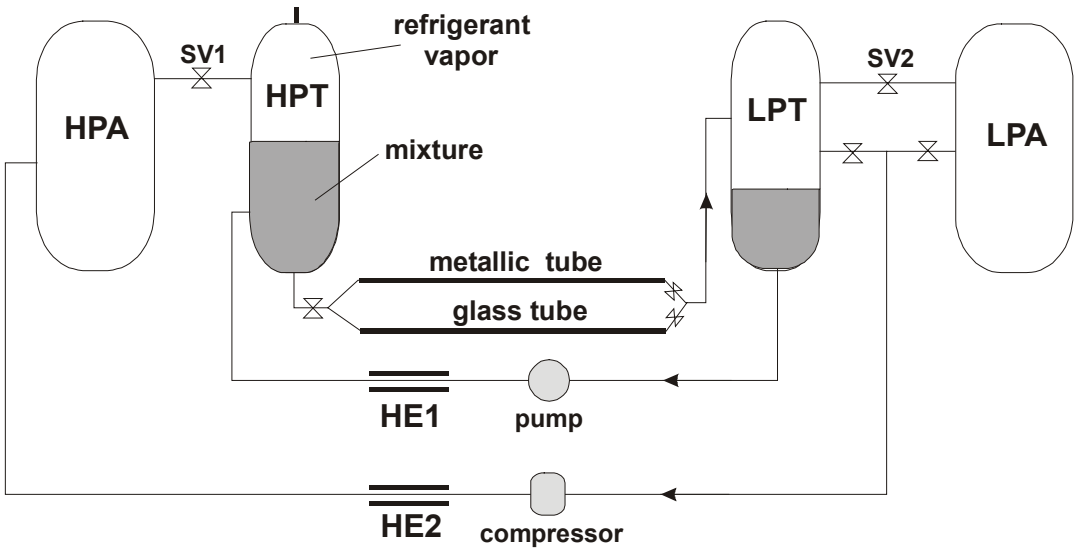

Figure 1: Experimental apparatus

The main objective of the four tanks is to maintain constant the pressure difference between the high and low-pressure tanks (HPT, LPT), which are connected by the two tubes building up the test section. The HPV is filled with oil and refrigerant, and an equilibrium liquid mixture at the bottom of the tank coexists with the refrigerant vapor at the top for desired temperature and vapor pressure. Pressure and temperature sensors monitor the conditions of the gas and liquid in both tanks. High and low pressure accumulators (HPA, LPA) operating at pressures higher and lower than those at HPT and LPT respectively, keep the pressure at constant levels in both tanks using two automatic solenoid valves controlled by a desktop computer. During operation the equilibrium liquid mixture existing in HPT is driven into either of the two tubes.

Auxiliary equipment consists of a compressor, an oil pump, and two heat exchangers (HE1, HE2). The compressor is employed to return the gas to the HPA and the pump returns the oil back to the HPT for undertaking other tests. The heat exchangers are used to cool both fluids if necessary before reaching the HPA and HPT. Sensors data allowed monitoring of flow conditions and were imputed into a PC-based data acquisition system. All instruments were calibrated using the data acquisition system.

2.2 Experimental Procedure

Firstly, the necessary parts of the apparatus were flushed with a solvent fluid to remove impurities and the system was evacuated to 10 Pa. After that, 80 kg of ester oil ISO VG10 was put into the HPT and heated until 60ºC for three hours to facilitate impurities removal while the vacuum pump was kept running. Next, 60 kg of R-134a was put partly into both the HPT and HPA.

All tests started with the saturation of the oil in the HPT at the desired test temperature and 100 mbar above the desired pressure, that is, at $p_i=p_t+100$ mbar. In order to increase the rate of abortion the refrigerant was circulated at the HPT by employing the compressor to drive the refrigerant gas from the top and compressing it at the bottom of the HPT. As gas is absorbed by the liquid mixture, the pressure tends to decrease, activating the automatic solenoid valve (SV1) which releases refrigerant from HPA to HPT in order to maintain the pressure in the HPT constant. This process continues until saturation is achieved in the HPT at p_i. The saturation process could last until six hours. After saturation is reached at p_i some amount of gas is released from the top of HPT to decrease the pressure to p_t, the desired test pressure. This pressure reduction promotes a fast outgassing and assures that saturation was indeed established at pressure p_t (±1% of the value). This new saturation state is reached within 30 to 60 minutes, which is observed when pressure stops increasing because of gas release. In all this processes the temperature is controlled at the desired value (±1°C).

Depending whether flow visualization or measurement run is desired, after the saturation process is finished the test section valves are arranged so that the mixture is forced into the glass or the Bundy tube, respectively. During the experimental runs the compressor remain running in order to circulate gas from the LPA to the HPA. Data acquisition is initiated after the steady flow is reached.

Prior to initiating the experiments with mixtures, some tests were performed with pure oil flow in the Bundy type tube and nitrogen to pressurize the tanks and accumulators. These tests were used in evaluating and validating the experimental loop, instrumentation, and data acquisition. In addition, they validated the methodology to obtain the mass flow rate of the mixture flows, which was based on the use of the linear pressure gradient established at the inlet of the tube when the flow was still a liquid mixture flow. Details about the validation of the experimental apparatus can be found in Poiate Jr. (2001).

2.3 Data Reduction and Interpretation

In order to avoid outgassing before the liquid mixture reaches the tube, a mass flow meter was not used to obtain the mass flow rate. Instead, the mass flow rate was calculated by using the linear pressure gradient measured at the inlet region of the flow, where the mixture was still in the liquid state and the flow was completely developed. The average velocity used to determine the mass flow rate was calculated using Equation (1):

$$\overline{V} = \left[\frac{2D}{\rho f} \left(-\frac{dp}{dz} \right) \right]^{1/2} \tag{1}$$

where D is the tube diameter, ρ is the density calculated at the inlet temperature of the mixture, f is the friction factor calculated by the equation proposed by Churchill (1977), and dp/dz is the pressure gradient along the flow direction measured at the linear portion of the pressure distribution.

The Reynolds number was defined as

$$\mathrm{Re} = \frac{\rho \overline{V} D}{\mu} \tag{2}$$

where μ is the absolute viscosity of the liquid mixture at the inlet of the tube. Both properties, μ and ρ, were given by the oil manufacturer. In addition, the saturation mass fraction of the refrigerant in the oil, w, was also taken from the oil manufacturer.

2.4 Uncertainty

The uncertainties of the reduced data were determined by propagating the measurement uncertainties using standard methods (Moffat, 1988). The uncertainty of the average velocity was ±5%, while the uncertainty of the Reynolds was ±10%. The uncertainty of the average velocity depends on the pressure gradient at the inlet of the flow and was estimated by the uncertainty of the pressure curve fitting accomplished in that region taking in account the uncertainties of the temperature and pressure.

3. RESULTS

Pressure and temperature profiles were measured and visualization results were obtained for more than 30 tests, but only some of the results are shown in this paper. Temperatures at the inlet of the flows were about 28 and 39 ºC. For temperatures around 28 ºC, the saturation pressures inside the HPT were 4.0, 4.5, and 5.0 bar, while for temperatures around 39 ºC they were 5.0, 5.5, and 6.0 bar. These saturation pressures were chosen in such a way that foam flow could be observed at the exit region of the flow. All those tests were undertaken using a mixture composed by an ester oil ISO VG10 and refrigerant R134a.

Pressure and temperature distribution for inlet temperatures around 28 ºC are shown in Figs. 2 and 3, respectively. Saturation pressures in the HPT were 4.0, 4.5, and 5.0 bar, yielding to refrigerant mass fraction at the inlet of the flow of 35, 40, and 53%, respectively. Pressure and temperature results are average values from measurements taken during 3 to 5 minutes after steady state flows were established. The refrigerant mass fractions at the inlet of the flow, w, and the Reynolds numbers, Re, are also indicated in those figures.

As can be observed from Fig. 2, all pressure distribution present a linear behavior at the inlet region of the flow, until about z=3 m from the inlet of the tube, indicating that single-phase flow prevails and pressure drop is due to friction only. The presence of few bubbles in this region, which could be visualized in the flow through the glass tube, was not sufficient to change the flow from the single-phase pattern. The constant temperature measured in this region, which is shown in Fig. 3, confirms the single-phase pattern predominance. After this region, the pressure gradient starts to increase due to the outgassing from the liquid mixture, which causes density reduction at each cross section along the flow. Consequently, the flow accelerates and the pressure drop considerably increases to comply with friction and fluid acceleration. As pressure decreases and gas is released from the liquid mixture, the temperature decreases to keep up with the latent heat requirements for evaporation. Figure 3 shows that the temperature profiles are qualitatively similar and the total temperature reduction is about 10 ºC for all tests. One can notice that the Reynolds numbers in all tests lie in the range of transition to turbulence, which makes the analysis of the two-phase flow still more complex because of its influence on the bubble nucleation.

Figures 4 and 5 present similar results for inlet temperatures around 39 ºC and saturation pressures in the HPT of 5.0, 5.5, and 6.0 bar, yielding to refrigerant mass fraction at the inlet of the flow of 22, 25, and 30%, respectively. One can observe that the results are qualitatively the same. In Fig. 5 it can be noted that for the lower Reynolds number, Re=2300, the behavior of the temperature profile is somewhat different from the others. Perhaps, the lower value of the friction factor caused a delay on the bubble nucleation, which diminished the total temperature

reduction to 5 ºC, while in the other two tests this reduction was about 9 ºC. However, other tests have to be performed in order to confirm this assumption.

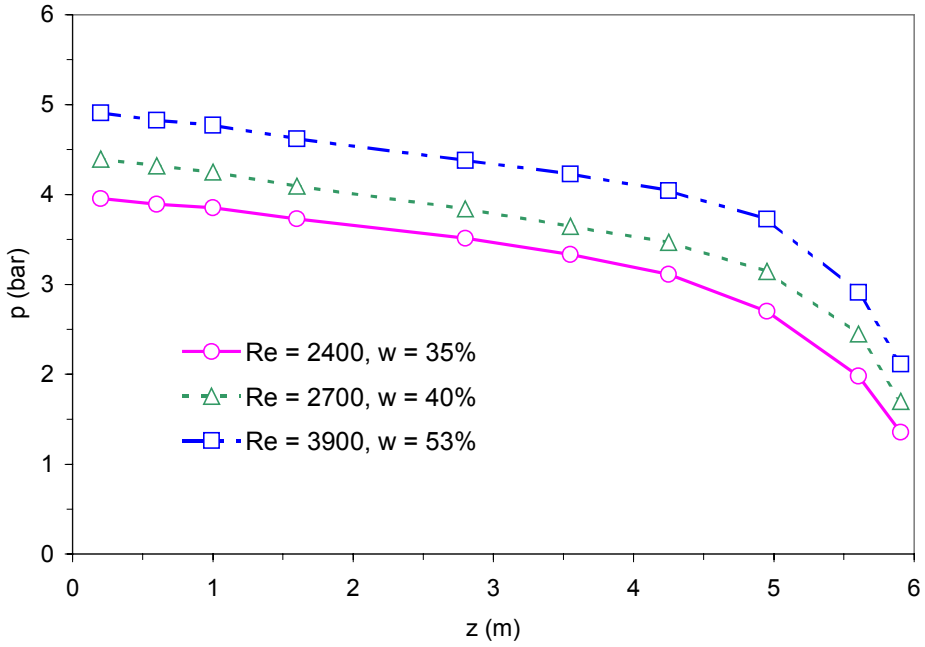

Figure 2: Pressure profiles for inlet temperatures around 28 °C

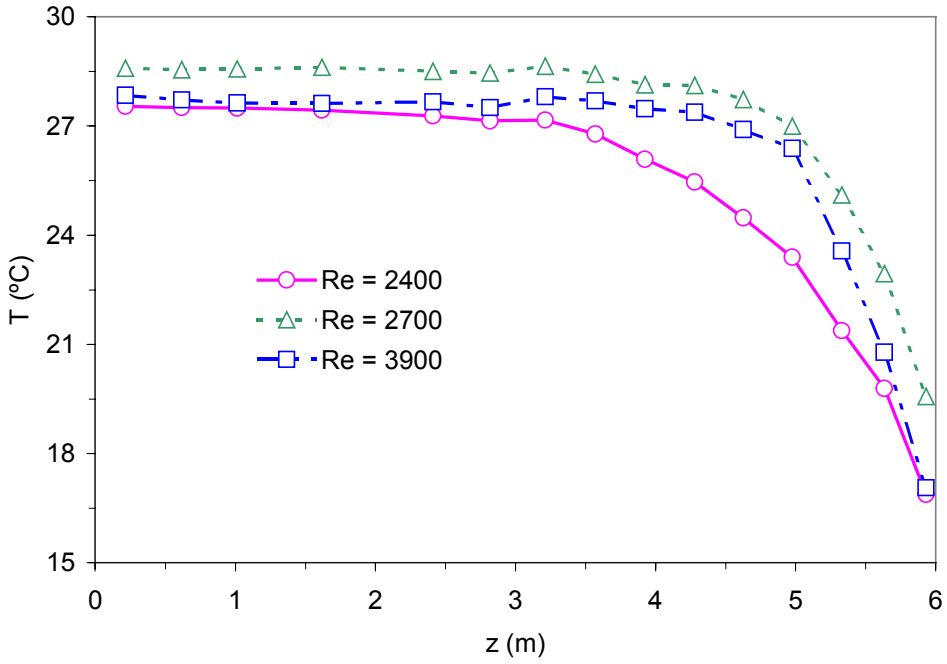

Figure 3: Temperature profiles for inlet temperatures around 28 °C

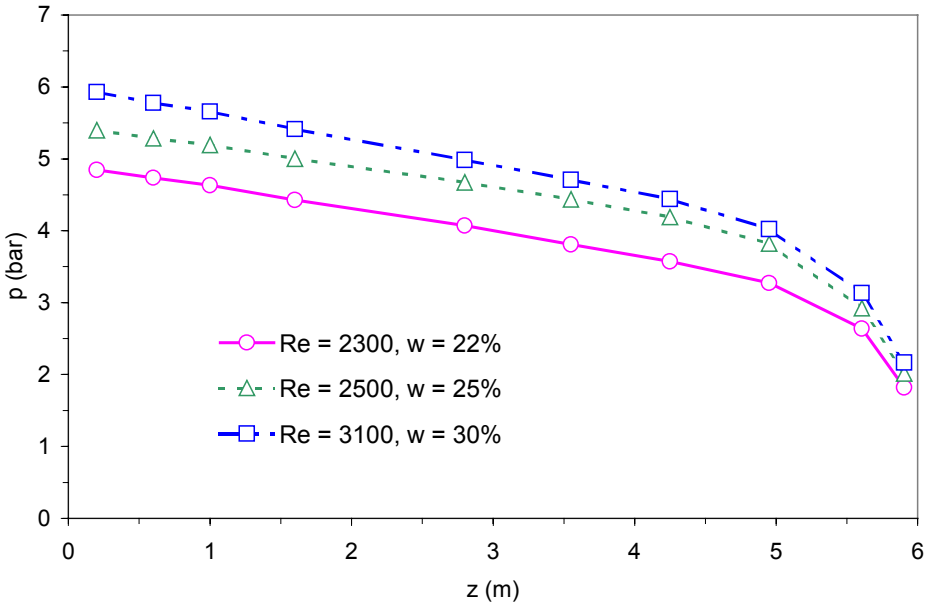

Figure 4: Pressure profiles for inlet temperatures around 39 °C

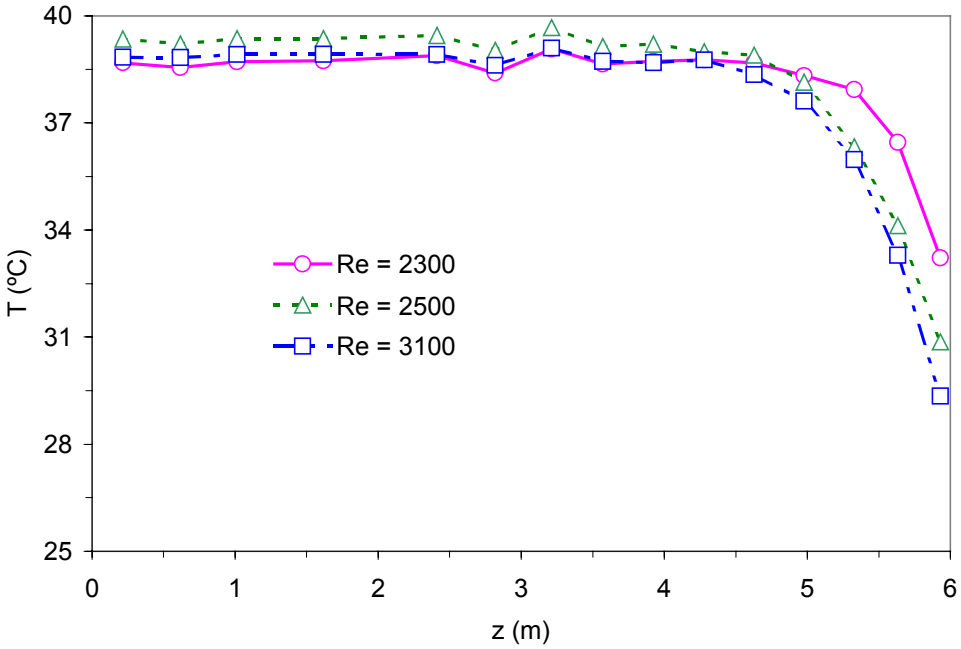

Figure 5: Temperature profiles for inlet temperatures around 39 °C

Figures 6 and 7 present flow visualization results for the Re=2400-test shown in Fig. 2, in which the high pressure was 4.0 bar, the inlet temperature of the flow was 27.5 °C, and the inlet refrigerant mass fraction was 35%. These figures depict several photographs taken in the same position at different instants. Figure 6 shows the flow patterns visualized in the region located from z=3.004 to 3.130 m. As can be seen, several flow patterns were found in this region. The first photograph shows small single bubbles flowing in line, while the second and third photographs

depict two types of configuration: some regions containing many tiny bubbles grouped together and other regions with long bubbles. The fourth photograph shows similar patterns with greater number of tiny bubbles. It can also be observed that the bubbles tend to flow mainly in the upper portion of the tube because of their buoyancy. One can classify the flow pattern as a mixture of bubbly and plug flow. Figures 2 and 3 show that in this region of the flow the pressure and temperature start to decrease fast.

Figure 7 shows that at the end of the tube, from z=5.730 to 5.830 m, only the foam flow pattern can be encountered as the number of bubbles increases. In this case, however, the vapor phase occupies the entire cross section of the tube. Furthermore, during the experiment, it can be noticed that the flow regime was intermittent. It is worthy noting that this type of flow pattern is not encountered in other two-phase flows.

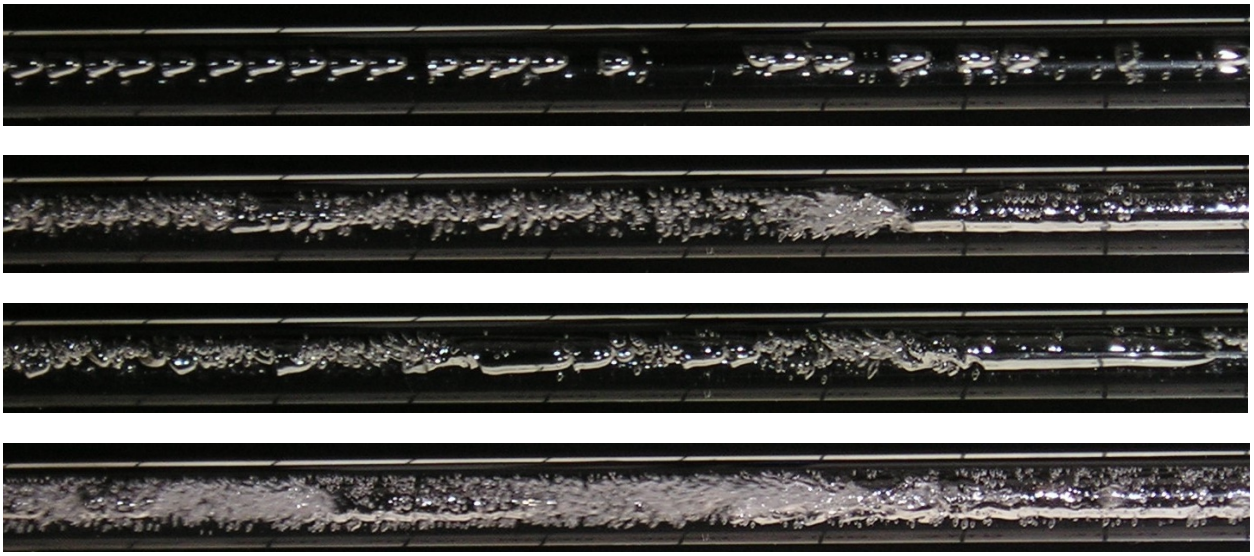

Figure 6: Flow patterns in the region from z=3.004 to 3.130 m for the Re=2400-test (high pressure of 4.0 bar, inlet temperature of 27.5 °C, and inlet refrigerant mass fraction of 35%)

Figure 7: Flow patterns in the region from z=5.730 to 5.830 m for the Re=2400-test (high pressure of 4.0 bar, inlet temperature of 27.5 °C, and inlet refrigerant mass fraction of 35%)

All the results shown here are qualitatively similar to those obtained by Lacerda *et al*. (2000) and Poiate Jr. (2001) for the mineral oil-R12 mixture.

4. CONCLUSIONS

An experimental apparatus was used to study the flashing flow of the ester oil ISO VG10l-refrigerant R134a mixture flowing through a straight horizontal 3.22 mm ID diameter, 6.0 m length tube. The main motivation to the work was to improve the understanding of this flashing mixture flow for developing physical models to be used in analysis and simulation of lubricating and leakage processes occurring inside refrigeration compressors.

Pressure and temperature distribution along the flow were measured for inlet temperatures around 28 and 39 ºC, considering several mass fraction of refrigerant in the oil and various Reynolds numbers. A liquid mixture flow with constant temperature and pressure gradient could be seen at the inlet of the tube. As the flow proceeded towards the exit of the tube the pressure drop produced a reduction of the refrigerant solubility in the oil yielding to formation of bubbles. Initially, small and few bubbles could be noticed and the flow behaved as a conventional two-phase flow. Eventually, the bubble population increased and foam flow was observed at the exit of the flow. Due to the great formation of bubbles, both temperature and pressure gradient of the mixture were greatly reduced in this region of the flow. Visualization results also showed that the flow regime was intermittent.

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