EXPERIMENTAL INVESTIGATION OF R-134a AND R-600a ABSORPTION IN SYNTHETIC LUBRICANT OILS

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Abstract. Refrigerant absorption and mixing in lubricant oil are important in compressor and system design. Experimental work is reported on absorption of refrigerant vapour through the top interface of an initially stagnant layer of pure lubricant oil. Depending on the refrigerant-oil pair, the liquid refrigerant is heavier than the oil and mixing is enhanced due to natural mass convection. This behavior is typical of HFC refrigerants, such as R-134a. In contrast, in systems where the liquid refrigerant is less dense than the oil (for example, HC refrigerants, like R-600a and R-290) liquid density instability near the interface does not occur and absorption takes place by molecular diffusion alone. A test rig consisting of a transparent test section through which absorption is observed was specially constructed for the present experiments. During each experimental run, the overall mass of refrigerant in the test section was kept constant and, as a result, the pressure decreased with time. Tests were conducted for R-134a and R-600a with three POE oils of distinct viscosity grades and the effect of the initial depth of the oil layer (aspect ratio) on the velocity field and on the refrigerant absorption rate (i.e., pressure change rate) was assessed.

Keywords: oil-refrigerant mixtures, absorption, natural refrigerants, mass transfer, visualization

1. Introduction

Detailed knowledge of rates of absorption of refrigerant vapour in lubricant oil is very important in design of hermetic refrigeration compressors. In small-scale systems, refrigeration capacity control is performed by a succession of on-off compressor cycles whose frequency depends on the thermal load and on the cold ambient temperature requirements. During each one of such cycles, immediately after the compressor turns off, a process of absorption of the vapour refrigerant by the oil inside the compressor shell is initiated. The oil is present as a stagnant layer at the bottom of the compressor shell (carter) and the depth of the oil layer depends on the amount of oil present in the system. The refrigerant absorption process inside the compressor is important to the determination of the system equalizing pressure, i.e., the pressure attained by the whole system while the compressor is off. In reciprocating compressors, for example, high refrigerant absorption rates are desirable since lower equalizing pressure means reduced torque and power required for compressor start-up.

This paper reports a series of tests aimed at investigating systematically vapour refrigerant absorption in lubricant oil. A rig constructed from a section of transparent tube was used to enable visual recording of the absorption process. Three synthetic polyol ester oils of different viscosity grades (approximately 5, 7 and 10 cP at 40°C, respectively) were combined with refrigerants 134a and 600a. In absorption of R-134a in lubricant oil, the liquid refrigerant is heavier than the oil and the liquid flow field is a result of natural mass convection. Convection in the liquid promotes higher absorption rates and leads to a more pronounced decay of the system pressure as a function of time compared with the case for R-600a absorption, where only pure mass diffusion takes place. In the present experiments, the effects of initial depth of the oil layer (aspect ratio) and refrigerant-oil combination on the velocity field and on the refrigerant absorption rate were investigated. In addition to pressure measurements, temperature recordings of the liquid at the liquid-vapour interface were carried out in some experimental runs. The temperature increase as a function of time during refrigerant absorption was observed.

Fukuta *et al.* (1995) investigated both experimentally and analytically the absorption of R22 in three mineral oils of different viscosity grades (3GS, 4GS and 5GS) at constant temperature and pressure in stagnant oil layers of different depth to base diameter aspect ratios. The absorption rates decreased with increasing oil viscosity. The data were predicted using an *apparent diffusion coefficient* model, which was correlated in terms of the liquid layer aspect ratio and of an equivalent Grashof number. Rates of absorption of pure refrigerants and refrigerant blends in a polyol ester oil (POE 68) were measured by Goswami *et al.* (1998) over wide ranges of pressure and temperature. They correlated the instantaneous volume averaged liquid mass fraction with a complementary exponential decay function. Recently, Gessner and Barbosa (2006) revisited the analysis of Yokozeki (2002) for predicting absorption of single component refrigerants through a one-dimensional apparent mass diffusion model. The model was validated with the data of Goswami *et al.* (1998) for absorption of R-125, R-32 and R-134a in POE 68 at pressures ranging from 239 to 584 kPa and at a constant temperature of 24°C.

As far as visualization of the flow field during absorption is concerned, there is a lack of published studies in the open literature. Perhaps the most complete study of such kind is that by Okhotsimskii and Hozawa (1998), who employed Schieleren techniques to visualise absorption and desorption of CO_2 in 23 systems. In addition to the Rayleigh stability condition, they also investigated the effect of Marangoni (surface tension driven) stability on the mass convection flow pattern as well as on interfacial turbulence. A recent paper on visualization of absorption (and desorption) of R-600a in several types of oil was put forward by Fukuta *et al.* (2005). They performed experiments in which the refrigerant absorption rates were measured for a number of conditions. A diffusion model was also proposed. In addition to the fact that liquid R-600a is lighter than the oil and absorption takes place by diffusion alone, the most significant difference between the present study and that of Fukuta and co-workers is that in their study the pressure is kept constant during refrigerant absorption. Here, in contrast, the total mass of refrigerant is constant and hence system pressure is allowed to decrease with time as a result of vapour absorption.

2. Experiments

2.1. Material and Methods

A schematic representation of the experimental rig is shown in Figure 1. A 150 mm long section of a 40 mm ID (2 mm wall thickness) borosilicate glass tube is mounted between two 10 mm thick square (75 mm side) aluminium plates. The test cell is tightened with four sets of screws and nuts (one in each corner of the plates) that press the plates against both ends of the glass tube. Silicon rubber gaskets seal the contact between the plates and the tube. Three fittings are screwed on the top plate for connecting pressure (P) and temperature (T) measurement devices and to allow oil and refrigerant charging (C).

Initially, a specified amount of oil is placed inside the test cell. Vacuum is applied to the system to remove atmospheric air and moisture from the oil sample. Then, the cell is submerged into a transparent acrylic tank partially filled with glycerine, which has a light refraction index (1.47) very near that of borosilicate glass (approximately 1.5). In addition, any image distortion provoked by the curvature of the glass wall is cancelled out by visual observation of the flow field through the flat walls of the acrylic tank. Pressure is measured with a HBM P3MB absolute pressure transducer calibrated to an accuracy of $\pm0.1\%$ of the full scale (10 bar). Temperatures of the ambient air and of the liquid mixture in the test section are measured with Omega K-type thermocouples calibrated to an accuracy of $\pm0.1^{o}$C from 0 to 40°C. The thermocouple is mounted in the test cell so that only its tip is submerged in the liquid. Time is allowed for the system to reach thermal equilibrium with the surrounding air. The room temperature is maintained at 25 $\pm 0.5^{o}$C. Shortly before opening the valve that connects the test section with the refrigerant tank, the computerized data acquisition procedure is initiated.

Refrigerant (134a or 600a) is maintained at thermodynamic equilibrium at room temperature inside a 500 ml reservoir. At the beginning of the test, with the valve that connects the test cell with the vacuum pump fully closed, the valve connecting the test cell and the refrigerant reservoir is carefully opened for a few seconds. This allows equalization of pressures in the reservoir and in the cell. The valve is then closed and the cell pressure decreases with time as a result of vapour refrigerant absorption in the liquid layer. The height of the liquid layer is measured with a scale on the outside of the glass tube. The experimental runs are terminated after 5 h for the R-134a runs (this time is usually enough to reach saturation) and after 15 h or so for the R-600a runs (it was noted that saturation was not reached in these cases because of the very low, purely diffusive absorption mechanism). Image sequences of the absorption process were acquired with a Sony CCD-TRV65E video camera at 24 frames per second. They were subsequently digitalized in a computer with a TV capture card.

2.2. Experimental Conditions

The experimental conditions in the present study are as follows. Absorption of R-134a was performed in two different polyol ester oils, namely POE7H and POE10H. Absorption of R-600a was performed in POE5H and POE7H. The pressures at the onset of absorption corresponded to the saturation pressures of the pure refrigerants in the reservoir at ambient temperature, i.e., 25 $\pm 0.5^{o}$C. Three initial liquid layer (pure oil) depths were tested (nominal): 40 mm (1 *D*), 20 mm (0.5 *D*) and 4 mm (0.1 *D*).

3. Qualitative Results: Visualization of the Flow Field

Figure 2 shows an image sequence of the onset of R-134a vapour absorption in POE 10H at an initial depth of 1 *D*. In all sequences, a sheet of white paper with black stripes is placed behind the test cell for better contrast. In this particular run, the macroscopic motion of the solute is associated with the formation of a single buoyant plume issuing from the liquid-vapour interface. In the wake of this initial plume, several other plumes develop, thus triggering the convective liquid phase mass transfer process. Below each slide, the time elapsed from the first slide is shown. It should be noted that the convective process does not start immediately when the valve is opened and vapour R-134a and oil are brought into contact. At the early stages of absorption, pure mass diffusion takes place in the upper liquid layers. Eventually, as

the system becomes density unstable due to the presence of a critical amount of liquid R-134a in such layers, mass convection takes its place as the major mechanism of refrigerant absorption. Here, no attempt was made to measure directly the critical time associated with the onset of convection due to limitations in the experimental set-up. Figure 3 illustrates an interesting feature of the absorption process. As can be seen, the process is far from being symmetric with respect to the tube centre line and the main interface location from where the plumes originate wanders around the cross section of the tube. The present sequence is from the same run as that shown in Figure 2 (R-134a - POE 10H, 1 *D*), but was captured a few minutes later. The refrigerant source has moved to the left in the frames and some upward motion can be seen in the centre-right regions as a results of liquid recirculation in the test cell.
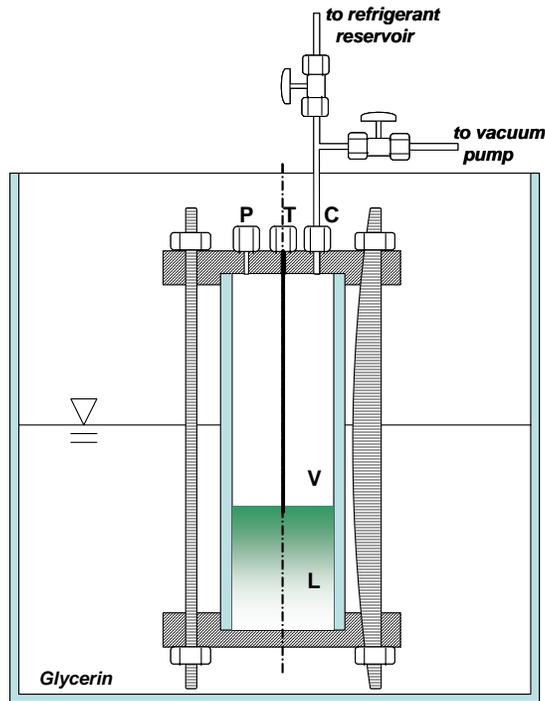
Figure 1. The experimental rig (drawing not to scale).
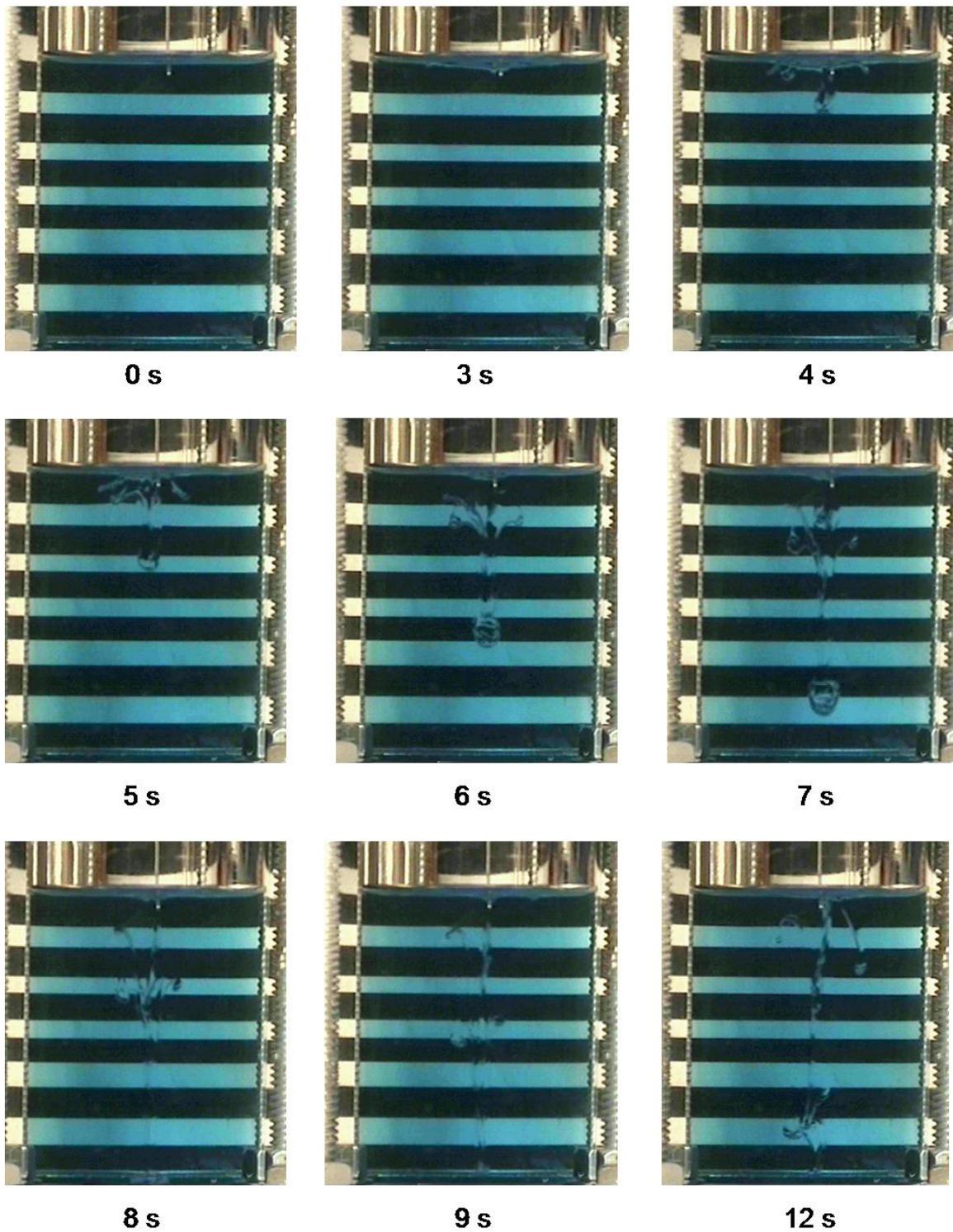
Figure 2. Onset of vapour R-134a absorption in POE 10H.
Initial pressure corresponds to saturation of R-134a at 25°C.

Figure 4 presents a sequence of images obtained at the onset of absorption of R-134a in POE 7H at an initial depth of 1 *D*. An absorption pattern totally different from those seen in POE 10H at an initial depth of 1 *D* is observed. Instead of

taking the form of a single plume, the pattern is characterised by several small-scale plumes developed simultaneously across the liquid-vapour interface.
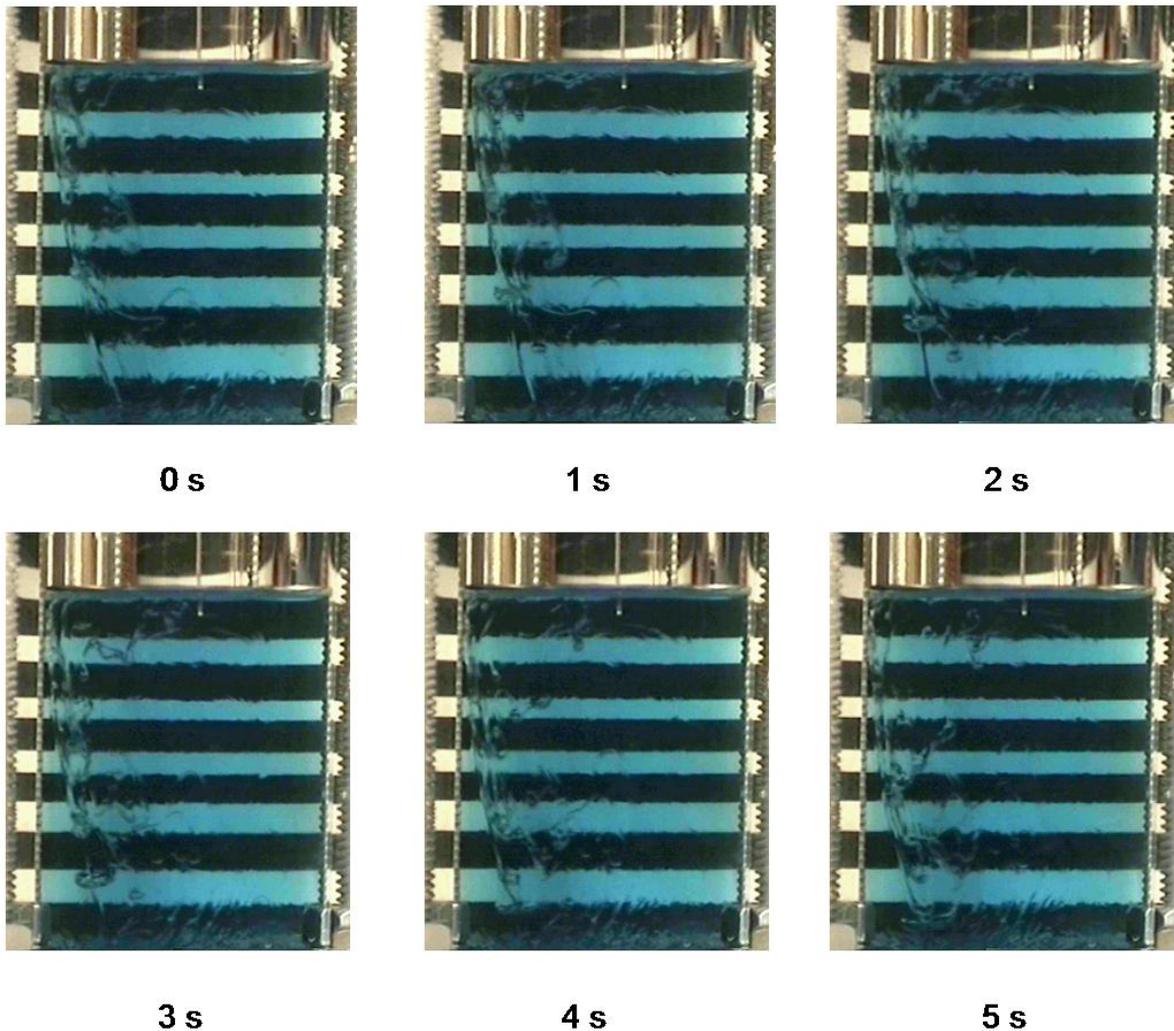
Figure 3. Vapour R-134a absorption in POE 10H.
Wandering of plume source and liquid recirculation (same conditions as in Figure 2).

In contrast with R-134a whose absorption is strongly influenced by convective effects, R-600a absorption is purely diffusive because of the lower density of the pure liquid refrigerant compared to that of the pure oil. In this case, the very slow advancing diffusion front is only barely distinguishable in the frame sequences (Fukuta *et al.*, 2005).

4. Quantitative Results: Pressure and Temperature during Absorption

Figures 5.a and 5.b show the pressure decay as a function of time for absorption of vapour R-134a in oils POE 10H and 7H, respectively. The pressure was normalised with respect to the maximum pressure at each run (the pure refrigerant saturation pressure at the ambient temperature). As expected, higher rates of absorption are sustained for longer as the initial depth of the liquid layer increases. This is because a smaller amount of refrigerant is required to saturate the liquid mixture at a small liquid height. As a result, lower pressures are observed for larger liquid depths. It can be observed that saturation is reached at lower pressures in POE 10H. This is an indication of lower solubilities of R-134a in POE 7H (at least for this particular temperature at which the experiments were performed).
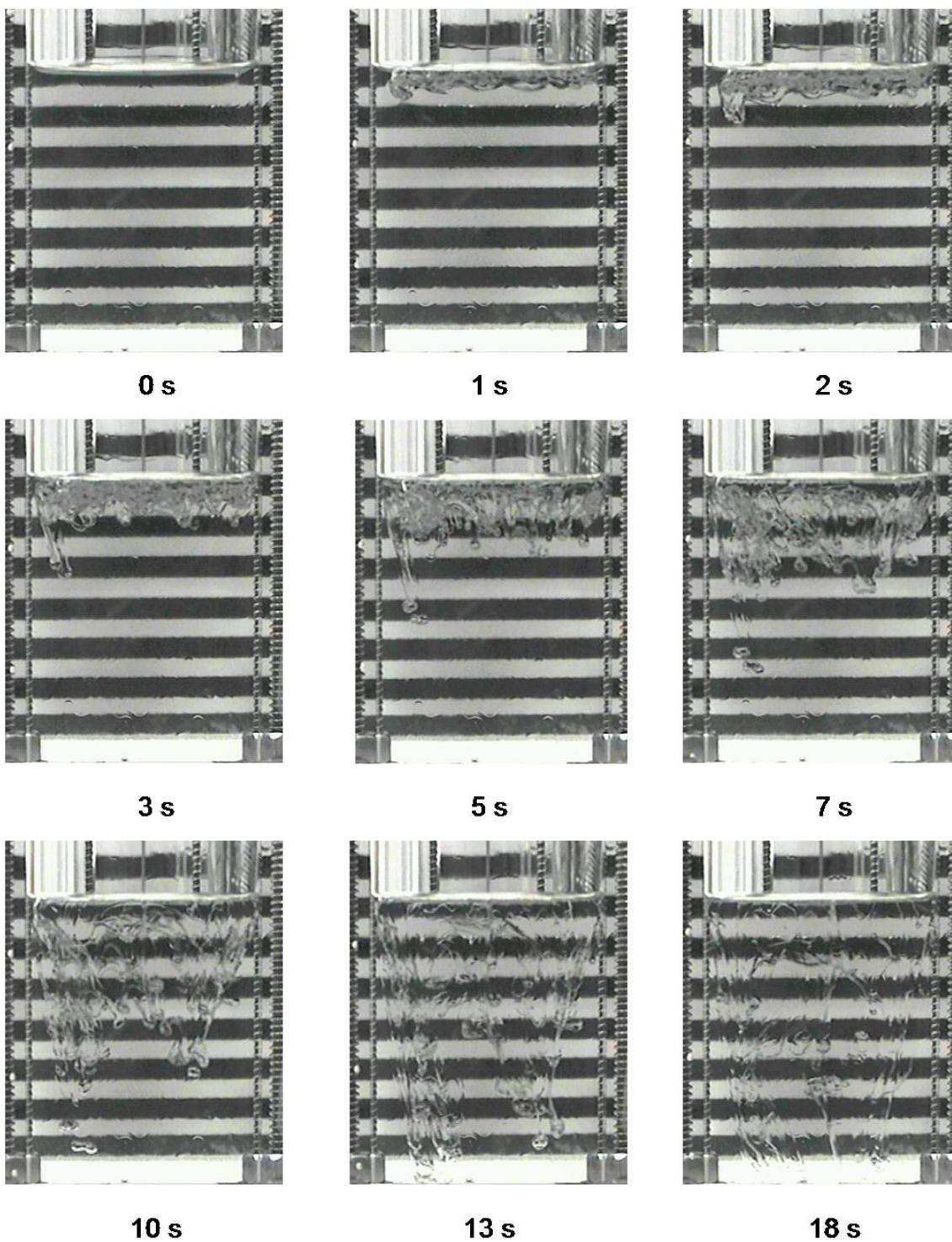
Figure 4. Onset of vapour R-134a absorption in POE 7H.
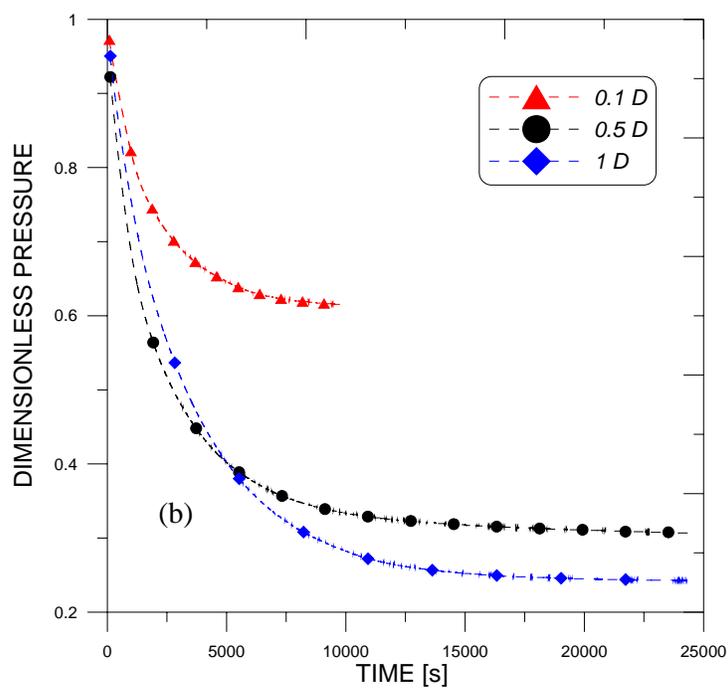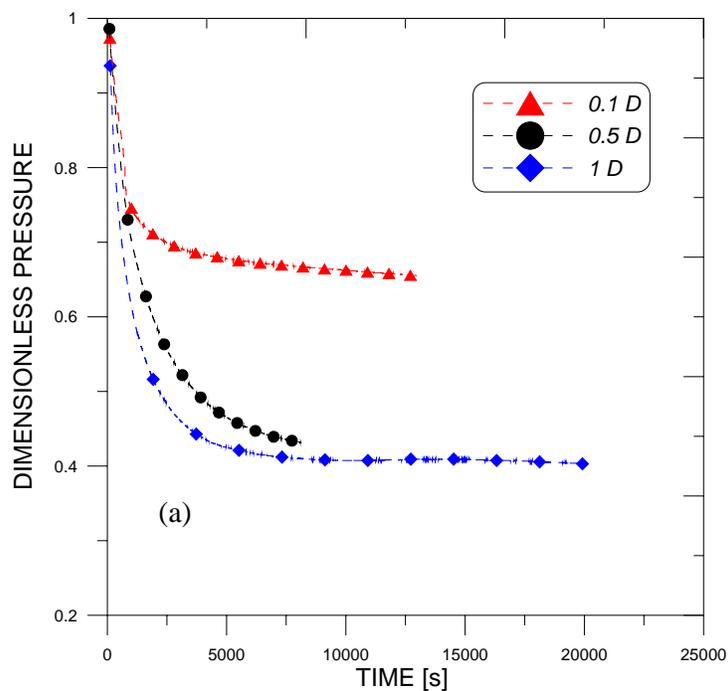Initial pressure corresponds to saturation of R-134a at 25ºC.

Figure 5. Pressure as a function of time: (a) R-134a/POE 10H, (b) R-134a/POE 7H.

Figures 6.a and 6.b exhibit the pressure behaviour during absorption of R-600a in POE 7H and POE 5H, respectively. As can be seen, the rate of pressure decay as a function of time is much less pronounced than for R-134a, as a result of diffusion-controlled absorption. Saturation was not reached in any situation, even after 12-hour experimental runs. It can be also verified that the absorption process for R-600a is much less dependent on the height of liquid layer than R-

134a. From the pressure decay curves, as seen in the R-134a data, there is an indication that the solubility of R-600a in POE 7H is lower than that of R-600a in POE 5H, at least for the temperature at which the tests were carried out.
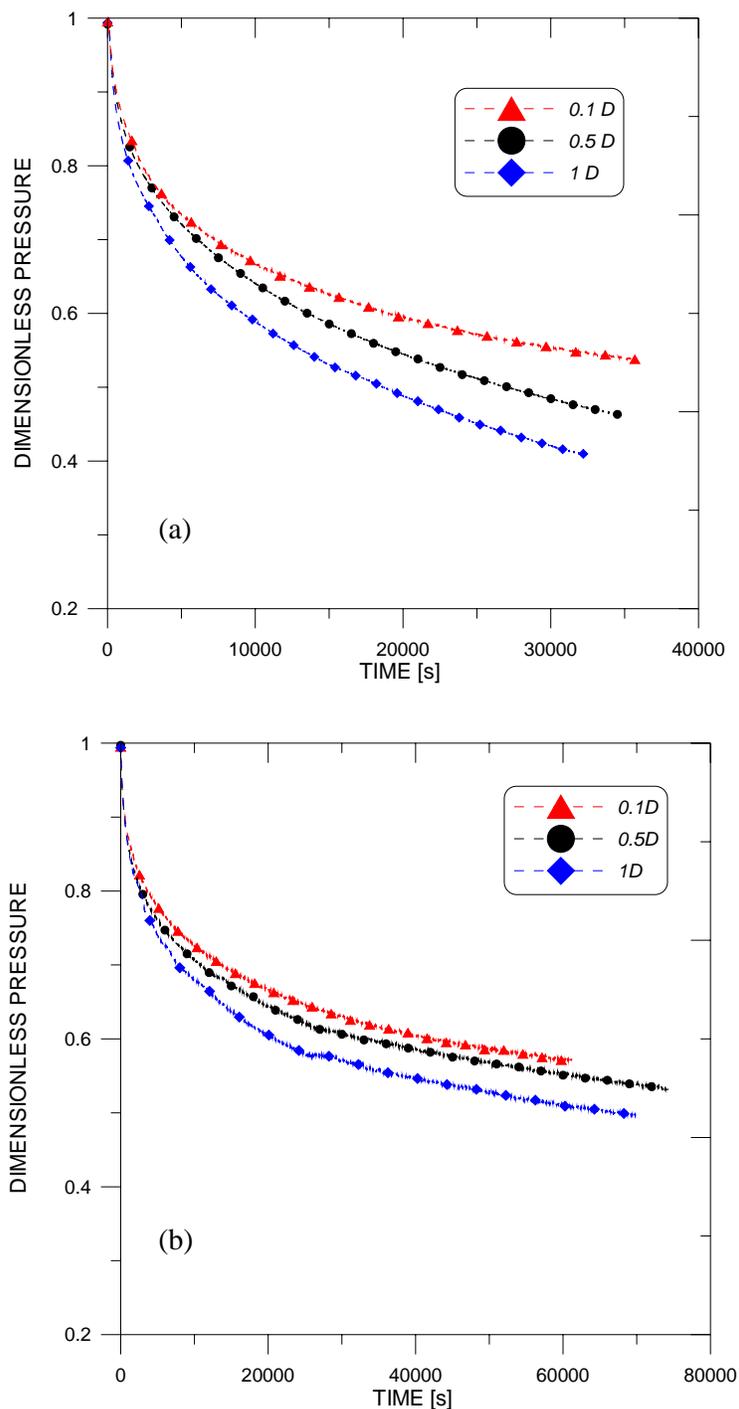

Figure 6. Pressure as a function of time: (a) R-600a/POE 7H, (b) R-600a/POE 5H.

Figures 7.a and 7.b present liquid and ambient temperature data as a function of time for runs with R-134a and POE 10H and POE 7H for a liquid depth of 1 *D* (in both cases), respectively. The liquid temperature is measured with a thermocouple whose tip is submerged a few mm from the liquid-vapour interface. To some extent, the temperature read by this sensor can be approximated as the interfacial temperature since, for the time period during which the

temperature recording is made, the amount of condensed refrigerant is not sufficient to raise the level of the interface significantly. Similar results are presented for R-600a in POE 7H and POE 5H in Figures 8.a and 8.b. As can be seen, the liquid temperature rises sharply (less sharply so for R-600a) as a result of latent heat release (exothermal absorption) during the first minute or so, but eventually, as absorption ceases the system regains thermodynamic equilibrium with the surroundings (see Figure 9).
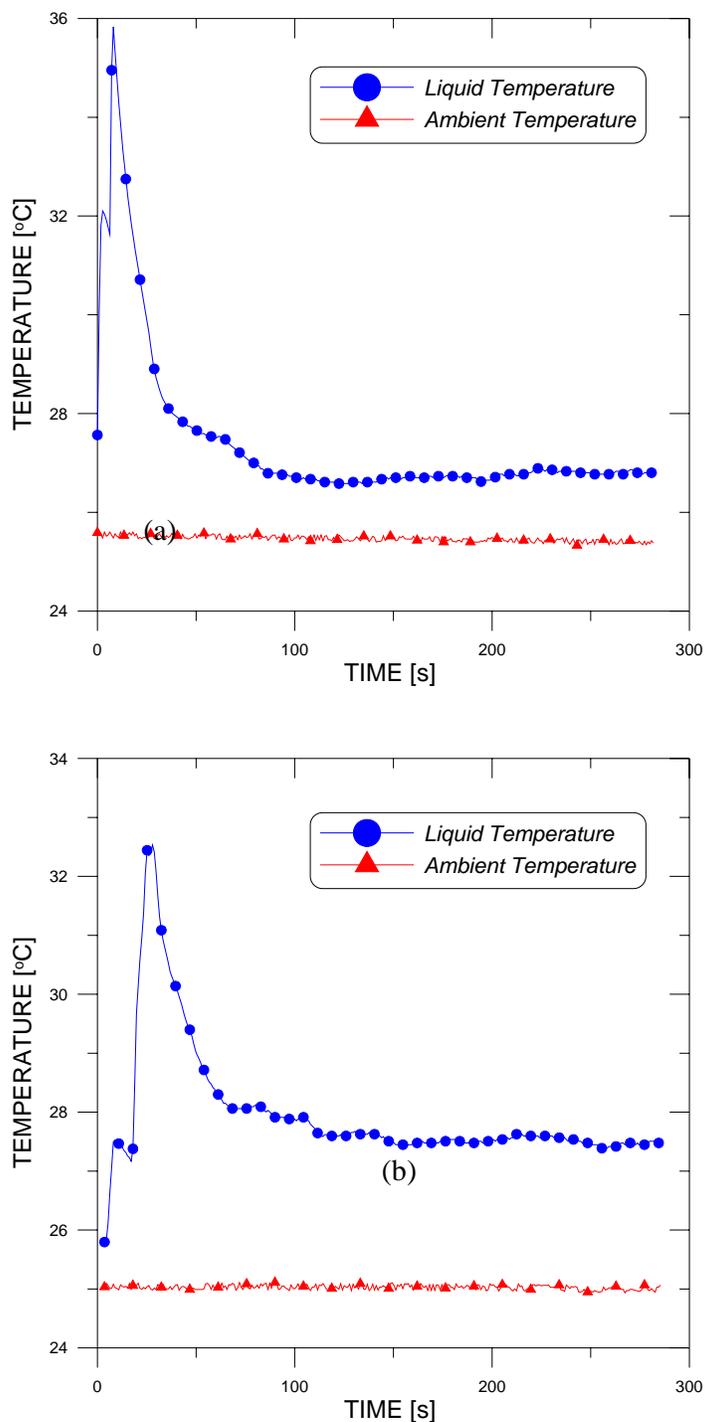
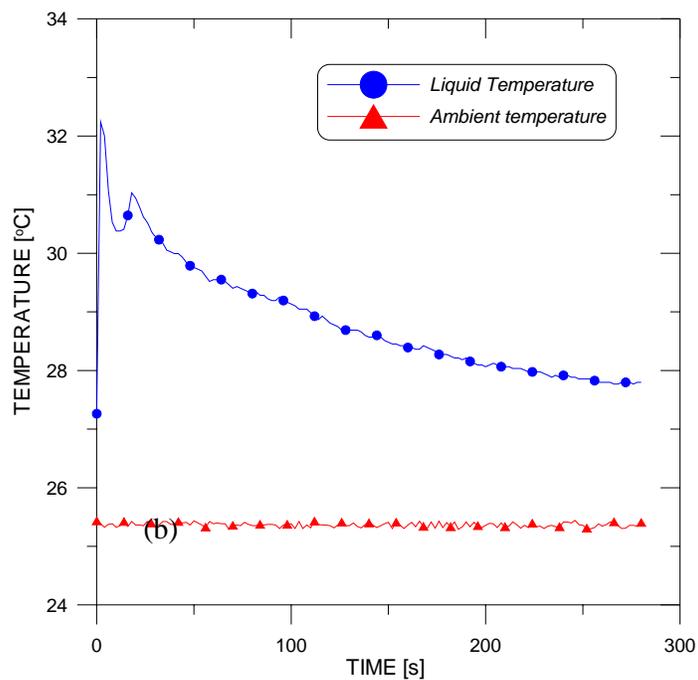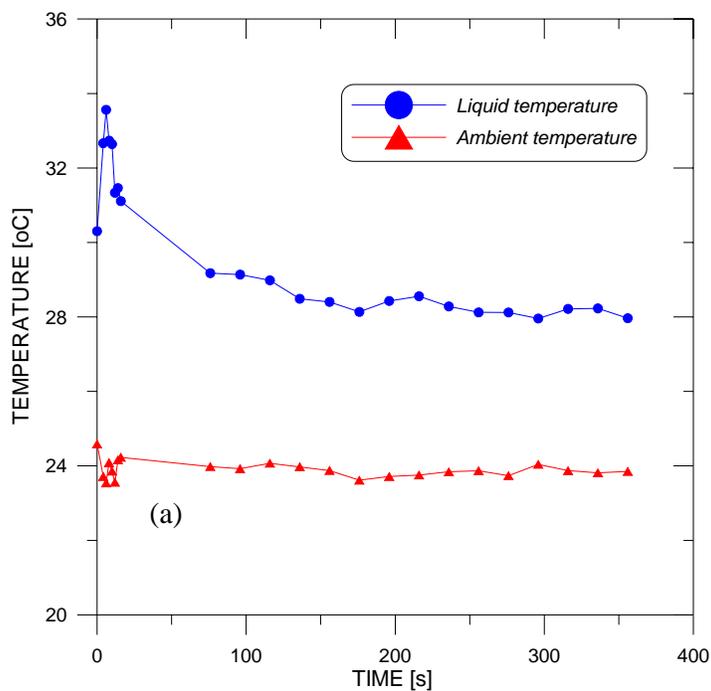Figure 7. Temperature behaviour as a function of time. (a) R-134a in POE 10H, (b) R-134a in POE 7H.

Figure 8. Temperature behaviour as a function of time. (a) R-600a in POE 7H, (b) R-600a in POE 5H.

5. Conclusions

This paper presented a study on flow field visualization and experimental assessment of absorption of vapour refrigerants 134a and 600a in polyol ester (POE) lubricant oils. While the absorption of R-600a is controlled solely by diffusion, the R-134a/POE system is Rayleigh unstable and the resulting flow field during absorption is due to natural

mass convection. Several features of the flow field during absorption of R-134a were identified through the image sequences, such as plume formation, plume structure, etc.

Liquid temperature and system pressure as a function of time were acquired for a number of experimental conditions including oil viscosity grade and aspect ratio of the liquid layer. The rise in temperature associated with the latent heat release was recorded during selected runs. Because of the associated mass convection, it was observed that the absorption of R-134a in lubricant oil was much more dependent on the height of the liquid layer than the absorption of R-600a. A mathematical model is under implementation to predict the behaviour of the system pressure and temperature as a function of time.
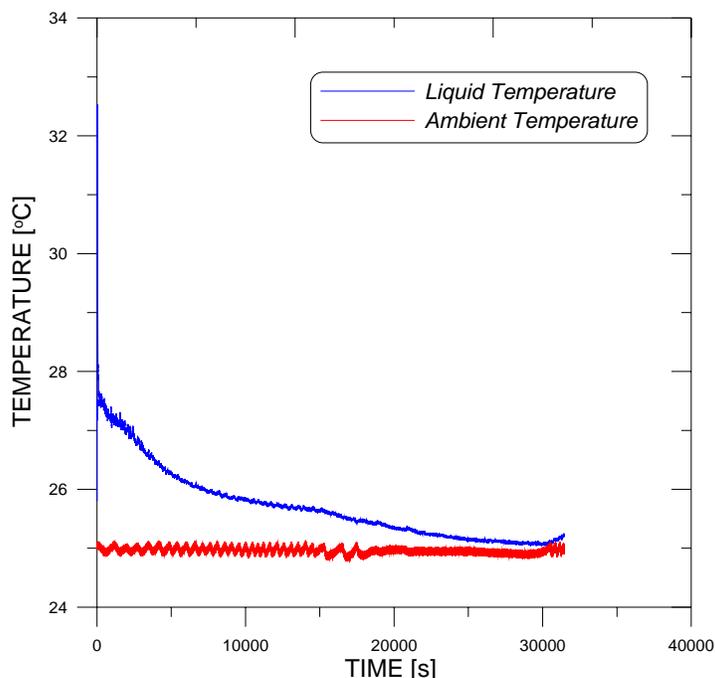

Figure 9. Temperature behaviour as a function of time. R-134a in POE 10H.

6. References

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