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An Experimental Study of Refrigerant Desorption from a Refrigerant-Oil Mixture Subjected to Rapid Depressurization

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ABSTRACT

This paper deals with the experimental assessment of refrigerant desorption leading to foam formation in R-134a/POE oil mixtures undergoing controlled depressurization. An experimental apparatus was designed and constructed to allow measurements of pressure drop rate, foam height and refrigerant gas mass flux resulting from decompression and desorption from a saturated liquid mixture. High-speed video recording of the phenomenon enabled the identification of three main periods during the depressurization/foaming process, namely, depressurization without cavitation, vapor flashing and rapid foam growth, and foam layer decay. The experimental results for the maximum foam height, foam lifetime and liquid supersaturation during desorption were explored as a function of the overall initial refrigerant mass fraction and physical properties of the liquid phase.

1. INTRODUCTION

In hermetic compressors, off-cycle refrigerant migration is responsible for increasing the crankcase pressure and hence the refrigerant concentration in the oil sump. As the motor starts up, the on-cycle initiates with a rapid depressurization of the crankcase that super-saturates the liquid mixture, thus giving rise to vigorous refrigerant desorption (i.e., foaming) from the mixture. Foam suction into the compression chamber should be avoided due to valve reliability issues (liquid compression) and unwarranted oil migration from the crankcase to other components of the cycle, most importantly the expansion device and evaporator.

Yanagisawa et al. (1991) carried out an experimental investigation of foam formation by a combination of mechanical agitation and gas injection in an experimental setup that modeled a rotary compressor casing. Mixtures of mineral oil (SUNISO 3GS and 5GS) and R-22 were used, and the temperature was varied between 20 and 60°C. They observed that foaming becomes more intense as the refrigerant mass fraction (solubility) increases, and that the proximity to the saturated mixture condition can be regarded as a criterion for the occurrence of foaming in refrigerant-oil solutions. The type of agitation (mechanical or vapor blow) also contributed to the height of the foam layer and its lifetime. The lifetime was observed to be inversely proportional to the refrigerant charge due to the volatility and reduced viscosity of the liquid phase, which facilitates foam drainage. The effect of temperature on foam height and lifetime was deemed more complex, since the reduction in viscosity and surface tension helped foam formation at moderated temperatures, but also contributed to reducing its lifetime at higher temperatures. Goswami et al. (1998) conducted extensive foaming tests involving mixtures of R-12 and R-22 and mineral oils (SUNISO 3GS and 4GS) and mixtures of HFCs (R-32, R-125, R-134a and R-143a) and POE ISO 68 oils. While the CFC and HCFC mixtures could be tested in an areation column, a specially constructed depressurization apparatus had to be used for the HFC mixtures did not produce stable foams at ambient pressure. The depressurization tests at high pressure were carried out as a function of the refrigerant overall mass concentration, pressure drop and depressurization rate. It was shown that the depressurization rate had a significant effect on the maximum foam height, which also increased with the refrigerant overall concentration. Average desorption rates were calculated by measuring the refrigerant mass collected in a recovery flask that was cooled with liquid nitrogen. Becerra and Parise
(2003) evaluated experimentally the formation of foam during depressurization of an initially saturated R-134a/POE mixture. The behavior of the foam layer height and its stability as a function of the refrigerant concentration was investigated in the light of the limiting operating conditions for the occurrence of foaming. Fukuta et al. (2005) investigated desorption (separation) of R-600a from mixtures involving three types of mineral oil (ISO 8, 10 and 22) undergoing controlled depressurization. Foaming was observed at some conditions, but in general it was classified as unstable for those particular systems. The evolved gas mass flow rate during the separation process was measured with a mass flow meter installed in the vent line. A comparison between a simple model and temperature measurements in both liquid and vapor phases indicated that heat transfer from the surroundings was an important factor in determining the liquid mixture temperature.

The objective of the present paper is to evaluate experimentally the physical aspects of R-134a desorption from POE oil following depressurization. A specially constructed facility allowed high-speed imaging of the whole desorption process, i.e., from the onset of bubble nucleation to the complete decay of the foam layer. The system pressure, desorption mass flow rate and foam height behavior as a function of time were measured for a number of experimental conditions (temperature and initial overall refrigerant mass fraction). The super-saturation was quantified in terms of the calculated instantaneous refrigerant concentration and of the solubility estimated from the instantaneous pressure and temperature.

### 2. EXPERIMENTAL WORK

#### 2.1 Experimental Facility

The experimental apparatus shown in Fig. 1 consisted of a refrigerant (R-134a) reservoir (R1), a mass flow meter (M1) and a transparent (glass) water tank (T1) in which the test section (C1) was fully submerged. The temperature of the water in the tank was set by a thermostatic bath (not shown in the figure). The pressure inside the test section was measured with a 20-bar absolute pressure transducer (P1), and several valves were available for controlling the flow of refrigerant into and out of the test section (V1-V6). The test section consisted of a 400-mm long 40-mm ID borosilicate tube equipped with a stainless steel top flange on which the pressure measurement and fluid charge connections were made. The mass of oil (POE ISO 10) inserted in the test section was measured with a digital balance with an instrument uncertainty of 10 mg. The mass of refrigerant vapor that flowed into and out of the test section was measured with a Coriolis effect mass flow meter (M1) with an uncertainty lower than 0.2% of its absolute reading. The heights of the foam and liquid layers were measured with a millimetric ruler attached to the wall of the transparent tank and aligned with the centerline of the tube. In some experimental runs, a high-speed video camera (Vision Research Phantom V12) equipped with a Zeiss Makro-Planar 2/50 mm lens was used to acquire detailed images of the foam growth and decay processes. The data were recorded by an acquisition system connected to a computer.

![Figure 1: Schematic diagram of the experimental setup.](image)
2.2 Experimental Procedure

A specified amount of oil was initially introduced in the test section. Vacuum was produced to remove moisture and dissolved gases from the system. The refrigerant was introduced in the test section via the mass flow meter by opening all valves, except for V2 and V5. The total mass of refrigerant that entered the test section during the charging process was recorded by the mass flow meter. As the refrigerant was absorbed in the oil, the thermostatic bath was switched on so that the system reached thermodynamic equilibrium at the desired temperature.

The depressurization was initiated with the refrigerant-oil mixture in thermodynamic equilibrium. Valves V1 and V3 were closed and V2 and V5 were opened. In this way, the refrigerant passed through the mass flow meter before being discharged. Refrigerant evolution from the liquid mixture gave rise to the formation of a foam layer, while the instantaneous system pressure and mass flow rate were recorded by the data acquisition system.

It is worth mentioning that artificial nucleation sites (small metal pieces) had to be inserted in the test section in order to facilitate bubble nucleation upon depressurization. In some runs, mechanical agitation (a gentle nudge) of the test section was also needed to initiate the vaporization process. In these cases, a somewhat explosive gas evolution was seen, resulting in a rapid formation of the foam layer.

In total, 18 test runs were carried out (see Table 1), with different values of temperature, masses of oil and refrigerant (independent variables), pressure and height of the liquid layer before depressurization, \( \text{L}_{\text{m,exp}} \) (dependent variables). In Table 1, \( Z_R \) is the overall refrigerant mass fraction and \( L_O \) is the height of the pure oil layer before introduction of the refrigerant. The second from last column in Table 1 is the liquid height before depressurization calculated assuming that (i) the liquid mixture behaves as an ideal solution and (ii) that the mass of refrigerant vapor in the gas cap is negligible. Thus,

\[
\text{L}_{\text{m,exp}} = \frac{1}{A} \left[ \frac{m_R}{\rho_{R,L}} + \frac{m_O}{\rho_O} \right]
\]

Due to the satisfactory agreement between \( \text{L}_{\text{m,exp}} \) and \( \text{L}_{\text{m,cal}} \), ideal solution behavior will be assumed in the subsequent analyses in this paper.

### Table 1: Summary of experimental conditions.

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<th>( Z_R ) (%)</th>
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3. RESULTS

3.1 Qualitative Evaluation Based on High-Speed Video Analysis

This section presents a qualitative analysis of high-speed imaging of refrigerant desorption under depressurization. The high-speed video sequences were acquired at a rate of 400 frames per second. The sequences illustrated here are divided into groups associated with a particular period during the foam layer growth and decay. The test shown in Figs. 2 to 4 was conducted with total initial masses of oil and refrigerant of 23.9 and 123.4 g, respectively. The initial temperature was 25°C.

Figure 2 shows images obtained from the initial period of bubble nucleation and aggregation. In Fig. 2.a, bubble nucleation starts at the artificial sites and the bubbles themselves act as sites for further nucleation as the bubble cluster seen in Figs. 2.b and 2.c travels upwards, grows somewhat explosively and turns into a “piston” before reaching the free surface (Fig. 2.d). Bubble nucleation from the artificial sites is sustained during the whole period.

![Image sequence during the bubble nucleation and aggregation period. Time elapsed since the opening of the valve (t = 0 s): (a) 3.1325 s; (b) 3.195 s; (c) 3.290 s; (d) 3.375 s.](image)

Images obtained from the second period of foam formation and growth are shown in Fig. 3. Figure 3.a registers the moment at which the bubble piston pierces the free surface, and a distinctive foam layer separating the liquid and the vapor layers starts to be formed. During the initial instants of this sequence (Figs. 3.a and 3.b), it is clear that bubble nucleation from the artificial site is somewhat vigorous, indicating that the liquid layer may still be considerably supersaturated. Figure 3.c shows the maximum height acquired by the foam layer during the test. From this time onwards, as can be seen in Fig. 3.d, the rate of bubble break-up as a result of liquid drainage in the foam column becomes larger than the rate of bubble nucleation and the height of the foam layer starts to decrease.

Figure 4 illustrates the video sequence associated with the period of foam decay. While the foam formation period is violent and chaotic, the foam decay stage is slow and fairly well behaved. In other words, there seems to be two characteristic time scales in the phenomenon of refrigerant desorption from supersaturated solutions leading to foaming: a short time scale associated with the processes of bubble nucleation, growth and foam formation, and a long time scale related to the phenomena of liquid drainage and foam decay. Despite the qualitative nature of this remark, the mere recognition of the existence of these distinct scales can lead to the development of different modeling strategies to tackle the problem of foam formation and decay in future studies.

Also apparent in the images of the foam decay period is the establishment of a gas volume fraction (holdup) gradient.
in the vertical direction in the foam layer (Jeelani et al., 1990; Bhakta and Ruckenstein, 1997). As the liquid drains due to gravity, the liquid films and channels become thinner at the top, causing the bubbles to break up from the top down. The height of the liquid layer is also seen to increase slightly as a function of time as a result of the return of liquid (drainage) from the foam layer back into the liquid layer.

![Image sequence during the period of foam formation and growth. Time elapsed since the opening of the valve (t = 0 s): (a) 3.465 s; (b) 3.6325 s; (c) 3.9825 s; (d) 4.2975 s.](image)

**Figure 3:** Image sequence during the period of foam formation and growth. Time elapsed since the opening of the valve (t = 0 s): (a) 3.465 s; (b) 3.6325 s; (c) 3.9825 s; (d) 4.2975 s.

![Image sequence during the period of foam decay. Time elapsed since the opening of the valve (t = 0 s): (a) 6.1525 s; (b) 6.990 s; (c) 7.635 s; (d) 8.250 s.](image)

**Figure 4:** Image sequence during the period of foam decay. Time elapsed since the opening of the valve (t = 0 s): (a) 6.1525 s; (b) 6.990 s; (c) 7.635 s; (d) 8.250 s.
3.2 Quantitative Analysis

In this section, results for the system pressure, mass flow rate and foam layer height behavior as a function of time are presented for a number of experimental conditions listed in Table 1. Although the absolute values of the parameters are dependent on the experimental conditions, the general behavior of the system pressure and mass flow rate during the system depressurization can be described by the profiles illustrated in Fig. 5 (Test No. 4 of Table 1), for which three main distinct stages can be identified. In the first stage, the depressurization occurs without the formation of vapor bubbles, and the flow of gas out of the system is due basically to the release of the high-pressure gas cap. The duration of the first stage is rather arbitrary, as mechanical agitation is needed to trigger the onset of nucleation in some cases. However, in cases where an intervention was not necessary, the first stage was seen to be of the order of a few seconds. It should be mentioned that a certain time delay exists between the pressure and mass flow rate signals due to the distance between the two sensors; while the pressure transducer is attached to the top flange of the test section, the mass flow rate is recorded further downstream. It is assumed that this time delay does not undermine the conclusions of the present study.

The second stage is characterized by vigorous flashing of the vapor in the form of bubbles, as seen in Figs. 2 and 3. The foam layer grows suddenly, and this growth is accompanied by a sharp increase in pressure (due to the increase in foam volume) and mass flow rate. The maximum height of the foam layer generally coincides with the pressure peak (see Fig. 6). The third and final stage is one of pressure, mass flow rate and foam layer height decay, with the decay rates depending on system parameters, such as the total masses of oil and refrigerant and the system temperature. In some cases, such as the one shown in Fig. 5, a fairly stable foam height is achieved over a given interval (between 25 and 45 s in Test No. 4), as a result of equivalent mass rates of bubble transport to the bottom and bubble break-up at the top of the foam layer.

![Figure 5: Pressure and mass flow rate curves for Test No. 4.](image)

Pressure and mass flow rate profiles for a test that was below the limit of foam formation (Test No. 5) is shown in Fig. 7. In comparison with Fig. 5, it can be seen that there is no intermediate pressure peak and only a single inflection in the mass flow rate curve, much in the same manner as reported by Fukuta et al. (2005) for the phase separation regime prior to the bubble nucleation inception.
The effect of the overall refrigerant mass fraction on the maximum foam height is shown in Fig. 8 for a constant temperature of 25°C. It should be mentioned that it was difficult to control the foaming process at higher temperatures (40°C) due to condensation of refrigerant vapor on the top flange of the test section. The condensate drops falling from the flange on the vapor liquid interface triggered short bursts of unstable foam, which were impossible to control. It is clear, however, that a situation such as this (i.e., refrigerant condensation inside the crankcase) is highly unlikely to occur in real applications. Despite the scatter and the limited amount of data points, the general behavior is one of increase in foam height with refrigerant mass fraction for the three data groups (total masses of oil of 23.9, 59.8 and 95.7 g). In each group, the maximum height was observed with the test run with the largest refrigerant mass, which seems to reflect the role of liquid supersaturation in the nucleation rate. In some runs with a relatively small refrigerant mass (Test runs No. 5, 13 and 18), it seems that the minimum amount of refrigerant necessary to generate the foam was not reached (at least for the activation energy associated with the artificial nucleation sites and mechanical agitation delivered to the test section).

Some scatter is also seen in the foam lifetime data shown in Fig. 9, but it is nevertheless apparent that the longest lifetimes were associated with values of overall refrigerant mass fractions around 0.82-0.84. Values of refrigerant mass fraction larger than this range gave rise to foam layers that, although higher, decayed quicker possibly because of higher volatility and lower liquid viscosity foams (faster drainage). On the other hand, foams generated with lower overall refrigerant mass fractions, despite the higher liquid viscosity, drained faster probably because of their comparatively smaller maximum foam height.
The behavior of the calculated supersaturation for two cases (Test Nos. 4 and 10) is shown in Figs. 10 and 11, respectively. The supersaturation is defined as the difference between the refrigerant mass fraction in the liquid phase, $x$, and the solubility, $\omega$, calculated using Raoult’s law for a given pressure-temperature. The instantaneous refrigerant mass in the test section (needed in the computation of the refrigerant mass fraction) was computed based on its initial value (determined experimentally) and on the time integration of the mass flow rate data obtained from the Coriolis-effect mass flow meter. It should be noted that $x$ takes into account only the mass of refrigerant dissolved in the liquid, so the instantaneous refrigerant mass in the vapor phase (whose density is obtained from the instantaneous pressure) is subtracted from the instantaneous refrigerant mass in the test section. The mass of refrigerant vapor in the foam layer was also subtracted from the total refrigerant mass. It was computed assuming a parabolic distribution of the vapor volume fraction in the foam layer (Pilon et al., 2002) between the limiting values of 0.74 at the bottom and unity at the top, which gives an average gas volume fraction of 0.82.

As can be seen from the figures, the supersaturation increases with time because the rate with which the solubility decreases (i.e., basically the rate of pressure decay) is larger than that associated with the mass fraction. Eventually, for very long desorption times, the mass fraction will become equal to the solubility. It seems, however, that the time to equilibrium will be longer than the off-cycle times usually encountered in practice in small capacity refrigeration applications.

**4. CONCLUSIONS**

The process of refrigerant desorption from a saturated R-134a/POE ISO 10 mixture during depressurization was investigated both qualitatively and quantitatively in this paper. A specially constructed experimental apparatus enabled the visualization of nucleation and foam formation processes from their inception to their complete decay. The main conclusions arising from this work are as follows:

1. There are two time scales in the foaming phenomenon: a short time scale associated with bubble nucleation, growth and foam formation, and a long time scale that is related to liquid drainage and foam decay;

2. The onset of foaming is very much dependent on the availability of nucleation sites and on a certain degree of mechanical agitation of the system. Control of this process was a great challenge in the present study;

3. The foam maximum height and the foam lifetime were observed to be strongly dependent on the refrigerant mass concentration. There appeared to be certain concentration levels below which foaming did not occur;
4. For the limited range of conditions investigated in the study, the foam lifetime reached a maximum at mass fractions of approximately 0.83. This was interpreted as a result of two competing mechanisms; vigorous nucleation, which was characteristic of the highest refrigerant mass fractions but was also associated with a fast decay, and slow drainage, which was typical of more viscous liquids with a higher oil concentration;

5. A significant supersaturation degree that increased with time was observed all conditions investigated. However, it should be noticed that high overall refrigerant mass fractions such as the ones evaluated here are unlikely to be encountered in real compressors. More experimental and modeling research are needed to fully understand the phenomenon.

NOMENCLATURE

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Greek

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