EXAMINATION ON SOLUBILITY AND VOLUME CHANGE OF POE/R454C MIXTURE

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ABSTRACT

In the refrigeration cycle, refrigeration oil plays the role of lubricating and sealing the compression chamber in refrigerant compressors. This refrigeration oil is typically compatible with the refrigerant used in the cycle. However, the physical properties of the oil change as the refrigerant dissolves in it. As a result, the oil's ability of lubrication and sealing is influenced. The density of the oil/refrigerant mixture may be required to examine the physical properties of the mixture. When a certain mass of refrigerant and oil is mixed, the mass of the mixture is conserved, while volume is not. It is, therefore, important to clarify the volume change of the mixture to measure the density as well as the solubility, and consequently to ensure the oil functions and prevent compressor failure. Due to global warming potential (GWP) concerns, zeotropic refrigerants with low-GWP are attractive alternatives. In this study, the POE/R454C mixture was employed to measure the solubility and volume change. A high-pressure-resistant vessel with a transparent glass was used to conduct the experiment. The temperature and refrigerant concentration were changed during 30–90 °C and 0–100%, respectively. The volume change of the mixture was monitored following the change in temperature and concentration. These results provided important information for adapting the refrigeration oil with R454C in the actual system.

Keywords: Solubility, Density, Volume, Zeotropic refrigerant, Refrigeration oil

INTRODUCTION

In response to concerns about global warming, an international mandate has been established for the phasedown of hydrofluorocarbons (HFCs) refrigerants, which have a high Global Warming Potential (GWP). Consequently, refrigerant mixtures primarily composed of hydrofluoroolefins (HFOs), which have a low-GWP, are regarded as promising next-generation alternatives [1]. One of the candidate alternative refrigerants as a substitute for high-GWP refrigerants is R454C (GWP < 150). It is a binary zeotropic blend of R32/R1234yf (21.5/78.5 wt%). However, when introducing these new refrigerants into refrigeration systems, it is essential to accurately understand their interaction with the refrigeration oil to ensure compressor reliability [2].

Generally, the refrigeration oil has a compatibility with the oil, i.e. solubility. A refrigerant's high solubility in oil reduces the viscosity of the oil in the compressor, while low solubility or partial immiscibility leads to oil accumulation within the system [3]. Thus, for adequate lubrication of the compressor, sealing performance and return of the lubricant to it, an optimal solubility of oil and refrigerant is necessary. Many researchers have conducted the solubility measurement of the refrigeration oil and refrigerant mixture. For example, Wang et al. [4] investigated the solubility of R290 in two mineral oils. The solubility measurement for five refrigerants (R32, R134a, R1234yf, and R1233zd(E)) in four types of polyol ester (POE) oils was investigated by Brocus et al. [5]. In the meantime, Tangri et al. [6] investigated the solubility of nonflammable low-GWP refrigerants (R515B and R471A) in POE oil. However, there was still limited information for the solubility and mixing behaviors of the oil and R454C mixture. In addition, the density of the oil and refrigerant mixture is still unclear, and the mixture's volume makes it possible to clarify its density.

Therefore, this study investigated experimentally the solubility and volume change of the POE and R454C mixture. The experiment was carried out in a high-pressure vessel with transparent glass to observe the mixture's behaviors. The testing conditions were varied by changing the refrigerant concentration from 0 to 100% and the temperature from 30 to 90 °C. The solubility curve and volume change of the mixture were demonstrated depending on the concentration and temperature. The data obtained from this research will provide fundamental knowledge for adapting the refrigeration oil with R454C in the refrigeration systems.

EXPERIMENTAL METHODS

EXPERIMENTAL SETUP

Figure 1 shows an experimental apparatus. The experiment was carried out in a high-pressure, cylinder-shaped test vessel. The internal dimensions of the vessel were 55 mm in height and 45 mm in diameter. To illuminate inside the vessel, a light source was set up and applied through a sight glass. A ruler was attached to the inside wall for measuring the liquid level. The liquid level was set at the same height (with a small variance of ±1 mm) at the initial temperature of 20 °C throughout the experiment. This initial liquid level was corresponding to a volume of 55 ± 3 cm^3. Two T-type thermocouples were used to measure and control the temperature via a PID controller, which connected to a heater. The vessel was also wrapped by a thermal insulator to reduce heat loss. A digital pressure sensor was used to monitor the pressure of the mixture. To mix the oil and refrigerant well and help them reach an equilibrium state faster, a stirrer bar inside the vessel was turned by a magnetic stirrer placed underneath it. A flare connector with a valve was fitted to the top of the vessel. This connector allowed the vessel to be disconnected from pipes for weighing. The refrigerant concentration was measured by a weighing method, which needed the mass of both the oil and the refrigerant. Importantly, the initial mass of the oil was weighed under vacuum conditions before any refrigerant was added. In this study, R454C and polyol ester (POE) oil were used as the refrigerant and refrigeration oil, respectively.

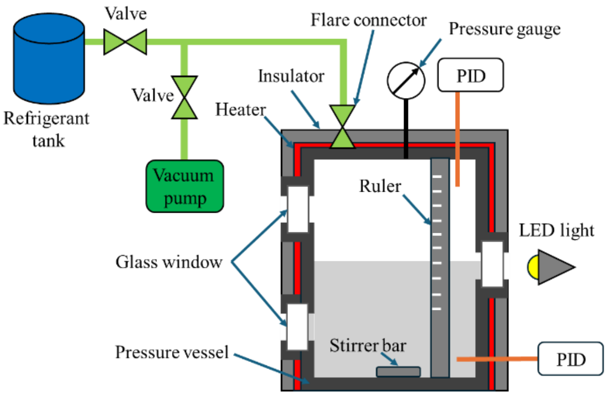

Fig.1 Experimental apparatus.

CALCULATION METHODS

Figure 2 demonstrates the volume model of the refrigeration oil/refrigerant mixture. It is well-known that when a refrigerant dissolves in refrigeration oil, the mixture volume is smaller than the sum of the oil volume and liquid refrigerant volume. Hence, the volume of the oil/refrigerant mixture is expressed in Figure 2, as shown in cases (a) and (b). In this model, a calculated volume of the mixture can be determined using Eq.(1) as follows:

$$V_{calc} = M_{oil} / \rho_{oil} + M_{ref.liq} / \rho_{ref.liq} \quad (1)$$

Thus, the volume of this mixture is the total of both individual volumes, which are calculated using mass and density. It should be noted that the refrigerant density in oil is not known so far. In this study, the refrigerant density in oil is determined by extrapolating the saturated liquid density curve obtained from REFPROP [7], as shown in Figure 3. The rationale for this assumption is based on the findings of Fukuta et al. [8], who revealed that the change in the refractive index of a refrigerant in oil is treated as linear when transitioning from a subcritical to a supercritical state. Consequently, it is hypothesized that the change in density is also linear across this transition. This extrapolation makes it possible to use Eq.(1) for comparison even in the supercritical conditions. This extrapolated line was made by the density data between 0 and 50 °C. In addition, the coefficient α is a correcting factor to compare the volume difference between the calculated volume and the measured one, as follows:

$$\alpha = V_{meas} / V_{calc} \quad (2)$$

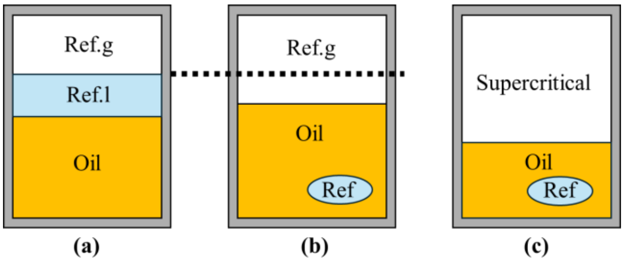

Fig.2 Volume change model of the refrigeration oil/refrigerant mixture.

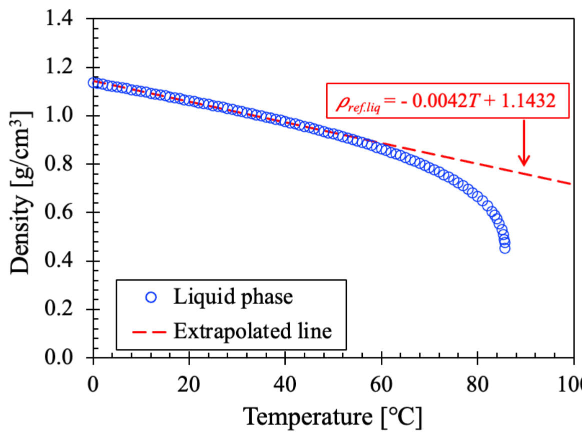

Fig.3 Liquid density of the R454C refrigerant from REFPROP and the extrapolated line from 0–50 °C.

RESULTS

Figure 4 shows the relationship between pressure and refrigerant concentration when R454C is dissolved in POE. The vertical axis presents the absolute pressure [MPa], whereas the horizontal axis represents the mass concentration of the refrigerant in the oil [%]. In the figure, the pressure increased with the concentration during 0–40% at all temperatures. During the concentration between 40% and 100%, the pressure gradually rose with the concentration. The maximum pressures of 1.36 and 2.68 MPa were recorded at 100% concentration for temperatures of 30 and 60 °C, respectively, corresponding with the saturation pressure from REFPROP. Meanwhile, the maximum pressure of 4.93 MPa was recorded at 100% concentration for 90 °C. Note that the pressure at temperatures exceeding the critical temperature depends on the amount of refrigerant charged.

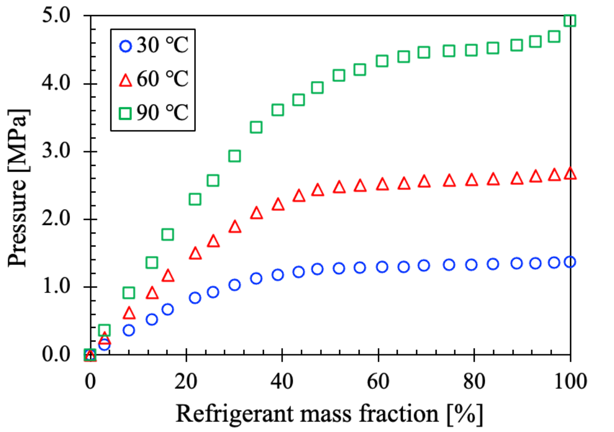

Fig.4 Solubility curves of POE/R454C mixture at 30, 60, and 90 °C.

The volumes of the refrigeration oil/refrigerant mixture at each temperature are shown in Figures 5, 6, and 7. The vertical and horizontal axes present the mixture's volume [cm³] and the refrigerant concentration [%], respectively. Noted that all measurements were taken under equilibrium conditions. The blue circle indicates the initial volume of the pure refrigeration oil. The red triangle indicates the experimentally measured volume of the mixture, corresponding to the volume represented by cases (b) and (c) in Figure 2. The green square shows the calculated volume of the mixture. This volume was calculated by Eq.(1) using the saturated liquid density of the refrigerant, as obtained from REFPROP or extrapolated line, for the refrigerant component within the mixture. Therefore, this volume corresponded to the volume represented by case (a). As shown in Figure 5, the measured mixture volume was smaller than the calculated volume with dissolution of the refrigerant in the oil, which caused a density change. This is because when the refrigerant dissolves in the oil, the smaller refrigerant molecules migrate into the gaps between the bigger oil molecules.

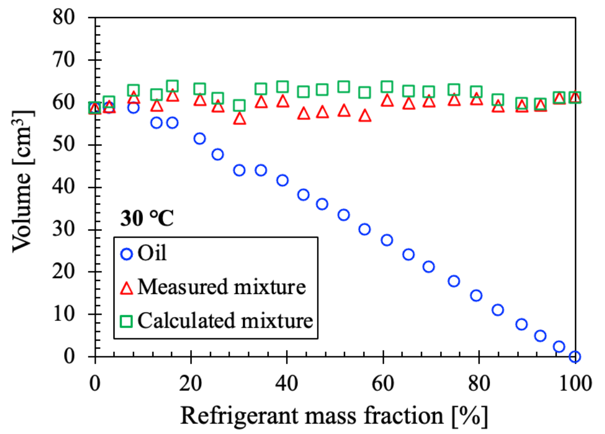

Fig.5 Comparison of the mixture volume at 30 °C.

Figure 6 shows the mixture volume at 60 °C, which is a higher temperature, but it has the same trend as the results at 30 °C from Figure 5. The dissolution of the refrigerant caused a reduction in the total volume; a particularly large difference between the calculated and measured volumes was observed at the refrigerant concentration of approximately 50%. Figure 7 illustrates the mixture volume at 90 °C, which is under supercritical conditions. In this state, the volume exhibited a trend similar to that observed at 30 and 60 °C for the concentration between 0% and 50%. However, at the concentration above 50%, a sharp decrease in volume was observed.

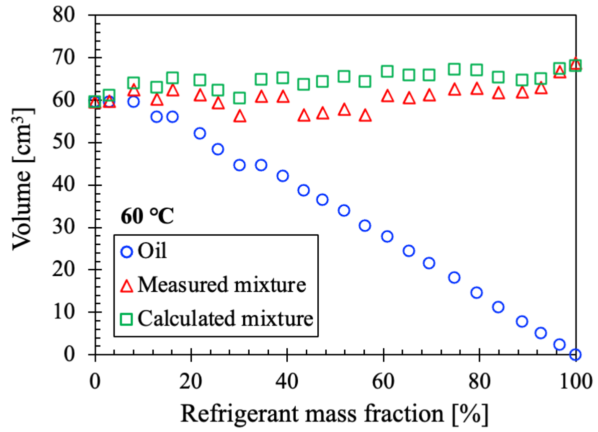

Fig.6 Comparison of the mixture volume at 60 °C.

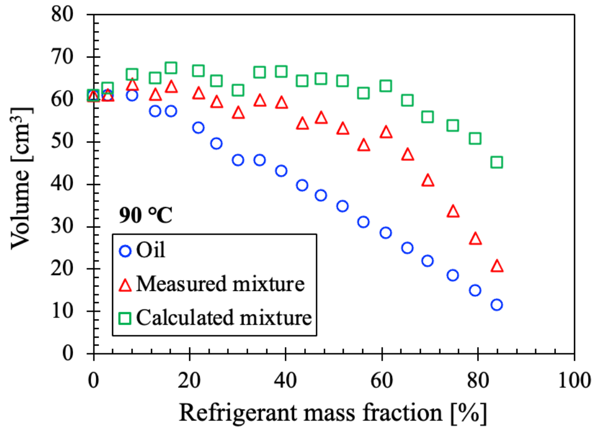

Fig.7 Comparison of the mixture volume at 90 °C.

Figure 8 shows the volume correcting coefficient, α, between the calculated and the measured volumes. The α value decreased as the temperature increased. For the temperatures of 30 and 60 °C, the α was found to be the lowest at about 0.91 and 0.88 when the concentration was 50%, respectively. The results confirmed that the mixture volume decreased when the refrigerant dissolved in the oil, compared to the liquid volumes of both pure refrigerant and oil prior to mixing. Furthermore, in the supercritical conditions at 90 °C, the α was observed to decrease sharply at the concentrations higher than 50%. It was implied that when the mixture was present at a concentration of more than 60%, the refrigerant became the dominant component, or the solvent, and that the mixture's volume was substantially lower under supercritical conditions than under subcritical conditions.

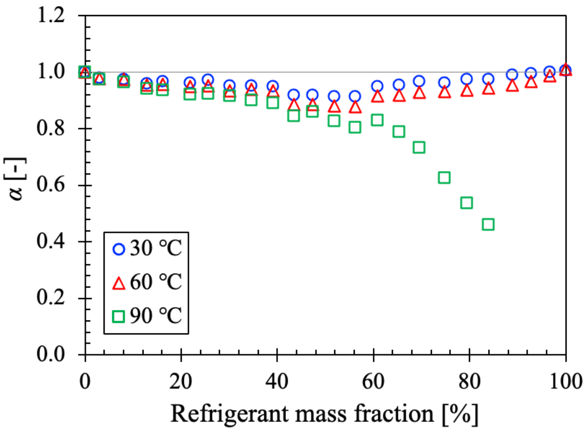

Fig.8 Coefficient of the volume difference between measurement and calculated value.

CONCLUSIONS

In this study, the volume change of refrigeration oil upon the dissolution of a refrigerant was experimentally investigated. The following conclusions were obtained.

1. The solubility curves showed that the pressure sharply increased with increasing the concentration during 0–40%, and it gradually increased at the concentration higher than 40%.
2. The mixture volume from the measurement was found to be lower than that of the calculation, and the lowest decreasing volume was found at a concentration of about 50% for the temperatures of 30 and 60 °C.
3. At 90 °C, the mixture's volume decreased sharply at the concentrations higher than 60%, indicating a reduction in the dominant component of the mixture.

NOMENCLATURE

V_{calc}	: Calculated volume of the mixture, cm^3
V_{meas}	: Measured volume of the mixture, cm^3
M_{oil}	: Mass of the refrigerant oil, g
ρ_{oil}	: Density of the refrigerant oil, g/cm^3
$M_{ref.liq}$	: Mass of the liquid refrigerant, g
$\rho_{ref.liq}$	: Density of the liquid refrigerant, g/cm^3
α	: Coefficient of the volume difference between measurement and calculated value

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