Investigation of Refrigerant Dissolution into Thin Oil Film During Compression Process

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ABSTRACT

Refrigerant dissolution into refrigeration oil considerably decreases the viscosity of refrigeration oil. The dissolution of refrigerant into the oil in a compression chamber during a compression process is generally neglected because it is thought that the compression process is instantaneous and the refrigerant cannot be dissolved into the oil film in such a short time. However, if the oil film is very thin, the dissolution of refrigerant may decrease the oil viscosity. In this study, the dissolution of refrigerant into thin oil film was examined by designing a test device that uses an optical-fiber probe (OFP) method to evaluate the transient change in refrigerant concentration in oil during the compression process. The OFP can detect changes in a returned light intensity by refractive index change due to refrigerant dissolved in the oil film. Since more light is reflected from the interface of the oil film as the oil film thickness decreases, which causes the intensity of the returned light to increase, a mirror is installed above the OFP to eliminate the reflected light from the interface. As a result, the returned light intensity from the OFP is not affected by the oil film thickness, even in conditions where the film is very thin. The dissolution process of the refrigerant into the oil film was successfully detected in the oil film, whose thickness ranged from 0.23 to 0.51 mm. In this thickness range, the refrigerant dissolution during the compression process can be ignored because the dissolution time is much longer than the compression time. Furthermore, the dissolution of R32 into the oil film was found to be faster than that of R410A. Based on the estimation of the refrigerant dissolution into the thin oil film by a one-dimensional diffusion model, it is suggested that the refrigerant dissolution during the compression process affects the oil viscosity when the oil film thickness is less than approximately 0.01 mm.

1. INTRODUCTION

The compressor is a crucial component in a refrigeration cycle since its performance directly impacts the cycle's performance. In compressors, losses typically consist of over-compression loss associated with compression behavior, leakage, and friction loss in sliding parts. Refrigeration oil is used in compressors to enhance lubrication and seal performance, reduce friction and leakage loss, and prevent breakdowns. When refrigeration oil and refrigerant are incompatible, the oil's viscosity in a suction line may increase, causing poor fluidity and making it difficult to return the oil to the compressor. For this reason, good compatibility of refrigeration oil and refrigerant is essential. The viscosity of the oil and refrigerant mixture decreases when the refrigerant dissolves in the refrigeration oil, which changes the lubricity and sealing performance. Since the refrigerant solubility in refrigeration oil increases when the pressure in the system increases, it is possible for the refrigerant to dissolve in the oil film formed in the compression chamber during the compression process. It should be noted that the dissolution of refrigerant during the compression process is generally ignored because compression is instantaneous. However, when the oil film is extremely thin, even if the dissolution amount is small, it may influence the oil viscosity. Therefore, research into the solubility of refrigerant in a thin oil film during a short compression time is interesting.

The influence of dissolved refrigerant in oils on the formation of oil films was investigated using a ball/plate reciprocating tester by Yamamoto *et al.* (2000). They indicated that the refrigerant dissolution in oil considerably decreased the oil's viscosity, even at low-pressure conditions. This reduction in viscosity was influenced by the refrigerant concentration as well as the average molecular weight of the oil. Akei *et al.* (1996) examined the impact of refrigerant on the film-forming capability of refrigeration lubricant using optical interferometry to evaluate the thickness of the oil film under a pressurized refrigerant atmosphere. The order and intensity of the interference fringe image were used to calculate the thickness of the oil layer. The findings demonstrated that refrigerant had a substantial impact on lowering refrigeration lubricants' capacity to create oil films. They also indicated that refrigerant dissolution might proceed rapidly due to an increase in pressure. However, the pressure change occurred over a period of 10 s and did not achieve immediate pressure changes, such as pressure changes in a compression chamber.

The sampling method is generally used to measure refrigerant concentration in refrigeration oil by measuring the weight of the refrigerant and that of the oil/refrigerant mixture. The long measurement time and difficulty in obtaining local or transient observations are disadvantages of the sampling method when the concentration distribution of the refrigerant concentration in refrigeration oil happens, despite its high degree of measurement accuracy. Many researchers have evaluated refrigerant solubility by measuring the physical properties of the mixture, which change depending on the refrigerant concentration in the oil. An example of the measured physical properties includes viscosity, surface tension, dielectric constant, and refractive index. Sun *et al.* (2021) investigated the viscosity of the mixtures using a dual-capillary method. The results indicated that the oil's viscosity was significantly decreased by the refrigerant that was dissolved in it. An apparatus to measure the mixture's surface tension by the differential capillary rise method was developed by Duan *et al.* (2018). The experimental results showed that the surface tension of mixtures increased as the lubricant concentration increased. Sedrez and Barbosa (2015) designed and created an experiment for determining the dielectric properties of mixtures at high pressures. The outcomes illustrated that the refrigerant concentration was directly related to the mixture dielectric constant, which was inversely proportional to temperature. In addition, Fukuta *et al.* (2004) experimented to measure the refractive index for determining the refrigerant concentration in refrigeration oil. A laser displacement sensor was employed to identify an optical path variation that varied based on the test medium's refractive index. It was discovered that the refractive index difference between the refrigerant and the oil was sufficient to measure the refrigerant concentration in the oil.

In this study, the refrigerant dissolution in a thin oil film during the compression process was investigated by measuring the change in refractive index using an optical-fiber probe (OFP) method. An experimental apparatus was designed and manufactured to measure changes in the concentration of refrigerant in refrigeration oil due to instantaneous pressure changes. POE/R410A and POE/R32 mixtures were employed as test fluids. Relationships for determining the refrigerant concentration were provided depending on the type of refrigerant. Additionally, using a one-dimensional diffusion model, the dissolution time was estimated for the refrigerant's dissolution process into a thin oil film until it reached a saturated condition.

2. EXPERIMENT

2.1 Principle of Measurement using Optical Fiber Probe

In this study, the optical-fiber probe (OFP) method is used to measure the concentration of refrigerant in oil. The OFP consists of a cladding with a high refractive index and a core in which light propagates, as displayed in Figure 1. The internal reflection is repeated between the cladding and core as light travels toward the fiber's end face. When the probe is inserted into the substance with a different refractive index, a part of the light traveling through the end face of the probe is reflected off the interface, and another part returns along the optical fiber. Light reflected from the interface decreases when the substance at the probe's tip has a high refractive index. Conversely, more light can be reflected from the interface when the substance has a low refractive index. When the refrigerant dissolves in oil, the refractive index of the oil decreases (Fukuta *et al.*, 2010). Therefore, the changes in refrigerant concentration can be measured by detecting the intensity of the reflected light from the interface. The relationship between the intensity of the returned light and the refractive index of the substance is expressed by the following equation based on Fresnel's law:

$$I = I_0 \left(\frac{n_1 - n_2}{n_1 + n_2} \right)^2 \tag{1}$$

where I and I_0 are the returned and incident light intensities, and n_1 and n_2 are the refractive indices of the optical fiber and the fluid, respectively.

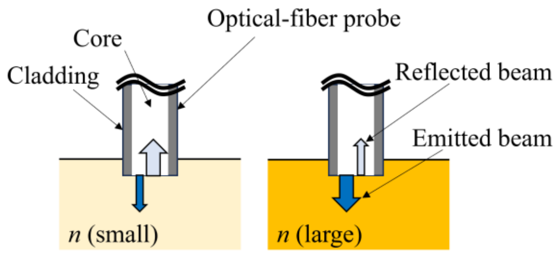

Figure 1: Optical-fiber probe measurement

2.2 Experimental Setup

Figure 2 shows the schematic diagram of the test setup. A compressor was designed and manufactured to instantly compress the refrigerant with a piston. The compressor was a reciprocating type without suction or discharge ports, and an O-ring was used to seal the piston's tip. This compressor was utilized to investigate the changes in refrigerant concentration in a thin oil film due to instantaneous pressure changes. The piston was driven by a cam controlled by a stepping motor. By rotating the cam 180 degrees, the refrigerant in the cylinder was compressed once and maintained in that condition. The compression time was set as short as possible by providing a section with a constant radius before and after the cam part, where the shaft was accelerated and decelerated. Through the experiment, the motor was set to perform with a compression time of 0.1 s. A bearing was attached to the contact area between the cam and the piston to reduce sliding friction resistance. Since a compression chamber had a very small volume, the influence of the clearance volume between the pipe and the valve was quite large. Thus, a small valve was designed and built into the cylinder to reduce the clearance volume. To measure the instantaneous changes in pressure and temperature due to compression, a pressure sensor and a thermocouple with a wire diameter of 25 μm were installed in the compression chamber. A vacuum pump and a refrigerant tank were connected to the chamber to create a vacuum state and then supply refrigerant.

Figure 3 illustrates the test section details. An FC connector tip of the optical fiber was inserted into an adapter at the bottom of the cylinder to detect the change in the returned light intensity. Hence, the change in the refractive index of the refrigeration oil during the refrigerant dissolution process was able to be measured at the bottom of the oil film. The end of the FC connector was also sealed with the O-ring. Oil was first put into the chamber provided in the adapter using a micropipette. The thickness of the oil film was adjusted according to the volume of oil. When the oil film was thin, the reflected light intensity from the oil film surface was larger than the returned light intensity from the interface between the optical fiber and the oil. As a result, it was impossible to measure the changes in reflected light intensity due to refrigerant dissolution. To eliminate the influence of reflected light from the oil film surface, a mirror was mounted in the chamber above the optical fiber to reflect light in a different direction from the oil film surface. This mirror was supported by a holder with holes for the refrigerant to pass through.

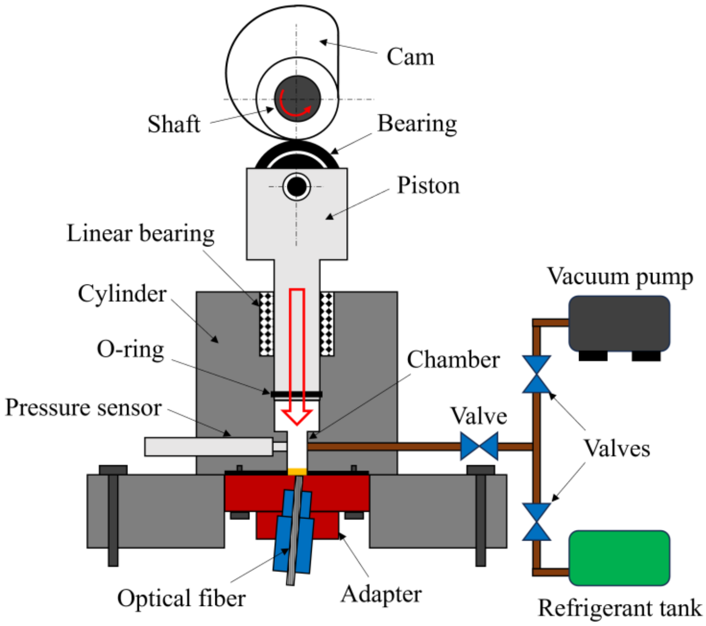

Figure 2: Schematic diagram of test setup

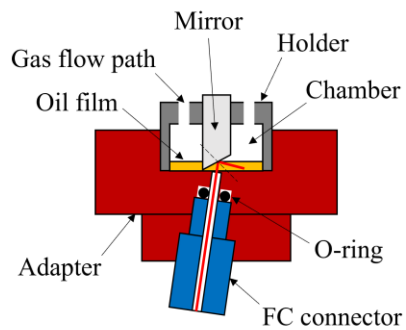

Figure 3: Test section details

Figure 4 shows the measurement results of the optical intensity of the returned light against the oil film thickness in the cases with and without the mirror installation. In the absence of the mirror, the intensity of the returned light tended to increase with decreasing oil film thickness. This is because the amount of reflected light at the interface between the oil film surface and gas phase increased as the oil film thickness decreased. The reflected light from the oil film surface appeared to be sufficiently minimized when the oil film thickness was thicker than 7 mm. Meanwhile, in the case with the mirror, the reflected light influence could be removed when the oil film thickness was thicker than 0.2 mm. Consequently, using the mirror made it possible to measure the refrigerant dissolution in a thin oil film. In the current study, the experiment of refrigerant dissolution in oil was conducted when the thickness of the oil film exceeded 0.2 mm by employing mirror installation.

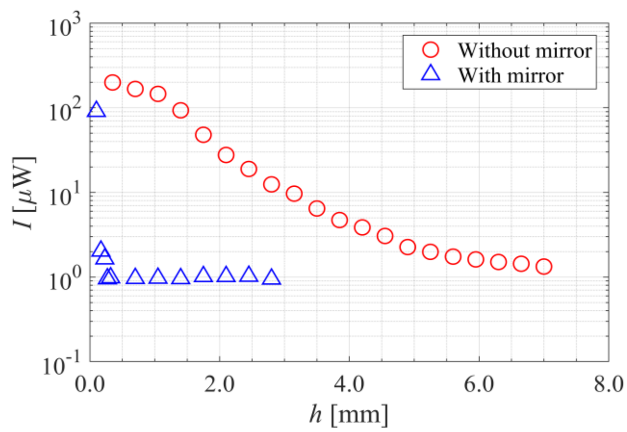

Figure 4: Comparison of optical intensity with and without mirror

3. RESULTS AND DISCUSSION

3.1 Relationship between Optical Intensity and Refrigerant Concentration

The intensity of the returned light was initially measured in fluids with varying refractive indices to ensure that the variations in refrigerant concentration could be observed using an optical fiber. In this study, the incident light intensity and the refractive index of the optical fiber were found at 15,000 μW and 1.46, respectively. The temperature of the test condition was set at 25 °C. The fluids used in the measurement are listed in Table 1.

Table 1: Refractive index of test fluids

Fluid	Refractive index, *n*
Water	1.333
Alcohol	1.382
Silicone oil 1.5cst	1.389
Silicone oil 50cst	1.402
Silicone oil 100cst	1.404
PVE oil	1.441
PAG oil	1.446
POE oil	1.449

Figure 5 displays the comparison of the optical intensity calculated by Equation (1) and experimental results. The calculation and the experiment results are represented by a dashed line and a circle marker, respectively. Note that the experimental results were an averaged value for three-time measurements. In the figure, the experimental results showed agreement with those from the calculation, especially in the intensity range of 1.38–1.45. By using the experimental results, the relationship between the optical intensity and the refractive index can be obtained. The second-order polynomial equation was formed with a goodness of fit of 0.99 as follows:

$$I = 1,760.955(n)^2 - 5,120.224(n) + 3,723.307 \tag{2}$$

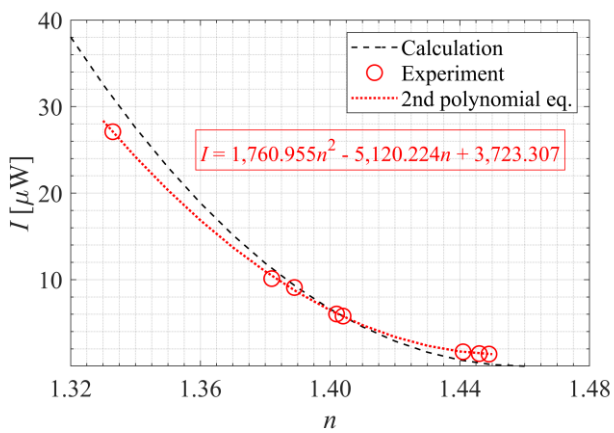

Figure 5: Relationship between optical intensity and refractive index

Figure 6 shows the relationship between the refractive index and the refrigerant concentration. For this investigation, POE was employed as the refrigeration oil, and R410A and R32 were used as refrigerants. The refractive index of oil/refrigerant mixtures exhibited an almost linear relationship as the refrigerant concentration increased (Fukuta *et al*., 2004). In the figure, the measured refractive indices of pure refrigeration oil (S_{ref} = 0 wt%) and pure refrigerant (S_{ref} = 100 wt%) are plotted together with a linear line. The refractive index of pure R32 was slightly higher than that of pure R410A. The refrigerant concentration in oil for POE/R410A and POE/R32 mixtures can be estimated by the linear equation, as follows:

$$n_{\mathrm{R410A}} = -0.00263 S_{\mathrm{R410A}} + 1.449 \tag{3}$$

$$n_{\mathrm{R32}} = -0.00258 S_{\mathrm{R32}} + 1.449 \tag{4}$$

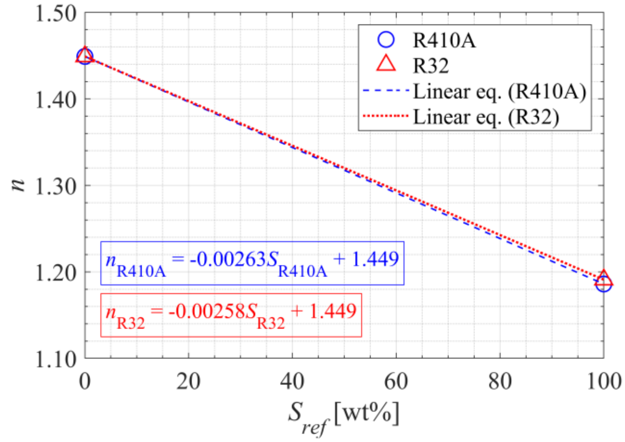

Figure 6: Relationship between refractive index and refrigerant concentration

By employing Equation (2) and Equations (3) or (4), the relationship between the optical intensity of the returned light and the concentration of refrigerant can be obtained, as illustrated in Figure 7. The refrigerant concentration in oil was plotted during the concentration of 0–15 wt% for both POE/R410A and POE/R32 mixtures. The plotted data in the figure was utilized to form a formula for estimating the refrigerant concentration depending on the optical intensity of the measurement by using the fourth-order polynomial equation. Thus, the refrigerant dissolution into thin oil film can be evaluated using the OFP method through Equations (5) and (6) for POE/R410A and POE/R32 mixtures, respectively, as follows:

$$S_{R410A} = -0.224I^4 + 3.170I^3 - 16.757I^2 + 42.458I - 34.252 \quad (5)$$

$$S_{R32} = -0.255I^4 + 3.535I^3 - 18.322I^2 + 45.406I - 36.203 \quad (6)$$

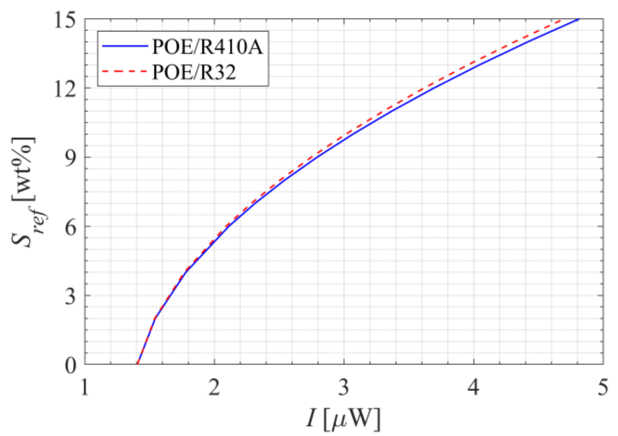

Figure 7: Relationship between refrigerant concentration and optical intensity

3.2 Dissolution after Compression Process

Figure 8 shows an example of how temperature and pressure changed over time during and after the compression process. The oil film thickness was set at 0.36 mm, and R410A was the refrigerant used to measure the dissolution process in the POE oil. The compression was initiated at t = 0 s with a compression time of 0.1 s, and the initial pressure and temperature were set at 0.37 MPa and 25 °C, respectively. The results revealed that both pressure and temperature increased immediately after compression started. The pressure increased up to approximately 1.0 MPa and then continued to decrease over time due to the dissolution process of refrigerant in oil. In the meantime, the temperature rose to around 60 °C and then dropped to near the temperature before the compression in approximately 5 s.

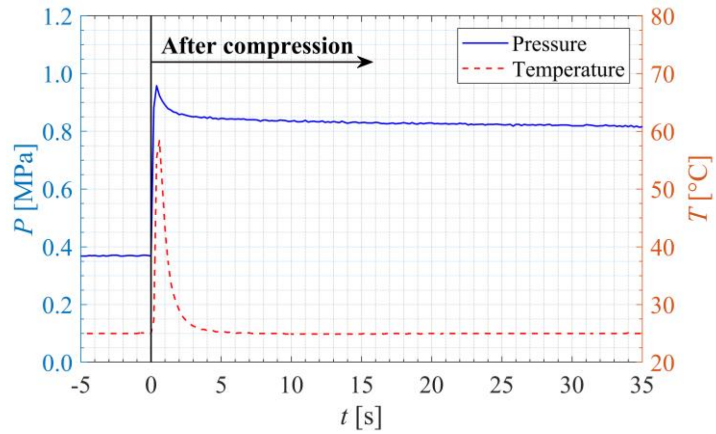

Figure 8: Changes in pressure and temperature against time of POE/R410A mixture

In the experiment, the optical intensity was also obtained along with the pressure and temperature results. Figure 9 demonstrates the measurement results of the optical intensity for the POE/R410A mixture with varying oil film thicknesses between 0.23 and 0.51 mm. The optical intensity was approximately 2.05 µW before compression for all oil film thicknesses. After compression, it was found that the optical intensity slightly decreased and then increased over time due to the dissolution process of refrigerant into oil. This optical intensity represented the refrigerant concentration in oil at the bottom surface. The results also observed that POE/R410A was found to be in a saturated dissolution state at t = 95 s for h = 0.23 mm and t = 145 s for h = 0.36 mm. Meanwhile, in the case of h = 0.51 mm, the refrigerant dissolution did not reach the saturation condition even at t = 150 s. These results confirmed that a thinner oil film causes the dissolution to reach a saturated condition more quickly.

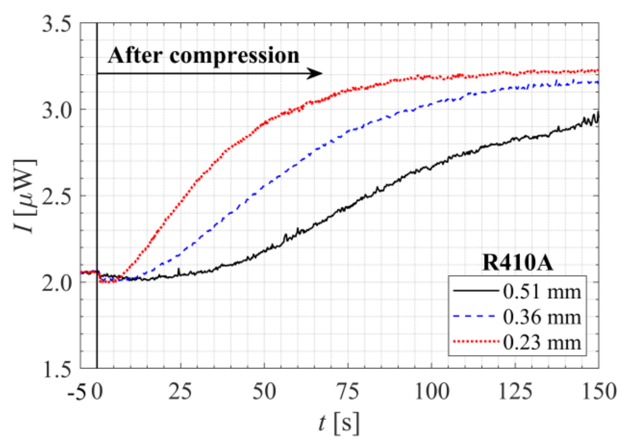

Figure 9: Optical intensity of POE/R410A mixture by changing the oil film thickness

The comparison of the dissolution between R410A and R32 refrigerants in POE oil with an oil film thickness of 0.36 mm is presented in Figure 10. The pressure of 0.37 MPa and temperature of 25 °C were set at an initial condition for both refrigerants. According to the relationship between the refrigerant concentration and optical intensity, there were slight differences in the optical intensities of R410A and R32 following the concentration. Consequently, the measured light intensity values for the two refrigerants were found to be nearly identical in the saturated dissolution condition. In addition, the concentrations of refrigerant in oil film via Equations (5) and (6) for R410A and R32 are also represented in Figure 10. The concentration results indicated that R410A and R32 had concentrations of roughly 5.7 wt% and 5.8 wt%, respectively, before compression. After compression under saturated dissolution conditions, R410A and R32 concentrations were approximately 10.3 wt% and 10.5 wt%, respectively. Also, the results of the concentration showed that the dissolution of R32 reached a saturated state at t = 85 s, which was faster than that of R410A. It may be said that R32 dissolves more quickly than R410A because it has a smaller molecular size than R410A.

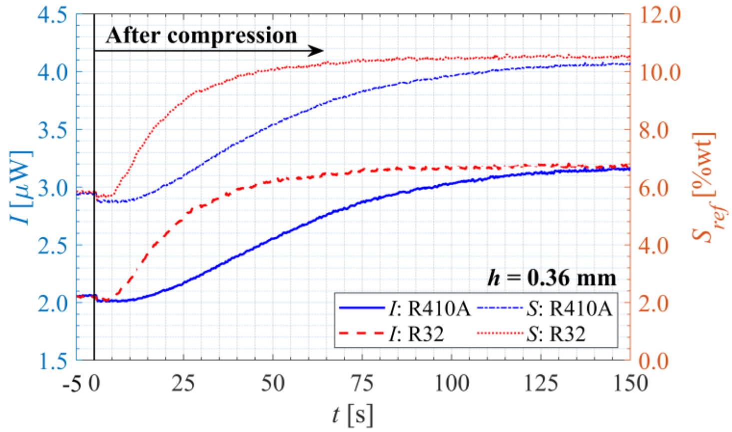

Figure 10: Dissolution process between POE/R410A and POE/R32 mixtures

Furthermore, the time used to reach a saturated dissolution state was much longer than the compression time, even though the oil film thickness was set at 0.23 mm, as seen in Figure 9. Thus, a one-dimensional diffusion model was employed in this study to predict how much time the refrigerant requires to dissolve in thin oil films. Assuming as a boundary condition that the oil film interface is in a saturated dissolution state upon compression, the equation can be expressed as follows (Fukuta *et al.*, 2005):

$$\frac{C}{C_s}=1-\frac{4}{\pi}\left(1-\frac{C_1}{C_s}\right)\sum_i \frac{1}{2i+1}\sin\left\{\frac{(2i+1)\pi}{2}\frac{z}{h}\right\}\times\exp\left\{-\left[\frac{(2i+1)\pi}{2}\right]^2\frac{Dt}{h^2}\right\} \tag{7}$$

$$C_s=\frac{\rho_0 C_s^*}{1-C_s^*} \tag{8}$$

where C and C_s are the mass concentration of refrigerant and the saturated mass concentration of refrigerant after compression, respectively, C_1 is the initial saturated mass concentration of refrigerant, z is the distance from the oil film interface, h is the oil film thickness, D is the diffusion coefficient, t is the time, ρ_0 is the pure oil density, and C_s^* is the mass fraction under the saturation condition.

The result in the case of the POE/R410A mixture with an oil film thickness of 0.23 mm was used to compare with the calculated result from Equation (7), as displayed in Figure 11. At the vertical axis, the ratio of C/C_s refers to the comparison of the refrigerant concentration at the bottom of the oil film and the saturated refrigerant concentration. The C/C_s value of 1 indicates a saturated dissolution condition. Utilizing D = 2.8×10^{-10} m^2/s as the diffusion coefficient, the calculated result exhibited good agreement with the experimental result at h = 0.23 mm and C_s^* = 0.145. This diffusion coefficient value was applied to predict the change in concentration when the oil film thickness was less than 0.23 mm. In the figure, the refrigerant dissolves to an almost saturated state under a compression time of 0.1 s at an oil film thickness of approximately 0.01 mm. Consequently, during the instantaneous compression process, the oil viscosity may change due to refrigerant dissolution when the oil film thickness is less than 0.01 mm.

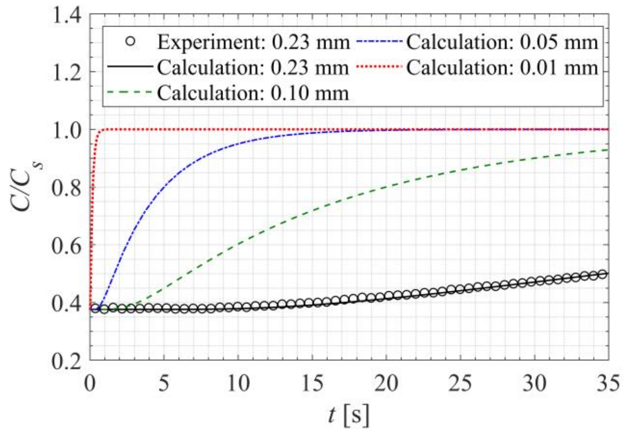

Figure 11: Prediction of the dissolution process

4. CONCLUSIONS

This study used the optical-fiber probe (OFP) method to measure the refrigerant dissolution in thin oil films under compression conditions. A compression device was designed and built to investigate the refrigerant dissolution behavior in oil films due to an instantaneous pressure increase. The mixtures of POE/R410A and POE/R32 were employed to measure the dissolution process. The following conclusions were obtained:

1. By utilizing a mirror to remove the reflected light effect, the measurement of the refrigerant dissolution in a thin oil film could be achieved.

2. The optical intensity result confirmed that the refrigerant dissolved in the oil film until it reached saturation condition quickly when the film was thin. The result of the refrigerant concentration in oil revealed that R32 dissolved in POE faster than R410A.

3. Using a one-dimensional diffusion model, it was suggested that when the oil film thickness was less than 0.01 mm, the refrigerant dissolution might cause changes in the oil viscosity under a compression time of 0.1 s.

NOMENCLATURE

C	mass concentration of refrigerant	[kg/m^3]
C_1	initial saturated mass concentration of refrigerant	[kg/m^3]
C_s	saturated mass concentration of refrigerant after compression	[kg/m^3]
C_s^*	mass fraction under the saturation condition	[–]
D	diffusion coefficient	[m^2/s]
h	oil film thickness	[m]
I	returned light intensity	[μW]
I_0	incident light intensity	[μW]
n_1	refractive index of the optical fiber	[–]
n_2	refractive index of the fluid	[–]
S_{ref}	refrigerant concentration in oil	[wt%]
t	time	[s]
z	distance from the oil film interface	[m]
ρ_0	density of pure oil	[kg/m^3]

REFERENCES

Akei, M., Mizuhara, K., Taki, T., & Yamamoto, T. (1996). Evaluation of film-forming capability of refrigeration lubricants in pressurized refrigerant atmosphere, *Wear*, *196*(1–2), 180–187.

Duan, W., Zhao, X., Zeng, X., & Liu, Y. (2018). Surface tension of HFC-161 and compressor oil mixtures, *Int. J. Refrig.*, *85*, 191–199.

Fukuta, M., Ito, M., Yanagisawa, T., & Ogi, Y. (2010). Refrigerant concentration measurement at compressor oil sump by refractive index (concentration of R410A in PVE oil), *Int. J. Refrig.*, *33*(2), 390–397.

Fukuta, M., Yanagisawa, T., Miyamura, S., & Ogi, Y. (2004). Concentration measurement of refrigerant/ refrigeration oil mixture by refractive index, *Int. J. Refrig.*, *27*(4), 346–352.

Fukuta, M., Yanagisawa, T., Omura, M., & Ogi, Y. (2005). Mixing and separation characteristics of isobutane with refrigeration oil, *Int. J. Refrig.*, *28*, 997–1005.

Sedrez, P.C. & Barbosa, J.R., (2015). Relative permittivity of mixtures of R-134a and R-1234yf and a polyol ester lubricating oil, *Int. J. Refrig.*, *49*, 141–150.

Sun, Y., Wang, J., Wang, X., He, M., & Hu, Y. (2021). An experimental investigation and correlation of the viscosity refrigerant/oil solutions, *Int. J. Refrig.*, *121*, 152–158.

Yamamoto, Y., Kim, J., Gondo, S., & Sugimura, J. (2000). The effect of HFC refrigerant dissolution on oil film thickness and wear characteristics of oils, In: Dowson, D., Priest, M., Taylor, C.M., Ehret, P., Childs, T.H.C., Dalmaz, G., Lubrecht, A.A., Berthier, Y., Flamand, L., & Georges, J.M. (Eds.), *Thinning Films and Tribological Interfaces, Proceedings of the 26th Leeds-Lyon Symposium on Tribology, Amsterdam: Elsevier*, (771–776).

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