Development of POE with Improved Low-temperature Fluidity

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ABSTRACT

Heat pumps have recently become popular as a means of heating in cold regions. When refrigerant is discharged from the compressor, a small amount of oil is also discharged. Assuming operation in cold regions, oil retention in the components due to the high viscosity can lead to a compressor failure and a decrease in efficiency. To solve these problems, we developed POE refrigeration oils that exhibit excellent low-temperature fluidity as a refrigerant-oil mixture. This paper presents results from a measurement of refrigerant-oil mixture's kinematic viscosity at low temperature and an estimation of pressure drop in suction line. R32, which is currently utilized for room air conditioners, and R454B, which is regarded as the major replacement to R32, were selected as refrigerants. Kinematic viscosities of refrigerant-developed POE oil mixtures at -20°C were reduced by modifying the solubility of refrigerant in oil with the selection of fatty acid. Additionally, estimated pressure drops of the refrigerant gas with developed oils were decreased.

1. INTRODUCTION

Heat pumps are expected to play a major role in creating a sustainable society from two main perspectives. The first is the realization of carbon neutrality. Fossil fuels account for the majority of heating energy sources for buildings, and CO_2 emissions need to be reduced by switching to heat pumps. The second is strengthening energy security. Particularly in Europe and North America, gas boiler heating is the mainstream, and the electrification of heating by switching to heat pumps is a crucial task. Considering this background, European countries are setting ambitious targets for the introduction of heat pumps.

Heat pump heating has been applied in cold regions gradually, such as the development of commercial air conditioners that can operate at temperatures as low as around -20°C. During heating operations in cold regions, the evaporator and the suction line to the compressor, both of which are located outdoors, are exposed to extremely low temperatures, which increases the viscosity of the refrigerant-oil mixture and reduces its fluidity. It has been reported that as the viscosity of the refrigerant-oil mixture increases, the amount of refrigeration oil retained in the compressor suction line increases (Cremaschi *et al*., 2005). If the refrigeration oil is retained in the system components, two serious problems may occur. The first is compressor failure. The refrigerant-oil mixture is returned to the compressor by shear force provided by the refrigerant gas. This shear force is influenced by the viscosity of the refrigerant-oil mixture and the flow rate of the refrigerant gas. If the viscosity of the refrigerant-oil mixture is very high, the refrigeration oil cannot return to the compressor sufficiently, which can lead to a shortage of refrigeration oil in the compressor, causing poor lubrication. The second problem is the decrease in efficiency. It has been reported that the pressure drop of refrigerant gas due to friction increases as the amount of oil retention increases (Zeng *et al*., 2021). In addition, simulation results show that an increased pressure drop of the refrigerant gas leads to a decrease in COP (Coefficient of Performance) (Constantino and Kanizawa, 2022).

In view of these issues, improving the low-temperature fluidity of refrigerant-oil mixture may be beneficial for the operation of air conditioners in low-temperature environments. We thus developed refrigeration oils that exhibit excellent fluidity at low temperatures by adjusting the solubility of refrigerants (R32, R454B) in oils. The pressure drop of the refrigerant gas when the refrigerant and the refrigeration oil coexist in the suction line was calculated, which showed POE oils with excellent low-temperature fluidity can contribute to reducing the pressure drop. The POE refrigeration oils introduced in this study are expected to be widely used in air conditioners for cold regions.

2. EXPERIMENTAL

The miscibility with refrigerant was evaluated using the method specified in JIS K2211. Both the refrigerant concentration in oil and the kinematic viscosity of refrigerant-oil mixtures were measured using the device shown in Figure 1. Refrigerant and oil were put into a pressure vessel and heated to the target temperature. Kinematic viscosity was measured after adjusting the amount of refrigerant to the target level of the pressure. The refrigerant-to-oil ratio was calculated from the weights of refrigerant and oil in the vessel. The kinematic viscosity of the refrigerant-oil mixture was measured by a viscosity sensor attached to the vessel.

When the refrigerant-oil mixture flowed annularly in the compressor suction line, the behavior of the oil retention and the pressure drop of the refrigerant gas were modeled using Equations (1) to (6) (Zeng *et al*., 2022). The pressure drop (*dp/dz*) of the refrigerant gas was estimated with the following parameters assumed: the inner diameter of the suction line is 10.7 mm, the oil mass fraction ($\mathrm{OMF_{no}}$) is 3%, the refrigerant mass flow rate is 90 to 230 $\mathrm{kg/m^2\,s}$, and the oil retention amount (OR) is 0.005 kg/m. *dp/dz* was calculated from the simultaneous equations of Equations (1) and (2) with *dp/dz* and interfacial shear stress (τ_i) as variables. The mass flow rate of oil ($\dot{m}_\mathrm{o}$) was calculated from Equation (3), the liquid film thickness (δ) was calculated from Equation (4), the cross sectional area of vapor phase (A_v) was calculated from Equation (5), and the interfacial perimeter (S_i) was calculated from Equation (6). For the density (ρ_liq), dynamic viscosity (μ_liq), and solubility of refrigerant (ω_ref) of the refrigerant-oil mixture, the values actually measured during the kinematic viscosity measurement were used.

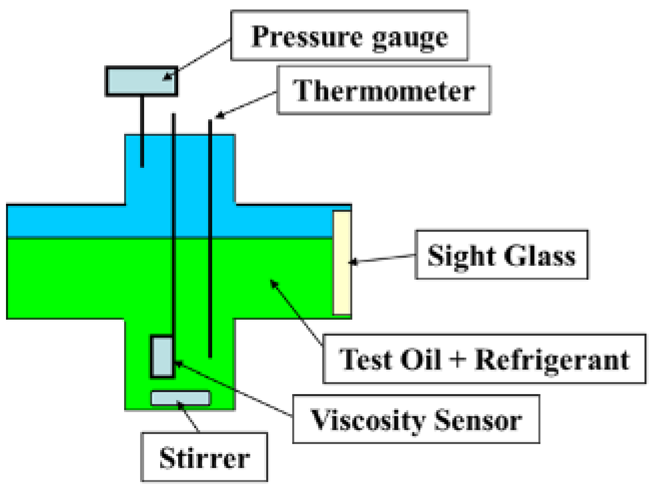

Figure 1: Schematic image of equipment for viscosity measurement of refrigerant-oil mixture

$$\dot{m}_\mathrm{liq} = \frac{\dot{m}_\mathrm{o}}{(1-\omega_\mathrm{ref})} = \frac{2\pi\rho_\mathrm{liq}}{\mu_\mathrm{liq}}\left[\left(\tau_\mathrm{i}(R-\delta) + \frac{(R-\delta)^2}{2}\frac{dp}{dz}\times\left(\frac{R^2-(R-\delta)^2}{4} - \frac{(R-\delta)^2}{2}\ln\frac{R}{R-\delta}\right)\right)\right] - \frac{\pi\rho_\mathrm{liq}}{8\mu_\mathrm{liq}}\frac{dp}{dz}[R^2-(R-\delta)^2]^2 \quad (1)$$

$$A_\mathrm{v}\frac{dp}{dz} + \tau_\mathrm{i}S_\mathrm{i} = 0 \quad (2)$$

$$\mathrm{OMF_{no}} = \frac{\dot{m}_\mathrm{o}}{\dot{m}_\mathrm{o} + \dot{m}_\mathrm{ref}} \times 100\% \quad (3)$$

$$OR = \rho_{\mathrm{liq}}\omega_{\mathrm{o}}A\left[1-\left(1-\frac{\delta}{R}\right)^{2}\right] \tag{4}$$

$$\alpha = \frac{A_{\mathrm{v}}}{A} = \left(\frac{D_{\mathrm{i}}-2\delta}{D_{\mathrm{i}}}\right)^{2} \tag{5}$$

$$S_{\mathrm{i}} = \pi(D_{\mathrm{i}}-2\delta) \tag{6}$$

3. DEVELOPMENT OF POE OILS WITH EXCELLENT REFRIGERANT SOLUBILITY

3.1 Properties of developed POE refrigeration oils

POE is composed of polyhydric alcohols and fatty acids, and various properties such as kinematic viscosity can be controlled by modifying the composition. The solubility of refrigerant in oil greatly influences the physical properties of the refrigerant-oil mixture. To improve the low-temperature fluidity of refrigerant-oil mixture, that is, to reduce the viscosity, the amount of refrigerant dissolved in oil needs to be increased. The chemical structures of POE B, C, and D were modified to improve the refrigerant solubility compared to POE A.

Table 1 shows the properties of POE A, which is widely used as a refrigeration oil for compressors in room air-conditioners with R32, and POE B, C, and D developed in this study. The viscosities of POE B, C, and D are designed to be VG68 like POE A. While increasing the amount of dissolved refrigerant makes it possible to lower the viscosity of refrigerant-oil mixture at low temperatures, the viscosity at high temperatures is also expected to decrease. This may lead to the poor lubricity, that is, a decrease in compressor durability, and there is a trade-off between improving low-temperature fluidity and ensuring compressor durability. The chemical structure of POE D was modified to maintain higher kinematic viscosity at 100°C than POE B and C.

Table 1: Properties of POE A, B, C, and D

Sample			POE A	POE B	POE C	POE D
Kinematic Viscosity	(40°C)	mm^2/s	66.4	66.7	65.5	63.0
	(100°C)	mm^2/s	8.2	8.1	8.0	8.2
Viscosity Index			90	87	84	97

3.2 Evaluation of miscibility with refrigerant

Refrigeration oils that have better miscibility with refrigerants increase the amount of refrigerant dissolved. Generally, miscibility with refrigerant is evaluated by using the phase separation temperature, and the lower the phase separation temperature, the better the miscibility with refrigerant. The phase separation temperatures of POE A, B, C, and D with R32 are shown in Figure 2. POE A was immiscible at the oil ratio of 10-30%. However, POE B, C, and D had a miscible area at the oil ratio of 10-30%, with POE C showing the best miscibility. The phase separation temperatures of POE A, B, C, and D for R454B are shown in Figure 3. All POEs had a miscible area at the oil ratio of 10-30%, with POE C showing the best miscibility. Furthermore, in R454B, all POEs showed higher miscibility than R32. The order of the miscibility with refrigerant for both R32 and R454B was found to be POE C > POE B ≒ POE D > POE A.

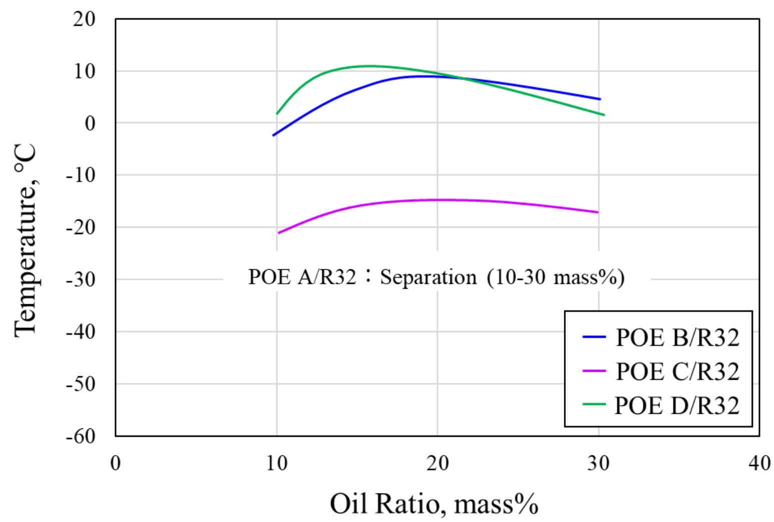

Figure 2: Phase Separation Temperature of POE A, B, C, and D with R32

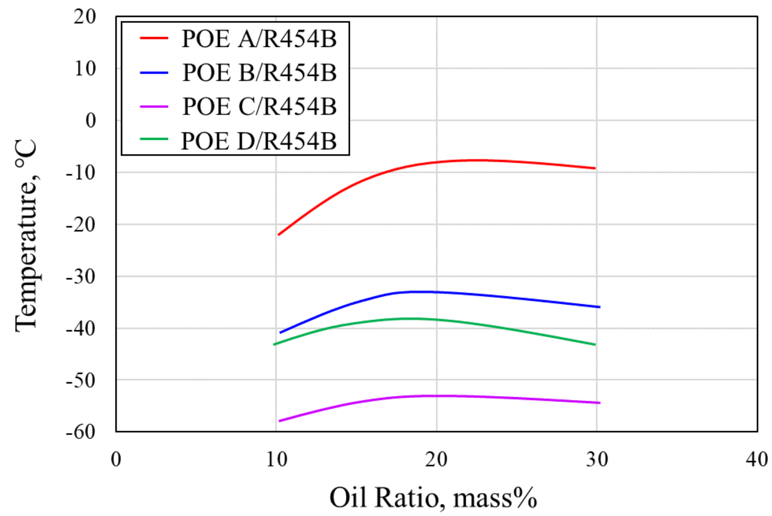

Figure 3: Phase Separation Temperature of POE A, B, C, and D with R454B

3.3 Evaluation of solubility and kinematic viscosity with refrigerant

Assuming the temperature and the pressure at the compressor suction line during heating operation in a cold region, we evaluated solubilities of refrigerants and viscosities of the refrigerant-oil mixture with R32 and R454B at -20℃. The results are shown in Tables 2 and 3. For both R32 and R454B, viscosities of the refrigerant-oil mixture decreased as solubilities of the refrigerant increased, and POE C and D showed excellent fluidity at low temperature.

While an increase of the solubility of refrigerant is advantageous in terms of low-temperature fluidity, it can also lead to a decrease in viscosity at high temperatures, which may lead to a decrease in compressor durability. This trade-off needs to be dealt with. Solubilities of refrigerants and viscosities of the refrigerant-oil mixture at 80℃ were evaluated. The results are shown in Tables 2 and 3. For POE A, B, and C, viscosities of the refrigerant-oil mixture decreased as solubilities of refrigerants increased with both R32 and R454B. As for POE D, although it showed the viscosity equivalent to that of POE C in the low-temperature range, it showed the viscosity equivalent to that of POE B with R32 and that of POE A with R454B in the high temperature range.

From these results, it is possible to maintain the viscosity at high temperatures while increasing low-temperature fluidity in the refrigerant atmosphere by modifying the chemical structure of POEs.

Table 2: Solubility and kinematic viscosity of POE A, B, C, and D with R32

Sample		POE A	POE B	POE C	POE D
Refrigerant		R32	R32	R32	R32
Solubility (0.27MPa, -20℃)	mass%	15.1	16.6	17.8	17.8
Kinematic Viscosity (0.27MPa, -20℃)	mm^2/s	119	77	60	63
Solubility (2.5MPa, 80℃)	mass%	11.0	12.1	12.8	12.3
Kinematic Viscosity (2.5MPa, 80℃)	mm^2/s	5.0	4.3	4.1	4.3

Table 3: Solubility and kinematic viscosity of POE A, B, C, and D with R454B

Sample		POE A	POE B	POE C	POE D
Refrigerant		R454B	R454B	R454B	R454B
Solubility (0.25MPa, -20℃)	mass%	17.5	18.9	20.1	20.7
Kinematic Viscosity (0.25MPa, -20℃)	mm^2/s	99	69	52	57
Solubility (2.3MPa, 80℃)	mass%	13.2	13.9	15.2	14.1
Kinematic Viscosity (2.3MPa, 80℃)	mm^2/s	4.3	4.0	3.8	4.4

3.4 Estimation of pressure drop in suction line

Oil retention in the system causes a pressure drop of the refrigerant gas. Particularly in the compressor suction line, the viscosity of the refrigerant-oil mixture increases at low temperatures, making it difficult for the oil to be returned sufficiently to the compressor by the shear force from the refrigerant gas. The compressor suction line is considered as the key component when taking into account the influence of oil retention and has been widely researched (Zoellick, K.F., & Hrnjak, P., 2010, Kim, H.S. *et al*., 2005 and Sethi, A, & Hrnjak, P., 2014). By using viscosities of the refrigerant-oil mixture evaluated in Section 3.3, the pressure drops of R32 and R454B with each POE at -20℃ were estimated in accordance with the assumptions described in the experimental method and Equations (1) to (6). The results are shown in Figure 4 and 5.

In both refrigerants, the estimated pressure drop decreased along with the reduction in viscosities of refrigerant-oil mixture shown in Tables 2 and 3, showing that POE C and D are probably superior in terms of reducing pressure drop.

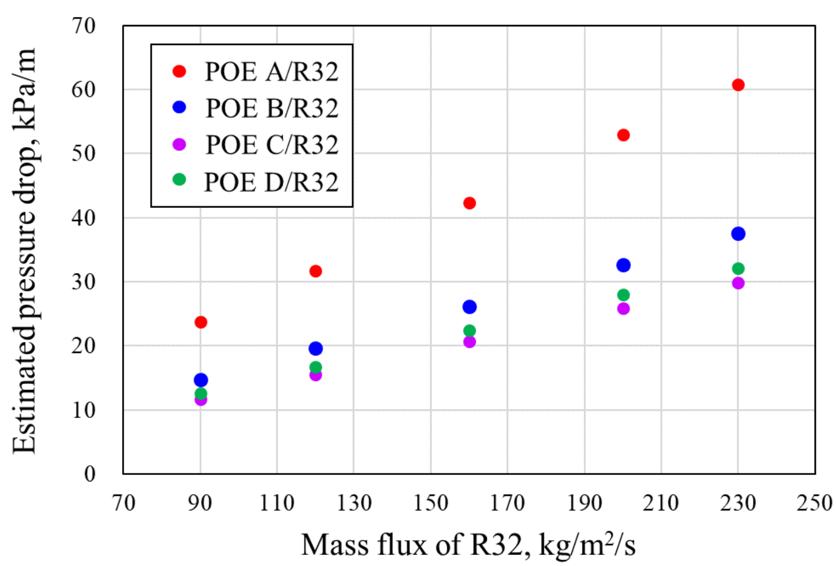

Figure 4: Estimated pressure drop of R32 at -20℃

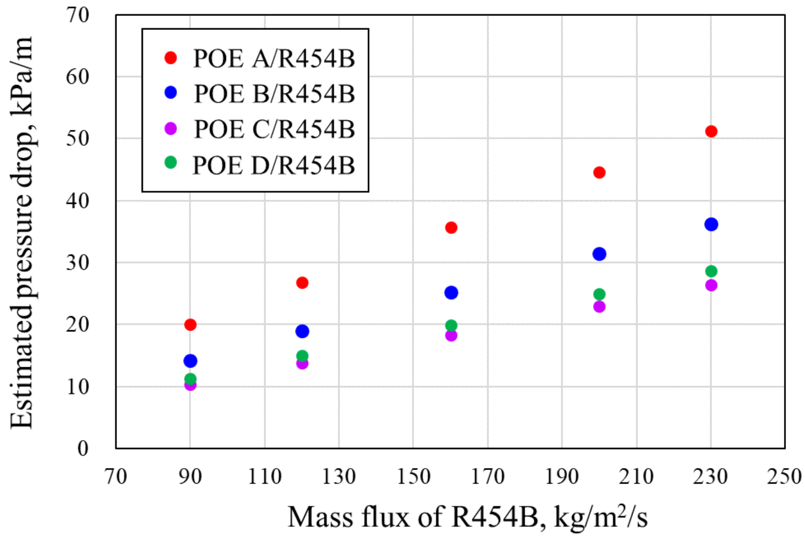

Figure 5: Estimated pressure drop of R454B at -20°C

4. CONCLUSIONS

In heating operations in cold regions, a refrigerant-oil mixture must have low-temperature fluidity to ensure that sufficient oil returns to the compressor and reduce pressure drop in the compressor suction line. The developed POE refrigeration oils exhibited excellent low-temperature fluidity when the refrigerant solubility was adjusted. At the same time, they maintained the viscosity at a sufficient level at high temperature, which is necessary to ensure the durability of the compressor. We estimated the pressure drop of the refrigerant gas in the suction line and found that the improvement of low-temperature fluidity may contribute to reducing pressure drop. Technology using the developed POE refrigeration oils is expected to be beneficial in promoting the spread of heat pump air conditioners in cold regions.

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NOMENCLATURE

A	cross sectional area	(m^2)
D	diameter	(m)
$\frac{dp}{dz}$	pressure gradient	(Pa/m)
$\dot{m}$	mass flow rate	(kg/m^2 s)
OMF	oil mass fraction	(m)
OR	oil retention	(kg/m)
R	radius	(m)
S	perimeter	(m)
α	void fraction	(-)
δ	liquid film thickness	(m)
ω	mass concentration	(wt. %)
μ	dynamic viscosity	(Pa S)
τ	shear stress	(Pa)

Subscript

i	interfacial
liq	liquid phase
no	nominal
o	oil
ref	refrigerant
v	vapor phase