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Development of Energy-efficient Refrigeration Oil for Refrigerator Using R600a

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ABSTRACT

Isobutane (R600a) is an eco-friendly refrigerant with zero ozone depletion potential (ODP) and low global warming potential (GWP), and has been widely used for household refrigerators. Refrigeration oils are applied in the refrigeration cycle together with the refrigerant to lubricate the compressor. Following the global trend aiming for sustainability, both energy efficiency and compatibility with R600a are needed for the refrigeration oils. Among the components in the household refrigerator, the compressor has the largest impact on power consumption. The reciprocating compressor consisting of a cylinder and piston is generally used, and the viscous resistance is reduced when the viscosity of the refrigerator oil is low. As a result, the low viscosity oil improves the coefficient of performance (COP) in the refrigeration system. Mineral oil-based refrigerator oils are commonly used for R600a considering the compatibility. Although their kinematic viscosity is commonly between 5 and 8 mm^2/s at 40°C so far, further improvement in COP is required. In this study, we have developed a refrigeration oil with a kinematic viscosity of 3 mm^2/s at 40°C. While the low viscosity leads to low friction loss, it potentially causes wear or seizure damage on the sliding parts due to the thinner oil film. The additive formulation technology is essential to deal with the issue.

1. INTRODUCTION

Refrigeration oils are applied in the refrigeration cycle together with the refrigerant to lubricate the compressor. The refrigeration oil needs to circulate through the refrigeration cycle and return to the compressor without building up and blocking the lines so that a suitable level of oil is maintained inside the compressor. For this to be possible, the refrigeration oil must be sufficiently soluble in the refrigerant (miscibility with refrigerant). Aside from lubricity, oil-refrigerant miscibility is one of the key performance requirements for a refrigeration oil.

Because various refrigerants have been applied to the compressors of refrigeration systems, it is necessary to optimize the molecular structure of the refrigeration oil in accordance with the refrigerant. Figure 1 shows the transition of refrigerants and refrigeration oils for household refrigerators since the 1990s. Isobutane (R600a) is an eco-friendly refrigerant with zero ozone depletion potential (ODP) and low global warming potential (GWP), and has been widely used for household refrigerators after the 2000s. Mineral oil-based refrigeration oil is mainly used because of its compatibility with R600a.

Reciprocating compressors, which are often used in household refrigerators, converts the rotation of the motor into reciprocating sliding with a conlot, and compress the refrigerant gas with a reciprocating piston. Most of the power consumption of refrigeration machines, including refrigerators, is from the compressors. Manufacturers are working to develop lower viscosity lubricating oils, especially for automobiles, to improve energy efficiency in an effort to reduce global warming. Similarly, lower viscosity refrigeration oils can play a role in improving efficiency. In particular, Matsumoto and Kaimai (2010) reported that the viscosity of refrigeration oils for household refrigerators has been trending downward. In the report of Gondo et al., (2021) they investigated how to reduce the viscosity of the refrigeration oil in the reciprocating compressor. The kinematic viscosity of refrigeration oil for R600a is commonly between 5 and 8 mm^2/s at 40°C so far, and further improvement in coefficient of performance (COP) is required. Thus, we have developed a refrigeration oil with a kinematic viscosity of 3 mm^2/s at 40°C. In this study, we focus on the flash point and anti-wear property, which are issues associated with the decrease in viscosity of lubricating oils, and report the details of the development.

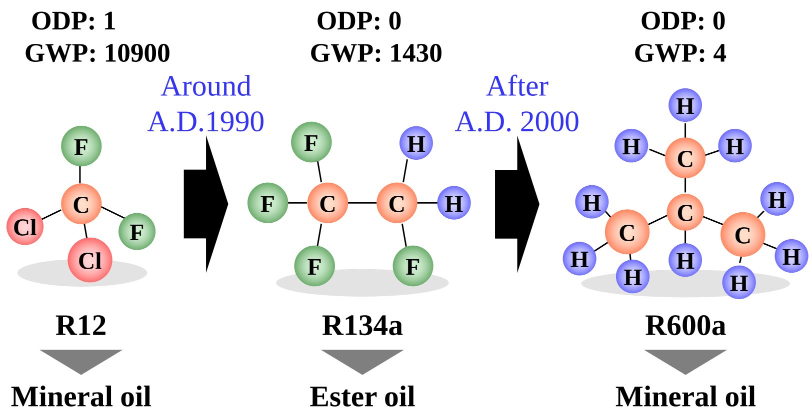


Figure 1: Transition of Refrigerant and Refrigerator Oil in Household Refrigerators

2. STUDY ON BASE OIL FORMULATION

2.1 Base Oil Considering Flash Point

As previously mentioned, reducing the base oil viscosity can lower the flash point. The flash point is the temperature at which the vaporized base oil burns during heating. In general, a lower viscosity oil has a lower flash point. Figure 2 shows the relationship between the kinematic viscosity at 40°C and the flash point of the mineral oils available on the market. The flash point of the general viscosity grade (VG) 3 mineral oils are below 120°C. From a safety standpoint, we believed that it was necessary to have a flash point of the same level as the current VG5 refrigeration oils. The flash point is strongly affected by the light fraction in the base oil. To create a VG3 mineral oil with a higher flash point, we reduced the amount of light fraction. Figure 3 shows the result of a gas chromatographic assay. It is found that the light fraction of the newly developed base oil decreased and the heavy fraction of that increased. As Figure 4 shows, the newly developed base oil has a higher flash point than the conventional VG3 base oil and is around the same as that of the VG5 base oil.

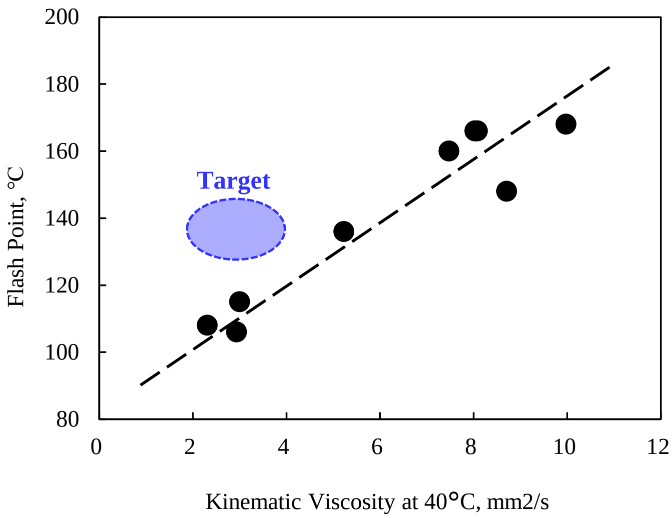


Figure 2: Relationship between Flash Point and Kinematic Viscosity of Mineral Base Oils

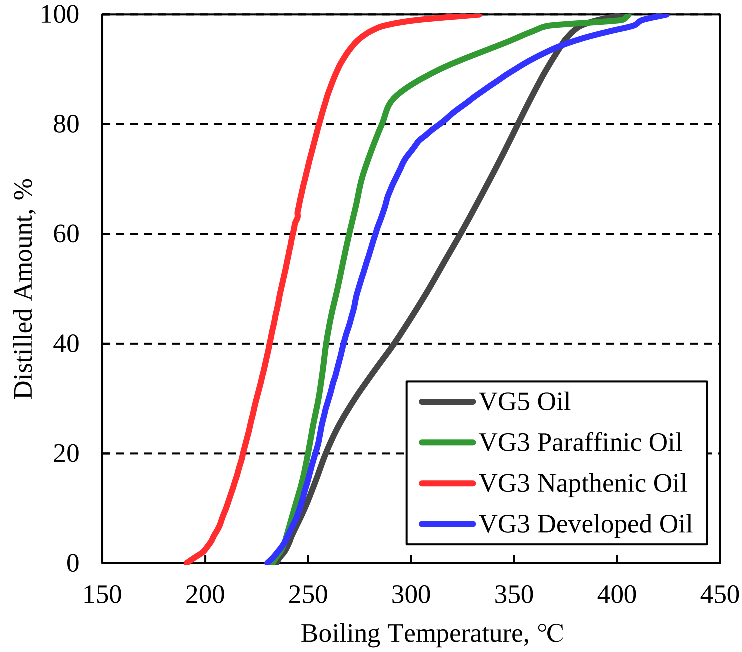


Figure 3: Comparison of Distillation Temperature between Conventional Base Oil and Developed Base Oil Measured by Gas Chromatography

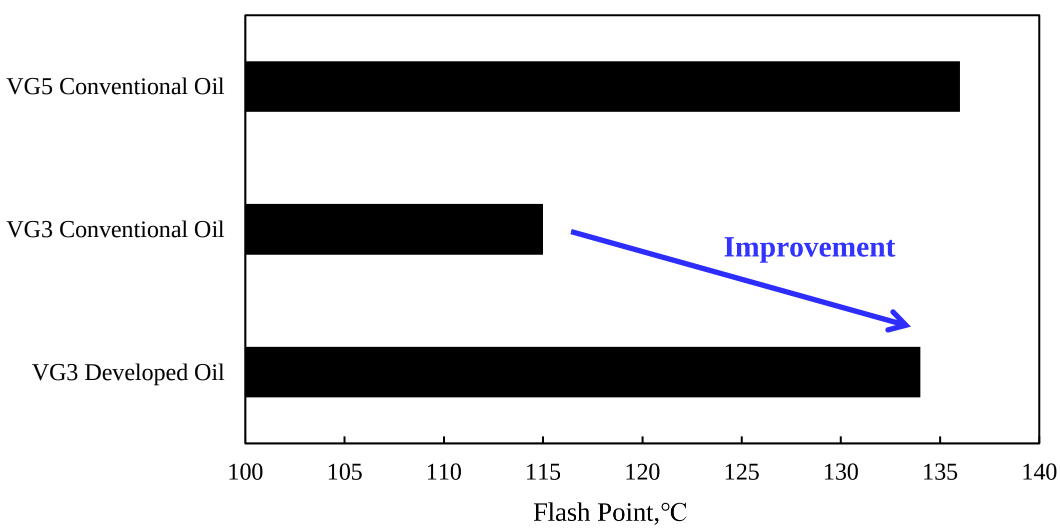


Figure 4: Flash Point of Developed Base Oil

2.2 Friction Study on Low Viscosity Oil

The traction coefficient was measured using a disc-on-roller type elastohydrodynamic lubrication (EHL) tester to confirm the reduction in friction due to the decrease in the viscosity of the base oil. In this test machine, only the disk is driven, the rollers rotate, and the contact part is given a side slip, as shown Figure 5. Both materials are made of SUJ2 in in terms of Japanese Industrial Standards (JIS). The diameter of the disk is 130 mm, and that of the thickness is 20 mm. The diameter of the roller is 25.4 mm. The friction characteristics were compared using the VG3 developed base oil, VG5 base oil, and VG8 base oil. The test results are shown in Figure 6. The traction coefficient decreases with the kinematic viscosity, which is considered to be due to the decrease in viscous resistance.

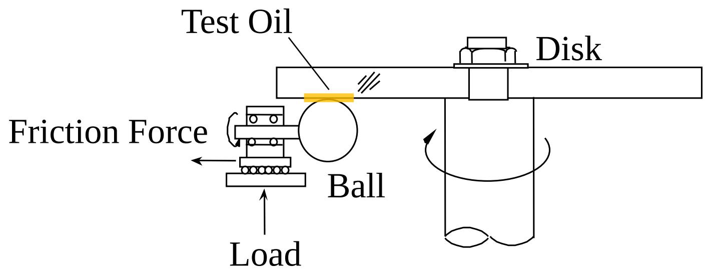


Figure 5: Schematic Diagram of Experimental Apparatus

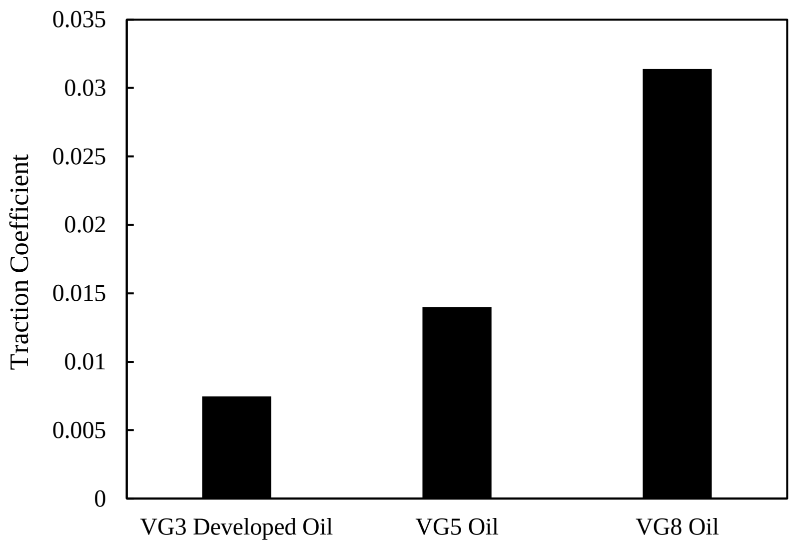


Figure 6: Results of Traction Coefficient

3. STUDY ON ANTI-WEAR ADDITIVES

Phosphorus-based additives are often used as an anti-wear agent in refrigeration oil. A number of phosphorus-based additives were added to the VG3 development base oil and the VG8 base oil. The anti-wear propriety was evaluated by the Schwingungs Reihungund und Verschleiss (SRV) test. In the SRV test, the ball is pressed from above the disc and the ball is slid back and forth to evaluate the friction characteristics and anti-wear propriety of the lubricating oil. Both disk and ball are made of SUJ-2, and the diameter of the ball is 10 mm. In this study, the anti-wear propriety was evaluated by measuring the wear mark diameter of the ball. As shown in Figure 7, the anti-wear propriety of VG3 Oil + P additive was inferior to that of VG8 Oil + P additive. Generally, the low viscosity leads to a thinner oil film thickness of the sliding part and a decrease in lubricant performance. Therefore, it can be said that this test result is valid.

While we applied various phosphorus-based additives to improve the anti-wear propriety, an effective improvement was not observed. Focusing on the lubrication mechanism of the phosphorus-based additives, the additives are adsorbed on the oxide film of the metal surface to form a reaction film. This lubrication film prevents wear. In the case of low viscosity oil, it was speculated that the oxide films on metal surfaces were removed because of high surface pressure, and nascent metal surfaces are exposed locally. This phenomenon might cause the formation of the film by the additive to be insufficient. We therefore investigated the application of sulfur-based additives that react with the nascent metal surfaces. However, copper alloys are used in the piping of refrigerators, and sulfur-based additives may decompose and react at high temperatures to corrode the copper alloys. Thus, four kinds of test oils containing sulfur-based additives were evaluated by the Copper Strip Test before the SRV test. This test complies with JIS K 2510, and the polished copper plate was immersed in a test oil in a constant temperature bath set at

150°C for 3 hours. The degree of discoloration in the copper plate is evaluated in four stages. The lower the value, lower the degree of discoloration. The test results are shown in Table 1. VG3 Oil + P additive + S4, which had the lowest degree of discoloration, was evaluated by the SRV test. As shown Figure 7, VG3 Oil + P additive + S4 showed around same the anti-wear propriety as VG8 Oil + P additive.

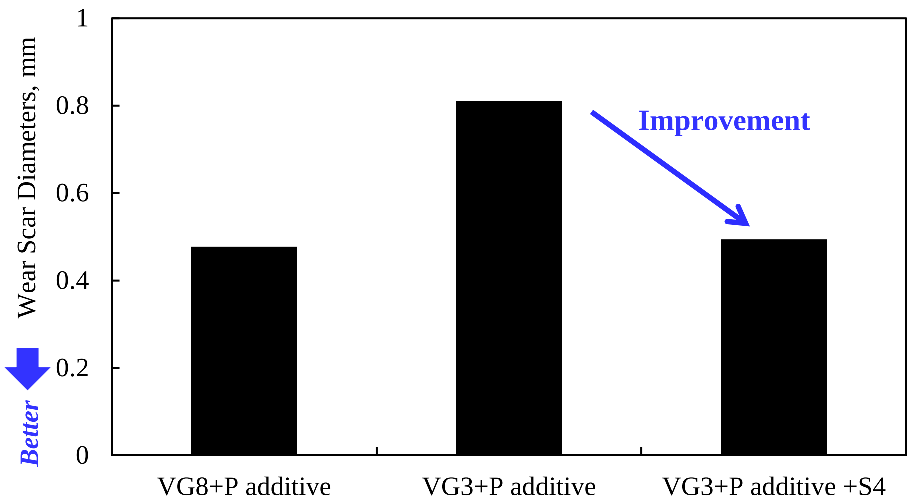


Figure 7: Wear Scar Diameters after SRV Tests for VG8 & VG3 Oils with Anti-wear Additives

Table 1: Results of Copper Strip Test

VG3 Developed Oil + P additive + S1	**4**
VG3 Developed Oil + P additive + S2	**4**
VG3 Developed Oil + P additive + S3	**3**
VG3 Developed Oil + P additive + S4	**2**

To better understand the action mechanism of the anti-wear additives, we carried out a surface analysis on the sliding part of the balls used in the SRV tests. An electron probe micro analyzer (EPMA) was used for the surface analysis, with an acceleration voltage of 15 kB, irradiation current of 1×10^{-7} A, and observation magnification of 100x. The phosphorus, oxygen, and sulfur detected from the sliding parts are shown in element maps in Figure 8. Large amounts of phosphorus and oxygen were detected from the sliding part of the ball tested with the VG3 Oil prepared with the phosphorus-based additive alone, suggesting that an iron phosphate film had formed on the sliding surface. Meanwhile, phosphorus and oxygen were detected in the sliding part of the ball tested with the oil prepared with the phosphorus-based and sulfur-based additives in combination. Although the amount of sulfur detected was small compared with that of phosphorus and oxygen, it was mainly detected at the edge of the wear scar, where the sliding was most severe. Therefore, it is suggested that by containing the sulfur-based additive as expected, it acts on the part where sliding is severe and plays a role in preventing the progress of wear.

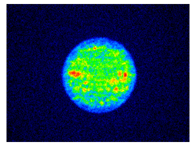
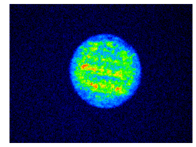
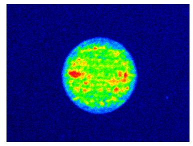
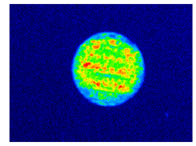
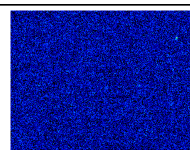
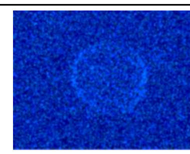
	VG3 Developed + P additive	VG3 Developed + P additive + S4
Phosphorus		
Oxygen		
Sulfur		

Figure 8: Elemental Mapping of EPMA Analysis for VG3 Oil with Anti-wear Additives

4. ACTUAL MACHINE TEST

A compressor manufacturer evaluated refrigerating capacity and durability of the developed oil in a household refrigerator equipped with a reciprocating compressor. Compared with VG5 oil, the energy efficiency of the refrigerator was improved by 1% or more. In addition, in the long-term durability test, no deterioration in anti-wear propriety due to the decrease in viscosity was observed.

5. CONCLUSIONS

In this study, considering the flash point for safety, we developed a refrigeration oil for household refrigerators of VG3, which has around the same anti-wear propriety as VG8. By improving the base oil and additives, the goal of a laboratory test was achieved. In addition, as a result of evaluating the refrigerating capacity of the developed oil by the compressor manufacturer, it was found that the efficiency was improved from the conventional oil. Even in a long-time durability test using an actual machine, no deterioration in anti-wear propriety due to low viscosity was observed, and we succeeded in developing a refrigeration oil with excellent efficiency and actual performance.

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