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Evaluation of Wettability of Solid Surface with Oil/Refrigerant Mixture

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ABSTRACT

In order to reduce an oil amount discharged with refrigerant from a refrigerant compressor, oil separation from the refrigerant in a compressor shell or an oil separator has been investigated by many researchers. The oil separation in the compressor shell or the separator strongly depends on droplet size of oil mist generated in the compressor and condition of oil film formed on an inner surface of the compressor shell or the separator. The oil mist diameter and generation mechanism of the oil mist are affected by surface tension of the oil, while the condition of the oil film on the inner surface is influenced by wettability of the surface with the oil. In addition, dissolution of the refrigerant into the oil changes the surface tension and the wettability of the surface. In this study, the surface tension of the oil/refrigerant mixture and the wettability of the solid surface with the oil/refrigerant mixture were examined as a first step of the study on the generation mechanism and the droplet behavior of the oil mist in the compressor. The surface tension of PAG oil/CO₂ mixture was measured by a pendant drop method and the wettability of a PTFE solid surface with the mixture was evaluated by measuring a contact angle. It is found that the surface tension of the PAG/CO₂ mixture decreases steeply with increasing the refrigerant concentration in the oil. The droplet of the mixture keeps its shape with equilibrium condition on the PTFE plate. The contact angle on the PTFE surface decreases with the refrigerant concentration in the oil due to reduction of the surface tension.

1. INTRODUCTION

A part of lubrication oil stored in an oil sump of a refrigeration compressor becomes fine oil mist in a compressor shell by motions of sliding parts and a discharge valve, an entrainment induced by gas flow and rotation of a motor rotor. Although some of the oil mist is separated from refrigerant in the compressor shell, a certain amount of the oil mist is discharged with refrigerant into a refrigeration cycle. The oil circulated with refrigerant in the cycle degrades the heat transfer efficiency of heat exchangers, increases pressure drop in lines and the heat exchangers and sometimes reduces reliability of the compressor when an oil return from the cycle to the compressor is insufficient. It is therefore important to reduce the oil discharge from the compressor to the cycle.

There are many researches on the separation of the oil mist in the compressor shell or an oil separator in a discharge line. The oil separation in the compressor shell or the separator strongly depends on droplet size of the oil mist generated in the compressor and condition of oil film formed on an inner surface of the compressor shell or the separator. The oil mist diameter and generation mechanism of the oil mist are affected by surface tension of the oil, while the condition of the oil film on the inner surface is influenced by wettability of the surface with the oil. In addition, dissolution of the refrigerant into the oil changes the surface tension and the wettability of the surface.

Weber number is inversely proportional to the surface tension and is one of the dominant parameters of liquid breakup (Majithia *et al.*, 2008; Sakurai *et al.*, 2012). Khosharay and Varaminian (2014) measured the surface tension of (CH₄+H₂O), (C₂H₆+H₂O), (CO₂+H₂O) and (C₃H₈+H₂O) binary system by a pendant drop method with changing pressure and temperature. The surface tension of the oil/refrigerant mixture was measured by Seeton and Hrnjak (2006) by a maximum bubble pressure method. Jensen and Jackman (1984) measured the surface tension of the mixture by a ring method and proposed a correlation between the surface tension and the refrigerant concentration. Fukuta (2016) also measured the surface tension of the mixture by the maximum bubble pressure method under high temperature pressure condition.

The condition of the oil film formed on the solid surface affects the mist generation due to the entrainment by the flow. It is influenced by the wettability of the surface with the oil and the wettability is evaluated by a contact angle of oil droplet on the surface. It is preferable that the contact angle of the oil on the inner wall of the compressor shell is small to avoid the entrainment of the oil mist by the gas flow. Vadgama and Harris (2007) measured a quasi-static advancing contact angle of refrigerant R134a on copper and aluminum surfaces by a direct optical observation technique where the liquid meniscus at the surface of a vertical plate was captured. It is shown that the contact angle varies between 8.3° and 5.6° for the aluminum and between 5.1° and 6.5° for the copper when the temperature rises from 0 °C to 80 °C. Lin *et al.* (2016) investigated the wetting behavior of refrigerant-oil mixture on copper surface by the capillary rise method. They found that the protuberant liquid film occurs in front of meniscus during evaporation of the refrigerant-oil mixture, and the presence of oil significantly enhances the surface wettability of refrigerant.

In this study, the surface tension of the oil/refrigerant mixture and the wettability of the solid surface with the oil/refrigerant mixture are examined as a first step of the study on the generation mechanism and the droplet behavior of the oil mist in the compressor. The surface tension of the oil/refrigerant mixture is measured by the pendant drop method that can be applicable to a pressurized condition like a refrigerant atmosphere. The contact angle of the mixture on the solid surface is measured by a Sessile Drop Method in parallel with the surface tension measurement. Polyalkylene glycol (PAG) oil and CO₂ are used as refrigeration oil and refrigerant respectively. As the test surface, polytetrafluoroethylene (PTFE) plate is used in the measurement of the contact angle of the mixture on the solid surface.

2. EXPERIMENT

2.1 Experimental Setup

Figure 1 shows a schematic of an experimental setup. A main vessel is designed to withstand pressure up to 10 MPa. Two sight glasses are installed at opposite sides of the main vessel. One is used to light up an inside of the vessel, and the other is used to take pictures of a droplet on a test plate. The oil/refrigerant mixture, i.e. PAG/CO₂ mixture in this study, is prepared in a sub vessel prior to the experiment and fed to the main vessel by a gear pump. The PAG/CO₂ mixture flows through a capillary tube and the droplet drops from the tip of capillary tube on the test plate. Since volume of the droplet in a Sessile Droplet Method is less than 4 μL, the capillary tube of 0.5 mm in outer diameter is used. The tip of the capillary tube is set at 5 mm above the test plate. The test plate is fixed on a rotary stage and the rotary stage is set on a thrust bearing. The rotary stage has two neodymium magnets on a side of the stage. This configuration allows us to rotate the test plate by operating other magnets from outside of the main vessel so that the measurement can be repeated at the same condition with changing the dropping position of the droplet by the rotation of the test plate to confirm reproducibility. Polytetrafluoroethylene (PTFE) plate is used in this study as the test plate. Refrigerant concentration is measured by a sampling method. In the experiment, the measurements of the contact angle, the surface tension and the refrigerant concentration of the mixture are carried out with changing the pressure and the temperature of the PAG/CO₂ mixture. Purity of CO₂ used in this experiment is 99.95%. Viscosity grade of PAG used in this study is 100 mm²/s at 40 °C.

2.2 Measurement of Contact Angle

The contact angle of the mixture is measured by the Sessile Drop Method for the wettability evaluation. Figure 2 shows a picture of the droplet on the test plate taken by a CCD camera. The contact angle of the droplet is an angle between a horizontal line and a tangential line of the droplet at a contact point of an edge of the droplet. The tangential line is calculated by a curve fitting method. Firstly, detection of droplet boundary is conducted

by using an image processing software and x - y coordinates (x_i, y_i) of points on the boundary are obtained. Then, an approximation curve of the droplet boundary is calculated by the curve fitting with an assumption that the shape of the droplet boundary is perfect circle when the volume of the droplet is small. Equation (1) is used to obtain the approximation curve of the boundary by a least square method with identifying a coordinate of the center (a, b) , and radius r of the circle from the discrete points on the boundary.

$$\begin{pmatrix} -2a \\ -2b \\ a^2 + b^2 - r^2 \end{pmatrix} = \begin{pmatrix} \sum x_i^2 & \sum x_i y_i & \sum x_i \\ \sum x_i y_i & \sum y_i^2 & \sum y_i \\ \sum x_i & \sum y_i & \sum 1 \end{pmatrix}^{-1} \begin{pmatrix} -\sum (x_i^3 + x_i y_i^2) \\ -\sum (x_i^2 y_i + y_i^3) \\ -\sum (x_i^2 + y_i^2) \end{pmatrix} \quad (1)$$

The broken line in Figure 2 is the approximation curve obtained by Equation (1). The tangential line at the contact point is calculated from the approximation curve and the coordinate at the contact point. The contact angle θ is obtained from the angle between the horizontal line and the tangential line of the approximation curve at the contact point. γ_S , γ_L , and γ_{SL} shown in Figure 2 expresses a balance of surface tension and interfacial tension, and are explained in the following section.

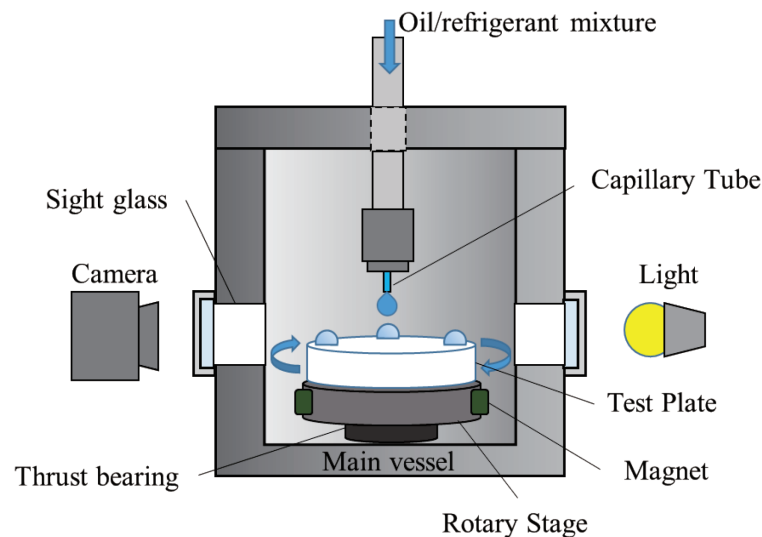


Figure 1 Experimental setup of wettability evaluation

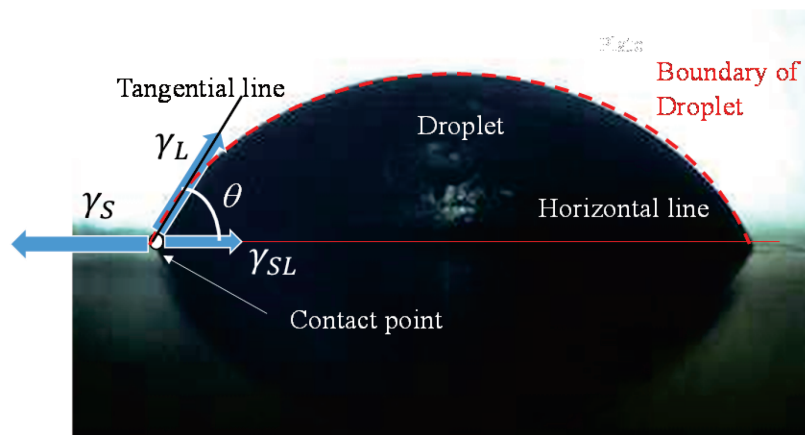


Figure 2 Measurement of contact angle

2.3 Measurement of Surface Tension

Since the surface tension of liquid is closely related to the contact angle of the droplet on the solid surface, the surface tension of the oil/refrigerant mixture is also measured by the pendant drop method in the same experimental setup shown in Figure 1. During dripping the droplet from the capillary tube, the surface tension of the droplet is calculated by the shape of the droplet when the diameter of the droplet becomes the maximum. When the maximum diameter of the droplet is d_e , and the diameter at the point where the height from the bottom of the droplet is equal to d_e is d_s (see upper left in Figure 3), the surface tension of the droplet is calculated from Equation (2).

$$\gamma = J \cdot g \cdot \rho \cdot (d_e)^2 \quad (2)$$

where, γ is surface tension, g is the gravitational acceleration, ρ is density of the oil/refrigerant mixture. J is a correlation factor and calculated by the following equation (Fordham, 1948).

$$J = -5.602x^3 + 17.669x^2 - 19.405x + 7.6496 \quad (3)$$

$$(x = d_s / d_e)$$

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 Contact Angle of Pure PAG on PTFE Plate

The contact angle of pure PAG on the PTFE test plate is measured at first. An observation results of the droplet shape are shown in Figure 3 when the droplet is dripped from the capillary tube and collides against the plate. The temperature condition is kept to 60°C during the experiment. The height from the plate to the capillary tube is set to 5 mm. Time is zero when the droplet collides with the plate. The droplet shape changes from sphere to hemi-sphere on the plate at an instant of the collision. Then, it slightly spreads and becomes equilibrium condition after 5 seconds from the collision. The contact angle at each moment is obtained from the images and time history of the contact angle of the pure PAG on the PTFE plate is shown in Figure 4. It is found that the contact angle decreases at the instant of the collision with the plate and becomes stable after 2 second after the collision. In the following experiment, the contact angle is measured by the image taken at 10 seconds after the collision. In addition, the surface tension of the droplet can be measured by the pendant drop method as previously explained at the section 2.3.

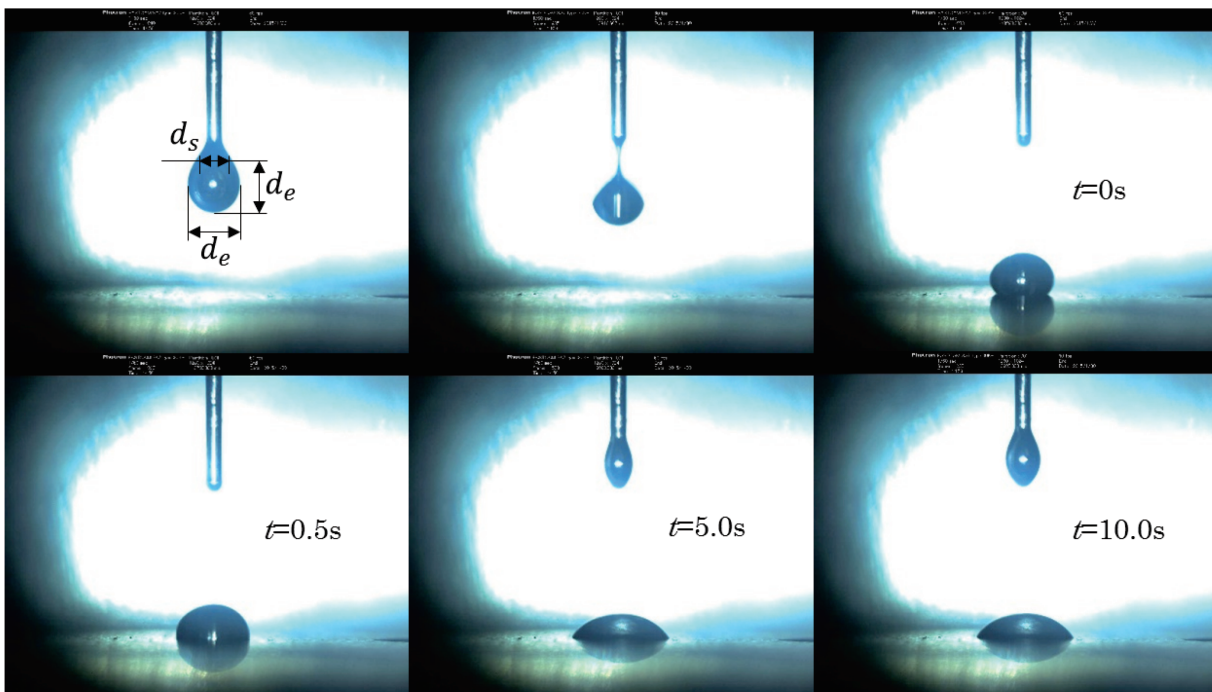


Figure 3 PAG Droplet dripped from capillary tube on PTFE plate

Figure 5 shows the contact angle of PAG on the PTFE plate measured with changing the temperature as a parameter. The contact angle is measured 5 times at each condition, and an average value is plotted against the temperature. The contact angle decreases with increasing the temperature. Under the equilibrium condition, Young's formula expressed by Equation (4) is established as shown in Figure 2.

$$\gamma_S = \gamma_L \cos \theta + \gamma_{SL} \quad (4)$$

where, γ_S is solid surface tension, γ_L is surface tension of liquid phase, γ_{SL} is solid-liquid interfacial tension, and θ is the contact angle. According to Equation (4), the contact angle depends on the liquid surface tension if the solid-liquid interfacial tension are assumed to be constant against the temperature since the solid surface tension hardly changes in this temperature range. The surface tension of PAG measured by the pendant drop method is shown in Figure 6 against the temperature. It is shown that the surface tension of PAG decreases with increasing the temperature, and it causes the reduction of the contact angle shown in Figure 5.

Relationship between the surface tension and the contact angle is shown in Figure 7. It is found that the contact angle increases with the surface tension. Duple's equation shown by the following equation expresses a work of

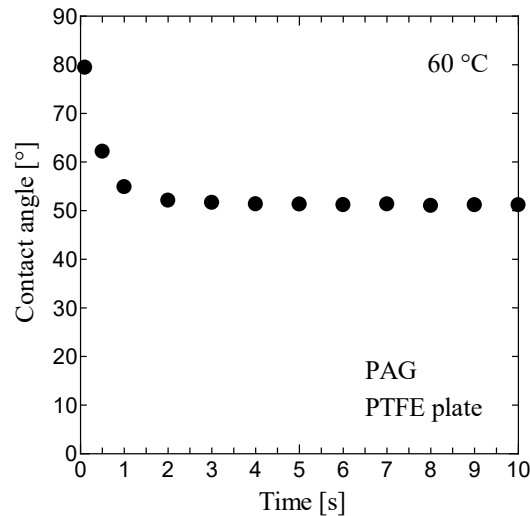


Figure 4 Change of contact angle from collision

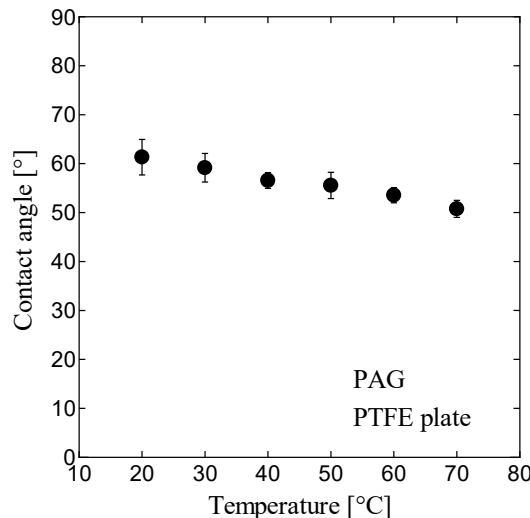


Figure 5 Contact angle of PAG on PTFE versus temperature

adhesion, which is the work per unit area required to separate the drop from the solid surface.

$$W_A = \gamma_s + \gamma_L - \gamma_{SL} \quad (5)$$

The work of adhesion is an index of the wettability and it is indicated that the wettability becomes better with large work of adhesion. With considering that the droplet of the PAG maintains its shape on the PTFE plate with equilibrium condition, Young-Duple equation is derived from Equations (4) and (5) as follows.

$$W_A = \gamma_L(1 + \cos \theta) \quad (6)$$

The work of adhesion under the equilibrium condition is a function of the surface tension of liquid and the contact angle as expressed by Equation (6). The work of adhesion is obtained by the surface tension and the contact angle, and found to be 45.5 mJ/m^2 [mN/m] when the surface tension is 29 mN/m . As a reference value, the work of adhesion of PTFE film with glycerol is shown to be 45.9 mN/m by Gilman (2014). The contact angle calculated by Equation (6) with an assumption of constant work of adhesion of 45.5 mN/m is shown in Figure 7 by solid line. Although the calculated contact angle shows the similar tendency as the experimental one, gradient of the calculated contact angle is larger than experimental one. It may be caused by the fact that the work of adhesion varies with the

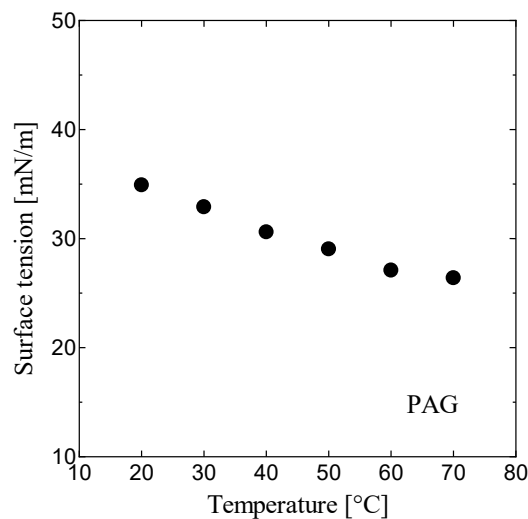


Figure 6 Surface tension of PAG versus temperature

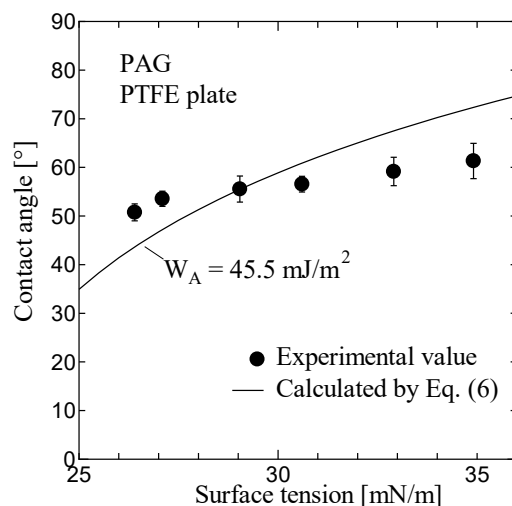


Figure 7 Influence of surface tension on contact angle (PAG on PTFE)

temperature. It is also supposed that contamination on the PTFE surface affects the wetting phenomena.

3.2 Contact Angle of PAG/CO₂ Mixture on PTFE Plate

The influence of refrigerant dissolved into the oil on the contact angle is investigated. Figure 8 shows the relationship between the mass fraction of CO₂ dissolved in the PAG and the surface tension of the mixture measured by the pendant drop method at 30°C. The surface tension of the PAG/CO₂ mixture decreases steeply with increasing the CO₂ concentration in the mixture. The contact angle of the PAG/CO₂ mixture is shown in Figure 9 against the CO₂ concentration in the mixture. It is shown that the contact angle of the PAG/CO₂ mixture on the PTFE plate decreases with increasing the CO₂ concentration in the mixture due to the reduction of the surface tension of the mixture. Therefore, it is supposed that the wettability of the solid surface with the PAG/CO₂ mixture having high CO₂ concentration becomes high. The contact angle is re-arranged against the surface tension as shown in Figure 10. When the surface tension of the mixture becomes smaller than 22.5 mN/m, the contact angle calculated by Equation (6) with the work of adhesion of 45.5 mJ/m² becomes zero, which means that the wetting becomes a perfect one in which the droplet spreads and does not keep the droplet shape. In the experiment, however, the droplet of the mixture with the surface tension of 20 mN/m keeps the equilibrium contact angle. This difference may be caused by the fact that the work of adhesion is not constant. Contamination on the PTFE surface is another factor that affects

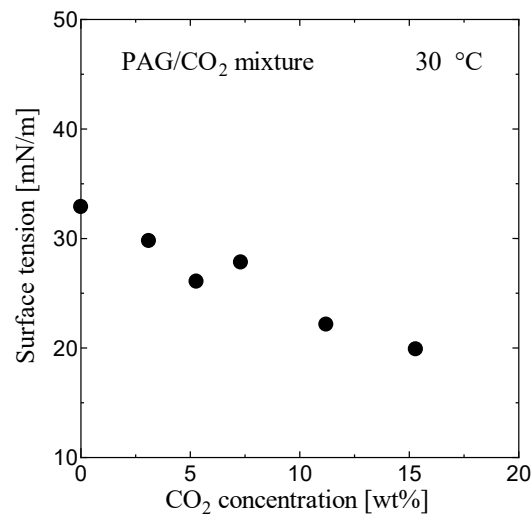


Figure 8 Surface tension of PAG/CO₂ mixture versus refrigerant concentration

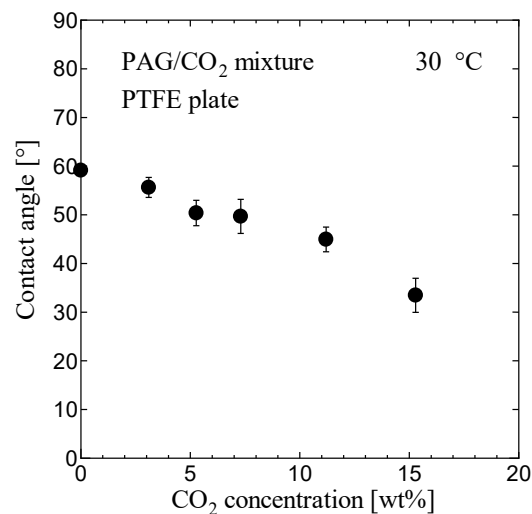


Figure 9 Influence of refrigerant concentration on contact angle of PAG/CO₂ mixture on PTFE

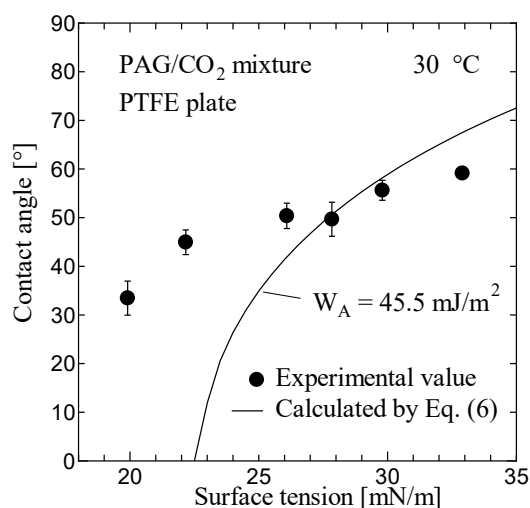


Figure 10 Contact angle of PAG/CO₂ mixture on PTFE versus surface tension

the wetting phenomena.

Since metal materials have much larger solid surface tension or work of adhesion than those of the PTFE, the wetting on the metal surface with the oil/refrigerant mixture will tend to be the perfect one.

4. CONCLUSIONS

In this study, the wettability of solid surface with oil/refrigerant mixture is evaluated experimentally. The following conclusions are obtained

1. The experimental apparatus developed in this study is applicable to measure the contact angle and the surface tension of oil/refrigerant mixture under high pressure and temperature condition.
2. The droplet of pure PAG on the PTFE plate becomes equilibrium condition after 2 second from the collision with the plate. The contact angle of the pure PAG on the PTFE plate decreases with increasing temperature due to the reduction of the surface tension of the PAG.
3. The droplet of PAG/CO₂ mixture keeps the droplet shape with the equilibrium condition on the PTFE plate, and the contact angle decreases with increasing the CO₂ concentration in the mixture since the surface tension of the mixture steeply decreases with increasing the CO₂ concentration.
4. The wetting of the oil/refrigerant mixture on the metal surface is supposed to be the perfect one due to the much higher solid surface tension of the metal than that of the PTFE.

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