Title: Refrigerant concentration measurement at compressor oil sump by refractive index (Concentration of R410A in PVE oil)

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Abstract:

The dissolution of refrigerant into refrigeration oil has great influence on oil viscosity. In this study, a refractive index measurement is applied to measure the refrigerant concentration in the oil at a compressor oil sump. Although the refractive index of the oil/refrigerant mixture is correlated with the refrigerant concentration using the refractive indices of the oil and the refrigerant, the temperature of the oil in the compressor is so high that the refractive index of the refrigerant cannot be defined because the temperature surpasses the critical temperature of the refrigerant. Therefore the correlation under such high temperature conditions is examined. It is found to be reasonable to use the refractive index of the refrigerant derived by an extrapolation of the refractive indices of the saturated liquid refrigerant under a sub-critical condition. In addition, a transient measurement of the refrigerant concentration in the oil was carried out in a practically operated compressor. Although the output signal of the sensor is disturbed by bubbles generated during the separation of the refrigerant from the oil, a data processing procedure which eliminates the over-ranged signal and averages the output within a certain time period is proposed for eliminating the influence of the bubbles.

Keywords: Compressor, Concentration, Measurement, Oil, R410A, Refrigerant

1. Introduction

In refrigerant compressors, refrigeration oil is used for lubrication, sealing, and cooling. Oil having good miscibility with refrigerant is most favorably employed in refrigeration systems. The refrigerant dissolves into the oil stored in an oil sump of the compressor. An excess dissolution of refrigerant into the oil reduces the viscosity of the oil and causes lubrication failure of the sliding parts in the compressor. In

addition, it causes an oil foaming phenomenon which results in an increase of oil delivery from the compressor, heat transfer resistance, as well as an increase in pressure drops in the heat exchanger. Measurement of the refrigerant concentration of the oil at the oil sump is, therefore, very important to ensure the reliability of the compressor and to improve the cycle performance. The most general way to measure the refrigerant concentration in the oil is using a sampling method [ASHRAE, 1996]. High pressure liquid chromatography [Cavestri and Schafer, 1999] is also used for precise measurement. However these measurement techniques are time-consuming and reduce the amount of refrigerant and oil in the cycle. Also a real-time measurement of the refrigerant concentration is impossible by these methods.

Several sensors and principles for the real-time measurement of the mixing ratio of oil/refrigerant mixture have been proposed. They detect viscosity [Baustian et al., 1986a, 1988a], acoustic velocity [Baustian et al., 1986a, 1988b, c; Meyer et al., 1994; Navarro de Andrade et al., 1999; Lebreton et al., 2001], density [Baustian et al., 1986a, 1988c, d; Bayani et al., 1995], absorption of light [Baustian et al., 1986b; Kutsuna et al., 1991; Suzuki et al., 1993] or dielectric constant [Baustian et al., 1986b; Fukuta et al., 1999; Hwang et al., 2003, 2008]. Refractive index [Baustian et al., 1986b; Jonsson and Höglund, 1993; Newell, 1996] is one of the properties which changes according to the mixing ratio of the refrigerant/oil mixture. The authors [Fukuta et al., 2004, 2006] developed a refractive index sensor and proposed to use the sensor for the measurement of the concentration of refrigerant/oil mixture. It was shown in the previous paper [Fukuta et al., 2004] that the difference in refractive index between the refrigerant and refrigeration oil is large enough to detect the mixing concentration of refrigerant/oil mixture and that the refractive index changes almost linearly according to the mixing ratio. The relationship between the refractive index and the concentration of the mixture was correlated with the refrigerant concentration using both refractive indices of the saturated liquid refrigerant and the refrigeration oil. A measurement of the transient change of oil circulation ratio in a refrigeration cycle was carried out successfully [Fukuta et al., 2006]. In addition, the refractive index measurement can be applied to high pressure conditions, an accurate measurement is relatively easily obtained even using commercially available sensors. There is no influence of electric noise such as an inverter noise on

the refractive index. Therefore, the refractive index measurement is preferable to measure the mixing ratio of refrigerant/refrigeration oil in refrigeration systems.

When the refractive index measurement is applied to the refrigerant concentration measurement in the compressor, however, the refractive index of the liquid refrigerant cannot be defined because the oil temperature is so high that the temperature surpasses the critical temperature of the refrigerant. In this study, the refractive index sensor is improved so that it withstands the high temperatures and pressures, and the refractive index of the oil/refrigerant mixture is measured under such high temperature conditions. How to correlate the relationship between the refrigerant concentration and the refractive index of the mixture is examined based on the measured results. In addition, a transient measurement of the refrigerant concentration in the oil is carried out in a practically operated refrigerant compressor. The output signal of the sensor is disturbed by bubbles generated in the compressor and a procedure for data processing is discussed for a robust measurement.

2. Experiment

2.1. Refractive index sensor unit

There are mainly four methods to detect the refractive index. The first is to detect a change in light intensity through a sensor whose output changes according to the refractive index of a test medium [Takeo and Hattori, 1982; Hinata et al, 1995]. The second method is to detect a change of optical path [Jonsson and Höglund, 1993; Yata et al., 1996; Jääskeläinen et al., 2000]. The third method is to detect the critical angle [Baustian et al., 1986a; Newell et al., 1996; Shedd and Newell, 1998; Shedd and Anderson, 2005]. The fourth method is to detect the interference fringe [Shurulinkov et al., 1999; El-Ghandoor et al., 2003]. In the previous papers [Fukuta et al., 2004, 2006], the authors developed a refractive index sensor which detects the change of optical path using a laser displacement sensor. As a detailed description was provided in the previous paper, only a simple outline is explained in this paper. Figure 1 shows the principle of the refractive index measurement. The test-medium, namely a oil/refrigerant mixture, is filled in a pressurized chamber that has a glass window. The incident light enters the test medium through the glass window and reflects off the surface of a base plate. When the incident beam passes through the

interface between the air and glass, and the interface between the glass and the test medium, refraction occurs due to the different refractive indices of air, glass and the test medium. The optical path changes according to the refractive index of the test medium as shown in Fig.1. The laser displacement sensor was used to detect the change of optical path. The sensor is a new type than the one used in the previous study [Fukuta et al., 2004, 2006] and has a resolution of 0.1 μm . A photograph of the refractive index sensor unit (measuring unit) incorporating the laser displacement sensor is shown in Fig. 2. Since the laser displacement sensor has a usage temperature range from 0 to 50 $^{\circ}\text{C}$, a heat rejection fin and a cooling fan is mounted on the sensor for temperatures up to 80 $^{\circ}\text{C}$. In addition, the glass window was minimized as compared with the previous unit in order to withstand high pressures up to 10 MPa.

2.2 .Experimental setup

Figure 3 shows the schematic diagram of an experimental setup. The measuring unit with the laser displacement sensor is connected to a mixture storage tank and the test medium chamber is filled with the oil/refrigerant mixture under a saturated condition. The test medium is circulated by a gear pump and the temperature is controlled by an electric heater. The temperature of the oil/refrigerant mixture is measured in the test medium chamber by inserting a T-type thermocouple, and the uncertainty of the temperature is 0.1 $^{\circ}\text{C}$. The refractive index of the mixture is obtained from the output of the sensor. Although the resolution of the laser displacement sensor is 0.1 μm and a corresponding resolution of the refractive index is 1×10^{-5} , the precision of the refractive index sensor is 2×10^{-4} due to fluctuations of output and inhomogeneity of the mixture. The concentration of the mixture is measured using a sampling method. A sampling vessel is installed between the oil pump and the measuring unit. There is a bypass line parallel to the sampling vessel. The sampling vessel is disconnected from the experimental circuit by changing the line using two three-way valves. Uncertainty of the concentration of the sampling method is ± 0.01 mainly caused by the insufficient separation of refrigerant from oil and the local concentration distribution of the mixture.

The refrigerant mass fraction of the mixture measured by the sampling method is converted to refrigerant volume fraction by the following equation with an assumption of ideal mixing.

$$\beta = \frac{x}{x + (\rho_r / \rho_o)(1 - x)} \quad (1)$$

where, β is the volume fraction of refrigerant, x is the mass fraction of refrigerant, and ρ_r and ρ_o are the densities of refrigerant and refrigeration oil, respectively. The density of the refrigerant used in Eq. (1) is that of saturated liquid refrigerant under a sub-critical condition, while the density of refrigerant under the super-critical condition is obtained by a linear extrapolation of the density in the sub-critical region. Validity of this treatment is discussed in section 3.2. The density of saturated liquid refrigerant is calculated by REFPROP ver.7 [Lemmon et al., 2002] with uncertainty of 0.1%, and the density of refrigeration oil is measured and correlated by ourselves within an uncertainty of 0.1%. The uncertainty of the volume fraction is mainly due to that of the mass fraction and has the same order as the mass fraction, i.e. 0.01.

In the experiments, the concentration of refrigerant ranges from 0 to 100 % and the temperature from 30°C to 80°C. The refrigerant tested in this study is R410A and the refrigeration oil is polyvinyl ether (PVE).

3. Results and discussions

3.1 Refractive indices of refrigerant and oil

The relationship between the refractive index and the mixing ratio of the oil/refrigerant mixture was correlated by the following equation in the previous study [Fukuta et al., 2006].

$$n = \beta n_r + (1 - \beta) n_o + c \beta (1 - \beta) \quad (2)$$

where, n , n_r and n_o are the refractive indices of the oil/refrigerant mixture, the saturated liquid refrigerant and the refrigeration oil respectively at a given temperature. β is a volume fraction of the refrigerant described above. Coefficient c which determines the curvature of the correlation curve is a function of the temperature. In the previous study, Eq. (2) was confirmed in a temperature range from 30°C to 50°C. However, in the case that the temperature is higher than the critical temperature of the refrigerant, Eq. (2) is not applicable because the refractive index of the refrigerant cannot be defined.

Since the temperature of the oil in the compressor is generally high especially in compressors having

a high pressure shell structure, the refractive indices of the refrigerant and the oil under the high temperature condition are measured first, and are shown in Fig. 4 against the temperature. The refractive index of the PVE oil is much higher than that of refrigerant and decreases linearly with the temperature. There are two plot series for the measured refractive index of R410A. In both cases, the charge amount of R410A in the storage tank is different and therefore the pressure in the super-critical region is different. The refractive indices of R125 and R32, components of R410A, are also plotted as a reference [Yata et al., 1996]. When a saturated liquid phase exists in the storage tank in both cases of the charge amount at a temperature less than 60°C, the refractive index of R410A shows a mean value between those of R32 and R125, and decreases almost linearly with the temperature. The refractive index of R410A in the case of a low charge amount sharply decreases with temperature around 60°C, and lineally at a temperature higher than the critical temperature of 71°C [Lemmon et al., 2002]. In the case of a high charge amount, the whole refrigerant becomes a sub-cooled liquid at about 60°C and the refractive index in this case continues to decrease linearly with the temperature up to the super-critical condition. These variations are caused by density change since the refractive index changes mainly by its density. Since the density of the refrigerant at the vicinity of the critical point or in the super-critical region changes significantly by both pressure and temperature, the refractive index of the liquid refrigerant in this region varies with pressure and temperature. As a result, the refractive index of R410A used in Eq. (2) is not defined at a temperature higher than 60°C.

3.2 Refractive index of oil/refrigerant mixture

Figure 5 shows the refractive index of the PVE/R410A mixture versus the volume fraction of refrigerant at several temperatures. The refractive index of the PVE/R410A mixture at a given temperature decreases with an increase in the volume fraction of refrigerant. When the volume fraction is 1.0, i.e. pure refrigerant, and the temperature is 70 or 80°C, the refractive index is not plotted, since the R410A becomes super-critical. In addition, the refractive index cannot be measured in the range of a volume fraction between 0.65 and 0.9 with a temperature over 50°C, because a two-phase separation

occurs and the condition of the mixture becomes emulsion-like. However, since the concentration of the refrigerant in the oil at the oil sump of the compressor is generally less than 0.5, the refractive index of a mixture whose refrigerant concentration is less than 0.5 is considered in the following section.

The data shown in Fig. 5 is rearranged against a magnified horizontal axis from 0 to 0.5 in Fig. 6. Figure 6 shows that the variation of the refractive index of the mixture over 60°C against the temperature change has a similar tendency with that under 60°C. It is therefore supposed that the refrigerant in the oil exists in the condition like the liquid refrigerant even when the temperature of the mixture is higher than the critical temperature of the refrigerant. The refractive index of the refrigerant in the mixture at the super-critical temperature is assumed to be expressed by an extrapolation of the refractive indices of the saturated liquid refrigerant under the sub-critical condition. Figure 7 shows the value of the coefficient c in Eq. (2) in the temperature range between 20 and 60 °C. The value of c at each temperature is obtained by substituting three measured refractive indices, i.e. those of the refrigerant, n_r , oil, n_o , and the mixture, n , with a refrigerant concentration of about 0.5, into Eq. (2). There are two set of c values, triangle is obtained in the previous study [Fukuta et al., 2006] and circle is obtained over a wider range of temperatures in this study. Although the data in the previous study shows a slight deviation from the present data, the difference between these two measured values in the range from 30 to 50 °C has little influence on the correlation curve expressed by Eq. (2). The difference is thought to be caused by an inaccuracy of the sampling method employed in the previous study in which the sample was extracted through a branch line. In the previous study, there were a few data in the narrow temperature range, and the data was approximated by a quadratic curve. However, a linear approximation seems better from the present data ranging from 20 to 60 °C. In the following figures, the linear approximation is used for the value c in Eq. (2).

Figure 8 shows the refractive index of the refrigerant at a temperature under 60°C and two approximations. One is quadratic as proposed in the previous study [Fukuta et al., 2006] and the other is linear. Although both approximations give almost the same value for the refractive index of the refrigerant from 20°C to 60°C, these give different values at a temperature above 60°C. It is discussed in the following that which approximation is better for the extrapolation to express the refractive index of the

refrigerant at a super-critical temperature. The refractive index of the oil is also shown in Fig. 8 and it is approximated by a linear correlation.

The correlation curve expressed by Eq. (2) using the refrigerant refractive index estimated by the linear approximation is shown in Fig. 9, while that using the refrigerant refractive index estimated by the quadratic one is shown in Fig. 10. The measured refractive index of the PVE/R410A mixture is also plotted in both figures. As described above, the refractive index of the refrigerant at the super-critical temperature is extrapolated by the approximation curves and has a smaller value when the quadratic approximation is used in comparison with the linear one. The coefficient c obtained by the linear extrapolation shown in Fig. 7 is used for the correlation curves in both figures. The average deviation for the data at 80°C is 0.0012 in Fig. 9, and 0.0035 in Fig. 10. From Figs. 9 and 10, it is found that the relationship between the refractive index of the PVE/R410A mixture and the volume fraction is better correlated when the refractive index of the refrigerant at the super-critical temperature is given by the linear extrapolation. These correlations are summarized in Table 1.

3.3 Refrigerant concentration measurement at compressor oil sump

Figure 11 shows a schematic of an experimental compressor. The compressor is a scroll type and has a high pressure shell. An additional shell is attached at the bottom of the compressor shell and the measuring unit for the refractive index and a sight glass are mounted on the shell. The reflection plate of the sensor unit is installed inside the oil sump. Besides the measuring unit, a fiber optic refractive index sensor is installed in the oil sump to double check measurements. The compressor is connected an experimental refrigeration cycle which consists of the compressor, a double tube condenser, a manual expansion valve, and a double tube evaporator. R410A and PVE are the refrigerant and refrigeration oil respectively. Temperatures and pressures are measured at several points in the cycle by a T-type thermocouple and a strain gage pressure transducer respectively. In the experiment, the refrigerant concentration of the oil is measured continuously under start-up, steady state and shut-down operating conditions. The refrigerant concentration is also checked using the sampling method at each step.

The upper graph of Fig. 12 shows time histories of oil temperature and pressure in the compressor

shell. The lower one shows the transient change of the refrigerant concentration in the oil measured with the refractive index sensor. The output of the fiber optic sensor almost shows a near same value. The compressor was started at twelve minutes, the discharge pressure was reduced at the one hour mark by opening the expansion valve after the cycle reached a steady state condition and was stopped at one hour and 45 minutes. Immediately after the compressor is started, the discharge pressure and the oil temperature increase. The refrigerant concentration increases due to the dissolution of the refrigerant into the refrigeration oil. When the discharge pressure, i.e. oil pressure, is suddenly reduced at the one hour mark, the refrigerant concentration decreases steeply at first and the output signal is eventually disturbed. This disturbance is caused by an interruption of the laser beam of the sensor by bubbles due to the separation of the refrigerant from the oil. Figure 13 shows photographs taken through the sight glass at the steady state (a) and at the conditions when the separation occurs (b). The metal surface in the glass window of the pictures is a reverse side of the reflection plate. Although the plate can be seen clearly in Fig. 13(a), it blurs in Fig. 13(b) by the bubble and a non-uniformity of the refractive index in the oil. After stopping the compressor, the discharge pressure and the oil temperature decrease and the refrigerant concentration decreases according to the pressure and temperature. During the shutdown operation, the bubble is again generated and the output signal is again disturbed. Circles in Fig. 12 show the refrigerant concentration measured by the sampling method. The refrigerant concentration measured by the sensor agrees well with the sampling results. Squares shown in Fig. 12 present refrigerant solubility corresponding to the temperature and pressure. Solubility is obtained based on data given by the oil manufacture. The solubility shows a much higher value than the measured refrigerant concentration. Although the refrigerant concentration of the oil stored in the compressor is generally almost the same as the solubility, the compressor used in this study has a big oil sump and therefore creates less stirring actions on the oil by the moving parts of the compressor. Hence, the refrigerant is hardly dissolved into the oil.

In order to achieve a robust measurement, the elimination of the influence of the bubble on the output signal is examined. When the bubble is generated, the output signal of the sensor becomes over-ranged as shown in Fig. 12. The over-ranged data is removed from the data shown in Fig. 12 and the

data after this process is shown in Fig. 14. Moreover, the data is averaged for a certain time period and shown in Fig. 15. The averaged period is one minute. The refrigerant concentration shown in Fig. 15 shows a relatively smooth variation. Thus, it is shown that this data processing is effective at eliminating the influence of the bubble on the refrigerant concentration measurement using the refractive index sensor.

4. Conclusion

A refractive index measurement is applied to measure refrigerant concentration in oil stored in an oil sump of a refrigerant compressor. Since the refractive index of the oil/refrigerant mixture is correlated using the refractive indices of the oil and refrigerant and the oil temperature in the compressor is high, the refractive indices of the oil and the refrigerant are measured at temperatures up to 80°C. The refractive index of the PVE/R410A mixture shows continuous variation against temperature even at the super-critical temperature. It is supposed that the refrigerant exists in the oil in a condition like liquid refrigerant even at a super-critical temperature. Although the refractive index of the saturated liquid refrigerant cannot be defined at a temperature higher than the critical temperature of the refrigerant, it is found that the refractive index of the refrigerant at a super-critical temperature can be calculated using a linear extrapolation of the refractive index of the saturated liquid refrigerant at a sub-critical temperature. The correlation obtained using the extrapolated refractive index of the refrigerant and the c value in Eq. (2) agrees well with the measured value even at temperatures higher than the critical temperature. In addition, a transient measurement of the refrigerant concentration in a practically operated refrigerant compressor was successfully carried out. Although the output signal of the sensor is disturbed by bubbles generated due to the separation of the refrigerant from the oil, a data processing procedure which eliminates the over-ranged signal and averages the output within a certain time period is proposed for eliminating the influence of bubbles.

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Table 1 Correlations (PVE/R410A)

	Correlation Equation	Temperature range
n_o	$-3.896e-4*T+1.4535$	20-80(100 ^{††})°C
$n_r^{\dagger}$	$-1.0868e-3*T+1.2188$	20-80(100 ^{††})°C
c	$2.608e-3*T-0.04720$	20-80(100 ^{††})°C

T: Temperature in °C

†: Note that the refractive index of refrigerant is that of refrigerant portion dissolved in oil.

††: not confirmed but probably applicable.

Figure captions

Fig. 1 Principle of measurement

Fig. 2 Refractive index sensor unit

Fig. 3 Experimental setup

Fig. 4 Refractive indices of R410A and PVE

Fig. 5 Refractive index of R410A/PVE mixture

Fig. 6 Refractive index of R410A/PVE mixture in range of volume fraction from 0 to 40%

Fig. 7 c value in Eq. (1)

Fig. 8 Extrapolation of R410A and PVE

Fig. 9 Relationship between refractive index and refrigerant volume fraction in case of linear extrapolation of n_r

Fig. 10 Relationship between refractive index and refrigerant volume fraction in case of quadric extrapolation of n_r

Fig. 11 Schematic view of experimental compressor

Fig. 12 Refrigerant concentration measurement in oil

Fig. 13 Condition of oil sump

Fig. 14 Removal of over ranged data

Fig. 15 Data processing with averaging procedure

Cooling fan

Base plate

Test medium chamber

Laser
displacement sensor

(a)

(b)