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INFLUENCE OF OIL ON FLOW CHARACTERISTICS THROUGH CAPILLARY TUBE IN REFRIGERATION CYCLE

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ABSTRACT

A capillary tube is widely used as an expansion device for small refrigeration cycles. Recently, immiscible oil is sometimes used in the refrigeration cycle to improve severe lubricating conditions and to prevent blockage of the capillary tube caused by the hydrolysis of ester oil. This paper discusses the influence of mixing of the immiscible oil with the refrigerant on the flow characteristics through the capillary tube. The combination of mineral oil and HFC134a is used, and mass flow rate and temperature and pressure distributions are measured experimentally under several conditions of subcooled degree and oil concentration. Even in the case of the immiscible combination, the oil droplet is pretty small and it mixes homogeneously in a liquid phase in the capillary tube. The mass flow rate of refrigerant decreases with increasing the oil concentration. The mixing of oil seems to delay inception of flash slightly, although the further increase of oil concentration does not affect the inception. Theoretical model is developed based on the same concept of a miscible oil-refrigerant combination, and calculated results are compared with experimental ones. The theoretical model for the miscible combination is applicable to the immiscible one, and the mass flow rate is estimated within an error of ±5 %.

INTRODUCTION

A capillary tube is commonly used as an expansion device for domestic refrigerators and small air conditioning units because of its low cost and simple structure. In contrast with the simplicity, the flow through the capillary tube is quite complex, and many studies(1)-(17) have been done both experimentally and theoretically to clarify the flow characteristics and to estimate the flow rate through the capillary tube. Although most of the studies discuss the flow characteristics of pure refrigerant, small amount of refrigeration oil is discharged from a compressor into the refrigeration cycle and circulates in the cycle with the refrigerant in a practical cycle. The oil flowing with the refrigerant increases viscosity of the refrigerant-oil mixture, and affects the flow characteristics and the mass flow rate through the capillary tube. Some papers reported the influence of oil on the performance of capillary tube. Bolstad(1) and Whitacre(2) reported that the oil increased the mass flow rate through the capillary tube. Wijaya(6) tested the influence of oil circulation and observed no significant difference between data obtained with and without an oil separator. Huerta(13) studied the oil influence experimentally and theoretically and showed that the presence of oil reduces the mass flow rate in the capillary tube. The authors(15) also investigated the oil influence both experimentally and theoretically by using a combination of mineral oil and HCFC22 and concluded that the mass flow rate through the capillary tube decreases by the mixing of oil because the viscosity of liquid phase increases. A mathematical model developed in the previous study took account of the mixing of oil and estimated the mass flow rate within an error of ±5 %. Recently, immiscible oil is sometimes used in the refrigeration cycle using HFC refrigerants in order to improve severe lubricating conditions and to prevent blockage of the capillary tube caused by the hydrolysis of ester oil that is miscible with the HFCs. When the immiscible oil mingles with the refrigerant circulating in the cycle and the refrigerant-oil mixture flows through the capillary tube, the flow pattern, the flow characteristics and the mass flow rate may be different from the case that the pure refrigerant flows through the capillary tube.

In this study, the influence of mixing of the immiscible oil with the refrigerant on the flow characteristics through the capillary tube is investigated by using the combination of HFC134a and mineral oil. The mass flow rate of refrigerant through the capillary tube is measured with changing the oil concentration quantitatively. Pressure and temperature distributions along the capillary tube are also measured under adiabatic condition. A sight glass and a glass capillary tube are used to observe the flow pattern before and inside the tube respectively. The mathematical model developed for the miscible combination is used and calculated results are compared with experimental ones to evaluate the applicability of the model to the immiscible combination.

EXPERIMENT

Figure 1 shows a schematic diagram of the experimental setup. The experimental refrigeration cycle consists of a compressor, a condenser, a subcooler, a capillary tube and an evaporator. The refrigerant is HFC134a and the refrigeration oil is naphthenic type mineral oil (ISOVG32), which is immiscible with the refrigerant. The compressor is a rolling piton type rotary compressor and its case has an additional volume on the top of the compressor for oil separation. The refrigerant delivered from the compressor condenses at the condenser. Then, it enters the capillary tube after its subcooled degree is controlled by the subcooler and an electric heater. The refrigeration oil stored in the compressor casing is fed through a needle valve to a liquid line at an outlet of the condenser. The mass flow rates of the refrigerant and the oil are measured respectively by positive displacement type flowmeters.

The capillary tube is a copper one of 1.04 mm I.D., 0.5 μm inside surface roughness and 0.8 m long. The inner diameter is obtained by a preliminary test using water. The pressure gradient and the flow rate under laminar flow condition are measured and these are substituted in Hagen-Poiseuille equation to calculate the inner diameter. The capillary tube is insulated by a urethane foam and twelve thermocouples are soldered on the outer surface of the tube to measure the temperature distribution along the tube. Eight pressure taps of 0.3 mm diameter are machined on the capillary tube wall and Bourdon type pressure gauges are connected to each pressure tap. Since the pressure and temperature distributions become steep as the flow goes downstream, interval of the pressure and temperature measuring point is arranged smaller in the portion of downstream. Besides the copper tube, a glass capillary tube whose diameter is 1.0 mm is used for visualization of the flow. Fluorescence dye is added to the oil so that the oil phase becomes clear by applying ultra-violet light. A glass pipe (8mm I.D.) as sight glass is installed in the liquid line just before the capillary tube to observe the flow pattern in the liquid line. In the experiment, the mass flow rate and the temperature and pressure distributions are measured under several conditions of the subcooled degree and the oil concentration. Test conditions are shown in Table 1.

THEORETICAL ANALYSIS

In this study, a mathematical model is developed based on the same idea for the miscible combination of refrigerant and oil. This paper focuses on the influence of the immiscible oil on the flow characteristics through the capillary tube and examines an applicability of the model to the immiscible combination. Discussion about what models are the best is, therefore, beyond the purpose of this study, and we employ correlations with which calculated results agree reasonably with experimental ones under the condition of no oil mixing. Figure 2 illustrates the flow model of the capillary tube. It is adiabatic and consists of a converging nozzle, single-phase region and two-phase region in the capillary tube having a constant cross section. The outline of the mathematical model is described in the following.

Entrance

The condition of the refrigerant entering the capillary tube is generally subcooled liquid and the pressure decreases when the velocity increases at the entrance of the tube. Under the assumption of an incompressible flow through the converging nozzle, the relationship between the pressure and the velocity across the entrance nozzle and mass continuity are given as follows.

$$\frac{P_i}{\rho_\ell}+\frac{V_i^2}{2}=\frac{P_t}{\rho_\ell}+(1+\zeta)\frac{V_t^2}{2} \tag{1}$$

$$\dot{m}=A_iV_i\rho_\ell=A_tV_t\rho_\ell \tag{2}$$

where, P_i and P_t are pressures upstream and downstream of the entrance nozzle, V_i and V_t are mean velocities at each section, ρ_ℓ is density of liquid, $\dot{m}$ is mass flow rate, and A_i and A_t are sectional areas. ζ is a loss coefficient at the entrance and is 0.5 in this study.

Single-Phase Region

The pressure decreases in the single-phase region in the capillary tube due to frictional loss. The pressure loss, ΔP, corresponding to a small distance, Δz, is expressed by Eq. (3).

$$\Delta P=\lambda\Delta zG^2/(2D\rho_\ell) \tag{3}$$

where, D is diameter of the capillary tube and G is mass flux. The frictional coefficient, λ, is given by Churchill's correlation(18) (Eq. (4)) which is used by Lin, et al.(5). Note that Eq. (4) is applicable to both laminar and turbulent flow and the frictional coefficient is not a monotonous decreasing function with Reynolds' number, Re.

$$\lambda=8\left[\left(\frac{8}{\mathrm{Re}}\right)^{12}+\frac{1}{(A+B)^{3/2}}\right]^{1/12} \tag{4}$$

where, $A=\left\{2.457\ln\left[\frac{1}{\left(\frac{7}{\mathrm{Re}}\right)^{0.9}+0.27\frac{\varepsilon}{D}}\right]\right\}^{16}$, $B=\left(\frac{37530}{\mathrm{Re}}\right)^{16}$, $\mathrm{Re}=\frac{GD}{\mu}$ and μ is viscosity.

Delay of Flash

The inception of flash hardly occurs at the saturation pressure in a straight, smooth and adiabatic capillary tube, and there exists the single-phase metastable region. The pressure difference between the saturation pressure, P_s, and the pressure, P_v, at which the flash of refrigerant occurs is designated as underpressure. Chen et al.(3) proposed the following correlation for the underpressure of R12.

$$\frac{(P_s-P_v)\sqrt{kT_s}}{\sigma^{3/2}}=0.679\left(\frac{v_g}{v_g-v_\ell}\right)\mathrm{Re}^{0.914}\left(\frac{\Delta T_{sc}}{T_c}\right)^{-0.208}\left(\frac{D}{D'}\right)^{-3.18} \tag{5}$$

where, k is Boltzmann constant, T_s is salutation temperature corresponding to the inlet pressure, σ is surface tension, v_g and v_ℓ are specific volume of gas and liquid, T_c is critical temperature, ΔT_{sc} is subcooled degree and D' is reference length given by $D'=\sqrt{kT_s/\sigma}\times 10^4$.

Two-Phase Region

The pressure reduction, ΔP, in the two-phase region is caused by acceleration of fluid, ΔP_a, and friction, ΔP_f.

$$\Delta P=\Delta P_a+\Delta P_f \tag{6}$$

The acceleration loss is obtained by using a specific volume(19), v_t, of two-phase flow expressed by Eqs. (7) and (8).

$$\Delta P_a=G^2\Delta v_t \tag{7}$$

$$v_t=[\chi v_g+(1-\chi)Kv_\ell]\left(\chi+\frac{1-\chi}{K}\right) \tag{8}$$

where, χ is quality of gas phase and K in Eq. (8) is slip ratio. Recently, a separated model which considered the velocity difference between gas and liquid phases was used to describe the phenomena of two-phase flow in the capillary tube(4)(11)-(13)(16). We use the slip ratio because the calculation with considering the slip between gas and liquid showed better result than that by a homogeneous model in our experiment. The Chisholm's slip ratio(20) expressed by Eq. (9) is adapted

$$K = \left\{1 + \chi\left[\left(v_g / v_\ell\right) - 1\right]\right\}^{1/2} \tag{9}$$

The frictional loss of two-phase flow is calculated by using Lockhart-Martinelli method(21). The two-phase multiplier, ϕ_ℓ, is a function of Lockhart-Martinelli parameter, X, and given by Eq. (11)(22).

$$\Delta P_f = \phi_\ell^2 \Delta P_\ell \tag{10}$$

$$\phi_\ell^2 = 1 + \left(C/X\right) + \left(1/X^2\right) \tag{11}$$

$$X^2 = \Delta P_\ell / \Delta P_g \tag{12}$$

where, ΔP_ℓ and ΔP_g are pressure losses if each phase is assumed to flow alone in the tube.

$$\Delta P_g = \lambda_g \frac{\Delta Z}{D} \frac{G^2}{2} \chi^2 v_g, \Delta P_\ell = \lambda_\ell \frac{\Delta Z}{D} \frac{G^2}{2} (1-\chi)^2 v_\ell \tag{13}$$

Although the coefficient C in Eq. (11) is 20 in the case that flows of gas and liquid are turbulent, it is reported that the value of C becomes small in a narrow flow channel(23). In this study, the value of C is decided to be 2 based on the comparison of the calculated results with the experimental ones.

The quality is calculated by the following energy equation. In this study, the two-phase metastable region, where the temperatures of gas and liquid are different, is not taken into consideration and it is assumed that the gas and liquid immediately become the saturation condition at the flash inception point.

$$h + \left(G^2 v^2 / 2\right) = Const. \tag{14}$$

Properties of Refrigerant-Oil Mixture

In the case that the refrigeration oil is mixed with the refrigerant, oil concentration α, quality χ, oil concentration in liquid phase α_ℓ and quality of refrigerant χ_r are defined as follows.

$$\alpha = \dot{m}_o / \left(\dot{m}_{rg} + \dot{m}_{r\ell} + \dot{m}_o\right) \tag{15}$$

$$\chi = \dot{m}_{rg} / \left(\dot{m}_{rg} + \dot{m}_{r\ell} + \dot{m}_o\right) \tag{16}$$

$$\alpha_\ell = \dot{m}_o / \left(\dot{m}_{r\ell} + \dot{m}_o\right) = \alpha / (1-\chi) \tag{17}$$

$$\chi_r = \dot{m}_{rg} / \left(\dot{m}_{rg} + \dot{m}_{r\ell}\right) = \chi / (1-\alpha) \tag{18}$$

where, subscripts rg, $r\ell$ and o stand for gas refrigerant, liquid refrigerant and oil respectively. The viscosity of liquid phase is given by a correlation of Kendall and Monroe(24) based on the mole fraction, y, with reference to an examination of Baustian(25).

$$\mu_\ell^{1/3} = y_{r\ell} \mu_{r\ell}^{1/3} + y_o \mu_o^{1/3} \tag{19}$$

The density, ρ_ℓ, the surface tension(26), σ_ℓ, of liquid phase and the enthalpy, h, of two-phase flow are expressed by the following equations.

$$\rho_\ell = \rho_{r\ell} \rho_o / \left[\alpha \rho_{r\ell} + (1-\alpha) \rho_o\right] \tag{20}$$

$$\sigma_\ell = \sigma_{r\ell} + \left(\sigma_o - \sigma_{r\ell}\right) \sqrt{\alpha} \tag{21}$$

$$h = \chi h_g + (1-\chi) h_\ell = (1-\alpha) h_r + \alpha h_o \tag{22}$$

The enthalpy of mineral oil, h_o, is calculated as follows(27).

$$h_o = \int C_p dt = c_0 + c_1 T + c_2 T^2 / 2 \tag{23}$$

where, T is temperature, C_p is the specific heat which is given as $c_1 + c_2 T$ (c_1, c_2:constants), and c_0 is a constant for the reference enthalpy.

Calculation Method

Equations (7) and (10) are substituted into Eq. (6), the small length, Δz, corresponding to the small pressure drop, ΔP, is obtained as follows.

$$\Delta z = \left(\Delta P - G^2 \Delta v_t\right) / \left[\phi_\ell^2 (\lambda_\ell / D)\left(G_\ell^2 / 2\right) / \rho_\ell\right] \tag{24}$$

With integrating Eq. (24) from the pressure P_t at the inlet section, one can obtain the pressure distribution along the capillary tube corresponding to the mass flux, G. The exit of capillary tube is generally under the critical condition and the position where Δz becomes 0 means the critical point in the analysis. In the calculation, the iteration is done with correcting the mass flow rate until the length from the inlet to the critical point becomes equal to the actual length of the capillary tube. The properties of refrigerant are calculated by using FORTRAN subroutines of Refprop ver.6(27).

RESULTS AND DISCUSSION

Experimental Results

Figure 3 shows a photograph at the glass pipe set horizontally just before the capillary tube. The flow direction is from left to right in this figure. The oil concentration is 1%. Transparent portion is the refrigerant and colored droplets are the immiscible oil containing the fluorescence dye. The oil flows upper part of the pipe with the droplet due to its smaller density. Figure 4 shows the flow pattern of refrigerant-oil mixture flowing from left to right in the capillary tube, which is observed by reducing flow velocity (5m/s) and using a stroboscope. As shown in Fig. 4, the oil flows in very small droplet. Under a normal operating condition with much higher velocity, it is supposed that the oil is mixed with the refrigerant homogeneously with extremely small droplet although the oil droplet was not identified even with using the stroboscope. It was also observed that when the oil concentration increase, a lot of oil accumulates at the upper part of glass tube and it blockades the capillary tube when it goes to the capillary tube at a time. It is, therefore, necessary to pay attention to eliminate the portion where the immiscible oil tends to accumulate.

Figure 5 shows the influence of the oil on the mass flow rate of the refrigerant for the different subcooled degrees. The dotted lines in this figure show the flow rate of refrigerant in the case that the refrigerant flow rate decreases with the same rate of the oil concentration. The mass flow late for the subcooled degree of 8 °C is larger than that of 5 °C since the liquid region with less pressure drop becomes large as the subcooled degree increases. The mass flow rate of the refrigerant decreases more than the dotted line since the viscosity of liquid phase increases by mixing the viscous oil.

The pressure and the temperature distributions along the capillary tube are plotted in Fig. 6. The temperature distribution is shown by the saturation pressure corresponding to the temperature. The inception of flash does not occur at the point that the pressure becomes the saturation pressure, and the metastable region is found as shown in Fig. 6. The underpressure, which is the pressure difference between the saturation pressure and the flash inception pressure, is obtained schematically for each experiment, and plotted against the oil concentration in Fig. 7 with the parameter of subcooled degree. The underpressure for the smaller subcooled degree is slightly larger, but there seems to be little influence of the concentration of oil on the underpressure.

Comparison of Calculated Results with Experimental Ones

The underpressure estimated by Eq. (5) with taking no account of the oil mixing is compared with the experimental one. It was found that the underpressure estimated by Eq. (5) is smaller than that derived by the experiment. However, it is not appropriate to develop a new correlation by the regression analysis based on limited data of this study. In this study, the underpressure is estimated just by multiplying the right hand side of Eq. (5). Figure 8 shows the comparison between the experimental result (the left hand side of Eq. (5)) and the calculated result in such manner (the right hand side of Eq. (5) multiplied by 3). In this figure, it is shown that the underpressure increases a little by the mixing of oil, although the data scatter due to instability of the metastable flow.

Figure 9 shows the quality change based on Eq. (14) in the two-phase region according to the pressure drop from the saturation pressure with the oil concentration as a parameter. The metastable region is not considered in this figure. In the case that the oil concentration is 0, there is no difference between the quality change calculated by Eq. (14) (thin solid line) and that calculated with neglecting kinetic energy (*h*=Constant, short dash line), because the kinetic energy of the flow in the capillary tube is small. On the other hand, the quality increases more in the case of 5 % of the oil concentration. Excessive evaporation of the refrigerant is needed in order to reduce the temperature of oil under assumption that the oil temperature is the same as the refrigerant temperature.

The mass flow rate is calculated by the mathematical model explained in the previous section. Figure 10 shows the calculated and experimental pressure distributions along the capillary tube when the oil concentration is 5%. Even in the case of mixing immiscible oil, calculated pressure distribution by the mathematical model which is developed for the miscible combination agrees with the experimental one. Figure 11 shows the comparison of the calculated mass flow rate of the refrigerant with the experimental one. The calculated results agree well with the experimental ones within ±5 % of accuracy. The influence of the oil concentration on the calculation accuracy is shown in Fig. 12. Although it shows good agreement over the tested oil concentration, the model tends to underestimate the mass flow rate slightly as the oil concentration increases. It is concluded that the influence of mixing of the immiscible oil with the refrigerant on the flow characteristics through the capillary tube can be analyzed with the mathematical model developed based on the same concept as the miscible oil-refrigerant combination. This is because the immiscible oil mixes with the refrigerant in the form of extremely small droplets in the capillary tube, and it can be treated as the homogeneous liquid phase.

CONCLUSIONS

The influence of immiscible oil on the flow characteristics through a capillary tube is investigated. The mass flow rate of refrigerant decreases with increasing the oil concentration because the viscosity of refrigerant-oil mixture increases. The oil mixing seems to increase underpressure slightly, but the further influence of the oil concentration on the underpressure is relatively small. Even in the case of the immiscible combination, the oil droplet is pretty small and the liquid phase can be treated as homogeneous one. The same theoretical model as the model for the miscible combination, therefore, is adaptable to the immiscible one. The mass flow rate of refrigerant is estimated within an error of ±5 % by the mathematical model with appropriate correlations although the model tends to underestimate the mass flow rate slightly as the oil concentration becomes large.

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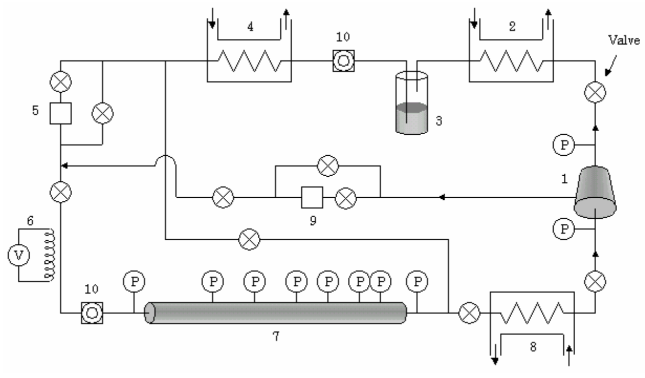

1.Compressor 2.Condenser 3.Receiver 4.Sub-cooler
5.Flowmeter 6.Heater 7.Capillary tube 8.Evaporator
9.Oil flowmeter 10.Sight glass

Fig.1 Experimental setup

Table 1 Experimental condition

Inlet pressure [MPa abs.]	0.81～1.28
Outlet pressure [MPa abs.]	0.4～1.08
Inlet temperature [°C]	15.0～46.4
Subcooled degree [°C]	2.4～34.0
Mass flow rate [kg/h]	9.0～25.3
Reynolds number at inlet	7000～49000
Mass concentration of oil	0～0.15

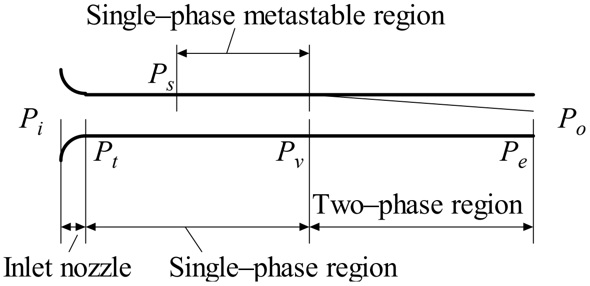

Fig.2 Mathematical model

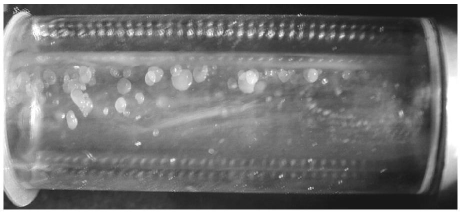

Fig.3 Flow at sight glass

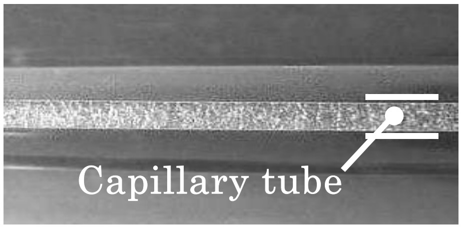

Fig.4 Flow in capillary tube

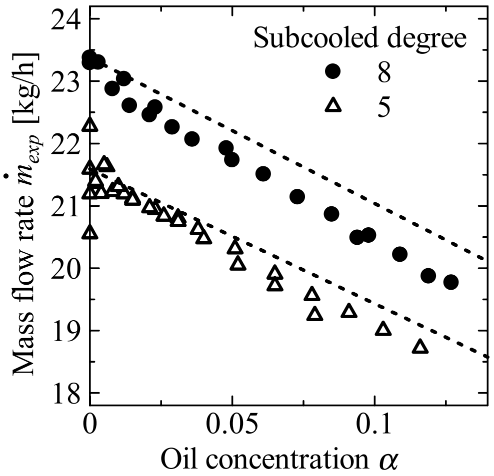

Fig.5 Influence of oil on mass flow rate of refrigerant

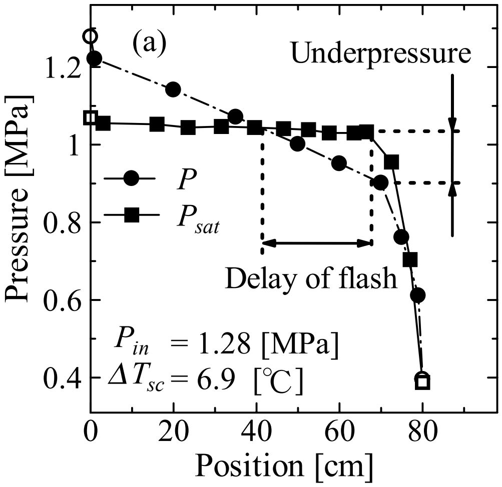

Fig.6 Pressure and temperature distributions

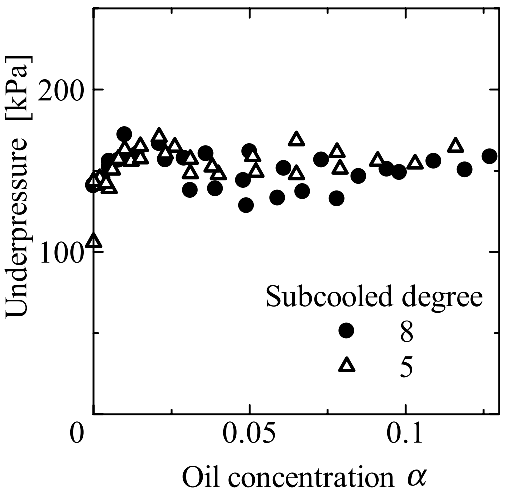

Fig.7 Underpressure versus oil concentration

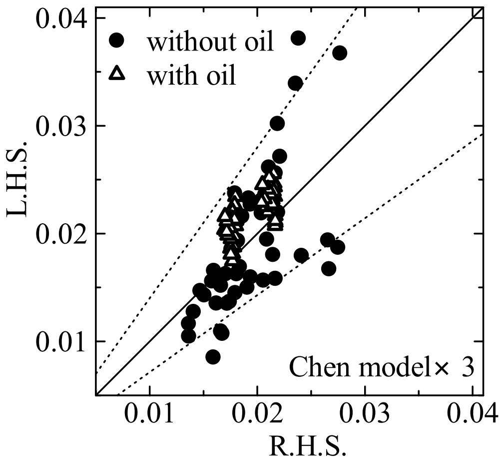

Fig8. Comparison of underpressure with Chen's Equation

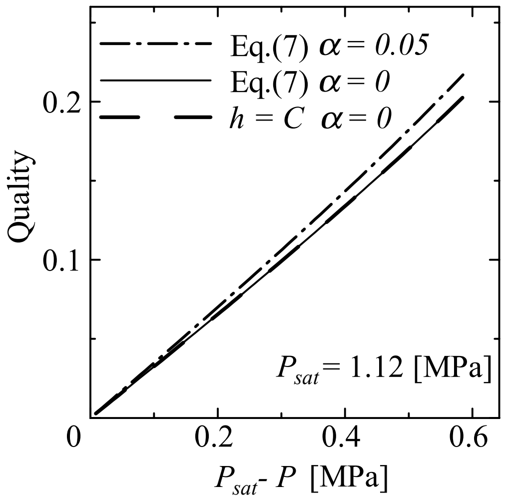

Fig.9 Quality change based on energy equation

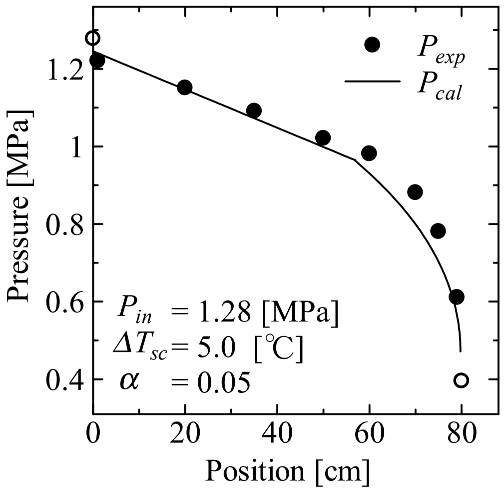

Fig.10 Pressure and temperature distributions

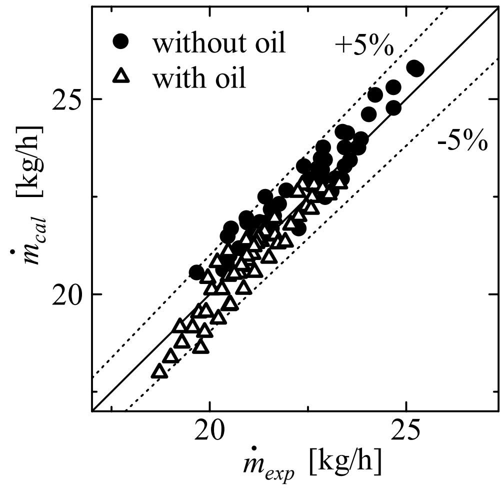

Fig.11 Comparison of calculated results with experimental ones

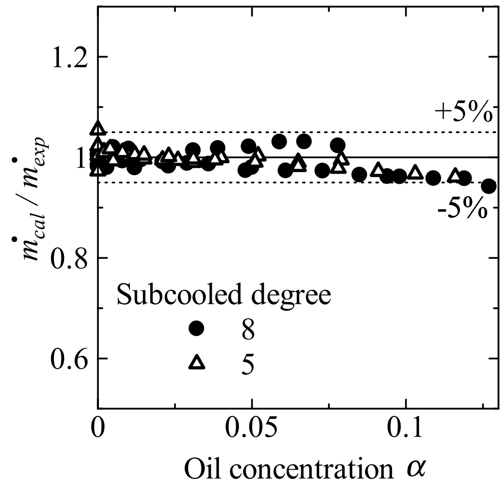

Fig.12 Influence of oil on calculation accuracy