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Numerical simulation of two-phase flow pattern of supercritical carbon dioxide with PAG-type lubricating oil in gas cooler

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ABSTRACT

It has been reported that lubricating oil has a significant influence on the cooling heat transfer of supercritical carbon dioxide. In this study, numerical analysis of the flow pattern of a carbon dioxide (CO2)-oil mixture in a gas cooler was conducted to analyze the change in oil film thickness and heat transfer coefficient against bulk temperature. Simulations were conducted using FLUENT software, and the volume-of-fluid (VOF) model was applied to capture the interface of the lubricating oil and CO2. The compatibility of lubricants was found to have a dramatic influence on cooling heat transfer. The flow regime changes due to CO2 dissolving into the oil causing changes in viscosity, surface tension, and density of the oil film. The comparison of simulated heat transfer coefficients with experimental results showed that the numerical simulation is an effective approach to analyze the characteristics of the flow and heat transfer of supercritical CO2-oil mixture, and the numerical approach proposed could be further extended to the actual gas cooler design.

1. INTRODUCTION

Carbon dioxide (CO2) has been used in heat-pump water heaters as an environmentally friendly, high-efficiency refrigerant. The shipments of the Eco-Cute CO2 heat pump water heater in Japan reached 2 million units in 2009 and keep increasing steadily. Many studies have been conducted to measure their overall system performance as well as the heat transfer characteristics of each component. One of the interesting research topics is the heat transfer characteristics of supercritical CO2, since the high pressure of the cycle is above supercritical pressures (i.e., Tanaka et al., 1967, Fang et al., 2001, Dang and Hihiha, 2004a, 2004b). It has also been found that operation in the presence of lubricating oil may have a significant effect on the flow and heat transfer performance inside the gas cooler and evaporator. Previous studies have shown that an oil concentration of 1% may result in a decrease in the heat transfer coefficient of as much as 30%–50%, mainly due to the thermal resistance of the oil film (Dang et al., 2007, 2012a). Due to the complex flow pattern and heat transfer mechanism, along with the lack of reliable thermophysical properties of the CO2-oil mixture, it is difficult to obtain a universal predictive model (Dang et al., 2008, 2012b).

In recent years, due to the development of simulation technology, particularly the free surface capturing method, two-phase flow and the heat transfer problem are increasingly being studied using the numerical simulation approach, which is low-cost and highly efficient, and it can provide detailed information on velocity and density profiles which are easily used to analyze the effects of thermodynamic properties and geometric parameters of the characteristics of flow and heat transfer. In this study, numerical simulations were conducted to study the characteristics of flow and heat transfer of supercritical CO2 with a small amount of polyalkylene glycol (PAG)-type lubricating oil entrained in order to understand the mechanism behind the flow and heat transfer and to clarify the feasibility of applying a numerical approach to the gas cooler design.
2. NUMERICAL SIMULATION MODEL

2.1 Description of the numerical simulation object

The PAG-type oil is commonly used in transcritical CO₂ heat-pump systems due to its good compatibility with the CO₂ refrigerant. However, this oil is partially miscible with liquid CO₂. Figure 1 shows the two-phase separation region of three types of lubricating oils, PAG100, PVE100, and ECP100, with CO₂ under subcritical conditions. It is seen that the PAG oil has the widest separation region. Only at extremely low oil concentrations or high oil concentrations can PAG oil become miscible with liquid CO₂. Therefore, a CO₂ heat pump may easily encounter oil return problems (Hwang et al., 2007) and the deterioration of heat transfer performance inside the evaporator.

Although there is no literature showing the two-phase separation of PAG oil from supercritical CO₂, by visual observation we found it is partially miscible, i.e., some of the CO₂ dissolves into the oil, and the oil-rich layer and the bulk CO₂ separate from each other when flowing through the gas cooler, as shown in Fig. 2. The CO₂ flows into the gas cooler from the left with the oil entrained as droplets. Inside the gas cooler, with the bulk CO₂ being cooled and accelerated, some of the oil droplets move towards the wall and are captured forming an oil film. The thickness of the oil film increases gradually with the decreasing bulk temperature till the mixture flows out of the gas cooler.

It is preferable to conduct a three-dimensional numerical simulation of the flow and heat transfer simultaneously taking into consideration the changes in thermophysical properties. However, due to the difficulty in dealing simultaneously with the changes in thermophysical properties of both the supercritical CO₂ and the oil and the change in the position of interface in the numerical simulation, in the present study, we solved the flow field in the gas cooler under an adiabatic condition by varying the inlet temperature to simulate the flow and heat transfer at different locations from the inlet. Special attention was paid to determining the thickness of the final oil film at each inlet temperature and its influence on the heat transfer coefficient by combining the heat transfer coefficient of pure CO₂ and the thermal resistance of the oil film. The interface between the oil and CO₂ was captured using a free surface tracking method.

2.2 Governing Equations

The governing equations include the conservation of mass and momentum, together with the transportation equation of turbulent energy and the dissipation of turbulent energy, as shown in Eqs. 1–4:

\[ \frac{\partial u_i}{\partial x_i} = 0, \]  
\[ \frac{\partial u_i}{\partial t} + \frac{\partial (u_i u_j)}{\partial x_j} = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_i} \left( 2(v + v_T) D_{ij} \right), \]  
\[ \frac{\partial k}{\partial t} + u_j \frac{\partial k}{\partial x_j} = P_k - \varepsilon + \frac{\partial}{\partial x_j} \left( \frac{v_T}{\sigma_k + \nu} \right) \frac{\partial k}{\partial x_j}. \]
\[
\frac{\partial E}{\partial t} + \mathbf{u}_j \cdot \nabla E = \left( C_{z1} \rho - C_{z2} \rho \right) \frac{E}{\rho} + \frac{\partial}{\partial x_j} \left( \frac{\nu}{\sigma} + \nu \right) \frac{\partial E}{\partial x_j},
\]
where \( \nu \) denotes velocity, \( \rho \) is density, \( P \) is pressure, \( \nu \) is viscosity, and \( \nu \cdot \frac{k^2}{e} \) is turbulent viscosity, determined from local turbulent energy and turbulent energy dissipation.

In the present study, special attention was paid to the flow near the wall area to simulate the thickness of the oil film, which is normally several micrometers. Therefore, for a low Reynolds number (Re), the \( k - \varepsilon \) turbulent model was adopted with the non-dimensional distance from the wall, \( y^* = \frac{\rho u_\tau y}{\mu} \), of the first node smaller than 0.1, where \( u_\tau \) is friction velocity.

2.3 Free surface capture model

The main difficulty of a numerical simulation of two-phase flow and heat transfer is how to capture the interface precisely. Several methods of capturing the free surface of two-phase flow have been proposed, including front tracking, volume-of-fluid (VOF), level set, and density function. The main strengths and weaknesses of these methods are summarized in Table 1.

<table>
<thead>
<tr>
<th>Method</th>
<th>Accuracy</th>
<th>Conservation</th>
<th>Usability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front tracking</td>
<td>○</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>VOF</td>
<td>× (SLIC)</td>
<td>○</td>
<td>△ (PLIC)</td>
</tr>
<tr>
<td>Level set</td>
<td>○ (PLIC)</td>
<td>○ (PLIC)</td>
<td>△</td>
</tr>
<tr>
<td>Density function</td>
<td>△</td>
<td>△</td>
<td>○</td>
</tr>
</tbody>
</table>

The most widely used free surface capture methods include the volume-of-fluid (VOF) and level set methods. The merit of the level set method is that although it does not explicitly calculate the interface, it gives each node a level set function showing its distance from the interface, and the interface, as well as the surface tension, can be calculated with high accuracy. Since the surface tension is the primary force to keep the interface stable, it is preferable to use the level set method in the simulation. However, the level set method was designed to be applied in a uniform grid, and it needs to be further developed to be used in a non-uniform grid layout. Therefore, the piecewise-linear interface construction (PLIC)-type VOF method, as opposed to the single-line interface construction (SLIC)-type method, was adopted in this simulation.

The effect of surface tension was converted into body force and applied to each control volume by using the continuum-surface-force (CSF) method (Brackbill et al., 1992).

2.4 Verification of the simulation model

The simulation model was first applied to the Kelvin-Helmholtz instability problem. The Kelvin-Helmholtz instability problem is an instability that arises in parallel shear flows where small-scale perturbations draw kinetic energy from the mean flow. Normally the two fluids have different densities with the denser fluid flowing along the bottom side while the lighter fluid flows along the top. When the interfacial velocity exceeds a certain value, the instability occurs, and even a tiny disturbance will generate a notable wave and eventually transition to turbulent flow.

The Richard number (\( R_i \)) can be used as a criterion for the onset of the Kelvin-Helmholtz instability of two immiscible, incompressible, and inviscid fluids, and is defined as

\[
R_i = \frac{2 \left( \rho_1 + \rho_2 \right)}{\rho_1 \rho_2} \sqrt{\frac{g \sigma (\rho_1 - \rho_2)}{u_1 - u_2}},
\]
where \( u_1, \rho_1 \) and \( u_2, \rho_2 \) denote the velocity and density of fluid 1 and fluid 2, respectively, \( g \) is gravitational acceleration, and \( \sigma \) is surface tension.
When $Ri < 1$, the interface becomes unstable even due to small perturbations. From Eq. 5, it is obvious that the Kelvin-Helmholtz instability takes place at a large interfacial velocity, a small density ratio of the lighter fluid to the denser fluid, and a small surface tension.

Numerical calculations were conducted on the basis of conditions shown in Table 2. Figure 3 shows the simulation results at 7.9 s from start at 2 different interfacial velocities of 0.4 m/s and 0.6 m/s, corresponding to $Ri$ values of 1.79 and 0.79, respectively. It is seen from Fig. 3 that at a $Ri$ greater than 1, the disturbance will attenuate and finally return to a smooth interface. However, when the $Ri$ decreases to less than 1, the disturbance will develop with time and finally become a well-mixed flow.

It was seen that the proposed simulation model is capable of simulating the onset of Kelvin-Helmholtz instability. Since the process of the breakup of oil flow and the formation of oil droplets is basically a Kelvin-Helmholtz instability problem, the same simulation model is applicable to this study.

### Table 2 Simulation of Kelvin-Helmholtz instability

<table>
<thead>
<tr>
<th>Mesh</th>
<th>x:200, y:100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>x:0.06, y:0.03</td>
</tr>
<tr>
<td>Boundary position</td>
<td>y:0.015</td>
</tr>
<tr>
<td>Density</td>
<td>Red:1000, Blue:200</td>
</tr>
<tr>
<td>Surface tension</td>
<td>0.072</td>
</tr>
<tr>
<td>Velocity difference (of $Ri = 1$)</td>
<td>0.5</td>
</tr>
<tr>
<td>Gravitational acceleration</td>
<td>9.8</td>
</tr>
<tr>
<td>Time step</td>
<td>0.01</td>
</tr>
<tr>
<td>Boundary condition</td>
<td>Top &amp; Bottom: Slip wall, Right &amp; Left: Periodic</td>
</tr>
</tbody>
</table>

**Figure 3 Simulation of Kelvin-Helmholtz Instability (flow time = 7.9 s)**

#### 2.5 Thermodynamic properties

Since the adiabatic flow is calculated, the thermodynamic properties of CO$_2$ can be assumed to be constant during the simulation, and they are calculated as the function of inlet temperature and pressure by using the REFPROP software (ver. 8); the thermodynamic properties of oil (film and droplet) are a function of the solubility of CO$_2$ into oil, and the thermodynamic properties of both the oil and CO$_2$. According to measurement data provided by the oil company, the thermodynamic properties of PAG oil are correlated as a function of temperature as follows:

- **Density**: $\rho_{oil} = 1000 - 0.0008(T - 15)$, (6)
- **Viscosity**: $\log\log(\nu_{oil} + 0.8) = -2.423748\log(T + 273.15) + 6.355036$, (7)
- **Thermal conductivity**: $\lambda_{oil} = -0.0000247T + 0.1477$, (8)
- **Specific heat**: $c_p = 3.35T + 1758.17$. (9)

where $T$ is temperature in °C, $\rho$ is density, $\nu$ is viscosity, $\lambda$ is thermal conductivity, and $c_p$ is specific heat.

The solubility of CO$_2$ into PAG oil was measured by Nagahama et al. (2001) and rearranged in Eq. 10. The solubility is primarily affected by the temperature; at a pressure of 8–10 MPa, the effect of pressure on solubility is not remarkable; therefore, only the effect of temperature is considered here:

$$ w = 0.006897T^2 - 1.418688T + 81.79. $$

The thermodynamic properties of oil film (or droplets) change with dissolving CO$_2$ into the oil, which can be expressed as a function of the solubility of CO$_2$ in oil and the thermodynamic properties of both the CO$_2$ and oil according to a traditional mixing function:
\[ \frac{1}{\rho_m} = 0.01w/\rho_{CO2} + (1 - 0.01w)/\rho_{oil}, \]  
\[ \mu_m = \left( x \mu_{CO2}^3 + (1 - x) \mu_{oil}^3 \right)^{\frac{1}{3}}, \]

where \( x \) denotes the molar fraction of CO\(_2\) in the CO\(_2\)-oil mixture and is determined from mass fraction \( w \) and the molecular weights of CO\(_2\) and PAG oil. The average molecular weight of PAG100 oil is 1600 g/mol.

\[ x = \frac{0.01w/44}{0.01w/44 + (1 - 0.01w)/1600} \]

\[ \lambda_m = 0.01w\lambda_{CO2} + (1 - 0.01w)\lambda_{oil} - 0.72 \times 0.01w(1 - 0.01w)(\lambda_{oil} - \lambda_{CO2}) \]

\[ c_{p,m} = 0.01wc_{p,CO2} + (1 - 0.01w)c_{p,oil} \]

In addition, experimental measurements of the thermophysical properties of a CO\(_2\)-PAG oil mixture, including the solubility of CO\(_2\) in PAG-type oil, and the corresponding density and viscosity, were conducted, and the following property correlations were proposed (Kim et al., 2007):

Solubility:
\[ w = (3.32P + 29.5) \times \exp(-1.60 \times 10^{-2}T) \]

Density:
\[ \rho_m/\rho_{oil} = -8.22 \times 10^{-4}T + 1.022 \]

Viscosity:
\[ \ln \mu_m = x \ln \mu_{CO2} + (1 - x) \ln \mu_{oil} + x(1 - x)G_i(w) \]

where \( G_i(w) \) is the interaction factor and is obtained from experimental results:
\[ G_i(w) = -5.85 \times 10^{-2}w^2 + 5.67w - 32.8 \]

In order to clarify the effect of viscosity on the flow and heat transfer of the CO\(_2\)-oil mixture, both the viscosity derived from the mixing function in Eq. 12 and the viscosity directly measured in Eq. 18 were applied in the simulation. As will be shown in a later chapter, the viscosity had a significant effect on the film thickness, and more detailed measurements on the thermophysical properties are needed.

Another important property, surface tension, remains unresolved. There is no theoretical or experimental result concerning the surface tension of oil inside a supercritical CO\(_2\) environment. In this report, the surface tension was given as a function of the surface tension of CO\(_2\) and PAG oil, neglecting the effects of temperature and pressure.

\[ \sigma_m = x\sigma_{CO2} + (1 - x)\sigma_{oil} \]

2.6 Boundary conditions

In this study, numerical simulations were conducted for a two-dimensional flow inside a circular tube with an inner diameter of 2 mm. A low-Re \( k-\epsilon \) model was applied to calculate the turbulence viscosity. A second-order precision upwind scheme was adopted for velocity. The interaction of pressure and velocity was calculated using a SIMPLE scheme. A first-order precision scheme was adopted for time. A PLIC-VOF scheme was adopted to capture the free surface. FLUENT software ver. 6.3 was used to conduct the simulation.

Unsteady simulations were conducted in order to obtain the transition of the oil film from the initial condition and the average thickness of the oil film under different conditions. The change in oil film thickness 50 mm and 75 mm downstream of the inlet was monitored together with outlet pressure. A steady state was obtained when these parameters were kept constant. The location 50 mm downstream was selected because it is outside the entrance region, and the 75 mm location was selected as the midpoint between the end of the entrance region and the outlet of the simulation region.

Detailed boundary conditions are illustrated in Fig.4.
3. SIMULATION RESULT AND DISCUSSION

3.1 Simulation conditions

The simulation conditions are shown in Table 3.

<table>
<thead>
<tr>
<th>ID [mm]</th>
<th>Oil type</th>
<th>Pressure [MPa]</th>
<th>Mass Flux [kg/(m²·s)]</th>
<th>Oil flow rate [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>PAG</td>
<td>8</td>
<td>800</td>
<td>0.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Density</th>
<th>Viscosity</th>
<th>Surface tension [mN/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>Oil</td>
<td>REPRO (ver. 8)</td>
</tr>
<tr>
<td>cal-1</td>
<td>Eq. 6</td>
<td>Eq. 12</td>
</tr>
<tr>
<td>cal-2</td>
<td>REPRO (ver. 8)</td>
<td>Eq. 18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

3.2 Pressure drop

First, the pressure drop was computed and compared with the experimental results of our previous study as shown in Fig. 5. Since the calculation can only be conducted for a relatively short length (100 mm in this study), and the measurements were conducted for a tube 500 mm long, the measured pressure drops were divided by 5 so they could be compared directly with the measurements for the shorter tube in the simulation. Both the measurement results and simulation results showed a similar tendency for the change in pressure drop with temperature. With an increase in temperature, the pressure drop increased, mainly due to the decrease in the density of bulk CO₂, and the increase became dramatic at the pseudocritical temperature. However, the simulated pressure drops are about 50% higher than those of the measured results. A possible reason for this may be due to the pressure drop in the entrance region, since the effect in the entrance region is more significant for the shorter tube than that for the longer tube.

3.3 Velocity profile and the film thickness

Figure 6 shows the simulated density and velocity profile. The blue region shows the flow of CO₂, while the red region shows the flow of oil. The oil film thickness shown in the figure is about 4 μm. The velocity profile showed that the flow inside the oil film is laminar flow, since the velocity increases linearly with the distance from the wall, while inside the CO₂ region, the flow is turbulent flow, and the velocity increases dramatically at a thin layer close to the wall.
interface. These results imply that the overall heat transfer coefficient can be calculated by combining the heat transfer coefficient of bulk CO2 with the thermal resistance of the oil film.

The sensitivity of the initial film thickness condition is discussed by comparing the calculated results at initial thicknesses of 10 μm and 50 μm, as shown in Fig. 7. It is seen from the figures that inside the entrance region, both the velocity profile and the final oil thickness change with the initial condition of the oil film—the larger the initial oil thickness, the longer entrance region is. However, the initial oil film thickness does not affect the final film thickness. In an extreme example, even with all the oil entering the test section as oil droplets, the oil film may form gradually when a sufficient amount of oil droplets adheres to the wall. As long as the test tube is long enough, the final oil film thickness is the same, which is determined by the interaction of the entrainment of oil droplets from the oil film and the movement of oil droplets back to the oil film.

![Figure 7 Influence of initial film thickness](image)

(a) $\delta_{ini} = 10 \mu m$ (final film thickness 3.96 μm)  
(b) $\delta_{ini} = 50 \mu m$ (final film thickness 4.08 μm)

In order to clarify the effects of thermodynamic properties on the flow and heat transfer, simulations were conducted at 5 different bulk temperatures of 30, 33, 35, 37, and 40 °C. Since the pseudocritical temperature at 8 MPa is about 34.5 °C, at which the thermophysical properties including density and viscosity change dramatically, the temperature conditions were selected to show the effect of property changes when the temperature crosses the pseudocritical temperature. The density profile for the entire calculation region is shown, together with an enlarged view of the density profile and velocity profile, to show the oil film wave and the entrained oil droplets in the local area. Please note that only the change near the wall region, 100 μm from the wall, is shown, since the oil film is very thin compared to the tube diameter.

![Figure 8 Calculated oil film wave](image)

Figure 8 Calculated oil film wave ($T = 30 °C$, cal-1)
Figure 9 Calculated oil film wave ($T = 33^\circ C$, cal-1)

Figure 10 Calculated oil film wave ($T = 35^\circ C$, cal-1)

Figure 11 Calculated oil film wave ($T = 37^\circ C$, cal-1)
Since for all the conditions simulated, $Ri$ is less than 1, the initially given oil film cannot remain stable; part of the liquid film may break up, and the excessive oil may be entrained by the bulk CO$_2$ and may flow as droplets. As the oil film becomes thin enough, the shear force from the wall helps the oil film remain stable, and thus a final stable wave may be obtained. If the viscosity is negligible, the flow can be assumed to be a potential flow, and the $Ri$ number can be adopted as a criterion for the oil film instability. However, due to the noticeably high viscosity of the oil film, the actual oil film profile can only be determined from the numerical simulation. It is seen from Figs. 8–12 that with the increase in temperature, the average thickness of the oil film decreases, which is attributable to the increased velocity of the bulk CO$_2$ with increasing temperature. The higher the bulk velocity, the easier the oil film breakup resulting in a thinner oil film is. However, the increase in temperature also leads to a decrease in the solubility of CO$_2$ in oil resulting in an increase in the surface tension and viscosity, and a decrease in the density ratio between the CO$_2$ and oil, which are all necessary to keep the oil film stable. As summarized in Table 5, the simulated oil film thickness decreases with the temperature under the conditions simulated in this study. However, the oil film thickness does not decrease monotonously with temperature, particularly in the pseudocritical temperature region.

Figure 13 shows the simulation results using the same thermophysical properties but a higher viscosity for the mixture. The simulated average oil film thickness is 15 µm, about 3 times that at lower viscosity as shown in Fig. 8. In addition, the wavelength is longer than that obtained at a lower viscosity.
4. HEAT TRANSFER COEFFICIENTS

After obtaining the averaged oil film thickness, the heat transfer performance of the supercritical CO$_2$ with PAG-type oil presence can be evaluated by considering the heat transfer coefficient of pure CO$_2$ and the effect of the thermal resistance of the oil film:

$$\alpha_{\text{CO}_2,\text{Oil}} = \frac{1}{\alpha_{\text{CO}_2} + \delta/\lambda_{\text{Oil}}}.$$  \hspace{1cm} (22)

where $\delta$ denotes the simulated average oil film thickness, and $\lambda_{\text{Oil}}$ is the thermal conductivity of the oil film as shown in Eq. 14.

Table 4 shows the density and viscosity conditions of each simulation, and Table 5 shows the thermal conductivity of the oil film and the simulated oil film thickness and calculated heat transfer coefficient according to Eq. 22 and the results depicted in Fig. 14. The solid line in Fig. 14 shows the change in the heat transfer coefficient of supercritical CO$_2$ against bulk temperature, which increases with temperature at low temperatures, obtaining a peak value in the pseudocritical temperature region, and then decreases at higher temperature. The black solid square symbols show the measured heat transfer coefficient of the CO$_2$ in the presence of oil at an oil concentration of 1%, which is about 30–50% lower than that of pure CO$_2$. The red hollow squares and triangles show the calculated heat transfer coefficient according to Eq. 22 using the viscosity from Eq. 12 and Eq. 18, respectively. Obviously, the heat transfer coefficients calculated by considering the effect of oil film resistance and using the oil viscosity from Eq. 12 fit the experimental results reasonably well.

<table>
<thead>
<tr>
<th>Temperature [°C]</th>
<th>Case</th>
<th>Density [kg/m$^3$]</th>
<th>Viscosity [Pa·s]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CO$_2$</td>
<td>Oil</td>
</tr>
<tr>
<td>30</td>
<td>cal-1</td>
<td>711</td>
<td>843</td>
</tr>
<tr>
<td></td>
<td>cal-2</td>
<td>603</td>
<td>783</td>
</tr>
<tr>
<td>33</td>
<td>cal-1</td>
<td>431</td>
<td>652</td>
</tr>
<tr>
<td></td>
<td>cal-2</td>
<td>317</td>
<td>547</td>
</tr>
<tr>
<td>37</td>
<td>cal-1</td>
<td>282</td>
<td>521</td>
</tr>
<tr>
<td></td>
<td>cal-2</td>
<td>15.3</td>
<td>13.6</td>
</tr>
</tbody>
</table>

It is seen from the comparison that the numerical simulation can give a reasonable interpretation of the deterioration of the heat transfer performance of supercritical CO$_2$ in the presence of oil. By resolving the governing equations of mass conservation and momentum conservation, together with properly predicting the location of the interface, the oil film thickness could be determined. This approach is feasible to be extended to actual gas cooler design and performance evaluation by extending the simulation model to three dimensions and collecting more accurate information concerning the thermophysical properties of the oil-CO$_2$ mixture.

<table>
<thead>
<tr>
<th>Temperature [°C]</th>
<th>30</th>
<th>33</th>
<th>35</th>
<th>37</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductivity of oil film [W/(m·K)]</td>
<td>0.103</td>
<td>0.106</td>
<td>0.110</td>
<td>0.094</td>
<td>0.092</td>
</tr>
<tr>
<td>Oil film thickness [μm]</td>
<td>cal-1</td>
<td>5.84</td>
<td>5.44</td>
<td>4.08</td>
<td>3.63</td>
</tr>
<tr>
<td>Heat transfer coefficient [W/(m$^2$·K)]</td>
<td>cal-1</td>
<td>4416</td>
<td>6524</td>
<td>10616</td>
<td>7442</td>
</tr>
<tr>
<td></td>
<td>cal-2</td>
<td>15.3</td>
<td>13.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>cal-2</td>
<td>2146</td>
<td>5539</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 14 Heat transfer coefficient vs. temperature
5. CONCLUSIONS

This study was the first attempt to understand the mechanism of flow and heat transfer of a CO₂-oil mixture inside a gas cooler using a numerical simulation. The main difficulty of such a simulation was how to determine the position of interface of the two fluids and to obtain reliable thermodynamic properties. From the comparison between the simulation results and experimental results, the main conclusions can be summarized as follows:

1. It was confirmed that the oil film thickness varies due to changes in physical properties.
2. With an increase in temperature, the simulated oil film thickness decreases.
3. The proposed simulation model was able to capture the qualitative changes in the heat transfer rate and these changes were comparable to the experimental results of previous studies.
4. The numerical simulation model can be further extended to the actual design and performance simulation of a real gas cooler.

Future work includes the development of a simulation model for simultaneously simulating flow and heat transfer with the change in the thermophysical properties of both CO₂ and oil and extending the model to three dimensions.

REFERENCES

Nagahama K., Yamato K., 2001, Phase equilibrium and density measurement of CO₂ + lubricating oil applied in CO₂ heat pump cycle, Proceedings of the 2001 JSRAE Annual Conference, 185-188.