VISUALIZATION STUDY FOR FORCED CONVECTION HEAT TRANSFER OF SUPERCRITICAL CARBON DIOXIDE NEAR PSEUDO-BOILING POINT

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Abstract

For development of new reactor, supercritical water is expected to be used as coolant to improve thermal efficiency. However, the thermal characteristics of supercritical fluid is not revealed completerly because its difficulty for experiment. Specific phenomena tend to occur near the pseudo-boiling point which is characterised by a temperature corresponding to the saturation point in ordinary fluid. Around this point, the physical properties such as density, specific heat and thermal conductivity are drastically varying. Although there is no difference between gas and liquid phases in supercritical fluids, a phenomenon similar to boiling (with heat transfer deterioration) can be observed around the pseudo-boiling point.

Experiments of heat transfer have been done for supercritical fluid in forced convective condition. However, these experiments were mainly realised inside stainless steel cylinder pipes, for which flow visualisation is difficult. Consequently, this work has been devoted to the development of a method allowing the visualisation of supercritical flows. The experimental setup is composed of a main loop and a test section for the visualisation. Carbon dioxide is used as test fluid. Supercritical carbon dioxide flows upward in a rectangular channel and heated by one-side wall to generate forced convection heat transfer. Through a window at mid-height of the test section, shadowgraphy was applied to visualize density gradient distribution. The behavior of the density wave in the channel is visualised and examined through the variation of the heat transfer coefficient.

Background

For developing a new reactor using supercritical water as a coolant[1], the importance of the heat transfer characteristics of supercritical fluids has been increased because its thermal dynamic behavior is quite different from the ordinary fluid. As shown in Figure 1, the physical properties of the supercritical fluid are highly varied around the critical point. The specific heat has a sharp peak at the pseudo-critical point. Pseudo-critical point is correspond to the saturation point of ordinary fluid.

Experimental or numerical studies about the forced convection heat transfer to the supercritical fluid have been developed since 1960s. Results of these previous studies revealed lots of unique phenomena of the heat transfer to the supercritical fluids. For example, the heat transfer deterioration from the heated surface to the fluid in higher pressure than that of the pseudo-critical area is well known[2][3]. The heat transfer coefficients also vary greatly around the critical temperature point influenced by increasing specific heat. Under this condition, unusual decrease and oscillation of the heat transfer coefficient were observed experimentally and numerically.

For example,Tanaka *et al.*[4][5] experimentally proved that the heat transfer coefficient near the critical point decrease when the heat flux is considerably high, with extension of the theory of the turbulent convection heat transfer.

Koshizuka *et al.*[6] performed a numerical analysis that agreed well with experimental data. They classified the mechanisms of the heat transfer deterioration phenomena of the supercritical water in a circular tube which involved flow rates. They found that viscosity increases locally near the heated wall by the heat input when the flow rate was higher. The viscous sub-layer became thicker and the Prandtl number smaller.

These phenomena which are quite different from non-critical fluid have been explained with lots of theories of thermal fluid dynamics and molecular dynamics. One category of them is to consider it as a single-phase flow, and the other is to consider as a two-phase flow. The single-phase theory explains that some parts of phenomena are attributed to the turbulent flow by excessive changes of the physical properties while other conditions such as boiling-like phenomenon can be shown like ordinary flow by the two-phase theory. These theoretical differences have not been solved completely yet.

In some theories, one of the factors involving these unique heat transfer is thought to be the pseudo-boiling. Although supercritical fluid has no clear distinction between liquid or gas in principle, there still remains the surface tension and the pseudo-boiling even occur. The density of the carbon dioxide along temperature is shown Figure 1. The critical point of the carbon dioxide are the pressure of 7.4MPa and the temperature of 31.4°C. Under this pressure, there is a saturation temperature where the density gradient becomes non-continuous. Over critical pressure, this is correspond to pseudo-critical temperature. The pseudo-boiling is generated near the pseudo-critical temperature. Using an enclosure cell, many visualized observation has been accomplished for pseudo-boiling around the critical point in natural convection. Although these experiments showed successful results which shows that the pseudo-boiling does exist and it appears like nucleate boiling or film boiling as ordinary fluid, forced convection data are limited.

Therefore, the flow visualization study for forced convection is thought to be required to provide useful knowledge to investigate the theoretical assumptions of the supercritical fluids.

Although the visualized measurements for natural convection of the supercritical fluid in an enclosure cell have been performed by many previous researchers, few flow visualization technique has been applied for measurements of the forced convection heat transfer of the supercritical fluids because of the experimental difficulties for high pressure and temperature. Furthermore, as a technical problem for visualization, the densities of the supercritical fluids varying continuously with pressure and temperature are considerably higher than those of the incompressible fluids. Because the density is the main parameter to determine the refractive index, it is so hard for the optical methods such as an interferometry or a particle imaging velocimetry(PIV) to measure those large variations of physical properties. Therefore, some phenomena such as pseudo-boiling in forced convection heat transfer have never been confirmed by the flow visualization.

Thus, the flow visualization of the supercritical fluid has been tried in this study.

The forced convection heat transfer of the carbon dioxide flow at the supercritical conditions in the vertical rectangular channel has been visualized by shadowgraphy to observe the density gradient distribution and the flow behavior especially involved the pseudo-boiling and analyze its characteristics according to the thermal conditions of the flow.

The heat transfer from the wall to the supercritical fluid should be affected by many physical parameters. Several pictures were recorded with variations of the pressure, bulk temperature and heat load in this study. These pictures showed relations between flow behavior around pseudo-critical point and heat transfer coefficient.

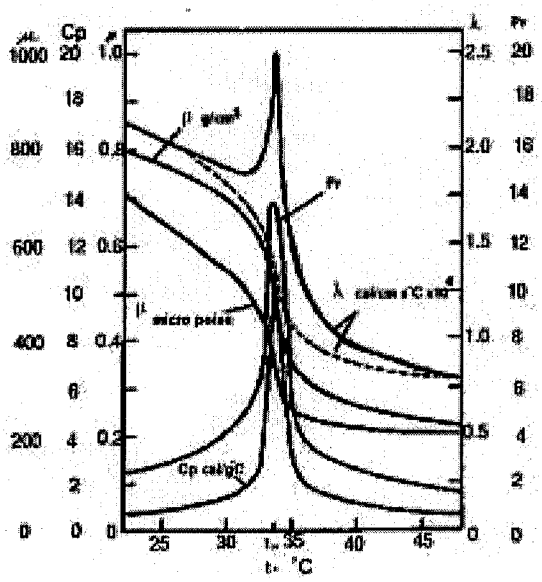

Figure 1: Physical properties of carbon dioxide(P=8MPa),[4]

Experimental setup

The forced convection heat transfer of the supercritical carbon dioxide around the pseudo-boiling point have been visualized with the experimental setup in the loop shown in Figure 2.

Pipes were made of stainless steel to endure high pressure to 15 MPa and the temperature over 100°C. The carbon dioxide is supplied in the tank with the pressure the 5MPa in room temperature initially.

Other parts of the loop worked as follows:

- Water coolant tank: to cool the heated carbon dioxide from the test sectio n to 10 °C by the coolant water in the pipes
- Chiller unit: to cool the carbon dioxide under 5°C in order to turn it into the liquid phase
- Diaphragm pump: to increase the pressure from 5 MPa to 15MPa and circulat e the liquid carbon dioxide. Frequency of two pistons is 81 Hz each. Piston stroke of the pump defines the flow rate from 0 to 155L/H, 3.4×10^{-5} m^3/s.

- Control valve: to control the pressure around the test section area, which is electrically manipulated.
- Preheater: to set a bulk temperature of the flow between 30 and 80 °C initially.

Through after the control valve, the fluid goes back to the coolant tank.

Pressures at several sections were measured by pressure gauges as shown in Figure 2.

A critical point of the carbon dioxide is as follows.

- temperature: 31.1°C
- pressure : 7.38 MPa
- density : 468 kg/m^3

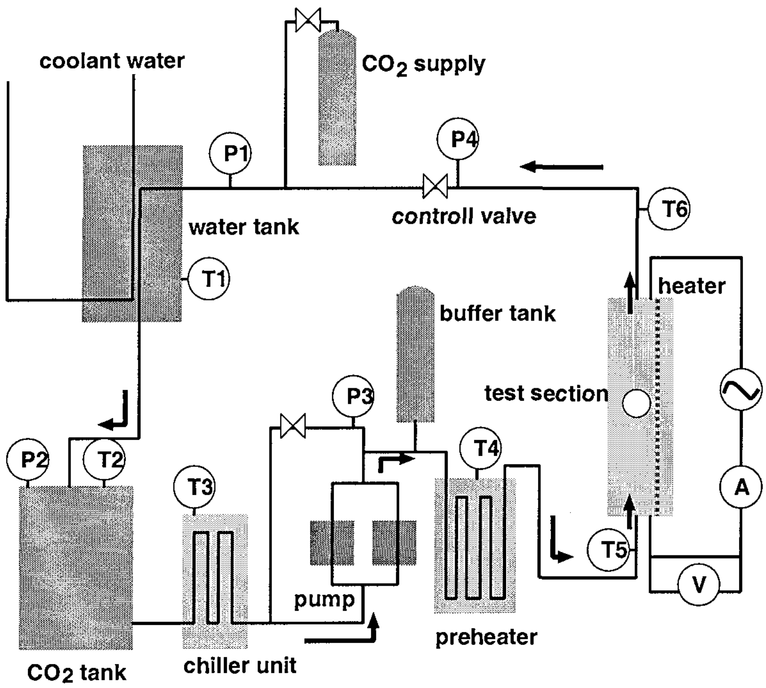

Figure 2: shematic view of the main loop

The test section in this experiment was made of stainless cylinder, a copper wall which is installed micro heaters, window glasses for high pressure, and 4 thermocouples. Schematic view of the testsection is shown in Figure 3 and 4.

The length of the channel in the test section unit is 600 mm, the size inside is 10 mm x 20 mm. Fluid is heated by the one-side wall. In the middle of the test section, there are windows for visualization with the diameter of 23 mm and the glass which thickness is 75 mm at each side to endure the high pressure.

Four thermocouples were installed to measure the flow and wall temperatures. One of them was placed in the center of the channel to obtain the bulk temperature of the fluid. Other thermocouples were set in the copper wall at the different positions from the wall surface in order to obtain the local heat flux of the heater and the wall surface temperature.

- T_{bulk}: bulk temperature of flow near the window
- T_a: temperature at 2mm from heated surface
- T_b: temperature at 4mm from heated surface
- T_c: temperature at 6mm from heated surface

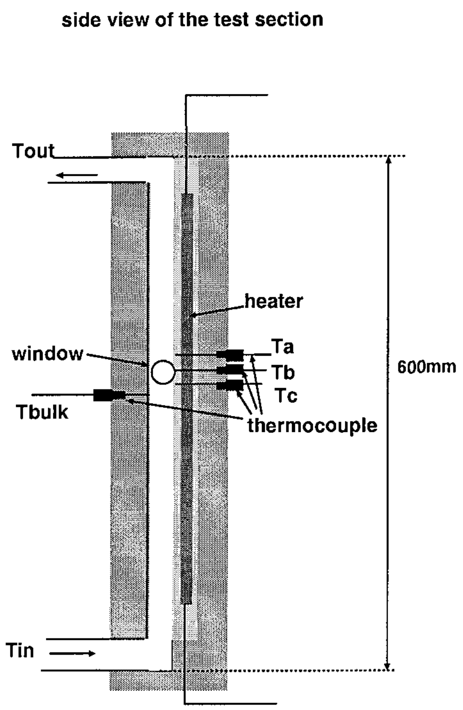

Figure 3: view of the testsection

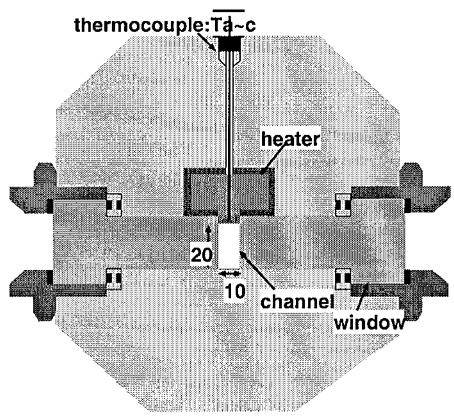

Figure 4: view of the testsection

To measure the forced convection heat transfer around pseudo-critical point, each parameters such as pressure, bulk temperature, and heat load were varied across pseudo-critical point. Ranges of each parameter is shown as follows.

- 1: pressure variation experiment (P=8 - 10 [MPa])
- 2: heat load variation experiment: (Q=400 - 1260 [W])
- 3: bulk temperature variation experiment: (T_{bulk}=35 - 45[°C])

In this experiment, P=9.0[MPa], T_{bulk}=40[°C] and Q=600[W] is defined as a basical condition. Mass flow rate was set 26[g/s] in every cases. When one parameter was varied, other parameters were fixed on basical values. P=9.0[MPa],T_{bulk}=40[°C] is one of the pseudo-critical condition.

As a visualization method, shadowgraphy was applied for this experiment. Shadowgraphy is the simplest technique to observe the refractive index variation in a target field. When light propagetes in heterogenius medium, it will be deflected from a original path by the gradient of its refractive index field. Therefore a point which original ray would reach will be dark. Refractive index is mainly affected by the density of the fluid. In this testsection, the density is proportional to the temperature of the fluid because pressure is controlled to be constant value. Such dark area implies density or temperature gradient. However this method is not quantitative measurement, it may show the structure of the density wave or flow behavior in the pseudo-boiling condition. In this experiment, halogen lump was used as a light source. The light passing through the testsection was captured by the high-speed video camera by 2000 frames per second.

Results

The heat transfer coefficient in experiment 1 is shown in Figure 5. As the pressure increases across the pseudo-critical point(P=9[MPa]), the heat transfer coefficient also increase by 9.4MPa. Then it begin to decrease. In this situation the peak of the heat transfer coefficient is around 9.2MPa. Shadowgraphy images in these pressures are shown in Figure 8. These are close-up images near the wall. Black area at left side is the heated wall. Density wave appear as dark lines. If the pressure is higher than the pseudo-critical point, supercritical fluid behave like in liquid phase. In 10[MPa] image, density wave generated by thermal convection near the wall can be seen cleary compared to image of 8MPa. In this image, fluid behave like gas-phase. Because the density of fluid in this condition is relatively low, clear dark lines can be hardly recognized and the heat transfer get decrease.

When the heat load was varied to 1260W, density wave in the channel is highly developed. That image is shown in Figure 9. Dark lines of the density wave was appear strongly all over the image not only the near of the wall. With decreasing the heat load to 400W, this density wave was weakened and finally can be seen only near the wall. Measured heat transfer coefficient in this condition is shown in Figure 6. Heat transfer coefficient decrease as the heat load increase.

Figure 10 shows images in experiment 3. When T_{bulk} is lower than pseudo-critical temperature, shadowgraphy is like right images(T_{bulk}=35[°C]). In this condition dark layer of the density gradient can be seen only near the wall. This dark layer is visible when the T_{bulk} is lower than the pseudo-critical point. If T_{bulk} is higher than the pseudo-critical temperature, 40°C, this dark layer vanished and density distribution is gently decrease from the wall to the other side of the channel. In this condition, all over the image is seem to be half-dark. Across the pseudo-critical point, the heat transfer coefficient also varied with T_{bulk} as shown in Figure 7. Where T_{bulk} is higher than the pseudo-critical temperature, supercritical fluid behave like gas phase resulting low heat transfer coefficient.

Conclusion

Forced convection heat transfer of the supercritical CO_2 around pseudo-critical point was investigated by the thermal hydraulic measurement and flow visualization technique. Shadowgraphy images show the density wave caused by thermal convection. Differences of the images between each case were verified with heat transfer coefficient.

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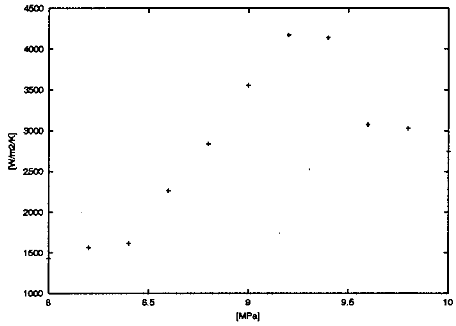


Figure 5: heat transfer coefficient in experiment 1

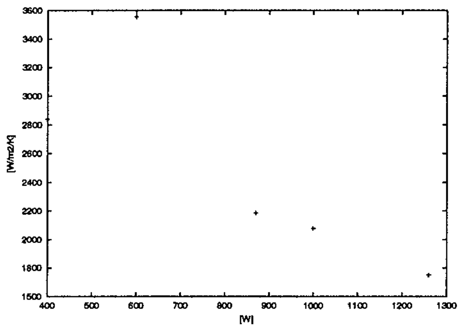


Figure 6: heat transfer coefficient in experiment 2

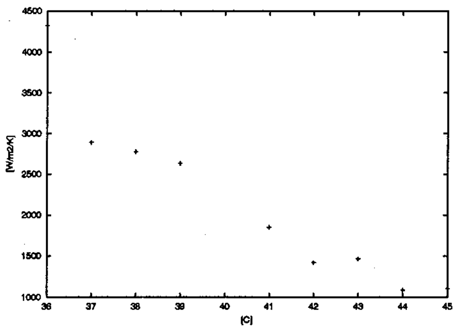
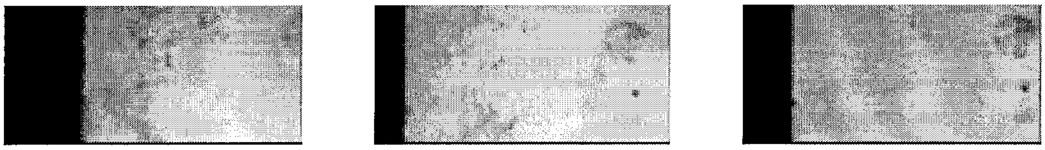


Figure 7: heat transfer coefficient in experiment 3



p=10.0(MPa) p=9.0(MPa) p=8.0(MPa)

Figure 8: shadowgraphy images in experiment 1

q=1260(W) q=400(W)

Figure 9: shadowgraphy images in experiment 2

Tbulk=45(C) Tbulk=35(C)

Figure 10: shadowgraphy images in experiment 3