NATURAL CONVECTIVE COOLING HEAT TRANSFER OF CO_2 AT THE SUPERCRITICAL PRESSURE

I. ISHIHARA[a], H. MORI[b], R. MATSUMOTO[a]

[a] Department of Mechanical Engineering, Kansai University,
3-3-35 Yamate-cho, Suita, Osaka, 564-8680 Japan
Fax: +81-6-6388-8785, e-mail: ishihara@kansai-u.ac.jp

[b] Air-Conditionings & Refrigeration Systems Headquarters, Mitsubishi Heavy Industries LTD.
3-1 Asahi-machi, Nishi-biwajima-cho, Nishi-Kasugai-gun, Aichi Prefecture, 452-8561 Japan

ABSTRACT

The present paper deals with the natural convective cooling heat transfer along the outside of the vertical cooled cylinder (heat transfer surface), which is obtained experimentally near the critical point at the supercritical pressure. Experiments were performed with changing in parameters: the CO_2 fluid pressure P_v=7.4, 7.5 and 7.6MPa, temperature of the heat transfer surface T_w being the pseudocritical temperature Tpsc and higher, temperature difference ΔT_v between T_w and the CO_2 fluid temperature T_v; ΔT_v=0-30K. The state and flow of the CO_2 fluid near the heat transfer surface was observed and the temperature distribution of the CO_2 fluid adjacent to the surface was measured. The local heat flux and heat transfer coefficient were obtained and discussed in connection with above measurements and transport properties of the CO_2. The "condensation-like" phenomenon was observed and the heat transfer characteristics have a close similarity to the condensation heat transfer obtained in the subcritical region.

1. INTRODUCTION

The CO_2 is used as one of the natural working refrigerants and works in the cooling process at the supercritical pressure, where the properties vary remarkably with both the pressure and temperature. This means that the characteristics of the CO_2 fluid flow and heat transfer depend strongly on the pressure and temperature.

The present paper deals with the natural convective cooling heat transfer along the outside of the vertical cooled heat transfer surface, which is obtained experimentally near the critical point at the supercritical pressure. For the subcritical region, present authors have been researched (Ishihara *et al*., 1994, 1995, 1996, 1996, 1997, 2002), (Okuno *et al*., 1996), (Kuroda *et al*., 1999), (Mori *et al*., 2001). Although the CO_2 works in the refrigerators under the forced convection in the small diameter tube, natural convection makes easy to observe the flow along the heat transfer surface and to measure the temperature of the CO_2 fluid adjacent to the heat transfer surface. And these results would be very helpful to good understandings of the dependence of the properties on the forced convective flow and heat transfer.

In case of the heat transfer from the heated surface in the supercritical pressure, the "boiling-like" phenomenon is well known and Nishikawa *et al*. (1962, 1965, 1972, 1974, 1973) and Yamagata *et al*. (1966) reported in their pioneering papers, and also Knapp *et al*.(1966), Goldstein *et al*. (1968) and Hahne *et al*.(1974) presented. On the contrary, the "condensation-like" phenomenon could be suggested. However, no report is found.

Experiments were performed with changing in parameters: the CO_2 fluid pressure P_v=7.4, 7.5 and 7.6MPa, temperature of the heat transfer surface T_w being the pseudocritical temperature T_{psc} and higher, temperature difference ΔT_v between T_w and fluid temperature T_v; ΔT_v=0-30K.

The state and flow of the CO_2 fluid near the heat transfer surface was observed and the temperature distribution of the fluid adjacent to the surface was measured. The local heat flux and heat transfer coefficient were obtained and discussed in connection with above measurements and transport properties of the CO_2. The ”condensation-like” phenomenon was observed and the heat transfer characteristics have a close similarity to the condensation heat transfer obtained in the subcritical region.

2. EXPERIMENTS AND PROCEDURE

Figure 1 shows the pressure vessel (1) made of Stainless steel with 234mm inner diameter and 860mm height and the heat transfer surface (2) shown in detail in Figure 2 is vertically installed on the inside of the upper flange of the pressure vessel. An electric heater (3) is located on the bottom of the vessel. The heat transfer surface has 40mm diameter and 200mm length, and the 150mm length of the surface was covered with thermal insulator and then, the effective cooling surface exposed to the CO_2 fluid is 50mm length. This part can be observed through the observation windows of the pressure vessel. The heat transfer surface was cooled from inside, in which temperature regulated cold water flows from a refrigerator. In order to measure the surface temperature and heat flux, a thermocouple is attached at inside wall and another is embedded from inside to the outer surface at x=30mm from top of the heat transfer surface. At the same vertical level as these thermocouples, a comb type thermocouple shown in Figure 3 was located to measure temperature distribution of the fluid adjacent to the heat transfer surface. The distance of these five thermocouples from the heat transfer surface is 0.6, 1.6, 2.3, 3.3 and 6.0mm respectively. The CO_2 fluid temperature was measured at 160 and 300mm from the lower flange and at 150mm from the bottom of the surface in the centre line of the vessel and at 25mm apart from the centre level of the heat transfer surface. These four temperature measurements indicated the same within 0.1K. All of the temperature data was stored in a data acquisition devise and was sent to a computer.

The experiment procedure is as follows; under the room temperature, after air is evacuated from the inside of the pressure vessel up to about 0.1 Pa, CO2 gas is charged and evecuated again. This procedure, the evacuation of air and charge of CO2 was repeated five times. Afterward, a certain amount of CO2 corresponding to the experimental condition was charged at the saturated state under the room temperature, and the pressure in the vessel depend on the amount of CO2, cooling rate and heating rate by the electric heater. All of the temperatures were measured under steady conditions and also the state and flow of the fluid on/near the heat transfer surface were observed and taken by a still camera and a video camera.

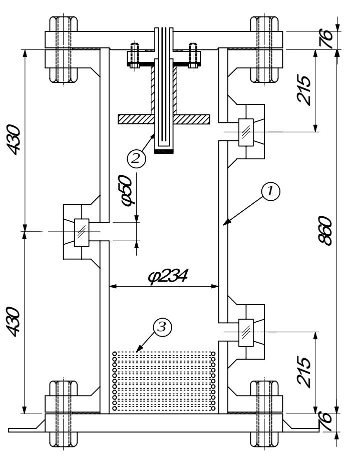


Fig.1 Pressure vessel and installations of transfer surface and electric heater

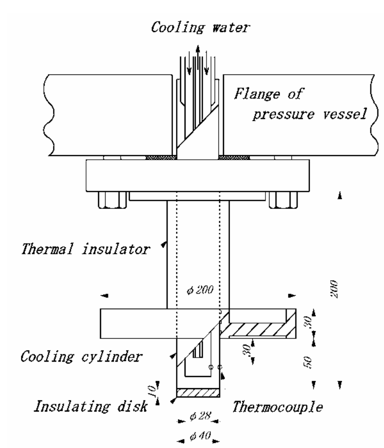


Fig.2 Details of heat transfer surface

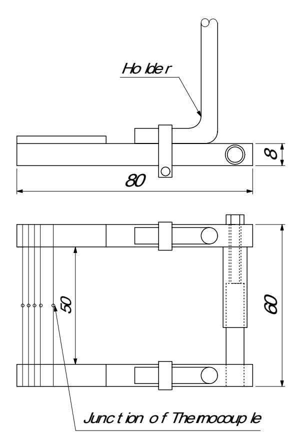


Fig.3 Comb-type of heat thermocouple

3. EXPRIMENTAL CONDITIONS

Experiments were performed at the CO_2 fluid pressure P_v from 6.5MPa in the subcritical pressure to 7.6MPa in the supercritical pressure, while the temperature of the fluid T_v was varied from the saturation temperature T_s to the superheated temperature in the subcritical pressure and was set to the pseudocritical temperature T_{psc} or higher temperature in the supercritical pressure. Temperature difference ΔT_v between the CO_2 fluid and the heat transfer surface was changed up to 30.2K.

4. PROPERTIES OF CO_2

The properties of CO2 vary strongly with the temperature near the critical point. Figure 4 shows some thermo-hydrodynamic properties at P_v=6.5 and 7.30MPa in the subcritical pressure and 7.50MPa in the supercritical pressure, which may concern with condensation and cooling heat transfer. As the temperature increases in the subcritical pressure, thermal conductivity, density and viscosity of the liquid state decrease continuously and sharply near the saturation temperature and discontinuously drastically at the saturation temperature. This is due to phase change from the saturated liquid to the saturated vapour and then large property change of liquid to vapour takes place. The superheated vapour still has large reduction of values of the properties due to temperature rise and their reduction rate deceases with further increase of the temperature. Isobaric specific heat however, shows a reverse change against other properties. The specific heat of liquid increases with temperature rise and reaches the maximum at the saturation temperature. After this increment keeps in the saturated vapour, the specific heat decreases monotonically in the superheated vapour.

While a discontinuous change of the properties occurs at the saturation temperature in the subcritical pressure region, the drastic change appears at the pseudocritical temperature (T_{psc}=31.8deg.C at P_v=7.50MPa). Therefore, the temperature dependence of the property indicates that the pseudocritical temperature corresponds to the saturation temperature. It is suggested that effect of the properties on thermo- hydrodynamics has a similarity between in the sub- and super-critical pressure regions.

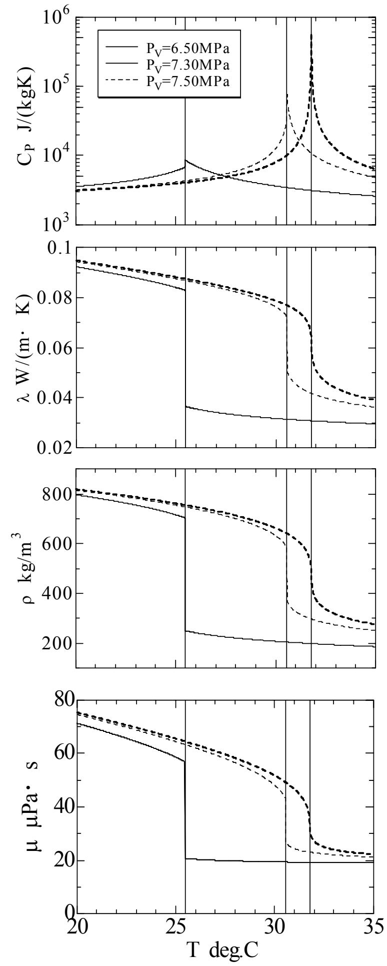
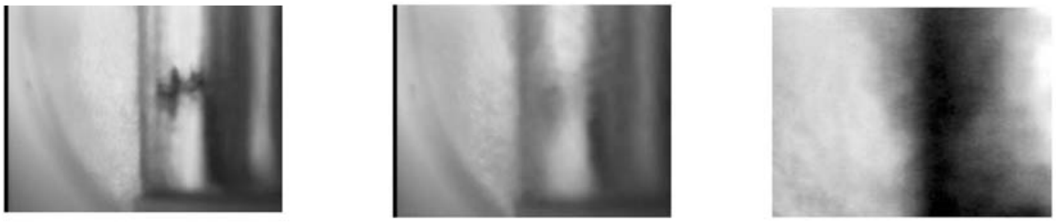


Figure 4. Some transport properties of CO_2 near the critical point

5. EXPERIMENTAL RESULTS AND CONSIDERATION

5.1. State of Fluid on/near Heat Transfer Surface

Figure 5(a-c) displays the state of CO2 for two different Δt_v in the supercritical pressure region near the critical point. As the CO_2 fluid density i.e. the index of optical refraction fluctuates locally and strongly in this region, the photographs are not clear in comparing with those in the subcritical pressure. In case of large Δt_v, the interface with relatively obvious contour superimposed on haze image due to variable index of refraction is observed in Figure 5(b) and (c). This means that "fluid layer similar to liquid", that is "liquid-like" layer exits in the supercritical pressure region. For small Δt_v such as Figure 5(a), "liquid-like" layer is thin and flows smoothly on the cooling heat transfer



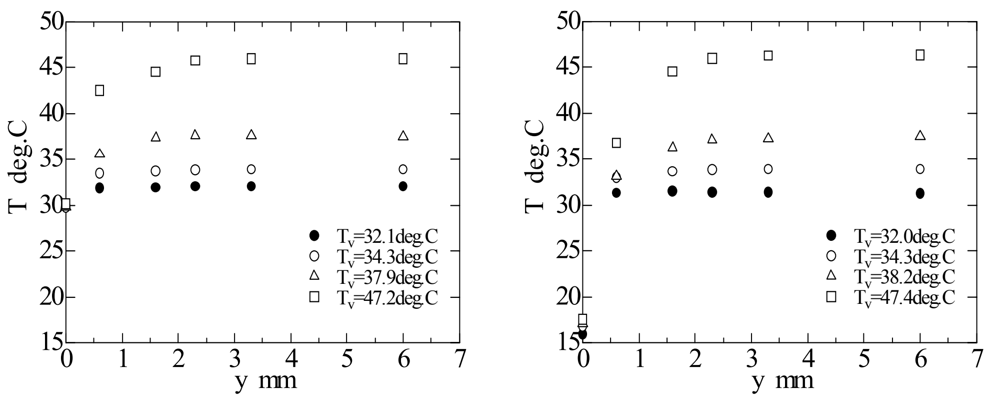
(a) P_v=7.50MPa, ΔT_v=1.2K (b) P_v=7.50MPa,ΔT_v=16.3K (c) Enlarged photo of (b)

Figure 5 State of CO_2 on/near the cooling heat transfer surface

surface. This is similar to the laminar film condensation in the subcritical region. when Δt_v increases, the “liquid-like” layer thickens and its flow fluctuates turbulently. This is similar to the state of the flow with fine droplets like fog in the subcritical region.

Thus, in case of the cooling in the supercritical pressure region, the state of fluid flow varies with Δt_v and this is similar to the variation of the flow state of the condensate with Δt_v. It means that “condensation-like” phenomenon for the cooling in the supercritical pressure corresponds to “boiling-like” phenomenon for heating.

5.2 Temperature Distribution of CO_2 Fluid Adjacent to Heat Transfer Surface



(a) T_w≈31deg.C (b) T_w≈17deg.C

Figure 6. Temperature distribution at P_v=7.50MPa

Figures 6 shows the temperature distributions measured at the vertical level of x=30mm by the comb type thermocouple shown in figure 3. The temperature at y=0 is the cooling surface temperature measured by the thermocouple embedded in the heat transfer surface. It is well known that in case of the condensation of the saturated vapour, the temperature changes only in the condensate film, while for the condensation of the superheated vapor, the thermal boundary layer is formed in contact with the outside of the condensate and then the temperature change takes place both in the condensate and the thermal boundary layer.

The temperature closest to the surface is positioned at y=0.6mm and it seems to be temperature at the outside of the ”liquid-like” layer. In the Figure 6(a) and (b), the data (marked●) indicate that the CO_2 fluid is in the pseudocritical temperature T_{psc}, the temperature does not vary in y direction regardless of the surface temperature difference. For lower temperature of the surface, larger temperature drop appears in the ”liquid-like” layer. This temperature distribution has a similarity with the temperature of the saturated vapur with the condensation.

On the other hand, When the CO_2 fluid has a higher temperature than T_{psc}, the fluid temperature increases in y direction and approaches a constant T_v. This has also a similarity with the temperature distribution with the condensation of the superheated vapour, so that there would be thermal boundary layer contacting with the ”liquid-like” layer on the cooling surface. Therefore, from these similarities of the temperature distributions between the sub- and super-critical pressure regions in addition of the similar variations of the properties and the state of the CO_2 around the cooling surface, the "condensation-like" phenomenon is confirmed.

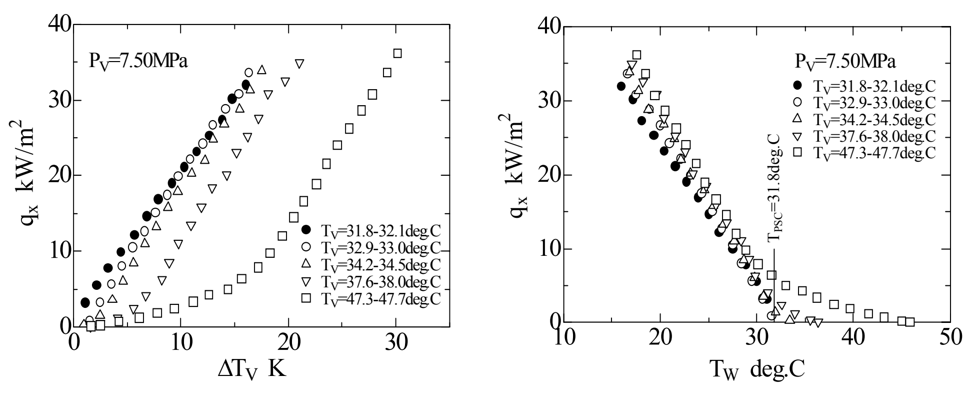
5.3 Heat Flux

The local heat flux is calculated from temperature measurements at the inside and outer surface of the heat transfer cylinder at x=30mm by assuming to be one dimensional thermal conduction, and the heat transfer coefficient is obtained from this measurement and CO_2 fluid temperature T_v. Local heat flux q_x at x=30mm is shown in Figure 7(a) and (b) for P_v=7.50MPa (the pseudocritical temperature T_{psc}=31.8deg.C). q_x increases with increasing the temperature difference ΔT_v and the rate of this increment against ΔT_v differs with the temperature T_v; T_{psc} or higher temperature than T_{psc}. In case of the CO_2 fluid with T_{psc} (data marked ●), the increment rate of q_x decreases slightly with increasing ΔT_v, while in case of the fluid with temperature higher than T_{psc}, the increment rate is very small for small ΔT_v, sharply increases beyond the certain value of ΔT_v and afterwards coincides with the same tendency as that for the fluid with T_{psc}. And for very high fluid temperature such as $T_v \approx$47.3deg.C, the region having small increment rate of q_x spreads over wide ΔT_v. The large change of the increment rate takes place when the heat transfer surface temperature T_w approaches and coincides with T_{psc} as shown in relationship between q_x and T_w in Figure 7(b).

From Figure 7, the relationship between q_x and ΔT_v or T_w is classified into three cases;

(1) Case 1: T_w is lower than T_{psc} and T_v is equal to T_{psc}. This case is the data (marked ●).
(2) Case 2: T_w is lower than T_{psc} and T_v is higher than T_{psc}.
(3) Case 3: T_w is higher than T_{psc}.

Assuming that T_{psc} correlates with the saturation temperature T_s in the subcritical region and the CO_2 fluid with higher temperature than T_{psc} corresponds to the superheated vapour. The case 1 is the condensation of the saturated and latent heat of the condensation is transferred i.e. large heat flux is transferred as shown in Figure 7. Case 2 is the condensation of the superheated vapour and the sensible heat due to the superheat is added to heat flux of case 1. Case 3 is no phase change, only sensible heat is transferred and then small heat flux is transferred in spite of large ΔT_v. From above consideration and the state of CO2 fluid shown in Figure 5, the "similarity" of heat transfer mechanism is recognized between the sub- and super-critical pressure regions.



(a) q_x vs. ΔT_v (b) q_x vs. T_w

Figure 7. Heat flux in the supercritical pressure

5.4 Heat transfer

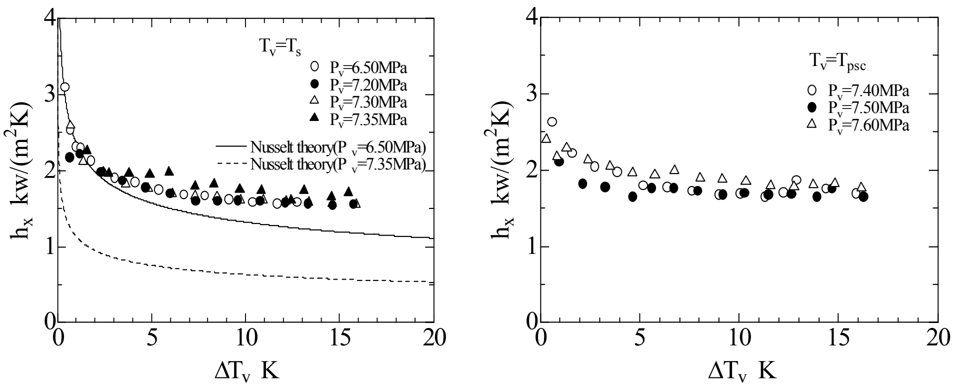
Local heat transfer coefficient h_x is calculated from heat flux obtained at x=30mm as follows;

$$h_x = \frac{q_x}{T_v - T_w} \qquad (1)$$

Figure 8(a) shows a relationship between local heat transfer coefficient of the CO_2 condensation and the subcooling ΔT_v as a parameter P_v. h_x deceases slightly with increasing ΔT_v. This is because the thickness of condensate layer proportional to the thermal resistance increases, as ΔT_v or P_v increases. However, the relationship between h_x and ΔT_v differs from the Nusselt's condensation theory. While theoretical values decrease largely with increasing the pressure, the experiments do not so much depend on the pressure. As the pressure rises, the latent heat and density difference between the vapour and liquid decreases, so that the condensate layer thickens. On the contrary, the entrainment of droplets from the condensate to the surrounding vapour due to the transition of laminar to wavy flow of the condensate or the reduction of the surface tension suppresses the thickening of condensate layer. Therefore, the heat transfer coefficient does not change so much with ΔT_v or P_v due to these conflicting effects.

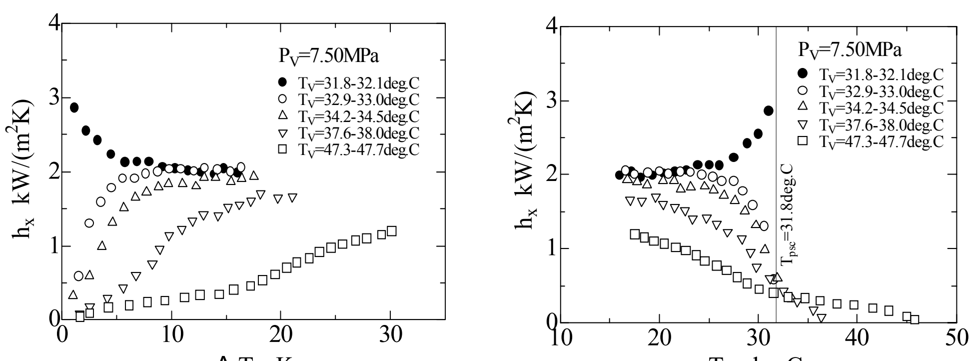
Figure 8(b) shows relationship between h_x and ΔT_v in case of the fluid with the pseudocritical temperature T_{psc} in the supercritical pressure region, and h_x deceases with increasing ΔT_v. This indicates the similar tendency to the heat transfer of the saturated vapour as shown in Figure 8(a). In addition, it is also similar that variation of the heat transfer coefficient with the pressure is small.

As mentioned in the section of the fluid flow, as ΔT_v increases in the supercritical region, the "liquid-like" layer thickens and h_x decreases. Therefore, it is suggested that this layer plays role the thermal resistance in the supercritical region such as the condensate in the subcritical region. Furthermore, since the heat transfer coefficients in the both regions have an approximate value mutually, a similarity and continuity of heat transfer mechanism between the both regions is suggested.



(a) Subcritical pressure region (b) Supercritical pressure region

Figure 8. Heat transfer coefficient



(a) h_x vs. ΔT_v (b) h_x vs. T_w

Figure 9. Heat transfer coefficient in the supercritical region

Figure 9 shows relationship between the heat transfer coefficient h_x and temperature difference ΔT_v

for the CO_2 fluid temperature close to the pseudocritical temperature T_{psc} (marked ●) and being higher than T_{psc}. The data (marked ●) are the same as those in Figure 8(b) and decrease with increasing ΔT_v. An approach of T_w to T_{psc} is the same as an approach of ΔT_v to zero and h_x increases because the thermal resistance in the "liquid-like" layer decreases. As ΔT_v becomes higher, h_x decreases due to the increase of another resistance contacting with the layer in addition, due to the definition of heat h_x as shown in Equation (1). When T_w exceeds T_{psc}, h_x reduces extremly such as the change from the condensation heat transfer to single phase heat transfer. As described above, the heat transfer in the supercritical pressure region can explain in the same way of the condensation heat transfer in the subcritical region. The "similarity of the heat transfer" between the super- and sub-critical pressure regions is conformed.

6. CONCLUSIONS

Experiments of the natural convective heat transfer of the carbon dioxide to a vertical cooling heat transfer surface were carried out in the supercritical pressure region near the critical point where transport properties vary sharply with the temperature and pressure, and the CO_2 fluid flow around the heat transfer surface were observed. Following conclusions were drawn from the measurements and consideration on properties, temperature distribution near the cooling surface, heat flux and heat transfer coefficient.

1. Comparing experimental condensation heat transfers of the saturated vapour with the Nusselt theory, the experiments shows higher value and does not change so much with the pressure variation.
2. In the supercritical pressure region, the “liquid-like” fluid layer close similar to the condensate film appears on/near the cold surface.
3. Heat flux q_x increases with increasing the temperature difference ΔT_v between the heat transfer surface and CO_2 fluid. The increment rate of h_x against ΔT_v changes at the pseudcritical temperature T_{spc} and decreases sharply beyond T_{spc}. At the certain T_w lower than T_{spc}, q_x increases with increasing in T_v. This corresponds to the condensation heat flux of the superheated vapour.
4. Heat transfer in the supercritical pressure can be explained in the same way of the condensation heat transfer. That is; the close similarity of the heat transfer exists between in the super- and sub-critical pressur region.
5. Finally, the “condensation-like” phenomenon in the supercritical pressure and the similarity of heat transfer mechanics between in the sub- and super-critical pressure region are confirmed.

NOMENCLATURE

Cp	Isobaric specific heat	(J/kgK)
h_x	Local heat transfer coefficient	(kW/m^2K)
P	Pressure	(MPa)
q_x	Local heat flux	(kW/m^2)
T	Temperature	(K,deg.C)
x	Downward distance from top of heat transfer surface	(mm)
y	Vertical distance from heat transfer surface	(mm)
ΔT_{psc}	T_v-T_{psc}	(K)
ΔT_v	T_v-T_w	(K)

Greek symbols

λ	Thermal conductivity	(W/mK)
μ	Dynamic viscosity	(μPa s)
ρ	Density of fluid	(kg/m^3)

Subscripts

psc	Pseudocritical state
s	Saturation
v	Vapour or fluid
w	Heat transfer surface

REFERENCES

Ishihara I et al., 1994, *Trans. of the JSRAE*, 11(3): 299-308.(in Japanese)
Ishihara I et al., 1995, *Proc. 2nd ICMF'95-Kyoto*, 3: p5-51-p5-57.
Ishihara I et al. 1996, *Trans. of the JSME, (B)* ,62(595): 1119-1123. (in Japanese)
Ishihara I et al. 1996, *Proc. 2nd European Thermal-Science & 14th UIT Conf.*, 3: 1223-1227.
Ishihara and R.Matsumoto, 1997, *Proc. ExHFT-4*, 2: 1091-1096.
Ishihara I et al. 2002, *Trans. of the JSME, (B)*, 68(671): 1878-1883. (in Japanese)
Okuno K et al. 1996, *Proc. National Heat Transfer Symposium of Japan*: 691-692. (in Japanese)
Kuroda H et al. 1999, *Proc. National Heat Transfer Symposium of Japan*: 565-567. (in Japanese)
Mori H et al. 2001, *Proc. Thermal Engineering conf.*, No.01-9: 421-422.(in Japanese)
Nishikawa K et al. 1962, *J.JSME*, 65(525): 1424-1431. (in Japanese)
Nishikawa K et al. 1965, *J.JSME*, 68(552): 28-37. (in Japanese)
Nishikawa K et al. 1972, *Trans. of the JSME,(2)*, 38(308): 842-847. (in Japanese)
Nishikawa K et al. 1974, *Trans. of the JSME,(2)*, 40(340): 3459-3466. (in Japanese)
Nishikawa K et al. 1973, *J. Heat Transfer*, 95: 187-191
Yamagata K et al. 1966, *Trans. of the JSME, (2)* , 32(233): 98-106. (in Japanese)
Knapp K.K et al. 1966, *Int. J. Heat Mass Transfer*, 9: 41-51.
Goldstein R.J et al. 1968, *J. Heat Transfer*, 90(1): 51-55.
Hahne E et al. 1974, *Proc. 5th Int. Heat Transfer Conf.*, 3: 5-9.