COMPARISON INVESTIGATION ON THE HEAT TRANSFER CHARACTERISTICS FOR SUPERCRITICAL CO_2 FLUID AND CONVENTIONAL REFRIGERANTS

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ABSTRACT

The obvious characteristics of transcritical CO_2 cycle are that the heat rejection process takes place in the supercritical region. The thermophysical properties of supercritical CO_2 change dramatically with the temperature and pressure near the critical region. According to the characteristics of CO_2 specific heat, the correlation of the pseudocritical temperature is obtained and the pseudocritical region is defined. The special properties variation of supercritical CO_2 fluid makes its heat transfer performance different from the conventional fluids. From the view of properties analysis and quantitative comparison, it can be seen that the heat transfer performance of supercritical CO_2 is equivalent to the condensation heat transfer of conventional refrigerants.

1. INTRODUCTION

In recent years, many researchers are studying the performance of transcritical CO_2 cycle. The obvious characteristics of transcritical CO_2 cycle are that the heat rejection process takes place in the supercritical region (about 8-12Mpa). The heat transfer features of CO_2 under supercritical pressure are different from those of the conventional refrigerants. The main reason is attributed to that the thermophysical properties of CO_2 change dramatically with the temperature and pressure near the critical region. The specific heat of CO_2 is mainly analyzed and then the properties of CO_2 and some conventional refrigerants are compared. It is helpful to understand the flow and heat transfer characteristics of CO_2 in the gas cooler.

2. ANALYSIS OF CO_2 SPECIFIC HEAT

The specific heat of CO_2 is obtained from Engineering Equation Solver software (Klein and Alvarado, 1996), as shown in Figure 1. It can be seen that at each supercritical pressure, the specific heat changes drastically as the temperature rises, and reaches a maximum value at a certain temperature. In general, the temperature at which the specific heat reaches a peak is called pseduocritical temperature for a given pressure. And the higher the pressure is, the larger the pseduocritical temperature is. The peak of the CO_2 specific heat decreases with the increasing pressure. This can be described by the following equation.

$$\left(\frac{\partial c_p}{\partial T}\right)_P = 0 \qquad (1)$$

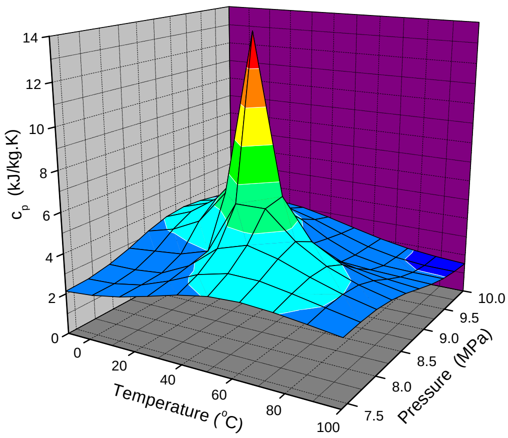

Figure 1. CO_2 specific heat versus temperature and pressure

In fact, it can be seen from the three dimension graph as shown in Figure 1 that the projection of CO_2 specific heat peak value is a curve on the temperature-pressure plane at different supercritical pressure, which is called pseduocritical curve. The correlation between the pseduocritical temperature and pressure is obtained as follows.

$$T_{pc} = -31.40 + 12.15p - 0.6927p^2 + 0.03160p^3 - 0.0007521p^4 \quad (2)$$

According to the variation characteristics of CO_2 specific heat, pseduocritical region is defined to a temperature strip near the pseduocritical curve, as shown in eq. (3).

$$0.7T_{pc} \le T \le 1.3T_{pc} \quad (3)$$

The range of supercritical pressure corresponding to eq. (3) is from $7.5MPa$ to $14.0MPa$.

2. HEAT TRANSFER CHARACTERISTICS FOR SUPERCRITICAL CO_2

The special properties variation of supercritical CO_2 fluid makes its heat transfer performance different from the low-pressure fluids. According to whether the impact of natural convection is taken into consideration or not, the supercritical fluid heat transfer is classified to simple forced-convection heat transfer and mixed convection heat transfer.

In the pseudocritical region, the special heat transfer features of supercritical CO_2 fluids is mainly expressed that sometimes the heat transfer coefficients are increased and sometimes they are decreased when comparing with that of the forced-convection heat transfer of single-phase fluids. The primary reason of the special heat transfer properties for supercritical CO_2 fluid is that the great change of properties with the temperature in the pseudocritical region, which results in the momentum and energy exchange and buoyant force change in the heat flux direction. When the pseudocritical temperature is between the wall temperature and the fluid temperature, the properties along the cross section vary greatly and the heat transfer performance is different from the constant properties heat transfer.

At cooling condition, when the pseudocritical temperature is lower than the fluid temperature and higher than the wall temperature, the heat transfer performance can be increased. This can be explained that at the above condition there is a layer of fluid in the boundary layer whose temperature is equal to pseudocritical temperature. It is known to all that the specific heat of supercritical CO_2 is reached to peak value at pseudocritical temperature. In addition, the conductivity is increased with the decreasing of temperature. Therefore, the fluid layer possesses large heat transfer performance near the pseudocritical temperature. Proceeding with the cooling process, the fluid temperature and tube wall temperature departure from the pseudocritical temperature. And the drop speed of specific heat is larger than that of the conductivity, and the heat transfer coefficient drops accordingly. In fact, the argumentation or deterioration is restricted by the experimental condition.

3. COMPARISON TO CONVENTIONAL CONDENSATION HEAT TRANSFER

Compared to the conventional vapor compression refrigeration cycle, the function of the gas cooler in the transcritical CO_2 cycle is similar to the condenser. But in the condenser the phase-change condensing heat transfer is undergoing, while in the gas cooler the single-phage forced-convection heat transfer is taking place. So the heat transfer mechanism for the two processes and their heat transfer performances are different. The explanation is given in the following by means of thermophysical properties analog analysis and experimental results quantitative comparison.

Figure 2 gives the density variation trends for supercritical CO_2 fluid, CO_2 saturated liquid and conventional refrigerant R134a and R22. It is found that the density of supercritical CO_2 is closer to that of the CO_2 saturated liquid near the critical point, which shows that the distance between molecule for supercritical CO_2 is correspond to its liquid. It also can be seen that the density of supercritical CO_2 is lower than that of the R134a and R22 saturated liquid, and higher than that of the R134a and R22 saturated gas.

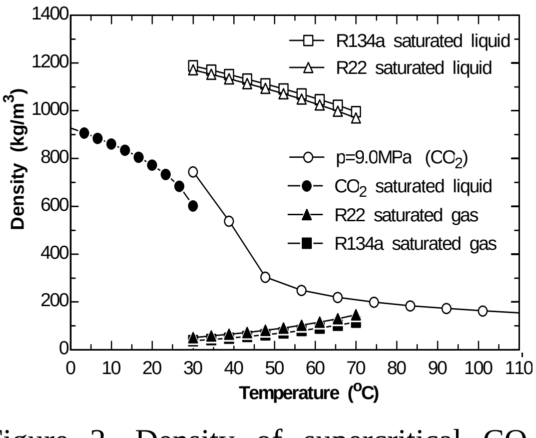

Figure 2. Density of supercritical CO_2 and conventional refrigerant

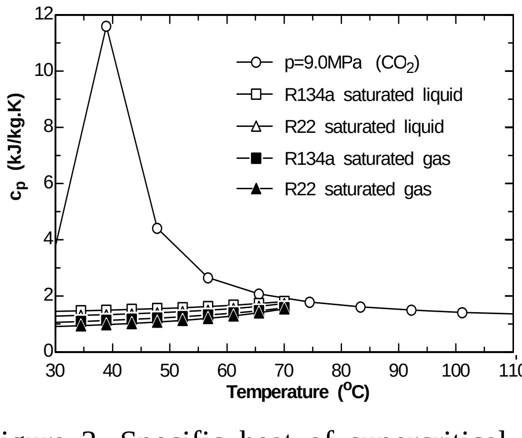

Figure 3. Specific heat of supercritical CO_2 and conventional refrigerant

The specific heat of supercritical CO_2 is far greater than that of the R134a and R22 saturated liquid and saturated gas, especially in the pseudocritical region, as shown in Figure 3.

Figure 4 presents the conductivity comparison for supercritical CO_2 to R134a and R22 saturated liquid and saturated gas. It is found that CO_2 conductivity drops quickly near the critical point, and it is lower than that of R134a and R22 saturated liquid and larger than their saturated gas.

The viscosity comparison of supercritical CO_2 to R134a and R22 saturated liquid and saturated gas is given in Figure 5. It is obvious that the viscosity of supercritical CO_2 is far lower than that of R134a and R22 saturated liquid, and a little higher than that of their saturated gas.

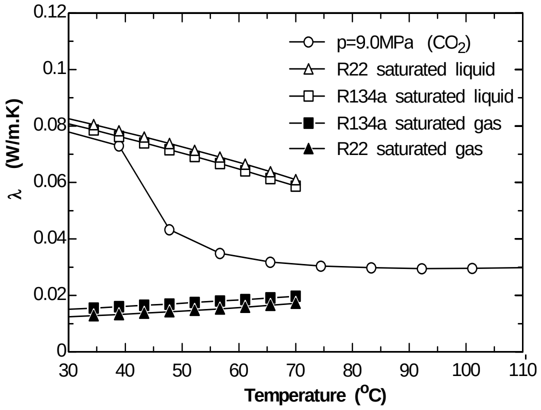

Figure 4. Conductivity of supercritical CO_2 and conventional refrigerants

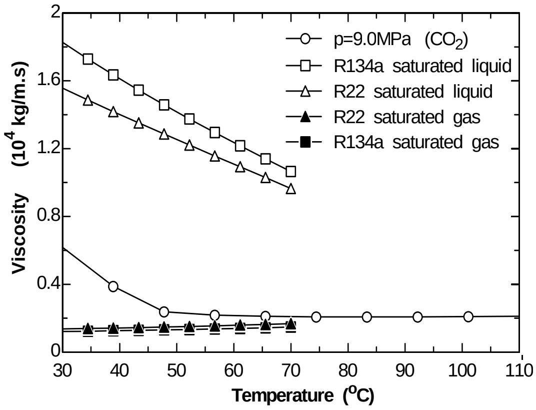

Figure 5. Viscosity of supercritical CO_2 and conventional refrigerants

From the view of properties analysis, it is found that the characteristics of supercritical CO_2 fluid are equivalent to those of the conventional refrigerants.

In order to explain from the other aspect, Figure 6 compares the specific heat capacity of cooled CO_2 and condensed R134a and R22 at the same equivalent condensation temperature. The equivalent condensation temperature is defined and calculated using the following equation for different process.

$$ECT = \frac{\int_1^2 T ds}{\int_1^2 ds} = \frac{\int_1^2 T ds}{\Delta s} \tag{4}$$

It is obvious that the specific heat capacity of cooled CO_2 is lower than that of the condensed R134a and R22 at lower equivalent condensation temperature. When the equivalent condensation temperature is higher, the specific heat capacity of cooled CO_2 is greater than that of condensed R134a and R22.

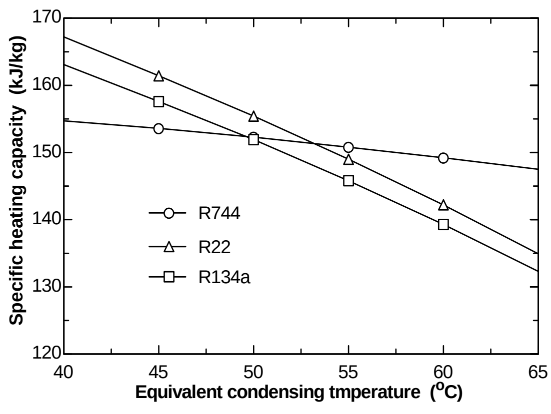

Figure 6. Specific heat capacity for supercritical CO_2 and conventional refrigerants

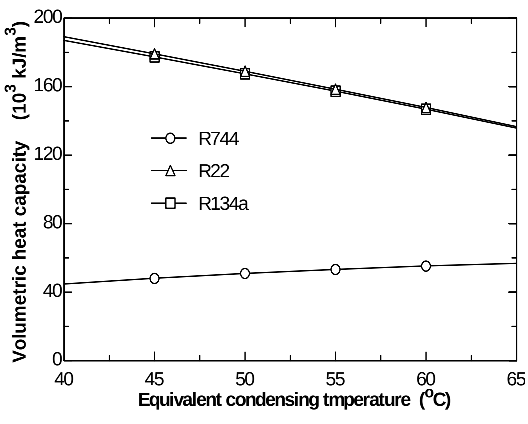

Figure 7. Specific volume thermal capacity for supercritical CO_2 and conventional refrigerants

Figure 7 shows the comparison results of their specific volume thermal capacity. Obviously, the specific volume thermal capacity of cooling supercritical CO_2 is far lower than that of the condensed R134a and R22. This can be explained that there is no phase-change and no latent heat transfer in the cooling process of supercritical CO_2.

If the above factors are considered comprehensively, the heat flux in the cooling process of supercritical CO_2 may reach that of the phase-change process. Of course, the above analysis is only the qualitative results determined from indirect analog.

In the following, the heat transfer coefficient of supercritical CO_2 at cooling condition is compared with the condensation coefficient of conventional refrigerants R134a and R22 quantitatively.

Cavallini *et al.* (2001) studied the condensation heat transfer performance of R134a and R22, as shown in Figure 8. It can be seen that their condensation heat transfer coefficient are both increased with the increasing of mass flow rate in the experimental range. While proceeding with the condensation process, their condensation heat transfer coefficient both drop. And their condensation heat transfer coefficient are in the range of 1.0-5.0kW/m^2.K.

At moment, many researchers perform experimental study and numerical calculation on the supercritical CO_2 cooling heat transfer (Yoon *et al.*, 2003; Pettersen *et al.*, 2000; Olson, 2000; Liao and Zhao, 2002; Dang and Hihara, 2002). In order to compare the experimental results of CO_2 with R134a and R22, the experimental results of Yoon *et al.* (2003) for supercritical CO_2 cooling heat transfer is selected, as shown in Figure 9. It can be seen that the cooling heat transfer coefficient of supercritical CO_2 varies a little with the increase of mass flow rate except in the pseudocritical region. Proceeding with the cooling process, the heat transfer coefficient is increased little by little and attains the maximum value at certain temperature, and then drops with the decreasing of temperature. The variation trend of CO_2 heat transfer coefficient is very similar to its specific heat. The main reason is that the specific heat varies dramatically near the pseudocritical region and attains maximum value at pseudocritical temperature. This also explains that specific heat puts great effect on the CO_2 heat transfer performance. It also can be seen that the supercritical CO_2 heat transfer coefficient is in the range of 2.0-15.0kW/m^2.K among the experimental condition.

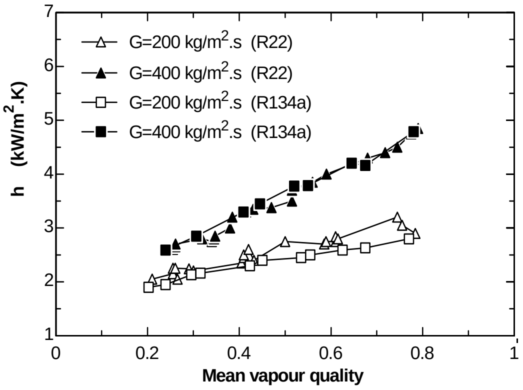

Figure 8. Condensation heat transfer coefficient of R134a and R22

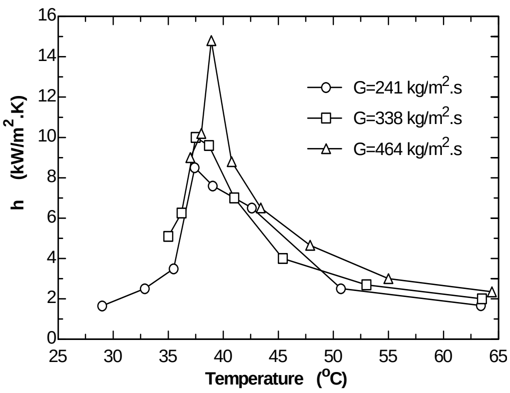

Figure 9. Supercritical CO_2 cooling heat transfer coefficient

By comparison of Figure 8 and Figure 9, it can be seen that although the variation trend of supercritical CO_2 cooling heat transfer coefficient is different from the condensation coefficient of conventional refrigerant, the coefficient scalar level is equivalent. And the heat transfer performance of supercritical CO_2 outperforms the condensation coefficient of conventional refrigerant especially near the pseudocritical point.

4. CONCLUSIONS

The specific heat of supercritical CO_2 changes dramatically with the temperature and pressure near the critical region. According to the characteristics of CO_2 specific heat, the correlation of the pseudocritical temperature is obtained and the pseudocritical region is defined. The special properties variation of supercritical CO_2 fluid makes its heat transfer performance different from the conventional fluids. From the view of properties analysis and quantitative comparison, it can be seen that the heat transfer performance of supercritical CO_2 is equivalent to the condensation heat transfer of conventional refrigerants. The reason may be that there is no liquid film in existence and the thickness of the boundary layer is very thin in the supercritical CO_2 cooling process.

ACKNOWLEDGEMENTS

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NOMENCLATURE

c_p	specific heat	(kJ/kg.K)	Subscripts	
ECT	equivalent condensing temperature	(K)	pc	pseudocritical
h	heat transfer coefficient	(kW/m^2.K)		
p	pressure	(Mpa)		
s	specific entropy	(kJ/kg.K)		
T	temperature	(^{o}C)		
λ	conductivity	(W/m.K)		

REFERENCES

1. Cavallini A, Censi G, Delcol D, *et al.* 2001, Experimental investigation on condensation heat transfer and pressure drop of new HFC refrigerants (R134a, R125, R32, R410A, R236ea) in a horizontal smooth tube, *International Journal of Refrigeration*, 24(1): 73-87.
2. Dang Chaobin, Hihara Eiji. 2002, Heat transfer coefficient of supercritical carbon dioxide, *Preliminary Proceedings of the 5th IIR-Gustav Lorentzen Conference on Natural Working Fluids at Guangzhou, China*: 100-107.
3. Klein S, Alvarado F.1996, *Engineering equation solve*r, Middleton, WI, F-chart software.
4. Liao SM, Zhao TS. 2002, Measurements of heat transfer coefficients from supercritical carbon dioxide flowing in horizontal mini/micro channels, *Transactions of the ASME Journal of Heat Transfer,* 124:413-420.
5. Olson DA. 2000, Heat transfer of supercritical carbon dioxide flowing in a cooled horizontal tube, *Preliminary Proceedings of the 4th IIR-Gustav Lorentzen Conference on Natural Working Fluids at Purdue*: 251-258.
6. Pettersen J, Rieberer R, Leister A. 2000, Heat transfer and pressure drop characteristics of supercritical carbon dioxide in micro-channel tubes under cooling, *Preliminary Proceedings of the 4th IIR-Gustav Lorentzen Conference on Natural Working Fluids at Purdue*: 99-106.
7. Yoon SH, Kim JH, Hwang YW, *et al.* 2003, Heat transfer and pressure drop characteristics during the in-tube cooling process of carbon dioxide in the supercritical region, *International Journal of Refrigeration,* 26(8): 857-864.