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Research on convection heat transfer character of super critical carbon dioxide flows inside horizontal tube

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ABSTRACT

This paper mainly studied the heat transfer character of super critical carbon dioxide, also named R744. Super critical carbon dioxide can be used in gas cooler for air conditioning system. Compared with traditional Freon coolant, R744 has higher density and lower viscosity, which is benefit for heat transfer process. So it is important to study heat transfer character for super critical carbon dioxide. The experiment research is taken for the temperature ranging from 29 to 55 °C, while pressure is 8, 9 and 10 MPa. The Reynold number is about 2×10^5. Thermal resistance method is used to measure heat transfer coefficient. The results found that convection heat transfer enhances near the pseudo critical point, in the region far away from pseudo-critical point, heat transfer character is just like ordinary single-phase fluid. The heat transfer coefficient violently changeable region is also the region where thermal property change rapidly. It is also found that heat transfer coefficient gets its max at the region near the pseudo-critical point. In addition, the results obtained in this paper are compared with other researchers' results.

1. Introduction

Ozone layer depletion and greenhouse effect are the two serious environmental problems, which are caused mainly by Freon coolant like R22. So forbidding the use of Freon and searching for environmental friendly coolant seem to be serious problems. As a result, reducing the carbon footprint and protecting environment come more and more popular in the world [1].

Carbon dioxide, is an environmental friendly gas existing in the atmosphere. Its ODP (ozone depression potential) equals to 0, and GWP (global warming potential) equals to 1. It can be used widely in industry, such as working fluid in Rankine cycle [2], refrigeration cycle [3–4] and seperated heat pipe system [5–7]. In the heat exchanger of Rankine or refrigeration cycle, carbon dioxide is super critical fluid, so it is important to study the heat transfer character of super critical carbon dioxide.

Researchers from all over the world have done a lot of work on super critical carbon dioxide heat transfer character. Yoon [8] and Son [9] study heat transfer character and pressure drop of super critical carbon dioxide flows in tube in tube counter flow heat exchanger, where carbon dioxide is cooled by water. Liao [10,11] study both heating and cooling condition when super critical carbon dioxide flows in mini tube, its tube diameter is 0.7 mm, 1.4 mm, 2.16 mm. Huai [12] does an experiment on flow and heat transfer of super critical carbon dioxide in multi-port mini channels under cooling condition. Jiang [13,14] has done some work on convection heat transfer when carbon dioxide flows in vertical mini-tubes and in porous media. Table 1 shows some recent work on super critical carbon dioxide convection heat transfer in horizontal tube.

Traditional method to test the heat transfer coefficient is to use the method of definition, which means $h = q/(T_f - T_{wall})$. In this equation, q is the heat flux, T_{wall} means the inside wall temperature and T_f means the fluid's bulk mean temperature. T_{wall} is calculated by one dimension heat transfer equation after getting the outside wall temperature. T_f is tested by thermal couples which is inserted into the tube. This is a simple method for its calculation equation is simpler. Literature [13] use the similar method, there is a little difference, the fluid bulk mean temperature is not tested but calculated by thermal equilibrium. Literature [17] also use this method, the difference is that temperature difference in not $T_f - T_{wall}$, but the LMTD, where it is defined by R744's inlet/outlet temperature and the inside wall temperature of each little section of the test section.

However, there are some shortcomings for this method. First, as for the super critical R744, its pressure is as high as 8–10 MPa, inserting thermal couples into the tube can be dangerous, besides, it is also difficult to seal. Second, the inside tube diameter of our experiment is 7.5 mm, which is very small, inserting thermal

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Nomenclature

Cp	specific heat, J/kg °C
h	heat transfer coefficient, W/m^2 K
LMTD	log mean temperature difference
Nu	Nusselt number
Pc	pseudo critical point
Pr	Prandtl number
Q	heat capacity, W
q	heat flux, W/m^2
R	thermal resistance, K/W
Re	Reynold number
T	temperature, °C

Greek symbols

ρ	density, kg/m^3
λ	heat conductivity, W/m K
μ	viscosity, kg/ms

Subscripts

i	enthalpy
m	mean
max	maximal
min	minimum

couples into the tube may influence the flow field. Third, it may not be accurate to use one dimension heat transfer equation to calculate the inside wall temperature after getting the outside wall temperature.

Besides, there is also another method to find the heat transfer coefficient [11]. In this method, there is a tube in tube counter flow heat exchanger where hot R744 flows inside the tube and cold water flows outside the tube. There are 6 thermal couples to measure the outside wall temperature of the inside tube (R744 tube). The author try to keep the out wall temperature of the inside tube as uniform as possible. The author uses the average of the 6 thermal couples as the outside wall temperature, and calculate the inside wall temperature. Finally, they use $h = Q/A{\cdot}\text{LMTD}$. Where A is the heat transfer area, and LMTD is the log mean temperature difference defined by the R744's inlet/outlet temperature and the inside tube wall temperature. However, this method also has a little problem, for it use the average of the 6 thermal couples as the outside wall temperature. In fact, cold water is used to cool the hot R744, as a result, there exists temperature difference of these 6 thermal couples, thus, it may be not very accurate to regard the outside wall temperature as constant.

In this paper, a different method to measure heat transfer coefficient is used, we called it method of thermal resistance. Literature [18] has used a similar method to determine in-tube evaporation heat transfer of carbon dioxide, in this paper, we have modified thermal resistance method which is different from literature [18]. This method has some advantages, for example, it is easy to do the experiment, for thermal couples only need to be put at the inlet/outlet of cold water and carbon dioxide. Thermal couples do not need to be inserted into the inside tube, thus, the problems of seal and dangerous can be solved. Besides, heat transfer coefficient is just calculated by the experiment results directly, there is nearly no assumption on calculating the results. As a result, this method is accurate, simple and safe. Super critical carbon dioxide flows in a tube in tube counter flow heat exchanger, where it is cooled by water. The diameter of the tube is 7.5 mm. Our research is taken for the temperature ranging from 29 to 55 °C, while pressure is 8, 9 and 10 MPa. The Reynold number is about 2×10^5.

2. Theoretical analysis of super critical carbon dioxide heat transfer

2.1. Physical property of super critical carbon dioxide

If temperature and pressure are lower than critical point, the fluid is ordinary. At a certain pressure, when absorbing heat, the fluid change its phase from liquid to two-phase and finally to gas. If temperature and pressure are higher than critical point, we call such fluid "super critical fluid".

There are mainly 2 significant characters for the super critical fluid.

First is that there is no phase change for super critical fluid. Super critical phase is a kind of uniform single phase. Its viscosity

Table 1
Researches on super critical carbon dioxide convection heat transfer.

Researcher	Heat exchanger type	Temperature range (°C)	Pressure range (MPa)	Inside tube diameter (mm)
Yoon [8]	Tube in tube Water cold	30 ~ 65	7.5 ~ 8.8	7.73
Son [9]	Tube in tube Water cold	20 ~ 90	7.5 ~ 10	7.75
Liao [10]	Electric heating pipe	20 ~ 110	7.4 ~ 12	0.7, 1.4, 2.16
Liao [11]	Tube in tube Water cold	20 ~ 110	7.4 ~ 12	0.7, 1.4, 2.16
Huai [12]	Multi-port mini channels	22 ~ 53	7.4 ~ 8.5	1.31
Pettersen [15]	Multi-port mini channels	15 ~ 70	8 ~ 10.1	0.79
Dang [16]	Tube in tube Water cold	30 ~ 70	8 ~ 10	1, 2, 4, 6
Lv [17]	Tube in tube Water cold	30 ~ 65	8 ~ 10	3.8

Table 2
Thermal properties comparable table of R744.

Fluid type(R744)	Condition	Density (kg/m^3)	Viscosity ($\times 10^{-5}$kg/ms)	Heat difusion rate ($\times 10^{-8}$m^2/s)
Liquid	5 MPa, $x = 0$	827.3	7.871	3.242
Gas	5 MPa, $x = 1$	156.7	1.674	5.825
Super critical	10 MPa, 40 °C	630	4.774	1.983