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Characteristics of heat transfer for CO_2 flow boiling at low temperature in mini-channel

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ABSTRACT

This paper presents an experimental and theoretical investigation on two-phase flow boiling heat transfer with carbon dioxide (CO_2 or R744) as the refrigerant in horizontal small diameter tube at low temperature. The experimental data were obtained in the following condition, the heat flux is 7.5–30 kW/m^2; the mass flow rate is 300–600 kg/m^2 s; the saturation temperature is 233–273 K; the test section is made of stainless steel tubes whose inner diameters are 0.6 and 1.5 mm. The experimental results show that heat transfer coefficient increases with the increase of mass flow rate, but decreases with the increase of tubes' inner diameter and saturation temperature, the boiling heat transfer of CO_2 has a greater effect on nucleate boiling and highly depends on heat flux. The comparative study indicates that: during the existed flow boiling heat transfer model, the model which has the best prediction accuracy presented with 79.8% of predicted points within ±30% and 21.8% mean deviation before the dryout phenomenon happened, while it was only 18.4% and 59.9% after the dryout phenomenon happened.

1. Introduction

The environmental pollution caused by traditional refrigerants has been a popular research field lately. Recent researches done to look for an environment-friendly refrigerant mainly focus on using natural substances as the alternative to traditional refrigerants. These substances can be divided into two types, of which one is HCs such as propane, butane, and iso butane; and the other is all kinds of natural minerals such as NH_3, water, air, and CO_2 [1]. Among all of these, CO_2 is one of the most popular alternative refrigerants in low-temperature refrigeration systems globally. In fact, using CO_2 as the refrigerant has its main drawback of high operating pressure and low cycle efficiency. Theoretical analysis and experimental researches showed that when using CO_2 as the refrigerant, the COP of single-stage compression refrigeration system is lower than that of systems using traditional refrigerants such as R22 and R134a. However, it was also showed that CO_2 was quite promising when used in automotive air conditioning systems, heat pumps and cascade cycles. Especially when used as the refrigerant of the lower-temperature stage of a cascade system, it had very low viscosity and good heat transfer performance.

Although there are already researches on the characteristics of CO_2 in low temperature refrigeration system such as the cascade refrigeration system, which still uses the tube fin heat exchanger. In order to meet the requirements of zero leakage, minimum refrigerant charge and high heat transfer coefficient in modern refrigeration system, the mini-channel heat exchangers will be the main-stream exchanger in refrigeration systems in the future. Nowadays the practice of using small and compact mini-channel heat exchanger in refrigeration systems brings new challenge to the calculation of CO_2's heat transfer coefficient in the process of boiling or condensing. The fact that the pressure of the refrigerant drops with the decrease of the heat exchanger channels has also become one of the hot subjects in recent researches. Yun et al. [2] suggested that during the CO_2 flow boiling heat transfer process, nucleate boiling played a predominant role in the low vapor quality area,CO_2's boiling heat transfer coefficient increased with the increase of the heat flux regardless of the change of the mass flux, Yoon et al.'s [3] study found that in the low vapor quality area, CO_2's boiling heat transfer coefficient increased while the heat flux increased, and that when vapor quality was above a certain value, the heat transfer coefficient declined, which was due to the likely occurrence of dryout phenomenon resulting from the CO_2's relatively low surface tension and viscosity. Other experimental results also demonstrated that (a) as the viscosity and the density of CO_2 was lower than traditional refrigerants, the layer on the heat trans-

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Nomenclature

Co	constraint number
D	hydraulic diameter, m
f	friction factor
F	two relative flow multiplier
h	heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/m K
L	test section length, m
P	pressure, MPa
Pr	Prandtl number
q	heat flux, W/m^2
Q	heat, W
q_m	mass flow rate, kg/s
m	mass flux, kg/m^2 s
R	radius, m
Re	Reynolds number
S	nucleate boiling inhibitory factor
T	temperature (K)
x	vapor quality
X	Lockhart-Martinelli parameter
z	distance, m
δ	liquid film thickness, m
ε	cross-sectional vapor void fraction
θ	angle of tube perimeter, rad
ν	viscosity
g	gravitational acceleration, 9.81 m/s^2
ρ	density, kg/m^3
σ	surface tension, N/m
λ	accuracy of prediction deviation within ±30% (%)
$\dot{\phi}$	heat dissipation potential

Subscripts

f	flow boiling heat transfer
h	pre-heat
l	liquid
leak	drain heat
nbc	nucleate boiling heat transfer
p	pressure
r	refrigerant
v	gas
w,i	inner surface of tube
w,o	outer surface of tube
z	accumulator

fer surface was thinner, which helped nucleate boiling to form more easily with a steady heat flux; (b) as CO_2's thermal conductivity and the density ratio of gas-liquid during evaporation was higher than traditional refrigerants, CO_2 have greater heat transfer efficiency [4–7]. Researchers generally consider that as an ideal alternative refrigerant, CO_2 has more advantages in thermal performance. However, due to the special thermal physical properties of CO_2, its heat transfer process is very complicated, and the relevant factors have never been clearly revealed. Moreover, most of existing research results are back of the experimental data before or after it dryout. As for CO_2's characteristics of heat transfer and dryout in low temperature, there aren't many researches. Thus, additional research is needed to study the boiling heat transfer of CO_2 because its heat transfer process yields different results with different system parameters. This paper mainly focuses on CO_2's flow boiling heat transfer and dryout characteristics at low temperature in mini-channels, experimentally analyzing the effect of heat flux, mass flow rate, saturation temperature and inner diameter on heat transfer and the phenomenon of dryout, comparing it with the existed theoretical heat transfer model of CO_2 and providing the basic data needed to design an evaporator that uses a CO_2 refrigerant. All of these researches offer the theoretical support to design the compact, high efficiency and low pressure-drop mini-channel heat exchanger which is used in the CO_2 refrigeration system.

2. The thermal physical properties of CO_2 in low temperature

Just because it is colorless, tasteless, non-toxic, non-flammable, and has good thermal property etc, CO_2 is the most promising environmental-friendly alternative refrigerant at present. And as it can be made easily as a by-product in industrial fields, it's pretty cheap and doesn't bring forward extra greenhouse effect. In low temperature working conditions, compared with other refrigerants (R717, R22, R410A, R134a, R290), the thermal physical properties of CO_2 have more advantages, having the lowest surface tension, liquid viscosity, liquid-gas density ratio, the highest volumetric refrigeration capacity, a relatively high liquid thermal conductivity and specific heat capacity. Comparisons between CO_2 and other refrigerants on their physical parameters, which are based on NIST (a software) are shown in Figs. 1–7.

As show in Fig. 1, compared with other refrigerants the surface tension of CO_2 is much lower, it means that CO_2 is more likely to form bubbles and develop into nuclear boiling during the process of heat transfer in low vapor quality area. Therefore it also has higher heat transfer coefficient.

Fig. 2 shows that in the condition of the same saturation temperature the pressure of CO_2 and the pressure changes of CO_2 in accordance to the temperature are both far greater than other refrigerants. For these characteristics, refrigeration system with CO_2 as the refrigerant can still stay in a positive pressure state even in lower evaporation temperature conditions. Moreover, as the temperature slip of CO_2 caused by resistance in evaporator is lower than other refrigerants, CO_2 can overcome the shortcoming of large temperature slip during the process of heat transfer in mini-channel.

Fig. 3 indicates that CO_2 has a smaller liquid-gas density ratio, which slows the changing speed of CO_2 in the liquid/gas two-phase transition with a constant mass flow rate, especially in mini-channel heat exchanger, in which the distribution uniformity of the two-phase fluid can be increased.

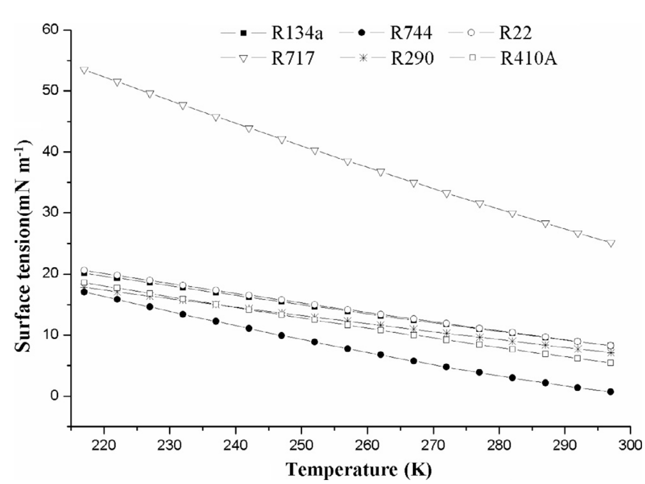

Fig. 1. Surface tension of CO_2 and other refrigerants at different saturation temperatures.