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Experimental investigations on the boiling heat transfer of horizontal flow in the near-critical region

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ABSTRACT

The critical point is the end point of a phase equilibrium curve; liquid and its vapor can coexist under designated points. Close to the critical point, thermophysical properties present clear variations, especially in the region of $0.85P_{cr}{\sim}P_{cr}$. Latent heat and liquid density in this region decrease more quickly than in lower-pressure areas, resulting in unique boiling heat transfer behavior. This region is also called the near-critical region. However, only a few scholars have discussed the heat transfer phenomenon; thus, it is difficult to ascertain the near-critical region's properties and characteristics from extant literature. In the present study, we conduct experimental investigations to explore the specificities of the heat transfer characteristics of carbon dioxide in horizontal flow within the near-critical region in a circular channel with a diameter of 4 mm. The operating pressure ranges from 6.26 MPa to 7.3 MPa with a mass flow rate between 200 and 400 kg/m^2 s, heat flux between 5 and 140 kW/m^2, and test section inlet temperature of −5 °C. Then, we examine the inner-wall temperature and heat transfer coefficient profiles at different pressures within the near-critical region. The results show that at high heat flux, departure from nucleate boiling (DNB) phenomenon presents with a sudden decrease in the heat transfer coefficient in the subcooled region. The higher the heat flux, the more seriously deteriorating the heat transfer is. Interestingly, the temperature reaches its peak in the post-DNB region rather than at the critical vapor quality point. With an increase in pressure, DNB occurs early with lower vapor quality, and the temperature peak decreases at the given heat flux and mass flux. On the contrary, DNB is delayed with an increase in mass flux. A series of boiling heat transfer correlations in a subcooled region, two-phase flow region, and superheated region are proposed in addition to a new predictive correlation for critical heat flux in the near-critical region at a given mass flux.

1. Introduction

Carbon dioxide (CO_2) is environmentally benign, cheap to produce, and readily available [1]. CO_2 has been widely used in many advanced thermodynamics systems. In 1993, Lorentzen and Pettersen [2] proposed the concept of CO_2 in a trans-critical cycle as a potential next-generation automotive refrigerant that offers high volumetric heat capacity and excellent heat transfer properties. The refrigerating cycle is being studied. Meanwhile, due to its superior cycle efficiency, compact system structure, and low engineer cost, the trans-critical CO_2 cycle has attracted increasingly more attention as of late. In these systems, the unique thermo-hydraulic characteristics of working fluids have become a primary concern.

The critical point (or critical state) is the endpoint of a phase equilibrium curve in thermodynamics. At the critical point (for CO_2, $P_{cr} = 7.3773$ MPa, $T_{cr} = 304.13$ K), only one phase exists, and the heat of vaporization is zero. Below this point, a liquid and its vapor coexist. As the pressure approaches the critical point, the latent heat of vaporization and liquid density quickly decreases and the surface tension of CO_2 gradually falls to zero, as seen in Fig. 1.

As indicated in Fig. 1, below the critical point of CO_2, liquid density and latent heat present approximately linear changes across a wide range of pressures (1.2–6.2 MPa). The dashed lines indicate that the pressure is close to a certain value (i.e., $\approx 0.85 \times P_{cr}$), where a rapid decrease is readily apparent. The variation in this region from $0.85 \times P_{cr}$ to P_{cr} is faster than in a lower-pressure range. Meanwhile, the surface tension is very low and gradually falls to zero as the pressure increases in this region.

More data on the thermophysical properties derived from NIST Refprop [3] in special regions are shown in Table 1: pressure and

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Nomenclature

c_p	specific heat, J/kg·K
d	diameter, m
G	mass flux, kg/m^2 s
h	heat transfer coefficient, W/m^2 K
I	current, A
H	enthalpy, kJ/kg
L	length, m
P	pressure, MPa
q	heat flux, kW/m^2
$\bar{q}$	averaged heat flux, kW/m^2
t	temperature, °C
T	temperature, K
U	voltage, V
x	vapor quality
X_{tt}	Martinelli parameter; $\left(X_{tt}=\left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_g}{\rho_l}\right)^{0.5}\left(\frac{\mu_l}{\mu_g}\right)^{0.1}\right)$
z	location, m

Greek symbols

β	contact angle, °
μ	dynamic viscosity, Pa·s
λ	thermal conductivity, W/m·K
ρ	density, kg/m^3
η	thermal efficiency
σ	surface tension, mN/m

Non-dimensional numbers

Bo	Boiling number; (q_{cr}/GH_{fg})
Nu	Nusselt number; (hd/λ)
Pr	Prandtl number; $\left(\frac{\mu c_p}{\lambda}\right)$
Re	Reynolds number; $\left(\frac{Gd}{\mu}\right)$
We	Weber number; $(G^2 d/(\rho_l \sigma))$

Subscripts or superscripts

b	bulk
bottom	bottom portion
cr	critical
cal	calculated
exp	experimental
f	bulk fluid
fg	from liquid-phase to gas-phase
g	gas
i	inside
in	inlet
l	liquid
o	outside
out	outlet
sl	saturated liquid
sg	saturated gas
ss	stainless steel
ref	reference
spl	single phase liquid
sh	superheat
top	top portion
tp	two-phase
w	wall
wi	inner wall
wo	outer wall

Acronyms and abbreviations

DNB	departure from nucleate boiling
NCR	near-critical region

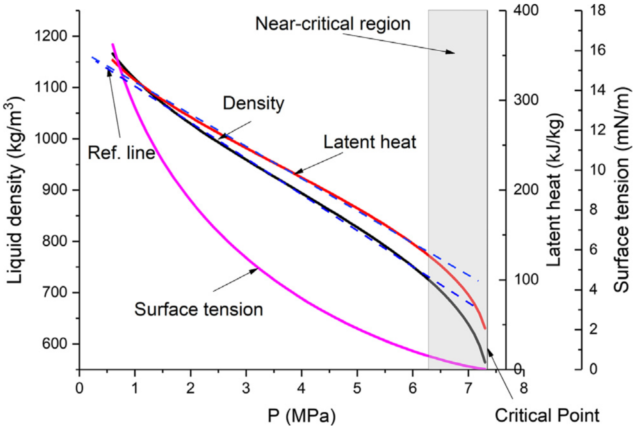

Fig. 1. Definition of the near-critical region.

corresponding saturated liquid density, saturated vapor density, latent heat, surface tension, two empirical coefficients related to the bubble departure diameter, and vaporization speed within the near-critical region (NCR).

As indicated in Fig. 1 and Table 1, with an increase in pressure, the latent heat decreases, but the parameter related to the vaporization speed increases, demonstrating that the required nucleation energy for bubble formation decreases. Thus, a larger number of vapor bubbles will be produced in cases with identical heat loads imposed on the heating wall. Meanwhile, the surface tension in the NCR is exceptionally tiny (10^{-4} order), especially near the critical point; the corresponding interface energy for a bubble is similarly small. Also, the surface tension and density difference between saturated liquid density and vapor density gradually decrease with an increase in pressure, and the bubble departure diameter becomes increasingly small (see parameter d_e in Table 1). Therefore, the size of generated bubbles is inevitably reduced and easily fractured, meanwhile the vapor density get heavier, potentially leading to an assembled vapor block. Heat transfer may get worse under such effects, as heat transfer occurs more easily under high pressure than under lower pressure. Furthermore, with an increase in pressure, the difference between the liquid and vapor phase monishes may slow the temperature from soaring in the NCR. Therefore, the boiling heat transfer characteristics in this region change significantly and become complex due to the steep variation in thermophysical properties.

To better understand boiling heat transfer in this unique region, the pressure range from $0.85 \times P_{cr}$ to P_{cr} is defined as the NCR based on the nonlinear variation in thermophysical properties. This definition applies to water in addition to other fluids. It should be noted that our NCR definition differs from that given in some existing studies [5,6], where concentrated convective heat transfer of fluid in the NCR is actually above the critical point that is considered supercritical pressure rather than subcritical pressure.

Much research exists on flow boiling heat transfer of water [7–10] and refrigerated fluids [9–16] in small-diameter tubes. Gasche [11] empirically studied CO_2 evaporation inside a 0.8 mm hydraulic diameter microchannel. Miyata et al. [12] performed an experiment to examine characteristics of flow boiling heat transfer of refrigerant R410A flowing in a vertical small-diameter tube. Aldana