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Numerical investigation on heat transfer of the supercritical fluid upward in vertical tube with constant wall temperature

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ABSTRACT

The supercritical fluid has been extensively applied in many industry applications and heat transfer characteristics of the supercritical fluid play an important role in system safety and economic design. In this paper, heat transfer characteristics and mechanism of the supercritical fluid upward in vertical tube with constant wall temperature are numerically investigated. Heat transfer fluctuation phenomenon is found at the trans-critical section where fluid experiences the pseudo-critical point. Heat transfer fluctuation takes place only when the wall temperature is higher than the pseudo-critical temperature and the bulk temperature is lower than the pseudo-critical temperature. The traditional prediction correlation can't predict heat transfer fluctuation at the trans-critical section correctly. Heatflux fluctuation is caused by the buoyancy effect. The buoyancy effect induces the periodic flow variation and the periodic convective heat transfer variation on the radial direction, which determine heatflux fluctuation on the wall. The fluctuation amplitude of heatflux on the wall decreases along the axial direction due to the weakened buoyancy effect. Influence of operating conditions on heat transfer of the supercritical fluid is investigated. R134a is chosen as the working fluid. Operating condition includes mass flow ranging from 500 to 800 kg/(m^2 s), inlet temperature ranging from 313.15 to 343.15 K, wall temperature ranging from 403.15 to 433.15 K and operating pressure ranging from 4.35 to 5.04 MPa. It is observed that heat transfer coefficient rises with mass flow, wall temperature and operating pressure increasing, but it doesn't vary obviously with inlet temperature. Fluctuation amplitude of heat transfer coefficient decreases with mass flow, wall temperature, inlet temperature and operating pressure increasing.

1. Introduction

Supercritical fluid has been extensively applied in many industry applications, such as supercritical water cooled reactors [1], supercritical thermal power plant, supercritical carbon dioxide Brayton cycle, Solar CO_2 Rankine system [2] and so on. In all of these applications, heat transfer characteristics of the supercritical fluid play an important role in the system safe and economic design. Therefore heat transfer characteristics of the supercritical fluid has been investigated by researchers for several decades.

Supercritical fluid has unique thermal physical properties compared to the sub-critical fluid. Taking R134a as an example (in Fig. 1), fluid at the supercritical pressure behaves like liquid when temperature is below the pseudo-critical temperature and like gas when temperature is higher than the pseudo-critical temperature. The pseudo-critical point is defined as the point at which the specific thermal capacity shows its peak at the given supercritical pressure. Near the pseudo-critical point, thermal physical properties such as density, specific thermal capacity, viscosity and thermal conductivity vary steeply and nonlinearly, which intensely influence the velocity and temperature fields when the fluid is heated in a single tube or bundle and therefore induce unique heat transfer characteristics which further influence the system performance and safety.

Much study on thermal hydrodynamics of the supercritical fluid has been implemented since 1950s and several comprehensive reviews have been published [3–5]. It has been found based on plenty of experiments that three types of heat transfer phenomenon of the supercritical fluid exist which are called "normal", "deteriorated" or "improved". Normal heat transfer is characterized in general with heat transfer coefficient similar to that of sub-critical convective heat transfer, which are calculated according to the Dittus–Boelter correlation. Deteriorated heat transfer is characterized with lower value of heat transfer coefficient and hence higher value of wall temperature at high heatflux and low mass

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Nomenclature

c_p	specific heat capacity (J/(kg K))
C_μ	empirical constant specified in the turbulence model, $C_\mu = 0.09$
D	inside diameter (m)
g	gravitational acceleration (m/s^2)
h	enthalpy (J/kg)
I	turbulent intensity (%)
l	turbulence length scale (m)
L	heated length (m)
Nu	Nusselt number, $Nu = hl/\lambda$ (–)
p	pressure (Pa)
Pr	Prandtl number, $Pr = \mu c_p/\lambda$ (–)
Pr_t	turbulent Prandtl number for energy (–)
q	heatflux (W/m^2)
r	radial coordinate (m)
Re	Reynold number, $Re = \rho \mathrm{u} D/\mu$ (–)
T	Temperature (K)
u	axial velocity (m/s)
u_{avg}	mean flow velocity (m/s)
$\bar{u}$	axial mean velocity (m/s)
v	radial velocity (m/s)
x	axial coordinate (m)

Greek letters

δ_{ij}	Kronecker symbol
k	turbulent kinetic energy (m^2/s^2)
λ	thermal conductivity (W/(m K))
μ	kinematic viscosity (kg/(m s))
μ_e	effective viscosity (kg/(m s))
μ_t	turbulent viscosity (kg/(m s))
ρ	fluid density (kg/m^3)
ν_t	turbulent kinematic viscosity (m^2/s)
ω	specific dissipation rate (1/s)

Subscripts

b	bulk
w	wall

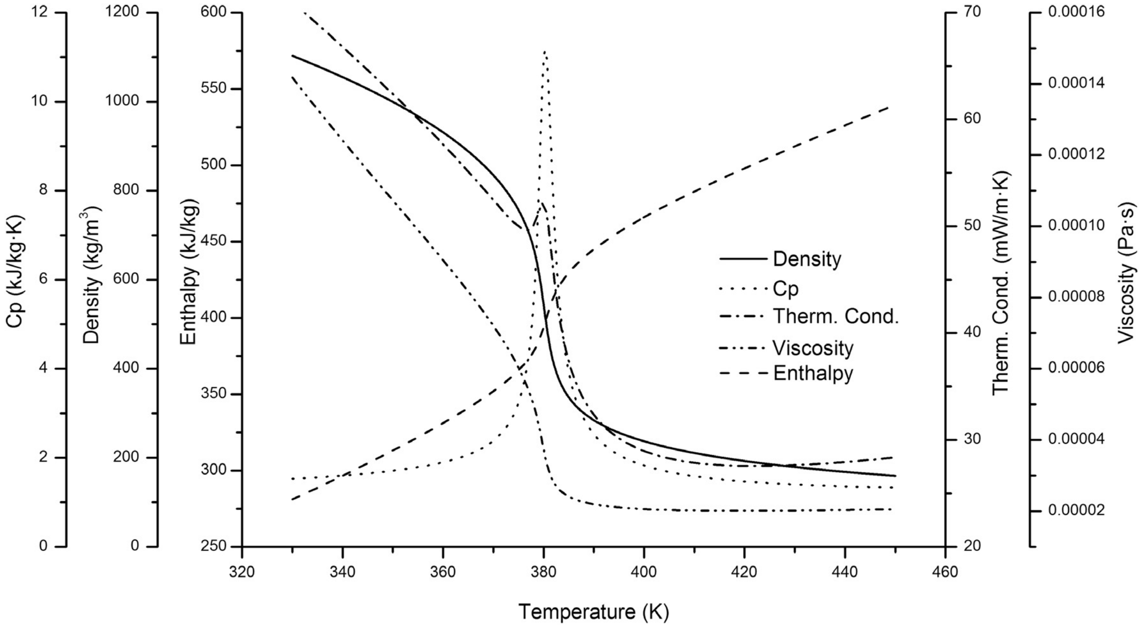

Fig. 1. Thermal physical properties of R134a at pressure of 4.58 MPa.

flux compared to that at the normal heat transfer. Improved heat transfer is characterized with higher value of heat transfer coefficient and hence lower value of wall temperature compared to that at the normal heat transfer. Since the deteriorated heat transfer will induce high wall temperature which has the potential to damage system severely and decrease system efficiency, it has achieved extensive attention for a long time.

Heat transfer deterioration is caused by the intense variation of thermal physical property of the supercritical fluid often accompanied with the turbulent flow state, which makes heat transfer mechanism very complicated and heat transfer prediction difficult and inaccurate. Some researchers [6–8] proposed their explanations for mechanism on heat transfer deterioration. It is concluded that thermal physical property, flow acceleration and buoyancy effect are the main factors. Jackson and Hall [9] considered that the buoyancy effect causes reduction in the velocity gradient which makes turbulence production reduced and turbulent diffusion impaired. With the buoyancy effect becomes strong, the laminarization is reached where turbulence production in the near-wall region ceases and heat transfer deterioration happens. Based on analysis on the buoyancy effect and the acceleration effect, some equations for onset of heat transfer deterioration are presented [8,10–13].

Influence of operating parameters on heat transfer has been investigated widely. Generally speaking, heat transfer coefficient increases as mass flux increases [14,15] and heatflux decreases [15,16]. For pressure, heat transfer coefficient increases as pressure decreases when other conditions are fixed [17,18], but effect of pressure on heat transfer is relatively small compared to that of mass flux and heatflux. However, contradict experimental results