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Experimental study of buoyancy effect and its criteria for heat transfer of supercritical R134a in horizontal tubes

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ABSTRACT

Supercritical organic Rankine cycles (ORCs) are a promising waste heat recovery technology because of their high thermal efficiency and lower exergy loss. Heat transfer characteristics must be considered for vapor generator design in ORCs. This paper focuses on the buoyancy effect on heat transfer characteristics in horizontal tubes of supercritical R134a, a widely used ORC working fluid, whose supercritical heat transfer characteristics have been less widely studied. Experiments of supercritical R134a flowing in horizontal tubes with different inner diameters of 10.3 mm and 16 mm were conducted to obtain basic experimental data. The influences of heat flux, mass flux, and tube diameter on heat transfer were investigated with an emphasis on the buoyancy effect. This study attempts to extend the applicability of existing buoyancy criteria to organic fluids in horizontal tubes to quantitatively analyze the buoyancy effect. Existing buoyancy criteria, which were developed for water, were evaluated and the threshold values determining the onset of the buoyancy effect in heated horizontal tubes were determined for the present data. A simple parameter of $qd^{0.7}/G^{1.2}$ not based on wall temperature was developed to be correlated with the maximum temperature difference between the top and bottom surfaces for convenience in engineering use. This parameter was validated with both the present data and supercritical water data from the literature.

1. Introduction

Supercritical organic Rankine cycles (ORCs) are receiving considerable attention owing to their advantages in the utilization of renewable energy and low-grade waste heat energy, such as higher thermal efficiency, lower exergy loss, and compact components [1,2]. In the vapor generator of a supercritical ORC unit, the working fluid is heated by the heat source at supercritical pressures, where the thermophysical properties of the working fluid undergo significant variations (as shown in Fig. 1), leading to unique and complex heat transfer phenomena [3]. Therefore, investigation of the supercritical heat transfer characteristics of organic fluids is of considerable importance for the vapor generator design of ORC systems.

Supercritical heat transfer has mostly been studied in the field of supercritical water-cooled reactors and fuel-fired boilers; thus, previous studies mainly focused on water and CO_2 in vertical heated tubes. Pioro and Duffey [4,5], Huang et al. [6], and Cabeza et al. [7] have comprehensively reviewed the experimental studies on water and CO_2, showing that the experimental parameters cover wide ranges: pressures of 22.5–35 MPa, heat fluxes of 0.018–9.44 MW/m^2, mass fluxes of 100–10,000 kg/m^{2}s, and inner diameters of 1.27–38.1 mm for water; and pressures of 7.4–21 MPa, heat fluxes of 3.5–2600 kW/m^2, mass fluxes of 100–4170 kg/m^{2}s and inner diameters of 0.099–29 mm for CO_2. However, there is a lack of heat transfer experimental data for organic fluids at supercritical pressures compared with water and CO_2. Limited studies can be found in the literature for organic fluids, the majority of which were conducted in vertical tubes, such as R134a [8–10], R12 [11], and R22 [12–14] heated in vertical tubes. The vapor generators in ORC units are commonly horizontally oriented, but unfortunately supercritical heat transfer of organic fluids in heated horizontal tubes has been seldom studied. R134a [15], 410a [16], and 404a [17] have been studied in horizontal tubes, but in a cooling process. Therefore, the development of a supercritical ORC raises new requirements for the study of supercritical heat transfer.

The buoyancy effect due to a density gradient is the most important factor for interpreting heat transfer mechanisms at

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Nomenclature

Bo	Jackson buoyancy criterion for vertical flow, $= \overline{Gr_b}/Re_b^{2.7}$
Bu_J	Jackson buoyancy criterion for horizontal flow, $= Gr_b Re_b^{-2}\left(\frac{\rho_b}{\rho_w}\right)\left(\frac{x}{d}\right)^2$
c_p	specific heat (kJ/kg·K)
d	diameter (m)
G	mass flux ($kg \cdot m^{-2} \cdot s^{-1}$)
Gr_b	Grashof number based on bulk density, $= gd^3(\rho_b - \rho_w)/\rho_b v_b^2$
$\overline{Gr_b}$	Grashof number based on average density $= gd^3(\rho_b - \bar{\rho})/\rho_b v_b^2$
Gr^*	Grashof number based on heat flux $= g\beta_b q_w d^4/\lambda_b v_b^2$
h	enthalpy (kJ/kg)
K_v	acceleration criterion, $= 4q_w d\beta_b/(Re^2\mu_b c_{p,b})$
Nu	Nusselt number
p	pressure (MPa)
Pr	Prandtl number
$\overline{Pr}$	average Prandtl number
q	heat flux (kW/m^2)
Re	Reynolds number
T	temperature (K)
ΔT_w	wall temperature difference between the top and bottom surface
x	axial location of the tube

Greek symbols

β	volumetric expansion coefficient (1/K)
ρ	density (kg/m^3)
$\bar{\rho}$	average density, $(1/(T_w - T_b))\int_{T_b}^{T_w}\rho dT$ (kg/m^3)
μ	dynamic viscosity (µPa·s)
λ	thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
ν	kinetic viscosity (m^2/s)

Subscripts

b	bulk
c	critical point
cal	calculated
exp	experimental
top	top surface
bottom	bottom surface
pc	pseudo-critical point
fc	forced convection
w	Wall
in	inner

Abbreviations

DB	Dittus–Boelter correlation
HTC	heat transfer coefficient
ORC	organic Rankine cycle

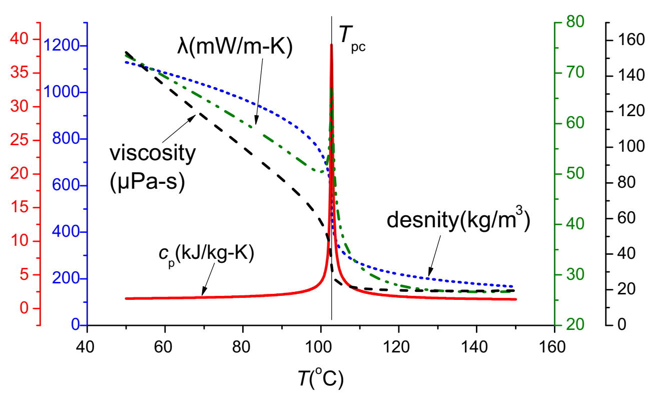

Fig. 1. Thermophysical properties variations of R134a at 4.2 MPa and data is taken from NIST Refprop database [44].

supercritical pressures in both vertical and horizontal tubes [18,19]. In vertical tubes, at a lower ratio of heat flux to mass flux (*q/G*, kJ/kg), forced convection heat transfer is enhanced near the pseudo-critical point because much of the boundary layer is covered with a high-specific-heat fluid, which is called the integrated effect of specific heat [20–22]. In mixed convection with a relatively high *q/G*, local heat transfer deterioration (HTD) [23] happens with a sharp wall temperature peak. Hall and Jackson [24] proposed a two-layer density theory to explain HTD. The buoyancy force due to a radial density gradient accelerates the flow near the wall and further modifies the shear stress distribution, which consequently causes "relaminarization" in turbulent flow. As a result, the heat transfer ability is reduced. Computational results have proven this theory [25]. Experimental results have shown that the heat flux, mass flux, and tube diameter affect the buoyancy intensity [26–28]. In horizontal flows, significant temperature variation was observed in the circumferential direction caused by the buoyancy force [29], which is a special phenomenon that differs from that of vertical flows. The top surface wall temperature is always higher than that of the bottom surface in buoyancy-aided flow. Heat transfer on the top surface will be impaired at high *q/G* conditions, leading to a local wall temperature peak, which is similar to that in vertical flows [30].

For the purpose of quantitative analysis, various criteria for determining the onset of buoyancy effect in vertical heated tubes were proposed, such as Gr_b/Re^2 [29,31], $Gr^*/(Re^{3.425}Pr^{0.8})$ [19], $\overline{Gr_b}/Re^{2.7}$ [19,32], and $Gr_b\left(\frac{\rho_b}{\rho_w}\right)^{0.5}\left(\frac{\mu_w}{\mu_b}\right)/(Pr_w^{0.4}Re_b^{2.625})$ [33]. Li [34] and Huang et al. [6] have reviewed the buoyancy parameters. Among these buoyancy parameters, $Bo = \overline{Gr_b}/Re^{2.7}$ (or $Bo^* = Gr^*/(Re^{3.425}Pr^{0.8})$, which is equivalent to *Bo*) obtained from the theory of Hall and Jackson [24] appears to be the most appropriate parameter and has been widely tested. Jackson noted that the effect of buoyancy on heat transfer would be >5% when $\overline{Gr_b}/Re^{2.7} > 10^{-5}$. Li [34] demonstrated that the mixed convection data of air in vertical flows (both upwards and downwards) was well described by the buoyancy parameter of *Bo*. Licht et al. [35] showed that *Bo* can distinguish forced convection from mixed convection for water in vertical flows. Jiang's [36] results indicated that *Bo* was consistent with CO_2 experimental data for upward flows. However, Liu [37] found that the threshold value of Bo^* for n-decane was much smaller than that proposed by Jackson. Experimental results of water in horizontal tube by Bazargan et al. [29] showed that *Bo* was not applicable to horizontal flows. Deng et al. [38] found that *Bo* was inaccurate in predicting the buoyancy force of RP-3 kerosene. Therefore, further examination is required to see whether these criteria are applicable for organic fluids in horizontal flows.

Compared with vertical flows, studies on buoyancy criteria for horizontal flows are relatively limited. Petukhov and Polyakov [39] have proposed a buoyancy criterion for horizontal flows of Gr_q/Gr_{th}. When $Gr_q/Gr_{th} > 1$, the buoyancy effect is expected to