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Special heat transfer characteristics of supercritical CO_2 flowing in a vertically-upward tube with low mass flux

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ABSTRACT

Due to limited studies on heat transfer of supercritical CO_2 (S-CO_2) at low mass flux, an experimental study was conducted on the High-TaP-SCO2 test loop to study heat transfer of S-CO_2 in a 16-mm diameter tube with low mass flux. Fundamental data were collected at a pressure range of 7.5–10.5 MPa, mass flux of 50–500 kg/m^2 s and heat flux of 5–100 kW/m^2. The effects of heat flux, mass flux, and pressure on heat transfer at low mass flux were analyzed. Results showed that, with increasing heat flux, a completely different heat transfer phenomenon was observed at lower mass flux ($G < 300$ kg/m^2 s) compared to a normal mass flux ($G \geq 300$ kg/m^2 s). Heat transfer at lower mass flux was not deteriorated but rather enhanced with a rising heat transfer coefficient, which is about 2.6 times higher than single-phase convective heat transfer. With mass flux decreasing from 400 to 100 kg/m^2 s, heat transfer was enhanced about 5 times and turned from deterioration to enhancement. The mechanism of this heat transfer transition was further discussed. Results suggested that the special heat transfer enhancement at lower mass flux was mainly induced by the combined effects of strong buoyancy and high c_p fluid. Based on the present dataset, existing Nusselt correlations for supercritical fluids were reevaluated, and these correlations failed in capturing the heat transfer enhancement occurring at low mass flux. Finally, a modified correlation for the heat transfer of S-CO_2 at low mass flux was proposed within ±20% error and is available for the design of relevant devices with S-CO_2.

1. Introduction

Due to notable advantages in convenience, economics, and system simplicity compared to the conventional steam Rankine-cycle, the Brayton-cycle with supercritical CO_2 (S-CO_2) has been broadly applied in industries such as concentrating solar systems [1], enhanced geothermal systems [2], and advanced nuclear systems [3]. Recently, application of the S-CO_2 Brayton-cycle to coal-fired plants has also been suggested, and attracted more attention due to its smaller size and higher thermal efficiency: up to 45.3% and 50% with respective main gas temperatures of 550 °C and 650 °C [4]. Nowadays, fundamental developments in new energy conversion systems with S-CO_2 Brayton-cycle are still in nascent stages. The convective heat transfer performance of S-CO_2 in heat exchangers remains a fundamental issue in the design and validation of these new systems. Previous studies have revealed the complexity of heat transfer characteristics of supercritical fluids (SCFs) due to dramatically changing properties near the pseudo-critical region (as shown in Fig. 1) [5]. Research on basic heat transfer of S-CO_2 should thus be seriously considered.

Since the 1960s, with the wide application of supercritical water (SCW) power plants, extensive experimental research [6–11] has been performed to explore the complex heat transfer characteristics of SCFs using CO_2, which has much lower critical parameters than water. Duffey et al. [12] reviewed the heat transfer of S-CO_2, and described three heat transfer modes to SCFs: normal heat transfer; heat transfer enhancement (HTE, with a higher heat transfer coefficient (*htc*) than single-phase forced flow when the ratio of heat flux to mass flux (q/G) is small); and heat transfer deterioration (HTD, with an impaired *htc* when q/G is large). Some defects in earlier research were also pointed out by Groeneveld [13] and Kurganov [11] via the poor accuracy of fluid properties and loss of necessary datasets. Fig. 2 displays a comparison between CO_2 properties in the 1960s [14] and the present. It shows a large discrepancy in previous properties near the pseudo-critical point, which can reduce the accuracy of experimental results to some extent. Now, thanks to the great potential of S-CO_2 Brayton-cycle, the heat transfer performance of S-CO_2 has garnered considerable empirical attention, with several updated experiments being carried out [15–26]. Jiang et al. [16,22] studied heat

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Nomenclature

Bo^*	Buoyancy number proposed by Jackosn
Bu	Buoyancy number proposed by Fewster
C	heat transfer state number, $= h_{\text{exp}}/h_0$
c_p	specific heat (kJ/kg K)
$\overline{c_p}$	average specific heat (kJ/kg K), $= (h_\text{w} - h_\text{b})/(T_\text{w} - T_\text{b})$
d	inner diameter of tubes (m)
g	gravity acceleration (m/s^2)
G	mass flux (kg/m^2 s)
$\overline{Gr_\text{b}}$	average Grashof number, $= (\rho_b - \overline{\rho})d^3 g\rho_b/\mu_b^2$
Gr^*	Grashof number, $= (g\beta_\text{b}d^4q \cdot \rho_\text{b}^2)/(\lambda_\text{b}\mu_\text{b}^2)$
h	fluid enthalpy (kJ/kg)
htc	heat transfer coefficient (kW/m^2 K)
I	current (A)
Nu	Nusselt number, $= htc \cdot d/\lambda_\text{b}$
L_heat	heated length (m)
P	pressure (MPa)
Pr	Prandtl number, $= c_p \cdot \mu/\lambda$
q	heat flux (kW/m^2)
Re	Reynolds number, $= G \cdot d/\mu$
T	temperature (°C)
U	voltage (V)
x	axial distance (m)

Greek symbols

β	thermal expansion coefficient (1/K)
λ	thermal conductivity (kW/m K)
ρ	density (kg/m$^{3)}$
$\overline{\rho}$	average density, $= \int_{T_\text{b}}^{T_\text{w}} \rho \text{d}T/(T_\text{w} - T_\text{b})$
μ	dynamic viscosity (Pa s)

Subscripts

b	at bulk fluid temperature
cal	calculated
cr	at critical point
exp	experimental
in	inlet of the tube
o	outer
out	outlet of the tube
pc	at pseudo-critical temperature
w	at wall temperature

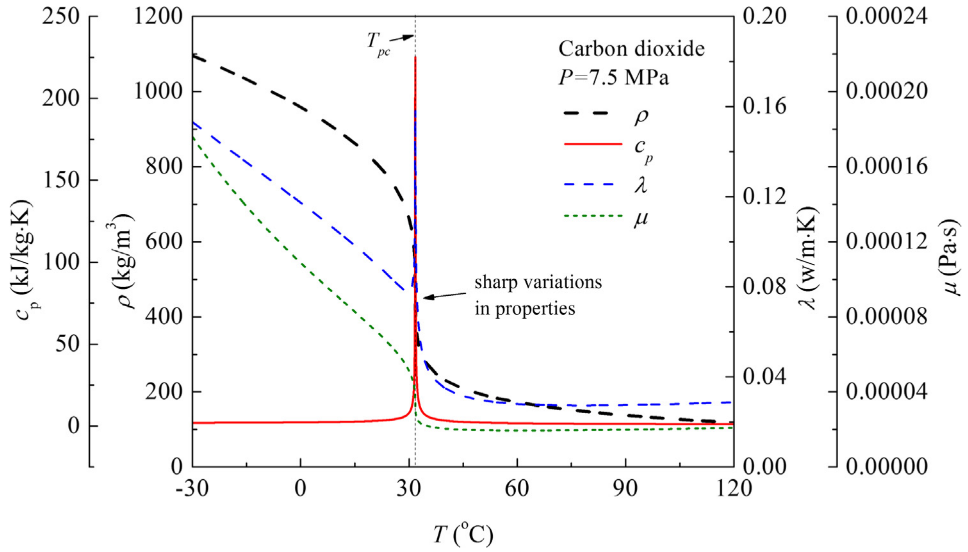

Fig. 1. Thermal property variations versus temperature of S-CO$_2$ at P = 7.5 MPa.

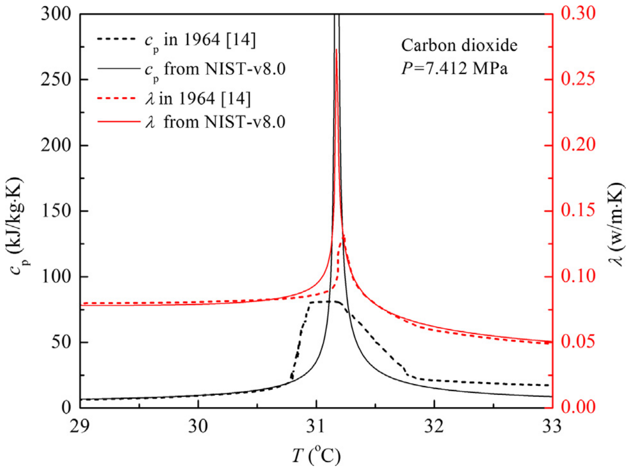

Fig. 2. Comparison between CO$_2$ properties in 1964 [14] and the present.

transfer of S-CO$_2$ in mini-tubes ($d \leq 2$ mm) and found that natural convection driven by buoyancy was weakened in small tubes, but flow acceleration effect induced by axial density gradient of S-CO$_2$ was strong. Bae et al. [17,19] experimentally studied heat transfer of S-CO$_2$ in tubes with d = 6.32 mm and 4 mm at a relatively large mass flux ($G \geq \sim$300 kg/m^2 s), and deteriorated wall temperature peaks were observed under high heat fluxes. Zahlan et al. [23] also investigated heat transfer of S-CO$_2$ flowing in an 8-mm tube and found similar results. Table 1 lists a detailed summary of experimental studies regarding the heat transfer of S-CO$_2$ in vertical upward tubes until 2017, most of which were conducted with small tubes ($d \leq 8$ mm). Yildiz et al. [27] discussed the influence of tube diameter and concluded that heat transfer of SCFs in large tubes was more likely to deteriorate. Thus, the results obtained with small tubes may not be suitable for S-CO$_2$ flowing in relatively large heated tubes (d > 10 mm), which are possibly used in future coal-fired plants and nuclear reactors. Moreover, heat transfer of SCFs is notably influenced by the continuous variations of thermal