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Orientation effect in helical coils with smooth and rib-roughened wall: Toward improved gas heaters for supercritical carbon dioxide Rankine cycles

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ABSTRACT

Helical coils have gained increasingly interest in the field of supercritical carbon dioxide ($SCCO_2$) Rankine cycles during the last decade due to the compact structure and high heat transfer rate. Past studies mainly focused on effects of operating conditions and the gravitational buoyancy, and are not sufficient to fully understand the behavior of $SCCO_2$ helically coiled gas heaters. Influence of some other key factors, such as the coil orientations and internal wall roughness, on overall performance has been seldom reported and is still unclear to date. In this work we filled this gap with a solid-to-fluid conjugate heat transfer model where supercritical flow turbulence is solved by the Shear-Stress Transport k-ω equations. The orientation effect on performance of helical coils was revealed with the coil axis arranged in horizontal, vertically upward and downward directions, respectively. Results demonstrate that the criterion of $Bo < 10^{-5}$ for negligible buoyancy effect was applicable to coils with dimensionless curvature $\delta = 0.01-0.1$. The Orientation effect only emerged when the buoyancy effect became significant with $Bo > 10^{-5}$. Deterioration and enhancement of heat transfer occurred alternatively in horizontal coils. The overall performance of horizontal coils was much worse than vertical coils, among which the downward orientation was slightly better than the upward one. The increase of δ barely improved the performance of horizontal coils. Instead, at larger δ the intensive fluctuation in heat transfer coefficients was more frequent due to the more drastic change of the flow direction. The location and extent of local impairment also varied with the inlet arrangement. Finally, the passive compound enhancement technique of helical coils in conjunction with internal helical-rib roughness was found to be very effective in mixed convection of $SCCO_2$, especially in the horizontal coils.

1. Introduction

Helically coiled heat exchangers have been widely used in engineering systems due to their compact structure and high heat transfer rate [1,2]. During the last decade, there has been a rapid growth of interest in the use of helically coiled heat exchangers within some advanced systems, such as supercritical carbon dioxide Rankine cycles and heat pump, where CO_2 is employed as heat transfer fluid and operated at pressures above the critical point. In supercritical carbon dioxide ($SCCO_2$) Rankine cycles the overall efficiency generally improves as a result of the higher operating pressure, and better thermal match between heat transfer fluid and heat source. As reviewed by Sarkar [3], currently researches concerning $SCCO_2$ Rankine cycles mainly focused on energetic/exergetic analysis, selection of operating parameters, system optimization, etc. Heat transfer performance of the gas heater, however, received much less attention. This is essential to the design/dimensioning of the gas heater, the techno-economic analysis and system optimization [4–6]. The layout of a typical $SCCO_2$ Rankine cycle and the corresponding *T-s* diagram is shown in Fig. 1a. In the gas heater (2 → 3), CO_2 goes through the supercritical

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Nomenclature

Bo	Jackson buoyancy parameter based on integrated density
D	coil diameter (mm)
d	hydraulic diameter the tube (mm)
d_i	major inside diameter, or diameter to root of ribs (mm)
e	rib height (mm)
G	mass flux ($kg \cdot m^{-2} \cdot s^{-1}$)
g	gravitational acceleration (9.81 m/s^2)
$\overline{Gr_b}$	Grashof number based on average density, $(\rho_b - \overline{\rho})d^3 g/\rho\nu^2$
H	fluid enthalpy (kJ/kg)
h	average heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
L	curvilinear length of the coil (mm)
N	number of turns of the coil
N_s	number of starts of the internal rib
Nu	Nusselt number
Pr	Prandtl number
p	operating pressure (MPa)
q	area-weighted average heat flux on the inner surface of tube (kW/m^2)
R	coil radius, $R = D/2$ (mm)
Re	Reynolds number
S	coil pitch (mm)
s	rib pitch (mm)
T	temperature (K)
t	wall thickness (mm)
X	curvilinear abscissa along the tube axis (mm)

Greek Symbols

α	helix angle of the rib (°)
φ	circumferential angle (°)
δ	dimensionless wall curvature
$\delta=$	d/D
λ	thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
ρ	density (kg/m^3)
$\overline{\rho}$	average density, $(1/(T_w - T_b)) \int_{T_b}^{T_w} \rho dT$ (kg/m^3)
μ	dynamic viscosity (Pa·s)
ν	kinematic viscosity (m^2/s)

Subscripts

ave	area-averaged
b	bulk
g	gravitational
h	heated
in	inlet
iw	inner wall
max	maximum
min	minimum
NG	no gravity
pc	pseudocritical point

Abbreviation

Exp.	experimental
HRW	helically coiled tube with internally ribbed wall
HSW	helically coiled tube with smooth wall
$SCCO_2$	supercritical carbon dioxide
ST	straight tubes

state. Though no phase change occurs, CO_2 experiences sharp property variations when fluid temperature T changes, especially near the pseudocritical point. The pseudocritical point is the state where specific heat c_p of supercritical fluids reaches the maximum when pressure is fixed at a value above the critical pressure. Fig. 1b shows that near the pseudocritical temperature T_{pc} thermophysical properties of CO_2 vary sharply. These sharp property changes can lead to serious impairment of heat transfer in gas heaters equipped with the most commonly used straight and smooth tubes [7,8]. Therefore, heat transfer enhancement techniques are needed in gas heaters to improve the overall performance of $SCCO_2$ Rankine cycle.

Among all the enhancement techniques, helical coils have been heavily investigated during the past decade due to their compact structure and low frictional resistance, and the coil-induced enhancement has been confirmed both experimentally and numerically [9–12]. Among those studies only wall temperatures were measured in experiments to give an insight on the average heat transfer performance, due to the difficulty to measure turbulence quantities in a high-pressure channel. On the other hand, numerical models present advantages of a detailed flow field and better explanation for mechanism of improved heat transfer. The selection of turbulence model is critical to the accurate dealing on the sharp property changes and subsequent modification on turbulent shear stress distribution. By now turbulence models employed mainly include the RNG k-ε model [13,14], the Shear-Stress Transport k-ω (SST) model [12,15–18] and some low-Reynolds number models [9,15]. Most of these models show acceptable agreement with validation experiments, among which the SST model presents good performance over a relatively wide range of operation conditions and is most widely used. One shortage of these studies, to the opinion of the present authors, is that they mainly focused on effects of operating conditions (e.g. fluid pressure, fluid temperature, heat flux and mass flux), coil geometries and gravitational buoyancy on average and local heat transfer. Helical coils were installed vertically upward in most of those studies and only the coil investigated by Xu et al. [12] and Yang [16] was arranged horizontally under conditions of supercritical cooling. The effect of coil orientation on heat transfer to supercritical CO_2 ($SCCO_2$) in heated helical coils is still unclear. Generally the orientations of helical coils depend on their specific applications. For example, when installation space is limited or coils are expected to be arranged with a low center of gravity due to safety consideration, the horizontal orientation is preferred. Extra attention must be paid to differences caused by orientations during the design of helically coiled heat exchangers.

Effects of the orientations on heat transfer have been extensively studied in subcritical single-phase and two-phase flows. Yu et al. [19] found that concerning to condensation heat transfer of R134a, the best performance was achieved by having the coil axis installed at 45° relative to the gravity direction. Following the inclined position, the horizontal position had the second-best performance and the vertical position performed worse. Results of convective heat transfer to subcritical single-phase water [20] also indicated that helical coils are more efficient when the coil axis is arranged horizontally than vertically. Moreover, even when the orientation of the coil's axis is fixed, heat transfer characteristics of helical coils varies with the rotation of the pipe along its coil axis. Mote et al. [20] revealed that when the axis of the coils was arranged horizontally, the greatest overall effectiveness occurred in the pipe where the inlet was at its lowest point. Shao [21] further explored this difference by examining local wall temperatures of a horizontal coil with the inlet at the lowest point. She found that