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Experimental research on the turbulent convection heat transfer of supercritical pressure CO_2 in a serpentine vertical mini tube

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ABSTRACT

Convection heat transfer characteristics of supercritical pressure CO_2 in vertical straight tubes were investigated experimentally and numerically extensively by the researchers. However, in some practical applications, the channel may not be straight but rather serpentine. The integrated effects of buoyancy and centrifugal forces on the convection heat transfer behavior of supercritical fluids in serpentine tubes need to be studied thoroughly. This paper presents experimental investigations of the turbulent convection heat transfer of supercritical pressure CO_2 in a serpentine vertical mini tube with an inner diameter of 0.953 mm and curvature diameter of 8.01 mm for various inlet Reynolds numbers, heat fluxes, and flow directions. Infrared temperature measurement was used to measure the continuous distribution of the wall temperature. The effects of variations in thermophysical properties, integrated effect of buoyancy force and centrifugal force were analyzed through comparison the heat transfer performance between the upward and the downward flow in serpentine tube and straight tube under similar experimental conditions. It was found that the heat transfer performance was better in the serpentine tube than in the straight tube because of the secondary flow attributable to centrifugal forces. At relative low Bo^*, the heat transfer in the serpentine vertical tube for downward flow performed better than upward flow due to the effect of gravitational buoyancy on the intensity of turbulence. At relative high Bo^*, in contrast with the existing research on turbulent convection heat transfer of supercritical fluid in straight vertical tubes, the turbulent convection heat transfer in the serpentine vertical tube for upward flow performed better than downward flow and no heat transfer deterioration occurred in the serpentine vertical tube.

1. Introduction

Convection heat transfer of supercritical fluids in various channels has extensive applications in many industries, such as supercri tical-pressure-water-cooled nuclear reactors (SPWR), supercritical pressure CO_2 cooled nuclear reactors, high temperature solar thermal power system using supercritical pressure water or CO_2, platelet transpiration cooling technology, trans-critical CO_2 heat pump and refrigeration systems, and enhanced geothermal systems using supercritical CO_2 instead of water as the working fluid has attracted wide attention due to the dual benefit of renewable energy utilization as well as the carbon dioxide emissions reduction [1–8].

In the supercritical pressures region, fluid thermophysical properties undergo dramatic changes with small variations in fluid temperature and pressure, and the specific heat, c_p, peaks at the pseudo-critical temperature, T_{pc}. This sharp variation in fluid thermophysical properties leads to many special features of the convection heat transfer of supercritical pressure fluid in various channels, such as the radial non-uniform density distribution, which causes the buoyancy force, axial variation in density, which is caused by variations in axial temperature, and pressure variation, which leads to flow acceleration during heating conditions.

Extensive experimental and numerical studies have been carried out on internal forced and mixed convection heat transfer of supercritical fluids flowing in straight channels of various sizes in the past few decades [9–23] and in porous media or media forms recently [24,25]. Jackson and Hall introduced a non-dimensional parameter, Bo^*, to evaluate the significance of buoyancy forces on the convection heat transfer behavior of supercritical fluids in vertical channels [13]. They suggested that, for upward flows in vertical circular channels with $5.6 \times 10^{-7} \leqslant Bo^* \leqslant 1.2 \times 10^{-6}$, the buoyancy would deteriorate the heat transfer due to the decrease

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Nomenclature

Bo^*	non-dimensional buoyancy parameter
C_p	specific heat at constant pressure [J/(kg K)]
d	tube diameter [mm]
D	curvature diameter [mm]
De	Dean number = Re $(d_i/D)^{1/2}$
g	gravitational acceleration [m^2/s]
G	mass flow rate [kg/s]
Gr^*	Grashof number
h	bulk specific enthalpy [J/kg]
$h(x)$	local heat transfer coefficient [$W/(m^2 K)$]
Kv	non-dimensional flow acceleration parameter
p	pressure [MPa]
Pr	Prandtl number
R	electrical resistance [Ω]
Re	Reynolds number
T	temperature [°C]
u	velocity [m/s]
x	axial coordinate [m]

Greek symbols

λ	thermal conductivity [W/(m K)]
μ	molecular viscosity [Pa s]
ρ	fluid density [kg/m^3]

Subscripts

f	fluid
i	inner surface
in	inlet
o	outer surface
out	outlet
pc	pseudo critical
p	induced by pressure variation
T	induced by temperature variation
w	wall

in the production of turbulence production near the wall region, while for $1.2 \times 10^{-6} \leqslant Bo^* \leqslant 8 \times 10^{-6}$, the heat transfer reduction will be gradually reduced as Bo^* increases, for $Bo^* \geqslant 8 \times 10^{-6}$, the heat transfer will be enhanced by the buoyancy. Li et al. investigated the convection heat transfer characteristics of supercritical CO_2 in a vertical circular tube of 2 mm inner diameter experimentally [14]. They proposed the following criterion in the mini tube according their experimental results indicating that, for upward flow, the heat transfer decreases with increasing buoyancy for $2 \times 10^{-7} \leqslant Bo^* \leqslant 6 \times 10^{-7}$, followed by recovery of the heat transfer for $6 \times 10^{-7} \leqslant Bo^* \leqslant 2 \times 10^{-5}$ and improved heat transfer for $Bo^* \geqslant 2 \times 10^{-5}$.

McEligot and Jackson introduced a non-dimensional parameter, Kv_T, to evaluate the influence of flow acceleration on the supercritical fluid convection heat transfer due to the variations in axial density caused by variations in axial temperature, suggesting that, for turbulent flow with $Kv_T \geqslant 3 \times 10^{-6}$, the turbulence may be significantly reduced and may even relaminarize as heat transfer deteriorates [19]. Jiang et al. were first to propose a non-dimensional parameter, Kv_p, to evaluate the effects of accelerations in flow attributable to the variations in axial density induced by the variations in axial pressure and results showed that for the microtube the Kv_p and Kv_T had similar values [20].

Jiang et al. investigated the convection heat transfer of supercritical pressure carbon dioxide in vertical heated circular tubes of various sizes [20–23]. Their results showed that for tube with inner diameter of 2.0 mm, the local wall temperatures varied in a complex and nonlinear manner with deterioration and recovery of the heat transfer observed in upward flows but not in downward flows, and the buoyancy was the dominant factor affecting the convection heat transfer rather than the flow acceleration. For tube with inner diameter of 0.27 mm [22,23], the buoyancy and flow acceleration effects were both insignificant at relatively high Reynolds numbers ($Re_{in} = 10^4$) for both low and high heat fluxes, while for cases with low Reynolds numbers (such as 2900), the flow acceleration significantly influenced the turbulence and reduced the heat transfer for both upward and downward flows when the heating was relatively strong (e.g. 113 kW/m^2), and the buoyancy effect was relatively weak. For tube with inner diameter of 99.2 μm, the flow acceleration was the main factor that resulted in the abnormal heat transfer phenomenon while the buoyancy effect could be neglected, and the effects of flow acceleration due to heating and pressure drop on the heat transfer were in similar magnitude in such micron scale channels [20].

In some practical applications, the channel may not be straight but rather serpentine or curved. The effects of both buoyancy and centrifugal forces on the convection heat transfer behavior for supercritical fluids in serpentine tubes needs to be analyzed thoroughly. The questions regarding whether the curvature or serpentine of the tubes can reduce or intensity the influence of buoyancy and enhance heat transfer, whether the heat transfer deterioration exits in the serpentine tubes, need to be answered.

So far, most of the studies on the convection heat transfer of the supercritical pressure fluid in curved tubes have focused on numerical investigations. There are few papers in the literature about experimental research into the convection heat transfer of the supercritical pressure fluid in curved tubes and no research has been performed on serpentine tubes to the author's best knowledge [26–32]. Prusa and Yao numerically solved for the combined effect of centrifugal force and buoyancy force on fluid flows in heated curved pipes, providing a flow regime map to indicate the three basic regimes in which the centrifugal force, the buoyancy force, or both forces were dominant [27]. Li et al. carried out a numerical study on the turbulent heat transfer of near-critical water in a heated curved pipe with a curvature ratio, the ratio between radius of the helical pipe and radius of the coil, of 0.05, and evaluated the features of the heat transfer under various conditions [28]. Li et al. numerically studied the turbulent heat transfer of supercritical pressure aviation kerosene in a heated curved pipe [29]. Their results indicated that the centrifugal force enhanced the heat transfer at the cost of the pressure drop increase and that when the curvature ratios were less than 0.05, the sharp changes of thermophysical properties did not enhance the effects of the centrifugal force but rather increased the effect of buoyancy.

This paper presents experimental investigations of the convection heat transfer of carbon dioxide at supercritical pressure in a serpentine vertical mini tube with inner diameter of 0.953 mm and curvature diameter of 8.01 mm for various Reynolds numbers, heat fluxes, and flow directions. The enhancement of heat transfer due to the curvature is studied and the effects of the significant variation of thermophysical properties, buoyancy, and centrifugal force were analyzed. The results presented here are meant to provide a better understanding of the special features that combine the effects of buoyancy and centrifugal forces on the convection heat transfer of supercritical fluids in mini-serpentine channels.