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Numerical investigation on heat transfer to supercritical CO_2 in rolling motion

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ABSTRACT

The numerical calculations with and without rolling motions are conducted to investigate the effect of rolling motion on flow and heat transfer of supercritical CO_2 in a vertical double-pipe heat exchanger. The purpose is to provide the detailed information on heat transfer behaviors for better understanding the abnormal heat transfer mechanism of supercritical fluid in rolling motion. It concludes that the effect of rolling motion on the supercritical CO_2 is much more notable than that on conventional single-phase fluid. The rolling motion can cause the periodic oscillation of the local heat transfer coefficients and suppress the whole heat transfer deterioration. As supercritical CO_2 temperature or mass flux increases, the influences of rolling motion and flow direction on the heat transfer decrease markedly. The secondary flow induced by the rolling motion for upward flow is stronger than that for downward flow, and the influence of rolling motion on the left and right sides of the tube is more obvious than on other locations. The heat transfer deterioration phenomenon weakens gradually as the rolling period decreasing or rolling amplitude increasing. It is important to note that the rolling motion may bring about the large wall temperature oscillation and the wall peak temperature increment to influence the safety of high-pressure pipeline.

1. Introduction

In recent years, there has been a growing interest in a barge-mounted floating nuclear desalination and power plant to provide potable water and electricity in coastal areas and islands. When compared to land-based nuclear power plants, such plants are cost effective, lesser construction periods and the potential to shift to any place, moreover, they have simplified anti-seismic design and decommissioning technology. With the development of the fourth generation nuclear energy technology, the thermal hydraulic characteristics of supercritical fluid in ship motions attract significant attentions.

The main difference between the land-based and ship-based equipment is the influence of sea wave oscillations on the latter. The thermal hydraulic behaviors of ship-based equipment are influenced by different motions, especially rolling motion. These motions alter the effective forces acting on the fluid, which results in the change in momentum, heat and mass transfer characteristics.

The previous researches on ship motions mainly focus on nuclear reactor such as lattices with fuel bundles and natural circulation. Murata et al. (2002) have performed some single phase natural circulation tests in a model reactor in rolling motion, in order to investigate the natural circulation characteristics of a marine reactor in a stormy weather. Tan et al. (2009a,b) have also finished a series of experiments for the single-phase flow and heat transfer in natural circulation under rolling motion condition.

Yu et al. (2008) and Yan and Yu (2009), Yan et al. (2009) analyzed the flow and heat transfer characteristics of laminar flow and turbulent flow in ocean rolling environment. Their results indicate that the rolling motion may affect the thermal hydraulic behaviors of nuclear reactor system, and the present empirical correlations could not capture the flow and heat transfer characteristics under rolling motion condition. Cao et al. (2006) and Zhang et al. (2009) experimentally studied the influences of rolling parameters, flow rates and tube sizes on single-phase flow resistance in forced circulation. They believe that the flow rate of forced circulation is nearly invariable even under rolling condition.

The previous researches (Yan et al., 2011; Pang et al., 1995; Pendyala et al., 2008) indicate that the flow in ocean rolling environment can be restricted by the wall, due to the small tube diameter (less than or next to 10 mm) in engineering application. As a result, the effect of rolling motion on the heat transfer characteris-

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Nomenclature

c_p	specific heat, J·kg^{-1}·K^{-1}
d	diameter of tube, mm
g	gravity acceleration, m^2·s^{-1}
G_k	buoyant production
G	mass flux, kg·m^{-2}·s^{-1}
h	local heat transfer coefficient, W·m^{-2}·K^{-1}
Nu	Nusselt number
P_k	turbulent shear production
Pr	Prantle number
Re	Reynolds number
T	temperature/period, K/s
t	time, s
u	velocity components in axial-directions, m·s^{-1}
y^+	non-dimensional distance from the wall

Greek letters

ε	turbulent energy dissipation
k	turbulent kinetic energy
λ	thermal conductivity, W·m^{-1}·K^{-1}
ρ	density of fluid, kg·m^{-3}
μ	dynamic viscosity, kg·m^{-1}·s^{-1}
θ_m	rolling amplitude, °
σ_k	diffusion Prandtl number for k
σ_ε	turbulent Prandtl number for ε

Subscripts

0	inlet conditions
Tube	parameters in tube side
pc	pseudo critical
w	wall

tics of single-phase water turbulent flow is limited. However, the flow field of supercritical fluid is more complex than that of single-phase fluid in land-based condition. Convection heat transfer of supercritical fluid exhibits many special features due to the sharp variations of the thermophysical properties in large-property-variation (LPV) region.

Many experiments of heated circular tubes cooled with supercritical CO_2 have been performed. Comprehensive reviews of earlier experimental studies on heat transfer to supercritical fluid in land-based steady condition were provided (Pioro and Duffey, 2005; Duffey and Pioro, 2005). Recently, many experimental and numerical studies on the convective heat transfer of supercritical fluid flowing in straight pipes and curved tubes (Pitla et al., 2001; Dang and Hihara, 2004; Jiang et al., 2004; Kim et al., 2007; He et al., 2005; Bae et al., 2005; Vashisth et al., 2008) were carried out, in which the effects of buoyancy and centrifugal inertia forces were considered.

Three low-*Re* number turbulence models and one mixing length model were employed by Dang and Hihara (2004) to study the heating process of supercritical CO_2 in horizontal circular tubes. They concluded that different y^+ yielded significantly different results on heat transfer of supercritical CO_2, but the difference caused by Pr_t is negligible considering the experimental uncertainty. He et al. (2004) conducted numerical simulations on the mixed convection of supercritical CO_2 in vertical tubes at the constant heat flux conditions. It had been found that most low-*Re* number turbulence models examined can reproduce the trend of heat transfer deterioration with the influence of buoyancy. Afterwards, He et al. (2005) used the more complicated V2F turbulence model to predict the wall temperature for supercritical CO_2 heating process. Although it was also able to reproduce the qualitative experimental trends, very significant discrepancies in wall temperature distributions were found. The results illustrate the AKN model showed better agreement with experiments than V2F model, and similar conclusions were also found by Sharabi et al. (2007) in comparisons with the experimental data of Pis'menny et al. (2006).

The turbulent flow of the supercritical fluid in a curved pipe features secondary flow caused by the centrifugal force and buoyancy force, which is more complicated than that in the straight pipe. The flow and heat transfer characteristics of China No.3 aviation kerosene in a heated curved tube under supercritical pressure are numerically investigated by Li et al. (2010). The results show that the centrifugal force enhances the heat transfer, but also increases the friction factors. Zhao et al. (2016a) conducted numerical simulations on conjugate heat transfer to supercritical CO_2 in helical coiled tube. The results show that the flow field of supercritical fluid was affected by both the buoyancy and centrifugal force.

In ocean rolling environment, the supercritical fluid flowing behaviors will be affected by the spatial and temporal varying buoyancy force, centrifugal force, tangential force and Coriolis force. Therefore, the heat transfer features of supercritical fluid in rolling motion become more complex than those in curved pipe, moreover, the flow and heat transfer characteristics of supercritical fluid play an important role in nuclear thermal hydraulic analysis and safety assessment under the ocean environment. However, the local flow details of supercritical fluid in rolling motion and the related influence mechanisms are unclear, so, the thorough understanding of these phenomena is necessary. The purposes of this paper are to obtain the local heat transfer performances and analyze the abnormal heat transfer mechanisms in rolling motion. In addition, the detailed information on the flow field distributions will be obtained for better understanding of the heat transfer mechanisms considering the influence of physical property change, buoyancy effect and additional rolling inertia forces.

2. Numerical modeling

2.1. Physical model

The conjugate heats transfer process widely exists in supercritical fluid heat exchanger. Because the heat flux changes significantly along the axial of the tube and the increase of wall temperature is limited by the hot fluid temperature, the constant heat flux condition is a questionable assumption since it is very different from the actual condition. Therefore, the double-pipe exchanger was chosen to study the conjugate convection heat transfer of supercritical fluid. The physical model of the studied heat exchanger is shown in Fig. 1. It is a vertical double-pipe counter-flow heat exchanger which covers the supercritical CO_2 in LPV region, the tube wall and the high-temperature CO_2. This heat exchanger consists of a circular inner tube with d of 5 mm and an annular outer shell with D of 10 mm. The length of the conjugate heat transfer section is L = 1 m, and the flow development section (L/d = 200) is used to assure that the turbulent flow is fully developed. As shown in Fig. 1, the high-temperature CO_2 flows in the shell side while supercritical CO_2 flows inside the tube with the system pressure 7.58 MPa. The heat from the hot CO_2 is transmitted through the tube wall to the supercritical CO_2. The fundamental simulated conditions performed in the present study are