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Research paper

Numerical investigation of supercritical LNG convective heat transfer in a horizontal serpentine tube

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A B S T R A C T

The submerged combustion vaporizer (SCV) is indispensable general equipment for liquefied natural gas (LNG) receiving terminals. In this paper, numerical simulation was conducted to get insight into the flow and heat transfer characteristics of supercritical LNG on the tube-side of SCV. The SST model with enhanced wall treatment method was utilized to handle the coupled wall-to-LNG heat transfer. The thermal–physical properties of LNG under supercritical pressure were used for this study. After the validation of model and method, the effects of mass flux, outer wall temperature and inlet pressure on the heat transfer behaviors were discussed in detail. Then the non-uniformity heat transfer mechanism of supercritical LNG and effect of natural convection due to buoyancy change in the tube was discussed based on the numerical results. Moreover, different flow and heat transfer characteristics inside the bend tube sections were also analyzed. The obtained numerical results showed that the local surface heat transfer coefficient attained its peak value when the bulk LNG temperature approached the so-called pseudo-critical temperature. Higher mass flux could eliminate the heat transfer deteriorations due to the increase of turbulent diffusion. An increase of outer wall temperature had a significant influence on diminishing heat transfer ability of LNG. The maximum surface heat transfer coefficient strongly depended on inlet pressure. Bend tube sections could enhance the heat transfer due to secondary flow phenomenon. Furthermore, based on the current simulation results, a new dimensionless, semi-theoretical empirical correlation was developed for supercritical LNG convective heat transfer in a horizontal serpentine tube. The paper provided the mechanism of heat transfer for the design of high-efficiency SCV.

1. Introduction

Due to the environmental pollution problem and energy shortage has become increasingly apparently, it's urgent to find some alternative sustainable energy to substitute those traditional resources such as petroleum and coal. Natural gas (NG) is the best choice because of the advantages of high calorific value and low carbon dioxide emissions. In general, NG is cooled to liquefied natural gas (LNG) in order to allow it to be economically transported over great distances. LNG is then heated and converted to ordinary NG before being transmitted into the pipeline to meet utility need. Therefore, the efficient and reliable vaporization devices for gasification of LNG are important for receiving terminals. Four types of LNG vaporizers are mainly used in the LNG import terminals, namely, open rack vaporizer (ORV), super ORV, intermediate fluid vaporizer (IFV) and submerged combustion vaporizer (SCV) [1].

Among them, SCV is a progressive shell-and-tube design utilizing the water bath system as the intermediate medium. And it is frequently applied for the peak-shaving regasification in LNG receiving terminals thanks to its advantages in rapid start-up capability (15–30 min), safety in water bath heating and thermal efficiency above 99%, etc. The main structure of SCV composes of combustion burner, water tank, weir, gas distributor and serpentine tube coils [2], as shown in Fig. 1. The low-pressure NG and boil off gas (BOG) from the LNG terminals are burned to hot exhaust flue gas as high-temperature heat source. The flue gas is then discharged into the weir via the gas distributor to keep the water bath temperature constant, whereas the cryogenic LNG is heated to the NG inside the serpentine tube coils which is submerged in the water bath. Due to the operating pressure of tube-side of SCV is well above of the critical pressure of LNG, and LNG temperature increases from subcritical to supercritical state during the whole heating process, thus, it can lead to supercritical LNG flow and heat transfer phenomena in the horizontal serpentine tube. Under this condition, though there will be no phase change with the increase of bulk LNG temperature, the physical properties of LNG may vary

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Nomenclature

L	length of tube
D	outer diameter
D_i	inner diameter
R	diameter of bend tube
δ	wall thickness
T	temperature
h	heat transfer coefficient
q	heat flux
A	cell area
P	pressure
G	mass flux
Gr	Grashof number
Re	Reynolds number
Ri	Richardson number
Pr	Prandtl number
u	velocity
Nu	Nusselt number
C_p	specific heat

Greek letters

ρ	density
μ	dynamic viscosity
λ	thermal conductivity

Subscripts

in	inlet
out	outlet
w,in	inner wall
w,out	outer wall
b	bulk fluid
sim	simulated
pred	predicted
f	based on bulk fluid
w	based on inner wall

dramatically with a small change in temperature. Consequently, dynamics and heat transfer of LNG under supercritical pressure play a key role for the SCV design. To the best of our knowledge, in spite of SCV is very important in practical applications, the unique and complicated flow and heat transfer characteristics of supercritical LNG is still far from being fully understood up to now.

The former studies have mainly focused on supercritical carbon dioxide and water flow and heat transfer in the straight tubes [3–9]. Du et al. [10] applied different turbulence models to investigate the cooling heat transfer of supercritical carbon dioxide in a horizontal circular tube. The LB low-Reynolds model showed the best agreement with the experimental data. Further studies were discussed on velocity, turbulence fields, buoyancy effect and heat transfer mechanism. They concluded that the mixed convection was the main heat transfer mechanism during supercritical carbon dioxide cooling process. Zhang and Yamaguchi [11] numerically studied low Reynolds number forced convection of supercritical carbon dioxide in a horizontal circular tube. The effects of mass flow rates and heat flux on the heat transfer behaviors were investigated. The mechanisms that were responsible for the heat transfer enhancement were identified. Liao and Zhao [12] numerically investigated the laminar convective heat transfer of supercritical carbon dioxide in the tubes. The influences of the buoyancy and the direction of flow on the convective heat transfer were analyzed. Simulation results indicated that the buoyancy effects were significant for all cases considered. He et al. [13] used low-Reynolds number eddy viscosity turbulence models to simulate turbulent convection heat transfer of carbon dioxide at supercritical pressures in a vertical tube. The results showed that the buoyancy effect in their study was insignificant. Heat transfer could be significantly impaired as a result of flow acceleration when the heating was strong. Dang and Hihara [14,15] investigated the turbulent convective heat transfer characteristics of supercritical carbon dioxide both experimentally and numerically. The mass flux, heat flux and tube diameters on the heat transfer coefficient were discussed. They proposed a modification of the Gnielinski correlation to correlate their experimental results. Lei et al. [16] performed the numerical simulation to study the mechanism of heat transfer phenomena of water in horizontal smooth tubes under supercritical pressure. Both the heat transfer enhancement and heat transfer deterioration in the so-called large specific heat region of supercritical fluids were analyzed based on the numerical results. Their numerical data showed that the non-uniformity fluid properties resulted in the complex secondary flows and mixed convection in the heat transfer process. Zaim and Nassab [17] studied the convection heat transfer of water at supercritical pressure in a narrow annulus. The influence of inlet Reynolds number, Grashof number and inlet temperature on the velocity distribution and heat transfer characteristics were investigated. They found that the effect of buoyancy was strong and caused extensive increase in velocity near the inner-wall, and consequently an increase in the convective heat transfer. Li et al. [18] numerically investigated for flow and heat transfer of supercritical water in a vertical circular tube which was heated on one side. The effect of heat flux on the heat transfer characteristics was studied. Results indicated that empirical Nusselt correlations for uniform heating could adequately predict the circumferentially maximum wall temperature of a one-side heated tube and buoyancy effect was much stronger in upward flow than in downward flow. Mokry et al. [19] conducted a dimensional analysis using the Buckingham Π-theorem to derive the general form of an empirical supercritical water heat transfer correlation for the Nusselt number. The correlation had an uncertainty of about ±25% for calculated heat transfer coefficient values and about ±15% for calculated wall temperature.

In the view of above, although there are extensive research concerning on the flow and heat transfer characteristic of the supercritical carbon dioxide and water, the thermal performance and mechanism of supercritical LNG in a horizontal serpentine tube is rarely reported in the open literature. This study presents a numerical approach to analyze the convective heat transfer of supercritical LNG on the tube-side of SCV under a constant outer wall temperature condition. The effects of main operating parameters on the surface heat transfer coefficient are revealed. The heat transfer mechanism and secondary flow phenomenon inside different bend tube sections are also discussed. Furthermore, a new Nusselt number correlation is proposed to predict the tube-side heat transfer performance of the SCV. The results and discussions are beneficial to the optimum thermal design and operation of high-efficiency SCV.

2. Numerical modeling

2.1. Physical model

The flow and heat transfer of supercritical LNG in a horizontal serpentine tube of the SCV is considered here. Fig. 2 shows the