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Numerical study on the shell-side flow and heat transfer of superheated vapor flow in spiral wound heat exchanger under rolling working conditions

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A B S T R A C T

In order to explore the shell-side flow and heat transfer characteristics for spiral wound heat exchanger (SWHE) in floating liquefied natural gas (FLNG), a model was established to simulate the flow and heat transfer of shell-side superheated vapor flow under rolling working conditions. The effects of rolling parameters and working parameters were investigated. By comparing, the deviations between simulation results and experimental data were generally within ±10%. Under static working conditions, both frictional pressure drop gradient and heat transfer coefficient increased with the increasing mass flux, which were consistent with the predictions of calculation correlations. After that, an improved heat transfer correlation was proposed with an error of ±5%. Meanwhile, rolling motions can affect the shell-side flow and heat transfer characteristics of superheated vapor flow and lead them to show obvious periodicity. The influence of rolling period was smaller than that of rolling amplitude, and 90% of the working conditions in FLNG SWHE can lead to the enhancement of heat transfer from −0.5% to 2.6%. These results can provide some instructions in the design and efficient running for FLNG SWHE.

1. Introduction

Recently, with the development of industry and the change of energy structure, the consumption of natural gas (NG) has increased sharply and floating liquefied natural gas (FLNG) has become an important way for the collection, storage and transportation of offshore NG [1–3]. At the same time, due to its advantages of high reliability, high compactness, high flexibility, better robustness, efficient heat transfer and so on, spiral wound heat exchanger (SWHE) has been widely applied as main cryogenic exchanger in large-scale onshore liquefied natural gas (LNG) plants, and also has enormous potential in FLNG [4,5].

Fig. 1 shows a principal sketch of SWHE, which is consist of two important flows: tube-side flow and shell-side flow. The process of liquefying natural gas in the SWHE is implemented through the heat transfer between the natural gas flowing upward in tube side and the refrigerant flowing downward in shell side [6–9]. As shown, the shell-side flow of hydrocarbon refrigerant is more complicated than tube-side flow, the thermal resistance of shell side is dominant. The shell-side flow and heat transfer characteristics has more significantly influence on the performance of SWHE [9–11]. However, it is difficult to directly investigate the shell-side flow and heat transfer in SWHE because of the complexities of composition and flow pattern. Therefore, in this paper, methane and ethane are used as the working fluids due to the following reasons: (1) the shell-side refrigerant in SWHE is a mixture of hydrocarbons, including methane and ethane; (2) the thermophysical properties of methane and ethane are similar to that of shell-side hydrocarbon refrigerant. Besides, only superheated vapor flow is investigated in this paper.

The existing experiments on the shell-side flow and heat transfer characteristics of superheated vapor flow were carried out under static working conditions. Fredheim [7], Aunan [8] and Neeraas et al. [12] experimentally studied the shell-side flow and heat transfer characteristics of superheated vapor flow in a 3-layer SWHE, with methane, ethane and nitrogen as working fluid. According to their researches, the shell-side frictional pressure drop gradient ($\Delta P_f/\Delta L$) and heat transfer coefficient increased with increasing Re; and when shell-side working pressure increased, $\Delta P_f/\Delta L$ decreased, while heat transfer increased. After that, Ghorbani et al. [13] carried out experiments to investigate the effects

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Nomenclature

$\vec{a}_r$	rolling acceleration
A_r	rolling amplitude
A_s	sloshing amplitude
c_p	constant pressure specific heat
D_{in}	inlet diameter
D_{tu}	tube diameter
E_{ij}	time-averaged strain rate
f	friction factor
$f_{A,inline}$	arrangement factor
f_{in}	friction factor of inline configuration
f_{st}	friction factor of staggered configuration
G	mass flux
G_{inline}	mass flux of inline configuration
h	heat transfer coefficient
k	turbulent kinetic energy
L	characteristic length
L_1	the distance between geometry model and plane YOZ
L_2	the distance between geometry model and plane XOY
Nu	Nusselt number
P	pressure
Pr	Prandtl number
P_l	longitude distance between tube centers
P_r	radial distance between tube centers
q	heat flux
Re	Reynolds number
Re_{inline}	Reynolds number of inline configuration
R_k	generation item of k
S_a	source term caused by rolling motion
t	time
T	temperature
T_r	rolling period
T_s	sloshing period
$\vec{v}$	velocity
W_a	winding angle
W_d	winding diameter
$\Delta P_f/\Delta L$	frictional pressure drop gradient

Greek symbols

ε	turbulent dissipation rate
λ	thermal conductivity
μ	dynamic viscosity
μ_{eff}	effective turbulent viscosity
μ_t	turbulent viscosity
ρ	density of fluid
ψ	void fraction

Subscript

COR	correlation
EXP	experiment
in	inlet
lam	laminar flow
out	outlet
SIM	simulation
turb	turbulent flow

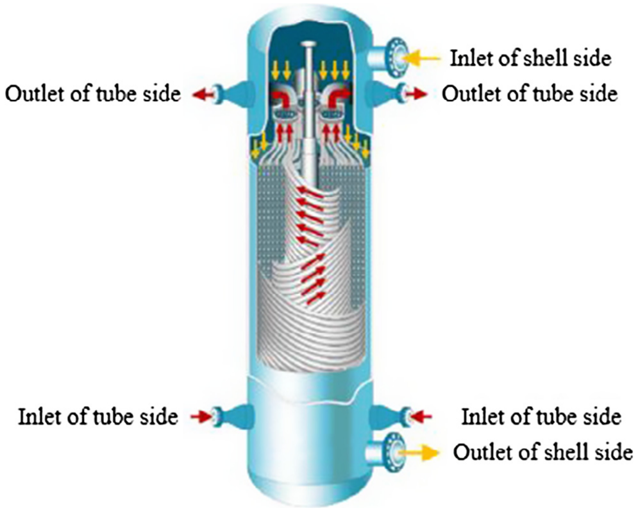

Fig. 1. A principal sketch of SWHE [9].

of structural parameters on the shell-side heat transfer of single-phase flow, with water as working fluid. It was found that the influence of tube diameter was negligible, and the shell-side heat transfer could be reduced with increasing coil surface. Then, the shell-side forced convection in helical coiled-tubes was studied experimentally with a constant wall heat flux by Moawed [14]. The experiments covered a range of Reynolds number (Re) from 6.6×10^2 to 2.3×10^3 with air as working fluid. Finally, a heat transfer correlation (correlated with $Re, W_d/D_{tu}$ and P_l/D_{tu}) was obtained to describe the shell-side forced convection, within an error of ±10%. At the same time, Yang et al. [15] experimentally explored the shell-side flow and heat transfer characteristics at high working pressure, with helium, nitrogen and their mixture as working fluid. The working conditions were designed from 0.5 MPa to 3.0 MPa, with $3.9 \times 10^3 < Re < 3.0 \times 10^6$. It was found that the higher the working pressure, the greater the heat transfer coefficient.

Similarly, the existing numerical investigations on the shell-side flow and heat transfer of superheated vapor flow were also carried out under static working conditions. In open references, the standard $k-\varepsilon$ model [16,17], Realizable $k-\varepsilon$ model [18–20] and RNG $k-\varepsilon$ model [21–23] were adopted to simulate the shell-side turbulent flow and heat transfer in heat exchangers, and the simulation results agreed well with experimental data. According to the research of Wang et al. [17], the shell-side flow and heat transfer characteristics depended on the velocity of fluid flow, especially the vertical velocity. Lu et al. [21,22] numerically studied the shell-side flow and heat transfer characteristics of air in a 3-layer SWHE, with constant heat flux as wall boundary. As a result, the deviations between simulation results and experimental data were below 13.4% when $3.0 \times 10^3 < Re < 5.5 \times 10^3$. It can be found that in most static simulations, the influence of structural parameters on shell-side flow and heat transfer was researched.

The existing correlations for the shell-side flow and heat transfer of superheated vapor flow were studied under static working conditions. A large number of investigations which describe methods to calculate the shell-side pressure drop in a heat exchanger have been published, and the comparisons among different calculation methods with a large number of experiments and industrial heat exchangers were made critically [24–26]. The method proposed by Barbe et al. [27] (as shown in Section 4.1) was expected to predict the shell-side pressure drop of superheated vapor flow