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Numerical study on thermal performance of a BOG heat exchanger in the inclined condition

Yan Yan [a], Zhonghua Ni [a, *], Xiaoqin Zhi [b], Jingsong Yin [c]

[a] School of Mechanical and Engineering, Southeast University, Nanjing, 21000, China
[b] Institute of Refrigeration and Cryogenics, Zhejiang University, Hangzhou, 310027, China
[c] Furui Special Equipment Co., Ltd., Suzhou, 215637, China

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ABSTRACT

This paper presents a numerical investigation of the inclination effect on the thermal performance of a tubular heat exchanger, which is utilized to extract the cold exergy from boiled-off gas (BOG). The finite volume computational fluid dynamics method and a $k-\omega$-based shear stress transport model were used to simulate the fluid flow and heat transfer process. The simulation model has been validated by the engineering specification data from its supplier. To study the inclination effect on the heat exchanger, it has been simulated in two inclination planes and under different mass flow conditions. The result reveals that in the longitudinal inclination, the outlet temperature of both fluids changes in a linear relation with the inclination angle in a high mass flow condition. Reducing the mass flow would dramatically enhance the sensitivity of inclination. The largest temperature shift is 21.32 K, appearing in the tube side with a $-30°$ inclination angle. However, the thermal performance is more stable in radial inclination, particularly in the high mass flow condition, and the temperature shifts of the shell and tube fluid are only 0.13 K and 0.31 K, respectively. Therefore, it is recommended to place the longitudinal direction of the heat exchanger on the normal position of the inclination plane and work at a high mass flowrate to weaken the inclination effect.

1. Introduction

Floating liquefied natural gas (FLNG) systems are increasingly important in the liquefied natural gas (LNG) industry. FLNG systems are ship-shaped floating systems that usually contain a liquefaction facility to liquefy natural gas near the remote natural gas field. The production of LNG will be stored as FLNG for a time and then transported by an LNG carrier to the world markets. LNG is produced by cooling the fluid to -110 K. Therefore, during its production, storage and transport, there will be a non-negligible volume of boiled-off gas (BOG) generated from the heat transfer with equipment boundaries (Querol et al., 2010; Miana et al., 2016a, b). However, FLNG facilities are designed to operate under ordinary pressure, so most BOG should be released to keep the system safe (Shin and Lee, 2009; Miana et al., 2016a). The BOG cycle is designed to utilize the cold energy from BOG and simultaneously heat BOG to a suitable temperature for fuel tank storage (Romero Gómez, 2014). The BOG heat exchanger is the key equipment in this cycle to perform the energy exchange. Unlike land factories, the working condition of FLNG is unstable, excited by wind, wave and ocean currents (Zhao et al., 2011; Tang et al., 2013). It is difficult to keep the deck in a horizontal position. As a result, an inclined condition would change the real operating parameters of the BOG heat exchanger and reduce the efficiency of entire recycling system (Zhao et al., 2013; Pessoa et al., 2015). Therefore, it is important to study the thermal performance of the BOG heat exchanger under the inclined condition.

To analyse the effect of inclination on thermal fluid flow, researchers have performed many experimental studies to investigate the flow characteristics inside inclined tubes. Experiments performed by Jijo Johnson et al (Johnson and Shine, 2015). studied the cryogenic chill-down process in horizontal and inclined pipes. The fluid and wall temperature, local heat transfer coefficient and heat flux were utilized to predict the chill-down period of pressurized liquid nitrogen in stainless steel pipes. They found that the inclination of the chilling line could lead to obvious variation in chill-down time, but the temperature profiles were similar. To study steam condensation in inclined tubes, Gianfranco Caruso et al

* Corresponding author.
E-mail address: nzh2003@seu.edu.cn (Z. Ni).

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(Caruso et al., 2013). performed research on a finned tube to evaluate the influence of geometry and inclination angle on heat transfer. They located the correlation between the heat transfer coefficient and the inlet Reynolds number but did not clearly quantify the influence of the tube inclination. M. Mozafari et al (Mozafari et al., 2015). then experimentally studied the condensation two-phase flow pattern of refrigerant R-134a inside U-bend tubes. Their observations indicated that the inclined thermal fluid flow is influenced by interfacial shear stress, surface tension, centrifugal and gravitational force, and particularly the inclination angle. This angle determined the magnitude and direction of affective gravitational force components on fluid flow and could result in different two-phase flow patterns.

With increasing computer power and the development of numerical methods, many numerical methods are widely used to study fluid flow. Adomian decomposition method (ADM) is an accurate and efficient analytic solution of nonlinear ordinary or partial differential equations without the need to resort to linearization or perturbation approaches (Adomian, 1994, 1990). It's widely utilized to solve non-linear problems. Adomian and K. Haldar has successively applied the ADM to the Navier-Stokes equations in Cartesian and Cylindrical coordinate system (Adomian, 1986; Haldar, 1996). It was applied to investigated the non-linear differential equation governing the glass transition phenomena (Fatoorehchi and Abolghasemi, 2013), evaluating the reflux ratio of a distillation column (Fatoorehchi and Abolghasemi, 2014) and approximately analysed a feneral RC circuit comprised of non-linear resistor and capacitor (Fatoorehchi et al., 2015). Adair applied a modified ADM for the vibration analysis of rotating non-uniform system (Adair and Jaeger, 2016). To simulate the two-phase flow pattern inside pipes, F. Behafarid applied a modified Level-Set Method (LSM) to simulate bubble motion and liquid film in inclined narrow channels (Behafarid et al., 2015). They used two sets of numerical simulations with specified inclination angles to display the liquid film between the bubble and the walls. Nianben Zheng used a k–ω-based shear stress transport (SST) model to investigate the heat transfer enhancement in a heat exchanger tube fitted by inclined ribs on the inner boundary (Zheng et al., 2015). They successfully determined the rib length ratio, pitch ratio and inclination angle for practical applications. However, few numerical studies of inclined heat exchangers have been conducted. In this case, finite volume and computational fluid dynamics methods were applied to investigate thermal fluid flow and heat transfer in a full-sized 3D heat exchanger model. The steady-state simulations were performed by ANSYS CFX code.

The object of the present work is to study the affection of inclination angle and mass flux on the cryogenic fluid flow inside a BOG heat exchanger. The simulation results have been validated by engineering data to ensure the accuracy of the thermal prediction. Inclination angles from −30° to 30° and mass flux of 0.14 kg/s and 0.68 kg/s were selected as variables. The distribution pattern of temperature, velocity, and wall heat transfer coefficient have been discussed.

2. Model description

2.1. Physical model

The BOG heat exchanger in this study is a real-sized tubular heat exchanger, as shown in Fig. 1. BOG flows in the tube domain, and ethylene glycol as intermediate fluid flows in the shell domain. Three bafflers are located in the shell-side to support the 30 thermal U-tubes. More geometry details are listed in Table 1. To study the inclination effect, the deck inclines in the zx-plane and the zy-plane to simulate the inclination condition in FLNG. The inclination angle varies from −30° to 30°.

2.2. Governing equations

A steady-state model is utilized to simulate the fluid flow and heat transfer processes between tube and shell domains. Because of the drastic thermal transfer on U- tube walls, the fluid flow is governed by the k–ω SST model, which usually produces a better boundary solution (Zheng et al., 2015). The general governing equations are as follows:

Continuity equation:

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

Momentum equation:

$$\frac{\partial}{\partial x_i}(\rho u_i u_j) = -\frac{\partial P}{\partial x_i} + \mu\left(\frac{\partial^2 u_i}{\partial x_i^2}\right) \tag{2}$$

Energy equation:

$$\frac{\partial}{\partial x_i}(\rho u_i \mathrm{T}) = \frac{k}{c_p}\left(\frac{\partial^2 T}{\partial x_i^2}\right) \tag{3}$$

k − Equation:

$$\frac{\partial}{\partial x_i}(\rho k u_i) = P_k + \beta^* \rho \omega k + \frac{\partial}{\partial x_i}\left[(\mu + \sigma_k \mu_t)\frac{\partial k}{x_i}\right] + S_K \tag{4}$$

ω − Equation:

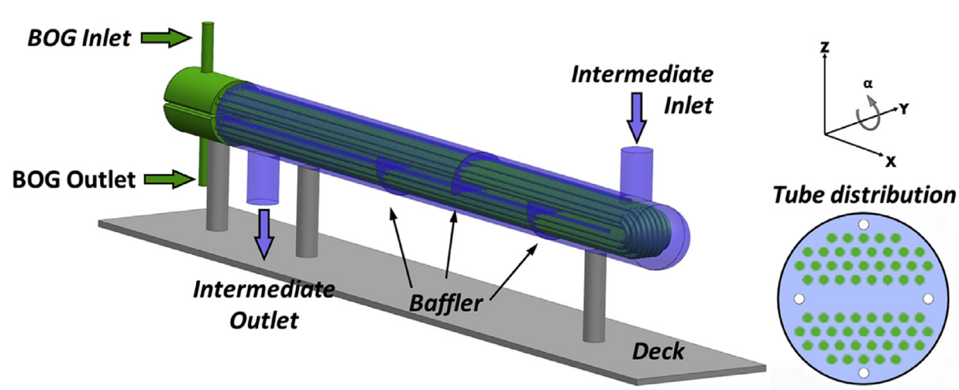

Fig. 1. 3D geometry of BOG heat exchanger.