CFD STUDY OF HEAT TRANSFER IN FALLING FILMS FOR LNG SPIRAL WOUND HEAT EXCHANGER UNDER OFFSHORE CONDITIONS

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The heat transfer and mass transfer in falling films for LNG Spiral Wound Heat Exchangers (LNG-SWHEs) were numerically investigated based on the experimental results. In which study, permanent tilt and dynamic roll motion were selected as representative offshore conditions for LNG-SWHEs, considered to be the most severe offshore conditions. A comparison between the heat transfer of the proposed model and that of experimental data was also presented. Using the experimental data and proposed model, the main characteristics of heat transfer for LNG-SWHEs under offshore conditions were investigated. The results obtained by the simulations agree well with those from the experiment. The validation results show that 89% of the predicted data can agree with the experimental data within a deviation of about 25%. Furthermore, the fluid flow and heat transfer performances for different boundary conditions can be obtained based on the proposed model. The results obtained from the numerical model could be the basis for the design of a LNG-SWHE installed on a buoyant platform like the floating production storage and offloading (FPSO) unit, which is used for liquefaction technology of nature gas.
1. Introduction

LNG is mainly produced in base-load plant, and the offshore conditions are also considered in recent years. Through this procedure, the natural gas is cooled to a temperature of 110 K. Because of the fast-developing of LNG, LNG-SWHE as a key equipment is becoming an increasing factor in some LNG plants and research institutions [1-3]. Despite the fact that several studies on the heat transfer have been performed [4], attentions should be paid to researches considering falling films for LNG-SWHEs at offshore conditions. Both numerical and experimental methods have been used by the researchers [5-6]. In numerical study, accurate representation of the interface is much important for the falling film flow. For this reason, a new VOF based interface tracking method was developed by Tsui et al [7]. Similarly, studies by the same authors [8-10] also proved that VOF model was effective for simulating the flow and heat transfer characteristics in falling film flow. Welch and Wilson [11] used a VOF model based algorithm in connection with a mass transfer model to simulate the falling film flow on a horizontal surface. Moreover, Ho et al [12] simulated the falling film flow for a falling film with a VOF model, and they proved that 3-D simulation is necessary to provide comprehensive flow profiles. Besides, in the experimental study, a series of structural parameters, such as winding angle of tubes, row number and arrangement of tubes for falling film flows in shell side were considered [13]. To study the heat transfer characteristics of the falling films flow, Reynolds number and vapor quality were mostly used as the parameter in the experimental method [14-15].

Direct numerical simulation of the falling film flow is not straightforward as the single phase flow. The following issues relating to the interface boundary separating the two phases require special attention [16]: evolution of this boundary with time, unequal material properties between the different phases, and jump condition across the boundary. Treatments of these issues affect not only accuracy but also stability of the numerical calculation. Therefore, experimental studies are much important to identify the results of numerical calculations. Experimental investigation of horizontal and vertical falling film flow has been studied for past few decades [17-18]. Feng et al. [19] proposed a computational fluid dynamics (CFD) methodology to investigate the effects of different Dean number on thermal hydraulic characteristic, and the simulation results agreed well with experimental data. Yang et al. [20] experimentally and numerically investigated the flow boiling of R141B in a horizontal coiled tube. The comparison indicated that the phase distributions predicted by VOF model were consistent with those observed in experiments. In the present studies, Norwegian University of Science and Technology (NTNU) and SINTEF Energy...
Research have worked with thermal design and laboratory measurements of heat-transfer coefficients (HTC) and pressure drop for LNG heat exchangers [21]. Neeraas et al [22] even constructed a test plant for measurements of local HTC and frictional pressure drops, and the average deviation is within ±7% compared with the measured values. However, a few studies on heat and mass transfer in falling films over horizontal tubes have been conducted. On the other hand, for the two-phase heat transfer procedure, the function of liquid film was firstly studied by Andberg and Vliet [23], they used a finite difference formulation, with a coordinate system fit to the shape of the film around the tube. Choudhury et al [24] modeled the same problem using a very similar approach. The major differences between their model and the model by Andberg and Vliet were that they assumed the fluid properties to be constant and the tube to be isothermal. Even though different analyses were subsequently performed [15,17,18], the boundary conditions did not meet the demand with this paper.

A floating liquefied natural gas (FLNG) vessel is a production device for offshore gas fields, particularly for those located in deep seas [25-26]. SWHE produces additional inertial forces on the working fluids under offshore conditions, and changes the flow and heat transfer characteristics in the tube and shell sides [27-28]. The comparisons of model predictions with experimental data show that the deviations of heat capacities are within 4.5% under the sloshing amplitudes among 0–9°, as well as the periods among 6–20s. On the other hand, based on the experimental results, pressure drop characteristics of gas-phase mixed refrigerant are influenced significantly under sloshing conditions was proved by the same authors [29].

To achieve the goal, a numerical model of LNG-SWHE to study the falling film flow was developed, and after that, the offshore conditions should be added. The Volume of Fluid (VOF) technique was chosen to model the flow under consideration. For the purpose, a commercially available CFD package [30] was used to develop and implement the model. Via the simulation, the effects of fluid properties and flow conditions on falling film flow are investigated. Furthermore, the experimental studies on LNG-SWHEs were carried out. This proposed numerical model was validated by the experimental data under steady state conditions, and was modified by that at offshore conditions.

2. Model set-up

2.1 Description of model
The simplified sketch of the test LNG-SWHE for outside tube bundle is shown in Fig. 1. Heat-transfer measurements have been performed with propane as the test fluid. Simultaneously, propane is used as the working fluid in numerical method. The fluid is circulated through the study object as two-phase flow.

Fig. 1 Test section of outside tube bundle for LNG-SWHEs

The study object consists of a flow stabilization zone, an isothermal zone and a heated zone. The tubes in the central coil are set as heated condition, and the HTC is measured in this zone. Correspondingly, the test section for the experiment is designed. In which test section is shown in Fig. 2, the tubes in the central coil are electrically heated by heating cables placed inside the tubes. The quality of the fluid is decided by the heat produced from the electric heater. It is much important to obtain uniform distribution two phase flow for the simulation process. Before the fluid enters into the test LNG-SWHE, it is distributed. For the offshore conditions study, a computer is used to control the sloshing machine as well as to adjust its roll motion parameters.
2.2 Numerical method

CFD simulations allow the determination of the hydrodynamics of the film flow, namely the film thickness, the film velocity and wave properties, the gas flow. In order to understand the characteristics of two-phase flow under offshore conditions, simulations using 3-D model were carried out. For the 3-D simulations, a geometry model with an analysis zone was illustrated in Fig. 3, the analysis zone has 3 tubes. Fig. 3(b) shows the grid diagrams of front view of analysis zone and heated tubes view. Three different mesh numbers for 3-D model with 571541, 628734 and 727617 were used in grid sensitivity tests. It was found that the grid of medium density is fine enough for calculations.

2.2.1 Assumptions
There were a number of assumptions, which simplified the simulation in the present study.

i. The ambient temperature was 300 K, and the LNG temperature was 113K;

ii. Heat leakage between the numerical model and its ambient environment was negligible;

iii. The fluid was fully developed, compressible, turbulent and steady flow.

2.2.2 Continuity equation

The mass, momentum and energy equations for the working liquid phase and vapor phase were solved by ANSYS Fluent 15.0 and user defined function. The Navier–Stokes equations are discretized with a semi-implicit projection method in time. Diffusion terms are discretized in time with the Crank–Nicolson scheme and the advection terms with the forward Euler scheme. Orthogonal finite volume method with staggered variable arrangement is used for spatial discretization. The second-order accurate scheme is used for the spatial discretization of the diffusion and advection terms.

\[ \frac{\partial}{\partial t} (\alpha \rho) + \nabla \cdot (\alpha \rho \vec{V}) = S_{m1} + S_{m2} \]  

(1)

\[ \frac{\partial (\rho \vec{u})}{\partial t} + \nabla \cdot (\rho \vec{u} \vec{u}) = -\nabla p + \mu \nabla^2 \vec{u} + F_e + \rho (\vec{a} + \vec{a}_n) \]  

(2)

\[ \frac{\partial (\rho \vec{h})}{\partial t} + \nabla \cdot (\vec{v} (\rho \vec{h} + p)) = \nabla \cdot (k \nabla T) + Q_1 + Q_2 \]  

(3)

Where \( t \) is the time, \( \rho \) the density, \( \vec{u} \) the velocity vector, \( \vec{V}_v \) the volume fraction vector, \( p \) the pressure, \( \mu \) the dynamic viscosity, \( T \) the temperature, and \( \alpha \) the phase mass rate. The subscripts \( v \) and \( l \) denote vapor and liquid, respectively. The momentum equation, shown as equation (2), is dependent on the volume fractions of all phases through the properties \( \rho \) and \( \mu \).

2.2.3 Interface tracking model

For the falling film flow where the two fluids are not interpenetrating, the VOF model can be adopted for tracking the wavy interface. The VOF model can model two or more immiscible fluids by tracking the volume fraction of each of the fluids throughout the domain, which is derived from the mass conservative equation. The VOF equation is shown as follows.

\[ \frac{1}{\rho_v} \frac{\partial}{\partial t} (\alpha \rho_v) + \nabla \cdot (\alpha \rho_v \vec{u}_v) = S_{a_v} + \sum_{i=1}^{n} (m_{iv} - m_{i}) \]  

(4)
\[ \sum_{i=1}^{n} a_i = 1 \]  \hspace{1cm} (5)

Where \( m_{hv} \) is the mass transfer from phase \( h \) to phase \( v \), and \( m_{lv} \) is the mass transfer from phase \( v \) to phase \( l \). And \( S_{\alpha} \) is the user-defined mass source for each phase. The primary-phase volume fraction could be computed based on equation (5).

2.2.4 Offshore conditions

For simulating the offshore conditions, roll motion machine was used, as shown in Fig. 4. The roll motion at four different conditions was considered, including yawing, rolling, surging and heaving. The permanent working frequency varied from 0.1HZ to 0.3HZ, under the sloshing amplitudes among 6°/mm to 9°/mm. For the stable operation of the sloshing machine, the displacement should be no more than 150mm. As the vapor qualities of the working fluid ranged from 0.15 to 0.75, the fluid was in falling film state.

![Schematic diagram for sloshing conditions](image)

2.3 Experimental method

During the heat transfer process in the actual heat exchange, the working fluid goes through various physical features. As well as the heat transfer process was simulated based on the inlet conditions of the tube side and the shell side, which is shown as Table 1, the state parameters of the fluid in falling film flow is shown as Table 2.

<p>| Table 1 | Detail parameters of experimental test section and numerical model |</p>
<table>
<thead>
<tr>
<th>No.</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Winding angle</td>
<td>4°</td>
</tr>
<tr>
<td>2</td>
<td>Radial pitch</td>
<td>14mm</td>
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<tr>
<td>3</td>
<td>Longitude pitch</td>
<td>16mm</td>
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<tr>
<td>4</td>
<td>Tube outer diameter</td>
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<td>5</td>
<td>Tube length</td>
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<tr>
<td>6</td>
<td>Height of heat transfer measurement part</td>
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</tr>
<tr>
<td>7</td>
<td>Length of test section</td>
<td>260mm</td>
</tr>
<tr>
<td>8</td>
<td>Width of test section</td>
<td>136mm</td>
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<tr>
<td>9</td>
<td>Height of test section</td>
<td>695mm</td>
</tr>
</tbody>
</table>

Table 2 Experimental and numerical conditions

<table>
<thead>
<tr>
<th>No</th>
<th>Pressure (MPa)</th>
<th>Vapor quality (kg/kg)</th>
<th>Mass flow density (kg/(m²·s))</th>
<th>Offshore conditions</th>
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<tbody>
<tr>
<td>1</td>
<td>0.28-0.33</td>
<td>0.15-0.75</td>
<td>80</td>
<td>Yaw</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15°</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td>0.1 Hz, 0.2 Hz, 0.3Hz</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td>Roll</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.1 Hz, 0.2 Hz, 0.3Hz</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td>Surge</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.1 Hz, 0.2 Hz, 0.3Hz</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td>Heave</td>
</tr>
<tr>
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<td></td>
<td></td>
<td>100mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.1 Hz, 0.2 Hz, 0.3Hz</td>
</tr>
</tbody>
</table>

3 Results and discussion

3.1 Numerical results

The CFD simulation allows the determination of the hydrodynamics of the film flow, namely the film thickness, film velocity and wave properties, and the gas flow. In order to understand the characteristics of the fluid flows under offshore conditions, simulations using 3-D model were carried out. The numerical results are shown as Fig. 5, and the working frequency increases gradually from Fig 5(a) to Fig. 5(c). For the purpose of observation, only the heated zone is shown, and the volume fraction contour means the liquid phase distribution outside tube bundle.
When the LNG-SWHE working at low frequency, such as Fig 5(a) shows, the liquid film could cover the tube bundle fully. Increments in period of the roll motion degrade the liquid mass distribution outside the tube bundle, and have an adverse effect on the heat transfer. From Fig 5(c), it is known that the tendency would be obvious under high working frequency conditions.

![Fluid flows across the tubes at yawing condition](image)

(a) Working frequency of 0.1HZ  
(b) Working frequency of 0.2HZ  
(c) Working frequency of 0.3HZ

Fig. 5 Characteristics for fluid flows across the tubes at yawing condition

3.2 Discussion

When the LNG-SWHE works at steady conditions, experimental data and simulated data of the thermal wall temperature for outside tube bundle is shown as Fig. 6. From Fig. 6, the validation results show that 89% of the predicted data can agree with the experimental data within a deviation of about 8%. The highest simulated uncertainty occurred at the around of 0.2 vapor quality.
Fig. 6 Data of the thermal wall temperature for outside tube bundle at steady conditions

Fig. 7 summarizes the results for LNG-SWHE with a working frequency of 0.16HZ considered in this study. Simulations were carried out under offshore conditions with 0.2 vapor quality. The vertical coordinates presents the difference of HTC between the offshore conditions and that of the base-load conditions. The influence caused by the offshore conditions presented periodical change with the increase of the time, which is an obvious trend. The influence of heaving condition is steady and very calm. Although heat transfer seems to decrease with the time, it is hard to estimate quantitatively within the sloshing influence simulated. The effect of yawing, rolling and surging conditions on heat transfer is volatile, and the heat transfer decreases very quickly with the time.

Fig. 7 Influence of offshore conditions on heat transfer performance

Based on the numerical and experimental results, Fig. 8 was intended to determine the influence of various sloshing frequencies on heat transfer performance outside tube bundle. As the figures present, it is known that the
roll condition has the highest influence on the heat transfer characteristics, as well as the yaw and heave conditions perform a minimal impact. In comparison with the base-load conditions as Fig. 8(a) and Fig. 8(b) show, yaw and roll conditions have a negative influence on the heat transfer performance. When the working frequency is fixed of 0.3Hz at 0.55 vapor quality, HTC descends by approximately 11% for yaw condition, which is 85% for roll condition. The value could be higher as working frequency increases due to much more liquid films escaping from the tube surfaces.

Furthermore, the heat transfer performance under different vapor qualities as well as sloshing forms lead to different sloshing influence results. Surge condition is observed resulting in significant heat transfer enhancement at the appropriate vapor quality, while the phenomenon for heave is dependent on the vapor quality and sloshing frequency. HTC is observed to increase quickly with sloshing frequency, it is thought that the sloshing motion improve heat transfer mainly by promoting the two-phase flow distribution outside tube bundle. As the sloshing
frequency increases to 0.3Hz at 0.2 vapor quality, HTC rises by approximately 13% for surge condition as shown in Fig. 8(c). However, the highest sloshing influence of heave is 6% under sloshing frequency of 0.1Hz at 0.2 vapor quality, as shown in Fig. 8(d).

4 Conclusions

In this paper, heat transfer and mass transfer in falling film outside the tube bundle of LNG-SWHEs under offshore conditions was investigated using the numerical method combined with experimental results. When permanent working frequency and four dynamic roll motions were selected as representative offshore conditions for the study. Experimental study with a test section of a LNG-SWHE was conducted, and vapor qualities range from 0.15 to 0.75 are considered the most representative conditions for falling film flow. Correspondingly, simulations with 3-D model show that 89% of the predicted data can agree with the experimental data within a deviation of about 8%. The highest simulated uncertainty occurred with vapor quality at the around of 0.2. The results obtained from the numerical model could be the basis for the design of a LNG-SWHE installed on a buoyant platform, like the floating production storage and offloading (FPSO) unit, which is used for liquefaction technology of nature gas.

References


