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Three-dimensional numerical analysis of the coupled heat transfer performance of LNG ambient air vaporizer

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A R T I C L E I N F O

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A B S T R A C T

Ambient air vaporizer (AAV) utilizes ambient air which belongs to low grade energy to regasify LNG in gas terminals. Study on the heat transfer performance of AAV is the foundation of its optimal design and operation. This paper presents a CFD-based coupled numerical model to investigate the heat transfer performance of AAV. The heat transfer coupling between the LNG boiling phase change and the natural convection of the air is taken into consideration. The mixture model combined with Lee model was used to calculate the heat and mass transfer in the process of LNG boiling. The coupled numerical model was calculated and validated by the operating data of a real-life AAV. Based on the simulation results of the coupled model, the influence of the air temperature, the inlet flow of LNG and the location in the fin tube bundle on the heat transfer performance of AAV were analyzed.

1. Introduction

Liquefied natural gas (LNG) greatly reduces the storage space and the transportation cost of natural gas (NG) and thus promotes the utilization of natural gas. In the energy sector, LNG plays an important role in the gas peak-shaving system and the remote area without natural gas pipeline. LNG should be vaporized using a heat exchanger which is called a “vaporizer” before entering the natural gas pipeline. Ambient air vaporizers (AAVs) are widely used for that purpose thanks to the advantages in energy and economic savings.

AAV is the key equipment in the LNG vaporization process, therefore, it should be compact and with high heat transfer performance. However, we have to face the problem that the heat transfer coefficient of AAV is relatively low and easily influenced by the atmospheric conditions and operation parameters. In the air side of the fin tube, heat is transferred to the surface by natural convection with low heat transfer coefficient. Especially in cold areas, the outlet temperature of vaporized natural gas usually cannot satisfy the inlet temperature requirement of the natural gas pipelines, hence the AAV should be combined with an auxiliary heat source. Besides, during the operation under these conditions, the moist air near the surface of the fin tube will frost, which can dramatically decrease the heat transfer performance of AAV. Therefore, the AAV operation personnel have to switch to the backup AAV periodically to avoid operating failures [1].

In order to optimize the design and operation of the AAVs, studies on the heat transfer performance of the AAV are required. Jeong et al. [2] conducted experiments by using two typical types of AAVs to investigate the influence of designed parameters, atmospheric conditions on the characteristics of the AAV in a test room. Liquefied nitrogen (LN_2) was used to substitute LNG for safety reason. In addition, the numerical analysis with two-dimensional models was also conducted by Jeong et al. [3] to study the optimal design of AAVs. Besides [4], studied the convective heat transfer of the AAV fins using computational fluid dynamics (CFD) under the assumption that the average outer surface temperature of the pipe was the same as the inlet temperature [5]. reviewed the physics of fog formation and used computational fluid dynamics to quantify the formation and dispersion of fog from the AAV arrays in LNG import terminals. A distributed parameter model consisting of applicable correlative formulae applying to different evaporation regimes was built by Ref. [6] to simulate the LNG evaporating process in a super open-rack vaporizer heat transfer tube. Bernert [7] proposed a new concept for the design and operation of cryogenic ambient air vaporizers for the tropical and subtropical climates with the promise of effectively decreasing the need for supplementary heat sources.

As can be seen from the previous studies, the main research

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methods of this problem are experimental study and numerical analysis. In the process of experimental study, the AAV is generally placed in a test room with controllable local environment, but an extra radiation heat transfer between the AAV and walls cannot be neglected when compared with the real-life operating conditions. Moreover, it is quite difficult to ensure a controllable atmospheric condition when the AAV was placed outside. Besides, the replacement of LNG with LN_2 causes systematic error to some extent. In the numerical analysis, the heat transfer in the radial direction of the AAV fin has been studied and calculated with a two-dimensional model, yet the study of the heat transfer in the longitudinal direction has not been developed. In addition, the boundary conditions of the solid walls were mostly preset in previous numerical analysis, hence the heat transfer performance coupling the LNG in the tube and the air outside of the tube was neglected, and thus cannot reflect the actual heat transfer process.

This paper developed a coupled three-dimensional simulation model for the AAV, and demonstrated it in the LNG vaporization process in a vertical star fin tube-the basic structural unit of the AAV. In the simulation model, the mutual restriction relation of the heat transfer between the fluid inside and outside of the fin tube was taken into consideration. The simulation results were validated by the real operating data of an AAV. The main purpose of this paper is to investigate how the whole heat transfer performance of the AAV fin tube can be influenced by the air temperature, the inlet flow of LNG and the location in the fin tube bundle.

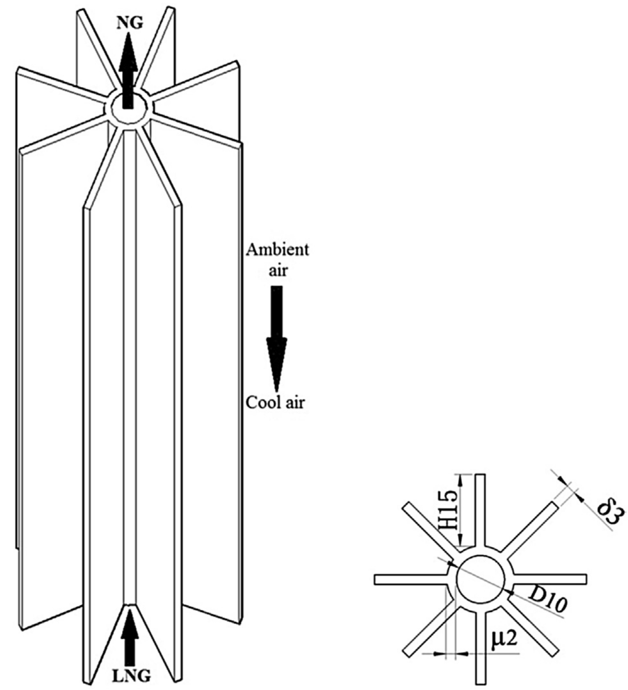

Fig. 2. The flow schematic diagram and the geometry model of the fin tube.

2. Numerical simulation

The CFD numerical simulation was used to solve the complex heat transfer process. Heat is transferred from the air around the fin tube to the cryogenic LNG because of the huge temperature difference. Cryogenic LNG flows into the inlet of the fin tube and flows out from the outlet in the form of natural gas (NG) after absorbing enough heat from the air. Meanwhile, the natural convection in the near vicinity of the outer surface of the fin tube is enhanced, because the air density is increased due to the decreasing of the air temperature. In turn, the natural convection of the air influences the vaporization of the LNG in the tube. Fig. 1 shows the heat transfer process of the whole model.

The heat transfer process is complex, therefore in the three-dimensional simulation model some assumptions were made as follows: we assume the problem in full developed steady-state; the thermophysical properties of the fin tube material remain constant; the heat transfer by radiation is negligible; frost formation and the velocity of ambient air are neglected; the components of LNG and its temperature are homogeneous in the tube.

The thermophysical parameters of LNG change with the temperature and pressure and they have influences on the simulation results to some extent. Therefore, it is of great importance to take them into consideration. Natural gas is a mixture which is mainly composed of light hydrocarbon and little non-hydrocarbon gases. In this model, the component of natural gas was simplified as methane (CH_4), ethane (C_2H_6)and propane (C_3H_8). The mixing rule of each thermophysical parameter is:

$$Q_m = \sum_i \sum_j z_i z_j Q_{ij} \tag{1}$$

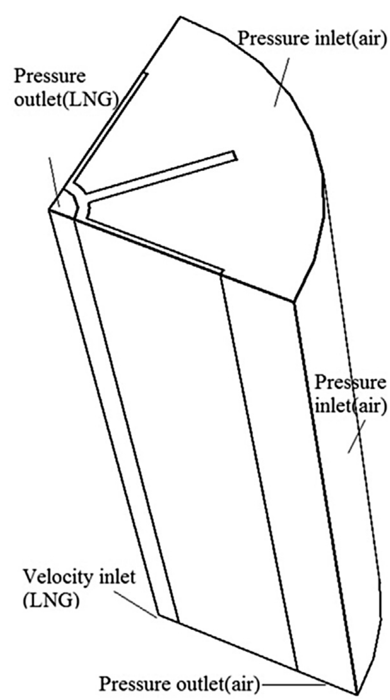

Fig. 3. The boundary conditions of the model.

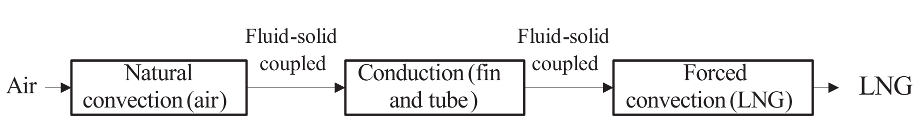

Fig. 1. The heat transfer process from the air outside of the tube to the LNG inside.