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Research Paper

Thermal performance calculation and analysis of heat transfer tube in super open rack vaporizer

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HIGHLIGHTS

- A distributed parameter model for SuperORV heat transfer tube was developed.
- Temperature and heat transfer coefficient profiles along tube length were estimated.
- The effects of operating parameters on thermal performance were discussed.
- The effects of inner fin or twisted tape insert on thermal performance were studied.

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ABSTRACT

As one of the most widely-used liquefied natural gas (LNG) vaporizer, super open rack vaporizer (SuperORV) consists of panel-shaped heat transfer tubes with duplex tube configuration. In this paper, an energy balance-based distributed parameter model for predicting the thermal performance of SuperORV heat transfer tube was developed, where introduces numerous empirical correlations. The results from the model exhibit a good agreement with the experimental data, which implies the calculation model is reliable. Based on this, the heat transfer process of SuperORV heat transfer tube was simulated numerically, the bulk fluid and metal temperature profiles along the heat transfer tube was obtained at the condition with ice formation and heat transfer enhancement measures, the thermal performance of SuperORV heat transfer tube was analyzed, and the effects of operating parameters and heat transfer enhancement measures on the thermal performance were discussed. The results show that the operating parameters have important effects on the thermal performance of heat transfer tube, and the heat transfer enhancement measures can improve the heat transfer performance markedly. The required minimum tube length while both inner fin and twisted tape insert were applied is shortened by 60% compared with that without heat transfer enhancement measures.

1. Introduction

Flexibility of supply and demand is essential for efficient operation of natural gas industry [1]. With the advantages consisting of high flexibility, and low storage and transportation cost, LNG links different markets together by allowing shifting volumes between regions, benefiting from differences in their supply and demand balance [2], and has become the world's fastest-growing primary energy commodity. The production and trade of LNG are increasingly active, and are becoming an important hotspot for oil and natural gas industry.

As important component of the LNG industry chain, numbers of LNG receiving terminals have been commercially developed or are under construction in many countries, where vaporizer as the key equipment is used to regasify LNG to meet the requirement of fuel gas in industrial and domestic purposes. There are several types of mainly-used vaporization schemes in LNG receiving terminal, including submerged-combustion vaporizer (SCV), intermediate fluid vaporizer (IFV), open-rack vaporizer (ORV) and SuperORV [3].

As one of the most representative LNG vaporizers, conventional ORV consists of panel-shaped heat transfer tubes, and seawater is used for the heat source. Whereas, it is limited for the increase of vaporizing capacity and the decrease of seawater consumption rate and installation space for conventional ORV due to the following reasons [4]: (1) the heat transfer efficiency reduces evidently with increasing LNG flow rate; (2) it is difficult to form a falling water film with uniform thickness over the external surfaces of the tubes when the rate of seawater decreases. Furthermore, the seawater tends to form a thick ice layer on the outside surfaces of heat transfer tubes due to direct heat transfer between seawater and cryogenic LNG, and the formed thick ice results in a tremendous thermal resistance that deteriorates the heat transfer efficiency greatly [5]. The

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fins outside the heat transfer tubes are also choked with thick ice layer until their configuration becomes almost invisible, which causes an effective decrease of heat transfer area [5].

Therefore, a new type of open rack vaporizer (namely SuperORV) was jointly developed by Osaka Gas and Kobe Steel (Japan), which consists of panel-shaped heat transfer tubes similar to conventional ORV except that the lower part of the tube panels has duplex tube configuration. Compared with conventional ORV, the vaporizing capacity of SuperORV was improved evidently and the seawater rate required for vaporization was reduced owing to the duplex tube configuration. As well, the required installation space for SuperORV is reduced and the operation cost was also cut down. The duplex tube configuration of SuperORV heat transfer tube is characterized with the annuli between outer and inner tubes, which enhances the heat transfer between LNG and seawater available by suppressing icing of seawater on the outside surfaces of heat transfer tubes, and the length and thickness of ice layer decrease remarkably since the fins on the heat transfer tubes are maintained in good temperature condition.

The heat transfer performance of superORV heat transfer tube was compared with that of conventional ORV heat transfer tube by Morimoto et al. [5], and it was found that SuperORV heat transfer tube can contribute to not only lowering the cost for gas production, but also saving energy. The results of pilot plant tests indicate that superORV increases LNG vaporizing rate per heat transfer tube 3 to 5 times, reduces the operating cost, construction cost and installation space by 15%, 10%, and 40% respectively, and seawater was reduced by approximately 15%.

With the aim to reveal and improve the performance of LNG vaporizer, numerous researchers respectively conducted a series of experimental study and numerical simulation. Jeong et al. [6] compared the characteristics of two types of longitudinal fin air-heating vaporizers experimentally by analyzing the inlet–outlet enthalpy difference and the outlet fluid temperature at different length scales and ambient conditions. A CFD analysis on longitudinally finned tube of air-heating vaporizer was conducted by Jeong et al. [7], the natural convection heat transfer for natural convection outside the tube was estimated, and corresponding heat transfer correlation was proposed. Jeong et al. [8] also carried out a numerical analysis of vaporizer for obtaining optimum design of longitudinal fin air-heating vaporizer and the prediction frost deposit formation on vaporizer fin, and proposed the optimum vaporizer geometry at the conditions of considering the frost thickness and without frost deposit presence. Pu et al. [3] developed a thermal model for intermediate fluid vaporizer based on the energy balance among evaporator, condenser and thermolator, which considered the mutual coupling and constraints fully. On this basis, the heat transfer performance of vaporizer, and the effects of operating parameters, such as seawater temperature and flow rate, LNG pressure and flow rate were also investigated. Himoto [9] analyzed the conventional designs of submerged combustion vaporizer, including the process and major factors impacting emissions, and systematically studied its advanced designs that have been newly developed to reduce NOx and CO emissions in exhaust gases. Hisada and Sekiguchi [10] established highly endurable structures through a variety of tests or finite element method analysis to develop best-suited shapes (such as sizes and internal/external surface shapes) of ORV heat transfer tubes by using numerical analysis and thermal stress design. Jin et al. [11] built a distributed parameter model to simulate the LNG evaporating process in a SuperORV heat transfer tube, and obtained some significant results by heat transfer performance analysis.

Complex heat transfer phenomena occur inside the heat transfer tubes of superORV. Whereas, above review shows that previous studies have mainly focused on air-heating vaporizer and few studies reported the thermal performance of superORV heat transfer tube, which is a key indicator for the thermal design of vaporizer and has important effects on the vaporization efficiency and reliably of vaporizer. In this paper, a distributed parameter model for predicting thermal performance of heat transfer tube is developed, which introduces numerous empirical correlations of heat transfer. Based on the results from the model, a thermal performance analysis of superORV heat transfer tube was conducted, the structure design for superORV heat transfer tubes was estimated, and the effects of operating parameters such as LNG pressure and flow rate, seawater/LNG flow rate ratio, LNG flow distribution ratio between annular channel, and inner tube and heat transfer enhancement measures on the heat transfer performance were discussed.

2. Physical and mathematical models

2.1. Description of physical problem

Fig. 1 illustrates the geometry of superORV heat transfer tube. As shown in Fig. 1, the lower half of the heat transfer tube is designed to be a duplex tube configuration differently from the upper section. The lower and upper parts of the heat transfer tube are called "vaporizing section" and "heating section" respectively. The vaporizing section consists of an outer tube with petal-shaped internal fin and similar triangular external fin, and an inner tube with double twisted tape inserts. The heating section is only a circular tube with petal-shaped internal fin and similar triangular external fin, where cross-shaped twisted tape inserts are applied.

LNG with low temperature of −162 °C is distributed to different heat transfer tubes by the distribution header at the bottom of vaporizer. The LNG flows upward inside heat transfer tubes while seawater flows downward along the outside surfaces of heat transfer tubes. At vaporizing section, some of the cryogenic LNG flows into the annular channel between outer tube and inner tube, and is heated by external falling seawater film and vaporized rapidly, and the other directly enters inner tube and is heated by absorbing the heat from outside NG until gasified to the saturated vapor. The superheated NG from the annular channel and the saturated NG flowing out of the inner tube are mixed and further heated in heating section. After adequate heat absorption in heating section, it turns to superheated vapor with ambient temperature, and at last assembles together in collection header at the top of vaporizer. Outside and inside fins for the external tube, as well as a twisted

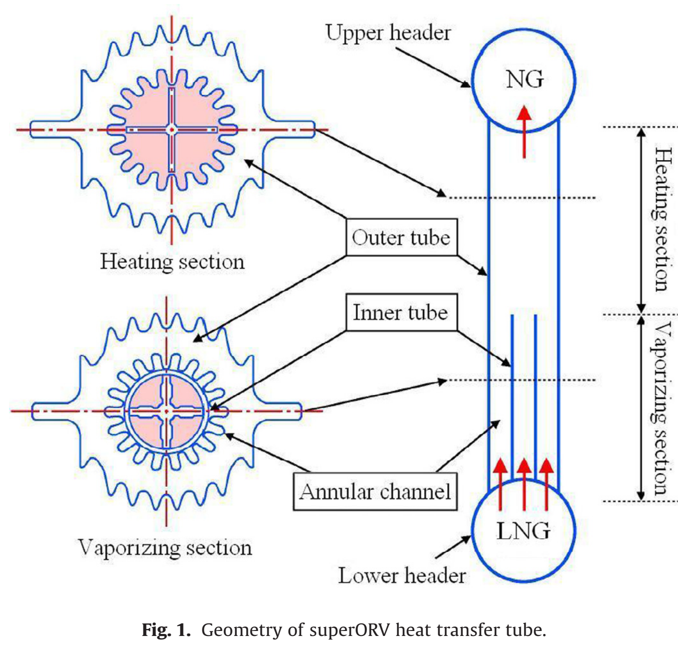

Fig. 1. Geometry of superORV heat transfer tube.