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Experimental study on liquid/solid phase change for cold energy storage of Liquefied Natural Gas (LNG) refrigerated vehicle

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ABSTRACT

The present paper addresses an experimental investigation of the cold storage with liquid/solid phase change of water based on the cold energy recovery of Liquefied Natural Gas (LNG) refrigerated vehicles. Water as phase change material (PCM) was solidified outside the heat transfer tubes that were internally cooled by cryogenic nitrogen gas substituting cryogenic natural gas. The ice layer profiles were recorded in different cross-sections observed by digital cameras. The temperatures of cryogenic gas, tube wall and bulk region were measured by embedded thermocouples continuously. The results of the smooth tube experiments and the thermal resistance analysis prove that the main thermal resistance occurs in the gaseous heat transfer fluid (HTF) inner the tube. The enhancement of the inner heat transfer is achieved by adding wave-like internal fins. Besides, the results show that the ice layer not only increases in radial direction but also propagates in axial direction. It distributes in parabolic shape along the tube length due to the parabolic axial distribution of the tube wall temperatures. This investigation provides valuable references for the design and optimization of the cold energy storage unit of LNG refrigerated vehicles and for the numerical study on the unsteady two-dimensional conjugated heat transfer with phase change.

1. Introduction

Liquefied Natural Gas (LNG) is known as a kind of clean fuel extensively used in industrial field. Feed natural gas is liquefied at cryogenic liquefaction units, and then is transported and stored at ambient pressure and corresponding saturated temperature of about 111 K. At the users end, LNG will be gasified again to be supplied as natural gas at ambient temperature. Gasification process releases a large amount of cryogenic energy which was transformed from electric power during the liquefaction process. Hence, it is very significant and imperative to recover LNG cold energy. A great deal of research has been conducted on the subject of theoretical analysis of LNG cold energy and its high-efficient utilization. Air separation systems and electricity generation plants based on cascaded power cycles were acknowledged as the most potential schemes for making the best of LNG cold exergy by many researchers [1–9]. Besides, some interesting applications of LNG cold energy, e.g. cryogenic thermoelectric generator [10], energy transport system for district cooling application by using so-called type-2 absorption cycle [11], seawater desalination and fresh and frozen food production and conservation [12], were proposed in many published literatures. Most of the above mentioned energy recovery schemes are large-scale and high thermodynamic efficient utilization of low-temperature cold exergy in LNG receiving terminals. However, the investigation on the subject of cold energy recovery based on LNG-fueled vehicles was rarely reported in literatures except automobile air conditioning utilization proposed by Wang and Li [13].

Recently, the present authors developed a kind of energy-saving and environment-friendly refrigerated vehicle recovering LNG cold energy.[1] It is a novel low-temperature refrigerated vehicle which utilizes LNG as both fuel and refrigerant (details in Section 2.1). We conducted a theoretical calculation of the cooling capacity supplied by the LNG vehicles. The results indicate that the cooling capacity is not only enough but surplus for the cold load of the refrigerated space. Besides, the LNG consumption per unit time fluctuates greatly with vehicle running conditions. Therefore, a Cold Storage System (CSS) is necessary for the management and adjustment of the LNG cryogenic energy. On one hand, the superfluous cold energy can be conserved with the CSS to avoid the unhelpful (even harmful) supercooling of the refrigerated room. On the other hand,

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the cold supply fluctuation induced by the fuel consumption variation could be diminished. Thus, the study on the high-efficient cold storage to balance the discrepancy between supply and demand of cold energy becomes more and more important.

The Latent Heat Cold Energy Storage (LHCES) uses a Phase Change Material (PCM), e.g. water/ice, that undergoes a liquid–solid phase change and a small temperature rise to store cold energy. Due to the advantages of its large energy storage density and isothermal behavior during the charging/discharging process, the LHCES becomes an important part of the Thermal Energy Storage (TES) technology, which is known as an appropriate solution to conservation of the available energy and adjustment of the discrepancy between the energy supply and demand. The TES applied in energy management systems such as solar energy accumulators, energy-saving building envelopes, and air conditioning systems with cold storage, etc. has been investigated intensively in the last decades [14–16]. As a typical LHCES technique, the static type ice storage is commonly applied in air conditioning systems of all kinds of buildings and successfully shifts all or part of the electricity requirement from the peak to off-peak period. Chan [17] conducted a parametric study making use of the DOE-2 to evaluate the District Cooling System (DCS) performance for a hypothetical site in Hong Kong. The investigation results indicate that the DCS is very suitable for the new urban developments in modern tropical or subtropical cities with high space cooling density.

As a key apparatus of high-efficient LHCES, the shell-and-tube heat exchanger is often regarded as the most promising device. In such an energy storage unit, PCMs are filled in the shell-side and heat transfer fluids (HTFs) flow in the tube-side. Cabeza [18] proposed and compared three methods to enhance the heat transfer in a CSS: addition of stainless steel pieces, copper pieces and a new PCM-graphite composite material. The PCM-graphite composite material showed an increase in heat flux bigger than that with any other techniques. Soltan [19] developed a numerical model based on a finite difference algorithm suggested by Du-Fort Frankle and simulated the solidification characteristics of water around a circular cross-section TES coil. Erek [20,22] and Kayansayan [21] intensively investigated the solidification of water outside externally finned tubes. They carefully analyzed the effects of HTF inlet conditions (inlet temperature and flow rate) and fin parameters (fin spacing and diameter) on the dynamic solidification performance of the system experimentally and numerically. Alawadhi [23] developed a finite element model and investigated the enhancing cooling process of water under a freezing condition by adding triangular corrugated fins in a cool-thermal storage system. The results indicated that the cooling time reached maximum when the aspect ratio of the triangular fins equals to 0.75. In these above mentioned cases, the heat transfer enhancement methods invariably conducted to the PCM side of the cold storage units (CSUs). It is because the main thermal resistance exists in PCM side for most of conventional ice storage systems due to the relatively high convective heat transfer coefficient inside the tube. The HTF has relatively high thermal conductivity and large specific heat (e.g. ethylene glycol based water solutions) flowing inside the tube as coolant. Therefore, axial variation of tube wall temperature is so little that it can be simplified as a constant wall temperature boundary condition.

Though the shell-and-tube heat exchanger is selected as the elementary cold storage configuration in this study, there are many characters distinct from the traditional CSUs. Firstly, the HTF is cryogenic gas and its heat transfer is very weak. Thus the main thermal resistance turns to this part. Addition of external fins to the PCM side is not an efficient way to enhance the heat transfer in LHCES any longer. Besides, because of rather small specific heat, cryogenic gas is heated substantially along the heat transfer tube. Correspondingly, the surface temperature of the tube varies greatly in the axial direction and thus freezing of PCM on the surface of the tube may show a distinct pattern. A classical literature by Sparrow [24] analyzed the two-dimensional freezing on the outside of a heat transfer tube which was cooled by gaseous coolants. Zhang et al. [25] studied the heat transfer enhancement in a TES system by using internal longitudinal finned tube numerically. But few experimental studies were reported in open literatures, and the investigation on the heat transfer enhancement of the LHCES by utilizing the internally finned tube is even rare.

The motive of this study is to experimentally investigate the solidification of PCM and the heat transfer of cold storage process in order to provide design references for the cryogenic energy storage unit of LNG refrigerated vehicles. The study is based on the cases of tubes to find the basic rules of heat transfer and solidification of PCM. The wave-like internally finned tube was proposed to enhance such conjugate heat transfer and correspondingly to accelerate the solidification process. The two-dimensional characteristics of the ice layer growth were analyzed under a specific varied wall temperature thermal boundary condition.

2. Physical model and experimental apparatus

2.1. The LNG refrigerated vehicle and the CSU

A schematic drawing of the LNG refrigerated vehicle and the CSU are shown in Fig. 1. LNG is controlled by Valve box and then flows into the CSU. PCM filled in the CSU is chilled and solidified by the cryogenic natural gas. After vaporized and heated in the CSU, the natural gas is superheated in the Heat Exchanger and then flows into the vehicle engine to combust. The heat transfer process in the CSU is illustrated in the partial enlarged detail. In view of the novelty of the recovering and storing LNG cold energy with liquid–solid phase change of water, as well as the complexity of the two-dimensional increasing characteristics of ice layer, it is necessary to investigate the ice formation phenomenon under the present application background. Meanwhile, the solid phase increase and the heat transfer characteristics should be measured experimentally to design the CSU geometrical parameters, e.g. the shell diameter and the length.

2.2. Experimental apparatus and procedures

A schematic diagram of a test apparatus is shown in Fig. 2. The test facility consists of a cryogenic Dewar to provide cryogenic coolant (here nitrogen gas is used to simulate natural gas), a thermostatic water bath, a gas turbine flow meter, a main solidification test section, and related piping systems. The main solidification test section is shown in Fig. 3, in which the locations of thermocouples are marked. The test section included a rectangular cavity of $1000\ \text{mm} \times 150\ \text{mm} \times 200\ \text{mm}$ $(L \times W \times H)$ filled with PCM, a copper tube submerged in PCM horizontally in the middle of the cavity. The test tube is 1000 mm in length, 20 mm in diameter (OD) and 1 mm in wall thickness. The rectangular test section was insulated with 50 mm thick Rigid Polyurethane Foam plates supported by outermost stainless steel crust. To record the images of ice layer growing outside the test tube, three pairs of round-shaped openings were embedded in the side walls. The openings are constructed with double layer transparent Plexiglas filled with nitrogen gas avoiding the condensation of moisture. The heat loss of the openings, including the heat conduction and radiation through the gas cavities, was found to be 5.3 W between a water