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Experimental approach to suppress two-phase flow in cryogenic liquid transfer process with the inverted U-bend pipe

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ABSTRACT

LNG (Liquefied Natural Gas) offloading process from LNG cargo to storage tank includes substantial vertical upward fluid transportation. During this LNG transportation process, local boiling may occur at elevated position of the transport pipe due to the decrease of hydrostatic pressure and obstruct liquid flow, concluding long transport time or insufficient transport to a tank. Small scale LN_2 (Liquid Nitrogen) transfer system has been fabricated to simulate this LNG transportation process and flow characteristics. Subcooled LN_2 is transferred to 5 m upward, 1 m horizontally, and 5 m downward through vacuum insulated stainless steel pipe. Glass pipes are installed at the middle part of transportation pipes to visualize the two-phase flow pattern during fluid transfer. Cryogenic valve is installed at the outlet of transfer pipe to regulate the system pressure inside the transfer tube. Pressurization by manipulating the cryogenic valve at the outlet, has effectively suppressed two-phase flow, which results in transportation advantages, such as low pressure drop and smooth flow. This paper presents the detailed experimental data of the whole procedure of the tested LN_2 transfer system.

1. Introduction

LNG (Liquefied Natural Gas) implies liquid state of natural gas, which has a normal boiling temperature around −161 °C (112 K) [1]. The composition of NG (Natural Gas) is mostly methane. The liquid density at the normal boiling point of methane is approximately 610 times greater than that of the gas at ambient temperature and pressure. Consequently, a given volume of liquid contains over 600 times the heating value as the same volume of ambient gas. This increased density at ambient pressure makes it attractive to liquefy, transport, and store natural gas in large quantities [2].

The offshore gas plant development is currently revaluated as one of the promising energy industries, because 20% of natural gas wells are under the sea. FPSO (Floating Production Storage & Offloading) is a useful method to refine, liquefy and store natural gas which is directly harvested from the ocean. The LNG-FPSO has a great advantage in that it does not need to transfer natural gas from offshore place to onshore plant to liquefy natural gas. FPSO can also allow direct transportation LNG from a storage tank to another transport ship, which is effective for cost [3].

During LNG transfer from LNG FPSO to LNG FSO (Floating storage & offloading), or to onshore LNG storage tank, LNG has to pass pipelines from the bottom of the tank to the top of the tank whose height is usually more than 30 m. Pipe line shape may resemble an inverted U-bend where LNG flows through vertical upward, goes horizontally, and falls downward to a storage tank as shown in Fig. 1. DSME (Daewoo Shipbuilding & Marine Engineering) identified a potential problem of two-phase generation and flow blockage at the top horizontal part of pipeline during LNG transfer. Flow blockage will increase the overall transport time and generate unnecessary additional BOG (boil off gas) which is a loss of LNG.

There are rare researches about two phase generation at high elevation; however some studies about LNG transfer were conducted. LNG transfer efficiency in FPSO is analyzed with varying transport parameters such as mass flow rate, pipe height, diameter, roughness, and LNG composition without two-phase effect [4]. There are experiments to verify liquid nitrogen two-phase flow regimes in microtubes recently [5,6], but large scale transport phenomenon is rarely observed. Suppression of bubbles under heat impulse on plate which is immersed in liquid nitrogen bath is similar to this work [7]. However, active suppression of two-phase flow during transfer is rarely discussed in cryogenic environment.

The research theme of this paper is focused on the experimental observation of local two phase generation at the top of the transfer pipe. Two phase generation related to cryogenic fluid transfer is effectively suppressed by increasing system pressure. Direct

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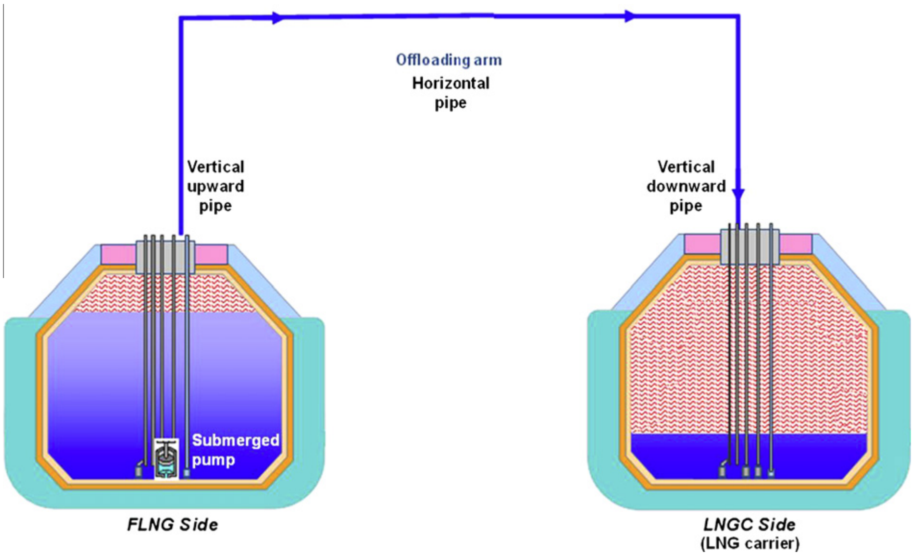

Fig. 1. Inverted U-bend shape of LNG transfer line from FLNG to storage tank.

experimental evidences of two-phase flow and its suppression characteristics are provided by using a high speed camera.

2. Simple analysis with first law of thermodynamics

The first law of thermodynamics can be applied to fluid transfer from ground level to a certain height with the following equation:

$$q - w = \dot{m}\left(h_{out} - h_{in} + \frac{V_{out}^2 - V_{in}^2}{2} + g(z_{out} - z_{in})\right) \tag{1}$$

In the case of non-cryogenic fluid transfer at constant mass flow rate with horizontal pipe lines, such as water and oils, the equation can be simply reduced to (2) virtually, assuming that the pipe system is completely adiabatic and there is no viscous loss. The enthalpy values always indicate same values if there is no gravity effect, and if there is negligible pressure drop with sufficiently large pipe diameter:

$$h_{out} = h_{in} \tag{2}$$

Horizontal cryogenic fluid transfer with imperfect insulations may accompany some heat leak from outside environment, then Eq. (2) needs modification. Heat leak is, in fact, the major cause of increasing the temperature of cryogenic fluids, and this condition is expressed as Eq. (3). Insulation is important to keep the low temperature of cryogenic fluid. Because the viscous loss is usually neglected, pressure will show the same value between the inlet and the outlet:

$$h_{out} = \frac{q}{\dot{m}} + h_{in} \tag{3}$$

When the pipe is vertically installed and the fluid is transferred in an upward direction, the enthalpy value at the top of the pipe can be expressed as Eq. (4) for transferring non-cryogenic fluid. The fluid enthalpy decreases as height increases. The hydrostatic pressure can be also expressed by the following equation:

$$h_{out} = h_{in} - gz_{out} \tag{4}$$

$$P_{out} = P_{in} - \rho_{fludi} g z_{out} \tag{5}$$

When fluid is pushed through a vertical upward pipe, the static pressure normally decreases because of its own weight. Therefore, the pressure at the top of the transfer line becomes lower than that at the ground level. When this pressure decrease effect is significant, there is a possibility of cavitation due to local low pressure [8]. Although cavitation occurs at the top of the pipe, the bubbles may collapse if the fluid flows back to the ground level again. The pressure would increase at the ground level due to fluid's own weight according to Bernoulli's equation.

An example of LN_2 vertical transfer with perfect insulation can be considered with Eqs. (4) and (5) by using REFPROP 8.0 [9]. The difference of enthalpy value induced from the height change is very small, and it results in temperature drop within very small range. When the subcooled liquid at 78 K and 200 kPa ($h = -120.63$ kJ/kg) flows upward to a 10 m long pipe, the pressure at the top would be 121.6 kPa according to Eq. (5). The enthalpy at the top shows lower value of −120.73 kJ/kg which is determined with Eq. (4). The temperature is, therefore, lowered to 77.98 K because the pressure and the enthalpy indicate lower values than those at the pipe inlet. The state of the fluid at the top is still a subcooled state. Fig. 2 shows the T–s (Temperature-entropy) diagram of inlet and outlet states for this example. Cavitation may occur, however, if there is more pressure decrease due to a longer vertical upward pipe than that of this example, giving rise to the fluid state to enter the saturation dome of the T–s diagram. If the inlet fluid has more subcooling degree or pressurized state, the possibility of cavitation would clearly decrease.

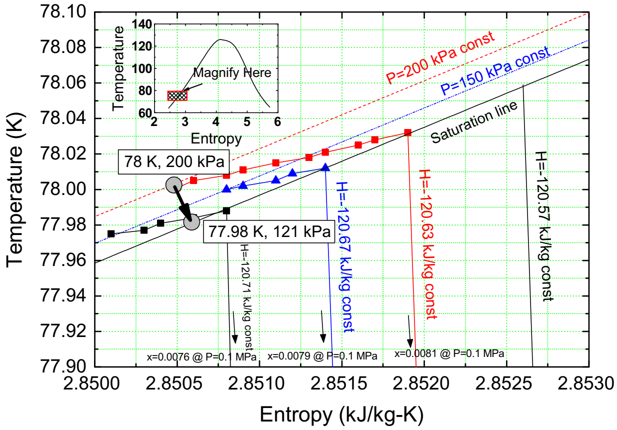

Fig. 2. Temperature-entropy diagram of liquid nitrogen.