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Investigation on the heat transfer characteristics during flow boiling of liquefied natural gas in a vertical micro-fin tube

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ABSTRACT

This paper presents an experimental investigation on the heat transfer characteristics of liquefied natural gas flow boiling in a vertical micro-fin tube. The effect of heat flux, mass flux and inlet pressure on the flow boiling heat transfer coefficients was analyzed. The Kim, Koyama, and two kinds of Wellsandt correlations with different F_{tp} coefficients were used to predict the flow boiling heat transfer coefficients. The predicted results showed that the Koyama correlation was the most accurate over the range of experimental conditions.

1. Introduction

As a kind of clean, efficient and economical energy source, natural gas (NG) is more and more widely used in industrial production, transportation, and other civilian fields. NG is typically stored and transported in the form of liquefied natural gas (LNG) after impurities are removed [1]. Finally, the LNG should be utilized in the form of natural gas at room temperature after vaporization. Therefore, the design of the heat exchanger and the study of the heat transfer characteristics are particularly important in both processes of NG's liquefaction and LNG's gasification. Moreover, the research of the heat transfer characteristics in an enhanced tube is very valuable.

There was very little research report on the study of two-phase flow boiling of LNG in the published literature, although research on two-phase flow boiling had been carrying on since the 1960s. Kravchenko et al. [2] investigated the heat transfer characteristics during pool boiling of methane in a vertical tube and presented recommendations for the design of evaporators for natural gas liquefaction plants. Moreover, current studies on two-phase flow boiling in enhanced tubes which had been carrying on since 1970s [3] were mostly on refrigerants which are liquid at room temperature. Kim and Seo [4] had measured the heat transfer coefficients of R22 in both smooth tube and micro-fin tube with outer diameters of 7 mm and 9.52 mm. Their report showed that the heat transfer coefficients of R22 in micro-fin tubes with outer diameter of 7 mm and 9.52 mm were approximately 1.2–1.8 and 2.2–3.3 times that of smooth tubes, respectively. Colombo et al. [5] experimentally investigated the heat transfer and pressure drop characteristics of the condensation and evaporation of R134A in micro-fin tubes. Furthermore, a visual inspection was performed to characterize how fins affect the flow pattern transitions. Wellsandt and Vamling [6] developed a new correlation, which could predict the heat transfer coefficients in micro-fin tubes for R134A with an average residual of 1.5% and a standard deviation of 21%.

This paper presents an experimental investigation on the heat transfer characteristics of LNG flow boiling in a vertical micro-fin tube. The effect of heat flux, mass flux and inlet pressure on the flow boiling heat transfer coefficients was analyzed. The Kim, Koyama, and two kinds of Wellsandt correlations with different F_{tp} coefficients were adopted to predict the flow boiling heat transfer coefficients and the results predicted by different correlations were compared with the experimental data to find out the most appropriate correlation.

2. Experimental apparatus

The test set-up was designed to measure the local heat transfer coefficient and pressure drop of the LNG flowing through the test tube. The test set-up consisted of the LNG flow loop, vacuum Dewar and signal acquisition system. Fig. 1 illustrates the schematic diagram of the experimental apparatus. LNG in the storage tank with a capacity of 500 L and adjustable operating pressure of 0.1–1.6 MPa was supplied to the test section after it was pre-cooled in the liquid nitrogen container. LNG from the outlet of

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Nomenclature

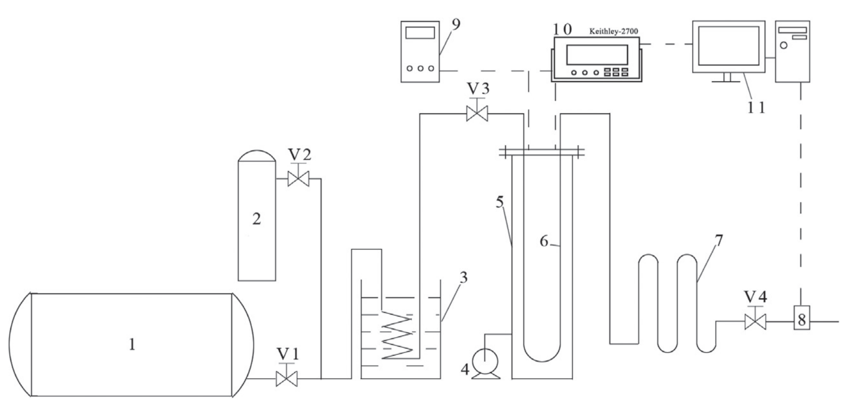
U	voltage, V
I	current, A
Q	Heating Power, W
q	heat flux, W m^{-2}
A_c	cross-sectional area, m^2
A_s	effective heating area, m^2
p	pressure, Pa
T	temperature, K
μ	dynamic viscosity, pa s^{-1}
ρ	density, kg m^{-3}
l	length of the test section, m
G	mass flux, kg s^{-1}
D_i, D_o	inner diameter and outer diameter respectively, m
h_{lv}	latent heat of vaporization, J kg^{-1}
x	quality
z	coordinate
λ	thermal conductivity, W m^{-1} K^{-1}
Re	Reynolds number
Pr	Prandtl number
X_{tt}	Martinelli parameter
M	molecular weight
h	heat transfer coefficient

Subscripts

in	inner
out	outer
v	vapor
f	fluid
w	wall

the test section was completely vaporized in the vaporizer and then flowed through the mass flow meter to measure the mass flow rate. Finally, the vaporized LNG flowed into the environment. The temperature and pressure of each test point and the voltage and current signals of the DC power supplier were tested and collected by the data acquisition instrument while the mass flow rate was directly measured by the mass flow meter and the results were stored in the computer.

Fig. 2 illustrates the schematic diagram of test section. 12 platinum resistance temperature sensors were installed symmetrically on 6 different test cross-sections which were distributed evenly on the test section. Moreover, one more platinum resistance



1.LNG storage tank 2.Nitrogen gas cylinder 3.Liquid nitrogen container 4.Vacuum pump 5.Vacuum Dewar 6.Test section 7.Vaporizer 8.Mass flow meter 9.DC power controller 10.Data acquisition instrument 11.Computer V1-V4.Valves

Fig. 1. System diagram of experimental apparatus.

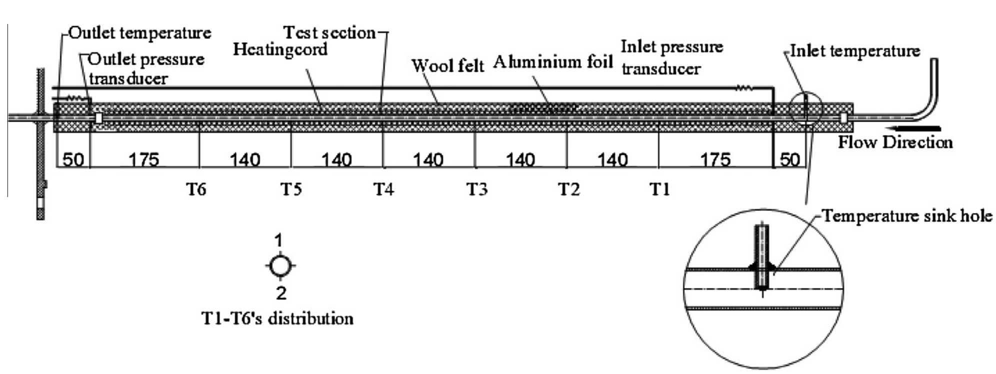


Fig. 2. Schematic diagram of test section.