Experimental investigation of line chill-down process with liquid oxygen

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Abstract. Cryogenic fluids, such as liquid oxygen (LOX) and liquid hydrogen are used as the propellants of space vehicles. Before initiating the normal operation state, all elements in the cryogenic system need to be chilled down by consumption of the incoming cryogenic liquid. As a result, the heat transfer characteristics during the chill-down process are extremely concerned by engineers. This paper describes the experimental research on the line chill-down process with LOX. The experiments are conducted under various mass flux conditions on a stainless steel horizontal pipe with the dimensions of 12.7 mm outer diameter, 1.25 mm wall thickness, and 7 m length. The heat transfer characteristics in various heat transfer regimes are experimentally examined and analysed for comparison with those in chill-down processes with liquid nitrogen. Additionally, the accuracy of the previously suggested transient heat transfer correlations is evaluated being based upon the current experimental data.

1. Introduction

The transfer line of cryogenic fluids is commonly required to be cooled down by the cryogenic liquid before the normal operation of cryogenic systems, which is so called cryogenic line chill-down process. This process accompanies with complex physical and heat transfer phenomena. Figure 1 shows the transition of fluid phase and heat transfer regime during the chill-down process. At the beginning of chill-down process, the cold liquid is vaporized quickly due to the heat transfer with the extremely “hot” pipe wall. As the wall temperature decreases, two-phase flow is observed, and the film boiling, transition boiling, and nucleate boiling occur with the change of flow patterns. After the cooling, the cryogenic liquid can be transferred stably in liquid state. The boil-off gas generated during the line chill-down process can no longer be used for the original purpose, which causes a large amount of undesired energy loss. Thus, it is important to shorten the chill down time and reduce the cryogenic liquid consumption.

![Figure 1. Transition of heat transfer regime during cryogenic line chill-down process](image-url)
Engineers made a lot of efforts to understand the cryogenic line chill-down process in order to numerically simulate the chill-down process and further optimize the operating conditions. In the most of the previous research, liquid nitrogen was selected as the working fluid, and the experiments were carried out on short transfer lines, where film boiling is the dominant heat transfer regime [1-4]. As the heat transfer characteristics during the cryogenic chill-down process are proved to be closely related to the physical and thermal properties of fluids [5], the heat transfer correlations need to be examined for various species of cryogenic fluid.

Here, the cryogenic line chill-down experiments are carried out with liquid nitrogen and liquid oxygen in the identical experimental apparatus, which is a 7-meter-long uninsulated horizontal pipe. According to the obtained experimental data, the empirical correlations for calculating the critical heat flux, the critical heat flux temperature, and the minimum heat flux temperature, which are examined by liquid nitrogen, liquid argon, and liquid oxygen, are suggested for cryogenic line chill-down process

2. Experiment

2.1. Experimental apparatus

The schematic diagram of the experimental apparatus is shown in Figure 2. The main test section is stainless steel horizontal pipe with 7 m length and 12.7 mm outer diameter. The test section is exposed to the atmospheric environment. Liquid nitrogen (LN$_2$) and liquid oxygen (LOX) are selected as the working fluids. The cryogenic liquid (LN$_2$ or LOX) is supplied by the pressurized tank and subcooled by the saturated liquid (LN$_2$ or LOX) at the atmospheric pressure. The transfer line from the cryogenic liquid tank to the inlet of the test section is pre-cooled, and the boil-off gas is vented through the vent line until the inlet fluid temperature becomes lower than the saturation temperature at $P_{in}$. In the test line, the wall and fluid temperatures are measured by T-type thermocouples in four different locations: 1 m, 2.5 m, 4.5 m, and 6.5 m away from the inlet of test section. TC4, 5, 6 and TC8, 9, 10 are installed at the top, side, bottom part of the cross section of the pipe wall to observe the temperature difference caused by gravity effect. The mass flow rate is measured by a Coriolis mass flow meter (MFM). The pressure is measured at the inlet and outlet of the test section (P1 and P2).

![Figure 2. Schematic diagram of experimental apparatus](image)

2.2. Experimental results

The experiments are conducted by controlling the pressure of the cryogenic liquid supply tank. The experimental conditions in this work are shown in Figure 3. As seen in Figure 3(a), the average mass
flux is almost linearly dependent on the average inlet pressure. The line chill-down time according to the average mass flux is presented in Figure 3(b). The mass flux significantly affects the line chill-down time in the low mass flux conditions (lower than approximately 80 kg/m²s); while the change of chill-down time slows down in the high mass flux conditions.

3. Heat transfer correlations

Based on the measured data of wall temperature, the transient heat flux is calculated by the inverse problem solving method [6]. The detailed calculation process can be found in our previous publication [7]. Figure 4 shows the typical temperature and heat flux transient during the chill-down process. One can see in Figure 4, as mentioned before, the heat transfer regime changes along decrease of the wall temperature, and there are several changing points of the heat transfer regimes like Leidenfrost point and critical heat flux point, which are extremely important to numerical simulation of chill-down process. This work presents some important parameters (critical heat flux, \( q''_{CHF} \), critical heat flux temperature, \( T_{CHF} \), and minimum heat flux temperature, \( T_{MHF} \)) are obtained from the computed heat flux data in each experimental case. At the same time, the empirical correlations are suggested for these parameters, which are valid for LN2, LOX, and LAr.

3.1. Critical heat flux, \( q''_{CHF} \)

The experimental data obtained in this work and from our previous research [8, 9] are used to establish a new empirical correlation for critical heat flux. In 2015, Darr S. et al. suggested a critical heat flux correlation for line chill-down process in a vertical pipe with liquid nitrogen as Equation 1 [10].
\[ q''_{CHF} = 0.0527 G h_f g (W_e_L)^{-0.2894} \]  \hspace{1cm} (1)

where, \( G \) represents mass flux, \( h_f g \) means latent heat, and \( W_e_L \) indicates Weber number, which is a measure of the relative importance of the fluid’s inertia force compared to its surface tension.

We used the form of Equation 1 to construct a new correlation for critical heat flux as following Equation 2.

\[ q''_{CHF} = 0.0217 G h_f g (W_e_L)^{-0.233} \]  \hspace{1cm} (2)

Figure 5(a) shows the derivation of Equation 2, which is the best fit curve of the experimental data. The comparison of the calculation results by Equation 2 and the experimental data is shown in Figure 5(b). As shown in Figure 5(b), Equation 2 predicts the critical heat flux with approximately ±30% error.

3.2. Critical heat flux temperature, \( T_{CHF} \), and minimum heat flux temperature, \( T_{MHF} \)

\( T_{CHF} \) and \( T_{MHF} \) mean the wall temperature at the critical heat flux point and the minimum heat flux point (Leidenfrost point), respectively. We suggested the correlations for these two parameters for the line chill-down process with liquid nitrogen and liquid argon as following Equation 3 and Equation 4.

\[ T_{CHF} = 0.0058 e^{-p/8.7} A^{0.6} + T_{sat} \]  \hspace{1cm} (3)

\[ T_{MHF} = 0.009 e^{-p/8.7} A^{0.6} + T_{sat} \]  \hspace{1cm} (4)

where, \( p \) is the average pressure of the test line, and \( A \) is calculated by following Equation 5.

\[ A = h_f g \rho_v \left[ \frac{g(\rho_l - \rho_v)}{\rho_v^2} \right]^{1/4} \]  \hspace{1cm} (5)

\( \rho_v \) and \( \rho_l \) are densities of liquid and vapour, \( g \) refers to gravity force, and \( \sigma \) means surface tension in Equation 5. All the parameters in the equations are in the international standard unit.

Figure 6 shows the comparison of the experimental data of various species of cryogenic fluid and the calculation results by Equation 4-5. As seen in Figure 6, the calculation results well match the experimental data with the error of ±10%. 
Figure 6. Comparison of experimental data and calculation results of (a) critical heat flux temperature and (b) minimum heat flux temperature

4. Conclusions
The line chill-down experiments are conducted on a stainless steel horizontal pipe. Both of liquid nitrogen and liquid oxygen are selected as the working fluid. According to the experimental data in this work as well as the experimental data of liquid nitrogen and liquid argon in previous research, the empirical correlations for the critical heat flux, the critical heat flux temperature, and the minimum heat flux temperature are suggested. The correlations can be used to analyse the heat transfer regimes in the cryogenic line chill-down process.

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