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Improvement in pipe chilldown process using low thermal conductive layer

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ABSTRACT

A method for reducing the time and total mass of cryogenic fluid required for a chilldown process in piping was experimentally investigated in this study. The inner wall of a pipe with an outer diameter of 1/4″ (=6.35 mm) was coated with Polytetrafluoroethylene, which has a low thermal conductivity. Liquid nitrogen (LN_2) was supplied to the pipe at a constant tank pressure of 120–170 kPa. The fluctuations of the two-phase flow, which were composed of LN_2 and gas phase nitrogen, were observed. A pipe without an insulating layer and three other pipes with insulating layers of thicknesses 23 μm, 63 μm, and 91 μm, respectively, were used in the experiment. The results indicated that the temperature of the minimum heat flux point (MHF) was higher for the pipe with the insulating layer. This increased temperature caused earlier transition to nucleate boiling. Furthermore, the total mass of LN_2 consumed in the chilldown process could be retrenched up to a maximum of 64%. The heat flux decreased after reaching the MHF point; however, heat flux after MHF point is not dominant to overall chilldown time. The effect of the layer to increase the temperature of MHF point is dominant to overall chilldown time, which results in the decrease in the chilldown time and the total mass of LN2 consumed in the chilldown process.

1. Introduction

1.1. Background

Cryogenic fluids have recently begun to be increasingly used mainly in the fields of aerospace and superconductive materials. In the aerospace field, liquid hydrogen and oxygen have long been used as fuels for rocket engines. The biggest advantage of using liquid hydrogen as a fuel is that its calorific value per volume is higher than that of hydrocarbon fuels, and a number of reports have reported its use as a fuel for aircrafts in the recent years [1]. In the field of superconductivity, liquid nitrogen and helium are used as coolants in commercial MRI (magnetic resonance imaging) and the Large Hadron Collider (LHC) [2,3].

For all the applications described above, a “chilldown” process is required before the use of cryogenic fluids in the systems. At initial stage these fluids flow into devices through piping systems that are in the ambient temperature state, which is significantly higher than the temperature of cryogenic fluids. Therefore, when these fluids are introduced into such piping systems, they intensively boil and evaporate. The gasification of the cryogenic fluids causes intense increase in the volume flow rate, resulting in increase of pressure loss. This makes the chilldown process time consuming and also leads to the discharge of the gases generated into the atmosphere during the process. According to Shaeffer et al. [4], only 8% of the calorific value of the cryogenic fluids is used for cooling the piping system during the chilldown process, which is extremely inefficient. Therefore, reducing the time required for chilldown along with retrenching the mass of the cryogenic fluids used is important.

In the earlier studies, mechanisms regarding boiling heat transfer and effects of gravity on this heat transfer in the chilldown process have been reported. Hu et al. [2] described the heat transfer phenomena in the chilldown of vertical pipes using liquid nitrogen. They also experimentally investigated the effects of the direction of the flow on the chilldown process. Shaeffer et al. [4] investigated the mechanism governing the heat transfer in the flow of liquid nitrogen with fluctuating flow rates during the process. For practical applications, chilldown is frequently processed at a relatively low flow rate. Yuan et al. [5] studied the heat transfer phenomena under such conditions. Studies have also reported for cryogenic fluids other than liquid nitrogen. Shirai et al. [6] studied the boiling heat transfer characteristics of liquid hydrogen, whereas Hartwig

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Nomenclature

c	specific heat (J kg^{-1} K^{-1})
q	heat flux (W m^{-2})
r	radius (m)
t	time (s)
T	temperature (K)

Greek

α	thermal diffusivity (m^2 s^{-1})
λ	thermal conductivity (W m^{-1} K^{-1})
ρ	density (kg m^{-3})

Subscripts

i	inner wall
o	outer wall

et al. [7] conducted a series of experiments using liquid hydrogen. However, only a few experiments have been conducted using liquid hydrogen because it is a fairly costly and dangerous substance.

1.2. Improvement in the boiling heat transfer

There have been a large number of studies on methods to use for improving the heat transfer rate during a boiling heat transfer. One of the main methods proposed involves coating the surface of an object: Vakarelski et al. [8] succeeded in drastically increasing the heat flux by using a hydrophilic coating, which promoted the transition to nuclear boiling. In their experiment, they immersed a heated steel sphere with this coating in water. A number of studies have also investigated improving the boiling heat transfer with coatings and not using cryogenic fluids. Shojaeian et al. [9] conducted a review of the results of such studies. Nevertheless, few studies have been reported where cryogenic fluids have been used. One of these studies was an experiment by Hu et al. [10]; they conducted their experiment under pool boiling using a rod that had a nanoporous surface. They increased the critical heat flux (CHF) by 160%. Unfortunately, the methods used seemed to be complex and expensive, which made them unsuitable for practical applications.

However, aside from the methods for improving the heat transfer mentioned above, another method for coating a surface of an object has been proposed, although this one uses thin layers with low thermal conductivity. This seems incongruous, as one would expect such layers to prevent heat transfer, and yet this method can reduce the time needed for the chilldown process. As a result of its contradictory nature, this method has been called the "Paradox of the Insulating Layer".

This technique has ancient origins. The technique has been used in the process of "Yakiire" (quenching) to manufacture katanas (*i.e.*, a Japanese sword). In the process heated iron is quenched in order to improve the strength of the sword [11]. As academic thesis, Cowely et al. [12] reported the method for improving boiling heat transfer using thin layers with low thermal conductivity in 1962. After a few years of this study, Maddox [13] conducted pool boiling experiments with coated tubes. Allen [14] applied this method for increasing heat transfer to space chamber cryopanels. Subsequently an experiment was conducted with various coatings using liquid helium [15], and another used water and liquid hydrogen [16]. A detailed mechanism using liquid nitrogen was studied by Nishio et al. [17,18], and an experiment using liquid helium was conducted by Chandratilleke et al. [19]. Kikuchi et al. [20], meanwhile, studied the heat transfer modeling in the case where a low thermal conductive layer was used. Recently, Tsoi et al. [21] studied the effects of the thickness of the insulating layers on the heat transfer by applying grease. All studies above were conducted under pool boiling, where cryogenic fluids cannot flow. Dreitser [22] investigated methods of heat transfer enhancement in channels. This study treated forced convection flow with coating. However, the main topic of this study is introductions of various methods for enhancing heat transfer. Therefore, the details of the experiments in this study were not explained well.

The biggest advantage of this method is its durability. When using hydrophilic coatings, surface contamination causes the performance of the heat transfer to deteriorate. However, by using thin layers with low thermal conductivity, it is possible that the surfaces can withstand longer use because the heat transfer performance is not subject to any contaminations.

With all of the above in mind, this study looks to discuss the applicability of the "Paradox of the Insulating Layer" to the chilldown process. We coat the inside of a pipe with a layer of low thermal conductivity, and we evaluate the chilldown time and the amount of cryogenic liquid consumed. Some previous experiments that chilled down piping systems were conducted at a constant flow rate [2,5]. However, rockets being launched have cryogenic fluids pumped into them at a constant tank pressure. In this study, we conduct an experiment at a constant tank pressure to evaluate the effects that a layer of low thermal conductivity can have under more practical conditions. Furthermore, we observed pulsation of the flow during the start of the chilldown process in spite of using a constant tank pressure. In this paper, report on this phenomenon is also presented.

1.3. Principle behind the paradox of the insulation layer

This section provides an explanation about the typical boiling regimes used during chilldown as well as the mechanism in the paradox of the insulating layer that reduces the chilldown time.

The temperature profile of a pipe during a typical chilldown process is shown in Fig. 1. During the chilldown process, the initial value of the pipe's temperature at point A is usually that of the

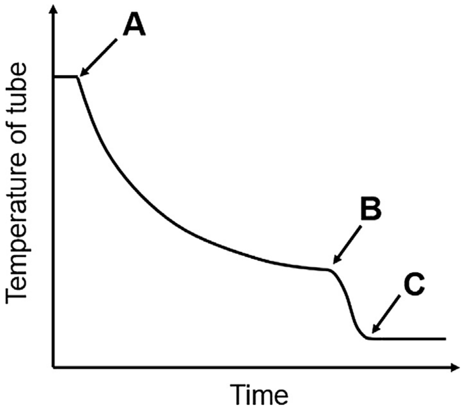

Fig. 1. Typical temperature profile of a pipe during the chilldown process.