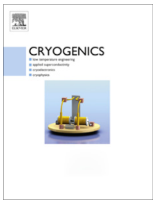
Cryogenics 79 (2016) 96–105

Contents lists available at ScienceDirect

Cryogenics

journal homepage: www.elsevier.com/locate/cryogenics



Research paper

Experimental investigation on chill-down process of cryogenic flow line

Lingxue Jin [a], Changgi Park [a], Hyokjin Cho [b], Cheonkyu Lee [a], Sangkwon Jeong [a,*]

[a] Cryogenic Engineering Laboratory, Division of Mechanical Engineering, School of Mechanical, Aerospace and Systems Engineering, Korea Advanced Institute of Science and Technology, 291, Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea
[b] Space Test Division, Korea Aerospace Research Institute, 169-84, Gwahak-ro, Yuseong-gu, Daejeon 34133, Republic of Korea

ARTICLE INFO

Article history:
Received 27 April 2016
Received in revised form 20 July 2016
Accepted 22 August 2016
Available online 30 August 2016

Keywords:
Liquid nitrogen
Chill-down
Horizontal pipe
Flow boiling
Critical heat flux
Minimum heat flux

ABSTRACT

This paper describes the cryogenic chill-down experiments that are conducted on a 12.7 mm outer diameter, 1.25 mm wall thickness and 7 m long stainless steel horizontal pipe with liquid nitrogen (LN_2). The pipe is vacuum insulated during the experiment to minimize the heat leak from room temperature and to enable one to numerically simulate the process easily. The temperature and the pressure profiles of the chill-down line are obtained at the location which is 5.5 m in a distance from the pipe inlet. The mass flux range is approximately from 19 kg/m^2 s to 49 kg/m^2 s, which corresponds to the Reynolds numbers range from 1469 to 5240. The transient histories of temperature, pressure and mass flow rate during the line chill-down process are monitored, and the heat transfer coefficient and the heat flux are computed by an inverse problem solving method. The amplitude of the pressure oscillation and the oscillating period become larger and longer at higher pressure conditions. In the low mass flux conditions, the critical heat flux in horizontal pipes is not sensitive to mass flux, and is higher than that in vertical pipes. Kutateladze's correlation with the constant coefficient, $B = 0.029$, well matches the experimental data in the current work. In nucleate flow boiling regime, heat transfer coefficient, h, is proportional to $(q'')^n$, and n is equal to 0.7.

1. Introduction

Cryogenic liquids such as liquefied natural gas (LNG), liquid oxygen (LOX), liquid nitrogen (LN_2), liquid hydrogen (LH_2), and liquid helium (LHe) are frequently demanded in energy industries as coolants or fuels. Cryogenic fluids are utilized as critical propellants for space launch vehicles due to its high specific impulse and environmentally friendly properties. Transporting cryogenic liquid through pipe line is an indispensable process for undertaking cryogenic mission and establishing a normally operated cryogenic system. In general, a part of transporting liquids are used as the coolant to initially precool the transfer line from a room to the desired cryogenic temperature. It is extremely important to minimize the line chill-down time and the cryogenic propellant consumption during this process. In order to manage the cryogenic line chill-down process and minimize the cryogenic liquid consumption, it is crucial to understand the transient heat transfer mechanism of the process. The physical phenomena during the cryogenic line chill-down are complicated, which are caused by extremely large temperature differences between pipe wall and cryogenic fluid, two-phase flow heat transfer in various flow patterns, and both of pressure and fluid velocity instabilities.

To examine the complex quenching phenomena and predict the line chill-down process, numerous experiments and parametric studies have been carried out so far. In 1969, Steward et al. conducted line chill-down experiments with both of liquid nitrogen and liquid hydrogen. They found that excessively subcooled inlet liquid, long transfer lines, high liquid density, and fast opening of inlet valve can cause or aggravate surging in line chill-down process [1]. In 1995, Krishnamurthy et al. measured the chill-down time under various interspace vacuum levels and supply dewar pressures, and an empirical correlation was developed for predicting the line chill-down time [2]. In 2004, Dresar and Siegwarth discovered that the optimum flow rate exists to minimize the cryogenic liquid consumption with LN2 [3]. In 2007, Kawanami et al. studied the effect of gravity on cryogenic line chill-down process, and concluded that the heat transfer coefficient and the quench front velocity are higher in microgravity condition than that of in 1-g gravity [4]. The experiment was carried out in mass flux from 100 kg/m^2 s to 300 kg/m^2 s. In the same year, Yuan et al. visualized the flow patterns in chill-down process, and the heat transfer characteristics of LN_2 with very low mass fluxes (3.6–10.8 kg/m^2 s) in a horizontal pipe were analyzed based on

---

* Corresponding author.

E-mail addresses: ukeekim@kaist.ac.kr (L. Jin), changgipark@kaist.ac.kr (C. Park), wittycho@kari.re.kr (H. Cho), cheonkyu_lee@kaist.ac.kr (C. Lee), skjeong@kaist.ac.kr (S. Jeong).

http://dx.doi.org/10.1016/j.cryogenics.2016.08.006
0011-2275/

Nomenclature

c_p	specific heat [J/kg K]
d	diameter [m]
G	mass flux [kg/m^2 s]
h	heat transfer coefficient [W/m^2 K]
h_{fg}	latent heat of vaporization [J/kg]
k	thermal conductivity [W/m K]
k_0	thermal conductivity of gas in atmospheric pressure [W/m K]
L	length [m]
L_c	characteristic length [m]
$\dot{m}$	mass flow rate [g/s]
T	temperature [K]
t	time [s]
th	pipe wall thickness [m]
OD	outer diameter [m]
P	pressure [Pa]
p_c	critical pressure [Pa]
$p_{1/2}$	pressure where thermal conductivity of gas becomes half of at atmospheric pressure [Pa]
q''	heat flux [W/m^2]
Re	Reynolds number [–]
r	radius [m]

Greek

α	thermal diffusivity [m^2/s]
ρ	density [kg/m^3]
σ	surface tension [N/m]
σ_B	Stefan-Boltzmann constant [W/m^2 K^4]
ε	emissivity

Subscripts

axial	axial conduction
cond	conduction heat transfer
f	fluid
g	gas
i	inner wall
in	inlet
l	liquid
max	maximum
min	minimum
o	outer wall
out	outlet
rad	radiation heat transfer
s	solid
sat	saturated
v	vapor
w	wall

the observed flow patterns [5]. In 2012, Hu et al. visualized the chill-down process in a vertical pipe, and compared the chill-down characteristics for both of upward and downward flows [6]. Baek et al. conducted a line chill-down experiment with LN_2 in a vertical pipe and numerically analyzed the experimental data to estimate the cool-down time [7]. In 2013, Shaeffer et al. investigated the LN_2 line chill down process in a vertical pipe with pulse flows and continuous flows in Reynolds number range from 2500 to 7000. They suggested that line chill-down by continuous flows with high Reynolds numbers is most efficient [8]. Recently, in 2015, Johnson and Shine experimentally examined the effect of the inclination of the transfer line and the mass flux in the range of 245–375 kg/m^2 s [9]. A numerical simulation method was developed by Darr for chill-down time of liquid nitrogen, which is well agreed with the experimental data obtained in a short, thin, vertical pipe [10]. Hartwig et al. compared the flow boiling heat transfer of LN_2 with that of LH_2 in the chill-down process [11]. Kashani et al. predicted the pressure and temperature dynamics in cryogenic chill-down process for their cryogenic testbed by using high level optimization solvers of SINDA/FLUINT [12]. Luchinskiy et al. developed a hierarchy of two-phase flow models for predicting the cryogenic chilldown [13]. In 2016, Hartwig et al. evaluated in detail the applicability of the existing two phase flow heat transfer coefficient and critical heat flux (CHF) correlations for predicting the cryogenic line chill-down process [14]. They indicated that the developed correlations based on steady state room temperature fluids do not well match the cryogenic chill-down data.

There are lack of precise experimental data for mass flux less than 100 kg/m^2 s in horizontal pipes. For more experimental database and further study of the flow boiling heat transfer characteristics in cryogenic line chill down, the cryogenic line chill-down process is investigated on a 12.7 mm outer diameter, 7 m long horizontal pipe by LN_2 in this research paper. Chill-down data are obtained in averaged mass flux ranges from approximately 19 kg/m^2 s to 49 kg/m^2 s. The physical phenomena are analyzed by the measured data of mass flow rate, pressure and temperature histories. The heat transfer coefficients and heat flux are obtained by solving the inverse heat conduction problem. The CHF, minimum heat flux (MHF) and nucleate boiling heat transfer are analyzed by comparing the experimental data in current work with numerically calculated results and the previous experimental data from other researchers.

2. Experiment

Cryogenic line chill-down process is investigated on a lab-scale 7 m long horizontal pipe. Experiments are conducted under the mass flow rates ranges from 1.5 g/s to 6.0 g/s, which are directly converted to the mass flux from 19 kg/m^2 s to 49 kg/m^2 s. The transient temperatures and pressures during the chill-down process are measured to analyze the transient heat transfer characteristics of the line chill-down process.

2.1. Experimental apparatus

The schematic diagram of the experimental apparatus is illustrated in Fig. 1. It is mainly composed of an LN_2 supply tank, a subcooler, a bypass line and a test section. Liquid nitrogen is supplied by a self-pressurized supply tank, and passes through the mass flow meter ahead of a subcooler. The subcooler is installed in front

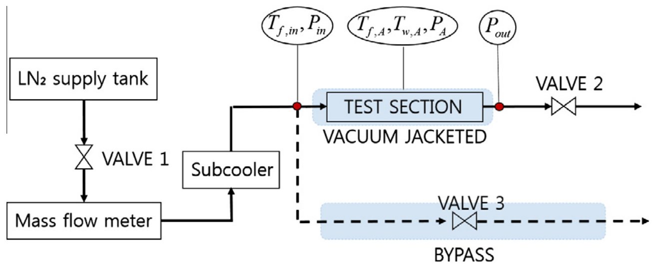


Fig. 1. Schematic diagram of experimental apparatus for cryogenic line chill-down.