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Transient cryogenic chill down process in horizontal and inclined pipes

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ABSTRACT

Experimental results are presented that describe the parametric effects of inclination of transfer line and mass flux on cryogenic chill down process. Experiments were performed in a pressurized liquid nitrogen transfer line made of stainless steel. Fluid and wall temperatures were measured at various axial locations of the test section to monitor the chill down process. The local heat transfer coefficient and heat flux were predicted for the transient chill down period using an inverse heat transfer technique. The results show that the chill down period is characterized by three distinct flow regimes at all mass flux rates. However the variation in chill down time is more predominant at low mass fluxes. Heat transfer coefficient and heat flux calculated using the inverse heat transfer technique further confirmed this and showed that peak heat flux increases with increase of mass flux. It is found that the inclination of the chilling line displayed similar temperature profile but accompanied with variation in chill down time. Results suggest the existence of an optimum upward line inclination minimizing the chill down time.

1. Introduction

Cryogenic liquids are used in many technological applications such as propulsion systems in rockets and missiles, cooling of superconducting magnets and electric motors, and cooling of computer hardware [1]. Transfer of cryogenic fluids to the installations is essential prior to the operation of such systems. Cryogenic liquid transfer is a complex process as it involves two phase flow with phase change, pressure surges and flow reversal during transfer line chill down. The design of such pipelines requires the knowledge of the prevailing flow patterns, pressure drops and heat transfer characteristics during chill down. The pioneering investigations on chill down have led to the development of functional cryogenic transfer systems. However detailed hydrodynamic and heat transfer processes occurring during chill down process are not well understood. An extensive investigation of the flow structure, heat transfer and pressure fluctuations are required to develop a comprehensive understanding of the chill down phenomena. Many researchers have used the term 'quenching' to mark this process. The end of the chill down process is usually characterized by a steady pipe wall temperature and the pipe is cooled enough to be rewetted. During chill down, whole boiling curve can be noticed at each pipe location [2]. Many definitions of rewetting temperature is available in literature such as (i) Leidenfrost temperature, minimum film boiling temperature, (ii) quenching temperature from thermocouple observations, and (iii) temperature at which critical heat flux occurs. The present paper considers the time required to achieve steady pipe wall temperature as the chill down time.

Experimental studies on chill down was initiated in 1960s with the work of Burke et al. [3], Graham [4], Bronson et al. [5], Chi [6], Steward [7] and other researchers. Burke et al. [3] experimentally investigated the chill down in a pressurized horizontal pipe using liquid nitrogen. He was able to predict the existence of single phase convective heat transfer and film boiling based on circumferentially averaged wall temperature profile. Graham [4] studied the chill down phenomena in vertical transfer line using liquid hydrogen at subcritical conditions. He examined the heat transfer and pressure drop characteristics of liquid hydrogen undergoing film boiling during the chill down process. Pressure drop measurements conducted by Graham [4] revealed that the momentum loss was significant compared to frictional loss. However information on flow regimes was absent in the studies performed by Burke et al. [3] and Graham [4]. Visual studies conducted by Bronson et al. [5] on horizontal pipelines dealt with the flow structures present in cryogenic two phase flow of liquid hydrogen. The study highlighted the existence of circumferential temperature variations and the presence of flow stratification. Bronson [5] further suggested that a good correlation exists between two phase flow of hydrogen and Baker's [8] empirical flow regime map for oil–water mixture. Chi and Vetere [6] experimentally investigated the chill down of copper test sections employing liquid hydrogen. This study was primarily focused on identifying flow regime

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Nomenclature

c	specific heat, J kg^{-1} K^{-1}
h	heat transfer coefficient, W m^{-2} K^{-1}
k	thermal conductivity, W m^{-1} K^{-1}
m	mass flux, kg m^{-2} s^{-1}
P	pressure, bar
q''	heat flux, W m^{-2}
r	radial distance, m
T	temperature, K
T^*	non dimensional temperature
t	time, s
t^*	non dimensional time
TF	fluid temperature, K
TS	test section outside temperature, K
z	axial distance from the inlet of the test section, mm
ρ	density, kg m^{-3}
ΔT	wall superheat, °C
θ	angle of inclination, °

Subscripts

f	fluid
in	inside surface
max	maximum
min	minimum
out	outside surface
sat	saturated
w	wall
∞	ambient condition

transitions by correlating visual observations with measured wall temperature. In this experiment, slug flow appeared upon initiating the chill down process, and persisted throughout the chill down period. Later work of Chi [9] focussed on the chill down of aluminum transfer lines using liquid hydrogen. He observed that 90% of cool down time was occupied by film boiling. Chi [9] further suggested that the dominant mechanism of the resulting two phase flow was mist flow rather than slug flow. He stated that the occurrence of predominant mist flow was due to higher heat flux and lower flow rates. The study revealed the existence of various flow regimes such as single phase vapor flow, mist flow, slug flow, annular flow, bubbly flow, and single phase liquid flow. Additionally, boiling regimes of single phase convective boiling, film boiling and nucleate boiling were established. These early experimental studies were focused only on the effects of supply pressure and mass flow rate of cryogen. These investigations provided a fundamental understanding of physical processes and have been useful in the design of chill down systems. It may also be noted that the studies were limited to horizontal and vertical pipes and information of flow structures present in inclined transfer lines is still lacking.

During 1970s, a series of chill down studies were performed on short transfer lines. Srinivasan et al. [10] investigated cool down process in un-insulated and vacuum insulated, short horizontal transfer lines made of glass, copper, aluminum and stainless steel using liquid nitrogen. He stated that the mass flow rate does not affect the chill down time very significantly. However the studies conducted by Chi [9], Krishnamurthy et al. [11], Dresar [12], and Yuan et al. [13] demonstrated that an increase in liquid mass flow resulted decrease in chill down time. The prediction of rewetting temperature is also important in applications such as lighter water reactor (LWR) after a loss of coolant accident. One of the pioneering works in this area is that of Carbajo [14] who proposed a model for the different possible types of reflood in LWRs. Barnea and Elias [15] studied the heat transfer regimes in a heated annular vertical channel with a sub cooled liquid. Volumetric void fraction and quenching front movement as a function of the distance from the quench front was studied in their experiments. Experimental data provided the existence of three major heat transfer zones such as (i) forced convection with sub cooled boiling liquid, (ii) transition boiling phase, and (iii) sub cooled inverted annular film boiling. Dresar et al. [12] conducted experimental studies on heat transfer characteristics and flow regimes of two phase flow of nitrogen and hydrogen. He concluded that at low flow rates, increasing mass flux aided the chill down. He further developed simple liquid consumption models to estimate the optimum flow rate, that would minimize the amount of liquid vaporized during chill down. Parametric effects of transfer line insulation was studied by Krishnamurthy et al. [11] using a demountable transfer line and liquid nitrogen. Cool down time required for transfer lines insulated with multilayer insulation (MLI), coarse vacuum and fine vacuum insulation were studied. Based on the observations, Krishnamurthy et al. [11] proposed an analytical expression for cool down time in terms of interspace vacuum pressure. Velat et al. [16] visualized the entire chill down process for a wide range of mass fluxes. The visual observations captured the transition from film boiling to nucleate boiling, and revealed rewetting front shape. Yuan et al. [13] investigated chill down process of a horizontal tube using liquid nitrogen with mass flux varying from 3.6 kg m^{-2} s^{-1} to 23 kg m^{-2} s^{-1}. Correlating the visual observations with circumferential temperature gradients, he suggested that the liquid filament–wall interaction was the major contributor to the chilling of bottom wall of transfer line. The upper wall of transfer line was quenched by forced convection of superheated vapor.

As cryogenic fluids are widely used for space applications, many researchers have investigated chill down phenomenon under microgravity conditions. Westbye et al. [17] conducted quenching experiments using liquid Freon (R-113) in horizontal stainless tubes in microgravity conditions. He noted that the rewetting velocity was slightly higher in microgravity compared to normal gravity condition and resulted in lower rewetting temperature. The nucleate and transition boiling regimes were observed at lower wall superheats as result of this. Antar and Collins [18] investigated the chill down of liquid nitrogen in vertical pipes in low gravity conditions using quartz and stainless steel tubes for visualizing the flow patterns. However, they did not report any heat transfer characteristics such as heat flux or heat transfer coefficient. Transient chill down process under terrestrial and microgravity conditions have been compared experimentally by Yuan et al. [19]. Film boiling, nucleate boiling and single-phase convection stages where clearly noticed under terrestrial conditions. Stratified flow regimes were absent with microgravity case and the chill down process was axis-symmetric and longer. A numerical two-fluid finite difference model was developed by Yuan et al. [19] also showed similar results. It was noticed that along the axial direction, the gravity effect increases as the two phase flow quality increases. Kawanami et al. [20] observed higher quench front velocity and heat transfer coefficient in microgravity for vertical quenching of a glass tube with liquid nitrogen. Verthier et al. [2] conducted reduced gravity chill down experiments using glass tube and FC72. Results showed decrease in film boiling heat transfer and an increase in chill down temperature under these conditions. Further experiments by Celata [21] under low gravity conditions showed that the mass flow rate of the liquid showed