EXPERIMENTAL INVESTIGATIONS ON THE TRANSIENT CRYOGENIC FLOW FEATURES OF A TYPICAL BALL VALVE UNDER LIQUID NITROGEN CHILLDOWN CONDITIONS

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Abstract **– In this paper, experimental result of cryogenic chilldown of ½" stainless steel cryogenic ball valve is reported. Experiments were done on horizontally placed test section. The test section is insulated by using nitrile rubber for reducing the heat inleak.LN2 is used as the working fluid. Liquid nitrogen is feed in to the test section by using external pressurization technique. Experiments were conducted for two sets of inlet supply pressure (7.5 psi and 12.5 psi).The mass flow rates obtained for two inlet pressures conditions are 2.292 g/s and 3.31 g/s. The experimental results show that the chilldown time of valve body is higher due to its high thermal mass and chilldown time decrease with increase in supply pressure at the inlet.**

Index Terms - Chill down, Cryogenic, Cryogenic ball valve, Liquid nitrogen, Thermal mass.

I.INTRODUCTION

Cryogenic fluids are widely used in many fields, ranging from industrial systems, cryogenic cooling of superconductive systems, cryo-medical systems, micro electromechanical systems, as well as cooling of nuclear systems and metal hardening processes. Space exploration is one of the applications where cryogenic fluids find wide use.

In many of these application the cryogen fluid is introduced in the piping system whose temperature are much higher than the saturation temperature of the working fluid. As a result of this evaporation of the fluid, thermal contraction and significant pressure fluctuation of the system components takes place .The temperature difference will also cause two phase flow through the system .The time required to cool the transfer line /piping system to the saturation temperature of the working fluid or the time required to attain a steady saturated flow of working fluid through the pipeline is known as chill down or cryogenic cool down, and although it was first investigated more than 4 decades ago, very little data are available on the momentum and energy transport during this transient process. Cryogenic chill down have many similarities to boiling curve experiments. But chill down can be said as the inverse process of boiling and can be explained by using the boiling curve.

Cryogenic chill down is encountered in many applications but is of particular importance in space vehicles. For example, in rockets or space shuttle launch facilities, cryogenic propellants fill the internal fuel tanks of a space vehicle through a complex pipeline system. The propellant feed line have to be apriori chilled to the saturation temperature of cryogen with in a minimal time to ensure that required amount of propellant are injected into the engine.

The fluid flow through the pipe line system prior to the turbo pump is controlled through a cryogenic valve, in the present study an experimental investigation of cryogenic chill down of valves are carried out using liquid nitrogen. The Cryogenic valve used here is cryogenic ball valve made up of stainless steel with half inch diameter. Experiments have been conducted on various flow rates. External pressurization technique is used to feed liquid nitrogen to the test section.

Studies on cryogenic chill down started in the 1960's accompanying the development of rocket launching systems. Srinivasan et al.,(1974) investigated cool down process in un-insulated and vacuum insulated, short horizontal transfer lines and s stated that the mass flow rate does not affect the chill down time very significantly for short transfer lines[1]. For the predictions of the heat transfer characteristics of the cryogenic fluids, the empirical correlations derived from the ordinary fluids are usually employed. It was pointed out by Klimenko [2] that several correlations of ordinary fluids not perform well on Steiner's two-phase flow boiling experimental data of LN2 [3]. The evocative thermo physical characteristics of Liquid nitrogen are one of the reasons that it is commonly used cryogenic fluids both in academic research and engineering applications. It is also safe and having low cost which makes it popular in a lot of experimental studies. In opinion of these reasons, liquid nitrogen is chosen as the test fluid for the present experimental research. Investigation on Cryogenic chilldown began in the 1960s with the development of rocket launching systems. Burke et al. [4] experimentally studied the cryogenic chilldown process in a horizontal stainless steel pipe by using LN2 as the quenching fluid and provided the flow regime information in chill down. Bronson et al. (1962) [5] visually studied the flow regimes in a horizontal pipe during chill down with liquid hydrogen as the coolant. The results revealed that the stratified flow is prevalent during the cryogenic chill down.Antar et al., (1993) studied the cool down of a vertical line with liquid nitrogen. Both analytic and numerical models were used to predict the thermo fluid parameters of the cool down process and four distinct flow regions were analyzed[6].V. Krishnamurthy et.al. (1996) conducted experiment on demountable transfer line kept horizontally to study the cool down and mass flow characteristics using liquid nitrogen as the fluid. Experiments were conducted at three different conditions (a) bare line (b) varying the pressure (c) using multi-layer insulation. The result observed were chill down time for bare line is more than that of multilayer insulation and also the chilling time decreases with increase in pressure[7]. Jelliffe Jacson et al., (2005) developed an inverse numerical procedure for predicting the transient heat transfer co efficient for two phase flow. The results obtained from this study is then used to evaluate the performance of various co relations for the heat transfer coefficient in the flow boiling regimes [8]. Yuan et al. (2007) investigated chill down process of a horizontal tube using liquid nitrogen with mass flux varying from 3.6 kg/m2s to 23 kg/m2s. 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 [9]. Hong Hu et al. (2012) conducted experiment on flow pattern and heat transfer during cryogenic chill down in vertical pipe. Cryogenic flow pattern and chilldown rates between upward flow and downward flow in a vertical pipe were compared. Liquid nitrogen is used as the working fluid. Mass flow rate on the flow pattern, heat transfer characteristics and interface movement were determined through experiments performed under several different mass flow rate. Results shows that both mass flow rate and flow direction affected the heat transfer characteristic and the chilldown time for the downward flow is lower than upward flow [10]. Jijo Johnson and S R Shine (2015) studied the transient cryogenic chilldown process in horizontal and inclined pipes. Experiments were performed in a pressurized liquid nitrogen transfer line and fluid and wall temperature were measured at various axial locations of the test section for monitoring the chilldown time. Local heat transfer coefficient and heat flux were predicted using inverse heat transfer technique. Results shows that peak heat flux increases with increase of heat flux and the existence of an optimum upward line inclination decreases the chilldown time [11]. Jeswin Joseph et al., (2015) studied the chilldown of cryogenic turbo pump coolant cavity. A computational model is developed by using the software SINDA/FLUENT to investigate the performance of cryogenic turbo pump bearing coolant cavity. Numerical data is validated with turbo pump chilldown experimental test data. Different analysis were carried out to study the effect of different chill gas flow rate on cavity chill down performance [12] .

II. Experimental Setup

The experiment set up mainly consists of 3 sections. They are Liquid nitrogen storage and supply system, Test section and Instrumentation system. Gaseous nitrogen cylinder, Liquid nitrogen Dewar, Cryogenic control valve, Thermocouples, DAQ, Heater, Flow meter are the different components used in the experimental setup. Cryogenic ball valve is the test section. Liquid Nitrogen is allowed to flow through the pipe at desired pressure and pressure regulators are adjusted to maintain constant inlet pressure throughout the experiment. The test section was insulated by using nitrile rubber for reducing the heat inleak. Experiments were conducted for different mass flow rates (2.292 g/s and 3.32 g/s) corresponding to different inlet pressures (7.5 psi and 12.5 psi). Experiments are done by placing the test section horizontally. Thermocouples are connected on the surface of the test section at different location and temperature measurements were made.

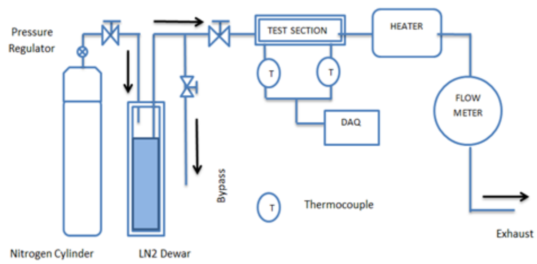

Fig. 1 Schematic diagram of chilldown experiment

A. Test Section

Two ways cryogenic ball valve of half inch diameter made up of stainless steel was used as test section. Stainless steel pipe of 12.7 mm outer diameter and 10 cm length are connected to the inlet and outlet of the ball valve. Ball valve is a valve with a spherical disc, the part of the valve which controls the flow through it. The sphere has a hole, or port, through the middle so that when the port is in line with both ends of the valve, flow will occur. When the valve is closed, the hole is perpendicular to the ends of the valve, and flow is blocked .Ball valve is a quarter-turn valve. The main reason for selecting ball valve as the test section because, ball valves are durable and usually work to achieve perfect shutoff even after years of disuse, hence they are an excellent choice for shutoff applications and are often preferred to globe valves and gate valve for this purpose .In most of the industries ball valves are used in the cryogenic fluid transfer lines.

B. Instrumentation

Wall temperature is the crucial measurement needed for a study in chilldown. They were measured using T-type thermocouples (Copper- Constantan) with a range of -200 degree to 400 degree with an accuracy of 0.5 degree Celsius and were calibrated using constant temperature bath. Thermocouples were placed on the surface of the valve (at three different locations), on the handle of the valve and also placed on the inlet and outlet pipe connected to the valve. At each location, 3 thermocouples were located circumferentially at equal separation distance. Data acquisition system used was Keysight 34972A Data Acquisition / Data Logger Switch Unit. It consists of a 3-slot mainframe with a built-in 6 ½ digit DMM and 8 different switch & control modules. It has built-in LAN and USB interfaces so you can easily connect to a PC or laptop without additional IO cards or converter interfaces. The intuitive graphical Web interface offers easy remote control over the network with per channel measurement configuration, data logging and data monitoring. A USB flash drive may be used to upload data logging configurations from Data Logger into the 34972A and to transfer large data sets back to the computer. Data analysis can be done by importing the data into spreadsheet. A single phase flow meter was employed for measuring the flow rate of the system. In order to ensure that only gaseous nitrogen enters the flow meter the outlet from test section was heated in a constant temperature water bath of 100 degree Celsius.

III. RESULTS AND DISCUSSION

A. Temperature Time Profile of Cryogenic Valve

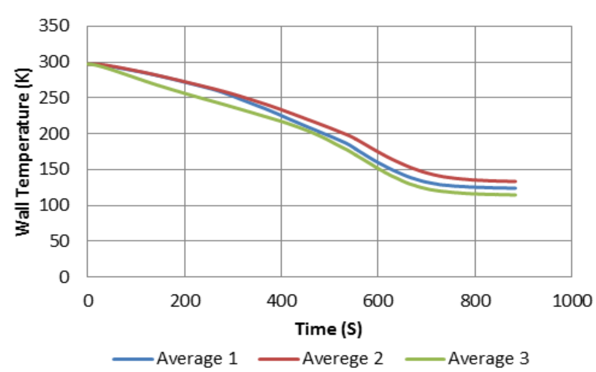

Fig. 2 Temperature time plot for valve body at 7.5 psi

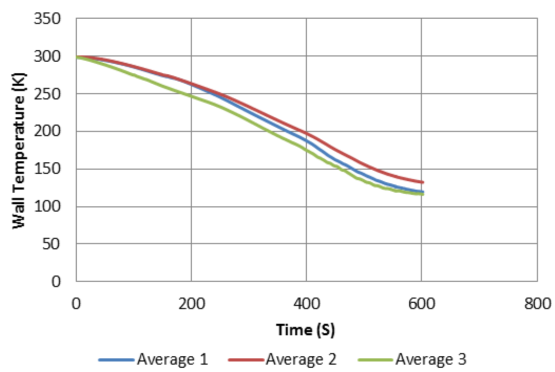

Fig. 3Temperature time plot for valve body at 12.5 psi

Outside surface temperature of the test section measured during chilldown period for different flow rates are shown in the figures below. In this figure 'Average 1' corresponds to average values of temperature readings of 3 thermocouples placed at 106 mm from the inlet. 'Average 2' corresponds to the average value of temperature readings of 3 thermocouples placed at 118.5 mm from the inlet and 'Average 3' correspond to the average value of temperature readings of 3 thermocouples placed at 131mm from the inlet. Fig. 2 represent the temperature time plot for inlet pressure 7.5 psi and Fig. 3 represent the time temperature plot for inlet pressure12.5 psi. The profile contains mainly three regions the region with constant temperature gradient, region with temperature drops suddenly and a constant temperature region. The first region represent the film boiling regime and the flow structure can be inverted annular or stratified flow, the second region represent the transition regime and third one is the nucleate boiling regime ,where either bubbly or slug flow can exist. From this figure we can see that temperature at the middle portion (Average 2) of the valve body is higher .This is due to the complex valve geometry. The average chill down time for 7.5 psi and 12.5 psi inlet pressure are 800 sec and 580 seconds respectively.

B. Temperature Time Profile Of Inlet And Outlet Pipe

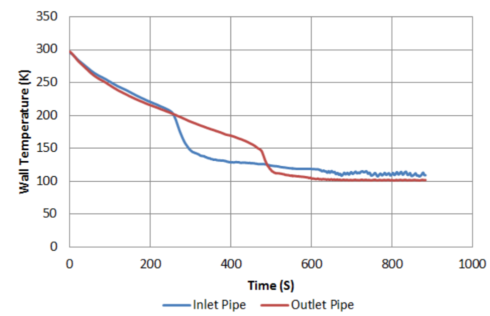

Fig. 4 Temperature time plot for inlet and outlet pipe at 7.5 psi

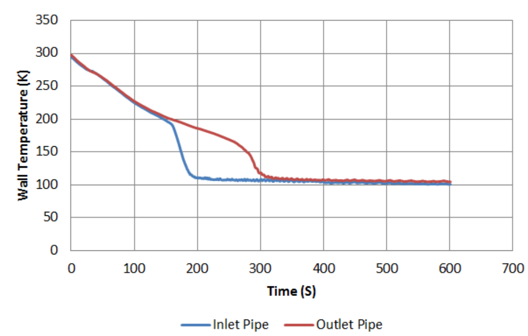

Fig. 5 Temperature time plot for inlet and outlet pipe at 12.5 psi

Figure (4&5) shows the temperature time profile for the inlet and outlet pipes connected at two ends of the cryogenic valve for flow rates 2.292 g/s and 3.32 g/s. In the present study it is observed that for 2.292 g/s the transition temperature for inlet pipe at 71 mm from the inlet was 204.535K with a drop of 69.601K in 90.797sec.The transition temperature of outlet pipe at 161 mm from the inlet was 146.032K with a drop of 33.416K in 34.153 sec. The temperature drop for the outer pipe is lower than that of the inlet pipe. Here temperature at the outlet pipe is lower than that of the inlet pipe. This may be due to the sudden flow convergence occurred at the inlet of outer pipe. For 3.32 g/s the transition temperature for inlet pipe at 71 mm from the inlet was 191.052K with a drop of 80.579 K in 38.372 sec. The transition temperature of outlet pipe at 161 mm from the inlet was 162.911K with a drop of 47.968 K in 40.875 sec. From temperature time plot of outlet pipe it can be observed that when flow rate increases then the transition from film boiling to the nucleate boiling occurs at the higher wall temperature. Film boiling is one of the major reasons for increasing the chilldown time.

C. Over All Temperature Time Plot For The Test Section

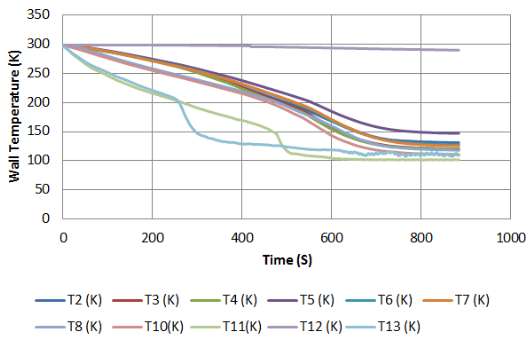

Fig. 6 Temperature time plot for the complete test section at 7.5 psi

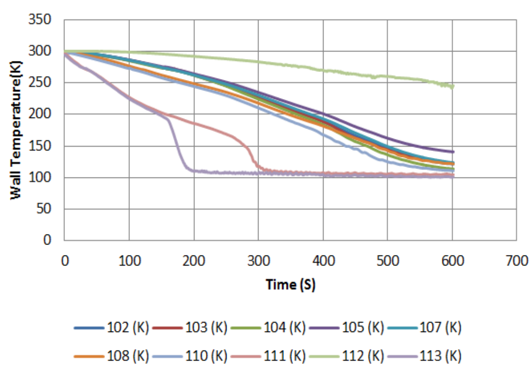

Fig. 7 Temperature time plot for the complete test section at 12.5 psi

Figures (6&7) show the overall temperature time profile for the test section. From these two figures we can see that there is no reasonable change in the valve handle temperature. The reason for this is that valve handle is made up of galvanized iron coating for reducing the conduction in to the valve body. Then another main observation from these figures is that the inlet and outlet pipe chilled before the valve body. The reason for slower valve body chill down is due to the higher thermal mass of the valve body.

D. Heat transfer coefficient and critical heat flux evaluation

In chilldown studies heat flux and heat transfer coefficients are of particular interest. However in the present study inner wall temperature measurement were the only measurement. In the similar studies conducted of other researchers use Burggraf Correlations. By using Burggraf Correlation inner wall heat flux can be calculated.

$$q_i'' = \rho c\left(\frac{r_i^2 - r_0^2}{2r_i}\right)\frac{dT_0}{dt} + \left(\frac{(\rho c)^2}{k}\left(\frac{r_i^3}{16} - \frac{r_0^4}{16r_i} - \frac{r_0^2 r_i}{4}\ln\frac{r_i}{r_0}\right)\right)\frac{d^2T_0}{dt^2} + \frac{(\rho c)^3}{k^2}\left(\frac{r_i^5}{384} - \frac{3r_0^4 r_i}{128} + \frac{3r_0^2 r_i^3}{128} - \frac{r_0^6}{384r_i} - \frac{r_0^2 r_i^3}{32}\ln\frac{r_i}{r_0} - \frac{r_0^4 r_i}{32}\ln\frac{r_i}{r_0}\right)\frac{d^3T_0}{dt^3}$$

+..............(1)

Heat transfer coefficient can be found using the equation

$$h_i = \frac{q''}{(T_i - T_{sat})} \qquad (2)$$

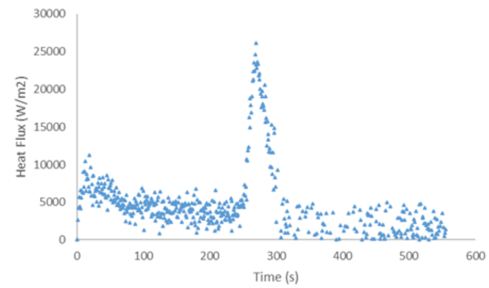

Fig.8 Variation of heat flux

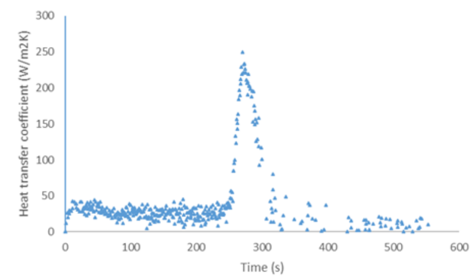

Fig. 9 Local heat transfer coefficient along the bottom side of axial length

Critical heat flux represents maximum heat flux for the nucleate boiling regime and for a chilldown curve, it represents the onset of nucleate boiling. In the present study it was found that the critical heat varies with the axial length as well as along the upper and lower side of the valve. Variation in critical flux and heat transfer coefficient with time is shown in Fig.8 and Fig. 9. Initially the heat flux decreases due to the transient effect and then attains a minimum value, q"min. The minimum heat flux point, also known as Leidenfrost temperature, is the point where liquid begins to rewet the bottom wall. Before the Leidenfrost temperature, the boiling regime is film boiling regime. The transition boiling regime begins after Leidenfrost temperature with a sharp increase in the heat flux. The maximum heat flux describes onset of the nucleate boiling. The maximum heat flux point is Critical heat flux. The curve is similar to boiling curve in pool boiling conditions. In the present study it was found that the critical heat flux varies with the axial length as well as along the upper and lower side of the valve. From the figures it can be seen that for a constant HTC, the heat flux decreases in film boiling regime due to the reduction in wall superheat (Ti – Tsat). A critical heat flux of 26 kW/m2, was obtained for a peak HTC 270 W/ m2K.

IV. Conclusion

This paper present the experimental results obtained during transient chilldown process of cryogenic valve associated with liquid nitrogen. The experiments were conducted for different inlet pressure conditions (7.5 psi and 12.5 psi).Temperature were measured at different locations. The flow rate obtained was 2.29 g/s and 3.31 g/s. Heat flux and local heat transfer coefficient along the bottom side of axial length of valve were obtained using Bugraff Correlation. It was found that the critical heat flux varies with the axial length as well as along the upper and lower side of the valve The average chilldown time for 7.5 psi and 12.5 psi are 800 sec and 580 sec respectively. The time taken for valve body chill down is higher compared to inlet and outlet pipe this is due to the high thermal mass of the valve body.

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