Experimental and Computational Investigations on two phase flow throughcryogenic ball valve using liquid nitrogen

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Abstract: In this paper cryogenic two phase flow experiments were conducted on a ½" stainless steel cryogenic ball valve which is provided with poly-isocyanurate foam insulation. LN2 is used as the working fluid and is fed to the test section by the method of external pressurization. Experiments were conducted for three mass flow rates 2.29 g/s, 2.71 g/s and 3.31 g/s. The experimental result shows that the chill-down time of valve body is higher due to its high thermal mass and chill-down time decreases with increase in mass flow rate. The experimental results were compared with CFD analysis. The flow is assumed to be unsteady with multiphase characteristics. The fluid properties are constant. The valve geometry is designed by using Solid works. Then the fluid domain is created by importing the valve geometry to the Design Modeller of ANSYS FLUENT. Meshing of the geometry is created by using ANSYS Mesh software. The measured wall temperature werecompared with the wall temperature obtained from the analysis.

Index terms: Chill-down, Cryogenic ball valve, CFD, LN2, Two phase flow.

1 INTRODUCTION

When cryogenic liquids are introduced into the warm transfer line, sudden boiling of the liquid takes place and it will results in a two phase flow. The process of cooling the transfer line wall to the temperature of cryogen is known as chill-down or cool down. When compared with the past history, the use of cryogenic fluids has increased now a days. They are used in industrial systems, food processing industries, cryo-medical systems, magnetic resonance imaging (MRI) techniques, for the cooling of superconducting magnets, and for the transmission of power through cables in big cities. In the present scenario, cryogenic fluids are predominantly used for the space exploration. It includes application such as propellants for space engines, thermal management and can be used for the cooling purpose. Cryogenic propellants are commonly stored in liquid form due to its high weight per volume ratio and it will also result in the weight reduction of the space craft. When compared with other propellants used for space mission, cryogenic fluids are more energetic, economic and ecofriendly.

For designing the delivery system for the propellant, proper understanding of the two phase flow of cryogen is required. The quantity of cryogen vaporized and the time required for the complete chill-down of the system are the prime factors considered during chill-down study. In space launch vehicles propellant is filled to the fuel tank by using complex transfer lines. So these transfer lines should be prior chilled to the saturation temperature of the cryogen to avoid the entryof evaporatedvapour in to the engine. If the transfer line is not chilled properly then the liquid propellant undergoes boiling and as a result, proper mixture ratio cannot be obtained. Even marginal under performance during the chill-down will increase the amount of vapour content in the propellant and it will harm the components of the rocket engine or may fail the mission itself. The main objective of two phase flow study is to obtain maximum chilling effect with minimum consumption of cryogen. So the basic requirement of a cryogenic propulsion system requires the finding of ideal mass flow rate required for the complete chill-down of the system with minimum expense of cryogenic fuel. In the present study an experimental investigation of cryogenic chill-down of standard port cryogenic valve is carried out by using liquid nitrogen. Experiments have been conducted on various orientation and mass flow rate.

2 LITERATURE REVIEW

Studies on cryogenic chill-down started in the 1960's accompanying the development of rocket launching systems. Early experimental chill-down studies were conducted by Burke et al,Graham, Bronson et al., Chi, Vetere[1-6] and by other researches. Burke et al.[1]conducted two phase flow experiments with liquid nitrogen and identified the existence of film boiling and single phase convective heat transfer. In 1965 Chi et.al.[4]conductedtwo phase flow experiments withaluminium transfer line and from the observations he stated that 90% of chill-down time was occupied by film boiling.Srinivasan et al.[6] investigated cool down process in un-insulated and vacuum insulated, short horizontal transfer lines made of glass, copper, aluminium and stainless steel using liquid nitrogen and observed that the mass flow rate does not affect the chill-down time very significantly for short transfer lines. M. V Krishnamurthy et.al. [7], in 1996 conducted experiment on horizontal transfer lines using liquid nitrogen. He studied the parametric effect of transfer line insulations. JelliffeJacsonet. al. [8] in 2005,developed an inverse numerical procedure for predicting the transient heat transfer co efficient for two phase flow. He evaluated the performance of various correlations for the heat transfer coefficient in the flow boiling regimes.By varying the mass flux from 3.6 kg/m2s to 23 kg/m2s, Yuan K et al. [9] (2007) investigated the two phase flow in a horizontal tube using liquid nitrogen. The visual observations were correlatedwith the circumferential temperature gradients and 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 vapour. Yuan K et al. [10], (2009) provided a procedure for the numerical modelling of cryogenic chill-down process in terrestrial gravity and microgravity condition for a vertical transfer line. Single phase vapour region, dispersed flow region, inverted annular flow region and the single phase liquid region are the different flow regions covered during the flow. Different heat transfer mechanism is used for different regimes. Inverted annular flow regime and the dispersed flow regime were analysed by using a two fluid model and the effect of gravity on the two phase flow were also analysed. Results shows that the effect of gravity along the axial direction increases as the two phase quality increases. Shaeffer R et. al. [11] (2013), investigated the LN2 line chill-down process in a vertical pipe with pulse and continuous flows with theReynolds number ranging from 2500 to 7000.In this paper he introduced a new terminology chill-down efficiency for finding an optimum strategy. Jijo Johnson and S R Shine [12] (2015) studied the transient cryogenic chill-down process in horizontal and inclined pipes. They predicted the values of local heat transfer coefficient and heat flux using an inverse heat transfer technique. Results shows that peak heat flux increases with increase of mass flux and the existence of an optimum upward line inclination decreases the chill-down time. Darr et al.[13], (2016) published a two-part series of papers which discusses the experimental results of a parametric effects of mass flux, inlet subcooling, equilibrium quality, pressure and flow direction with respect to gravity in liquid nitrogen chill-down tests of a stainless steel tube. Based on the observations, they developed a correlation to predict the heat transfer coefficients for the cryogenic two phase flow inside a straight transfer line. The correlation obtained is useful for the numerical simulation of cryogenic chill-down for predicting the propellant consumption and chill-down time for different system variables. Most of the experimental studies till date focused on the chill-down time requirements and transient flow structure encountered for transfer lines. The parametric effect of supply pressure and the feed line insulation were studied in the past research. However extensive studies that investigate the effect of mass flow rate, flow orientationin the two phase fow throughcryogenic valves are not conducted till date. More insight in this studies can leads to cryogen saving and hence results in the development of energy efficient transfer line system design.

3 EXPERIMENTAL SETUP

The schematic of the cryogenic two phase flow experimental set up is shown in the Fig.1. The experiment set up mainly consist of 3 sections. They are, Liquid nitrogen storage and supply system, test section, Instrumentation and Data acquisition system. Different components used in these sections are, Gaseous nitrogen cylinder, Liquid nitrogen Dewar, Cryogenic control valve, Thermocouples, DAQ, Heaters and Mass Flow meter. 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. Thermocouples are connected on the surface of valve at different locations and temperature measurements are made.

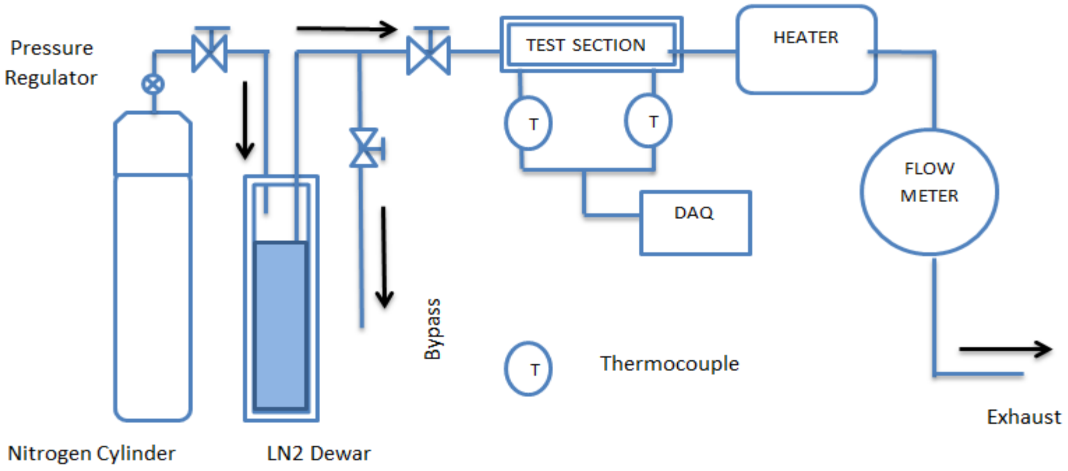

Fig.1. Schematic of Two phase flow experiment set up.

The test section used for the experiment is standard port cryogenic ball wall of half inch diameter made up of stainless steel. 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. The test section was insulated by using urethane modified poly-isocynurate foam insulation (thermal conductivity of 0.14 W/mK). Wall temperature of the test section were measured with T-type thermocouples (Copper-Constantan) connected at different axial locations. A single phase flow meter was employed for measuring the flow rate of the system. A volume flow meter was employed for this purpose. 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.

3.1 Experimentprocedure

Prior to the experimentation, entire test section was purged with gaseous nitrogen to avoid moisture condensation inside the tube. The data acquisition program was initiated to record data as soon as triggered. The gaseous nitrogen tank was connected to the liquid nitrogen Dewar. The required supply pressure was obtained by regulating the pressure regulator connected to the gaseous nitrogen cylinder.The lines before the test section were allowed to chill prior to the beginning of the experiment and the vapour generated were vented to the atmosphere via bypass line. Then the flow toward bypass line is closed and the flow is introduced to the test section, by that time the DAQ should also started for recording various thermocouple readings.Liquid nitrogen was allowed to flow through the test section until all the thermocouples that connected to the test section read a steady value corresponding to the saturation temperature of liquid nitrogen. By that time we can conclude that chill-down process was completed.Wall temperature and Flow rate and supply pressure were recorded.The above steps were repeated with the different supply pressures and at various flow direction so that a wide parameter range may be investigated.

4RESULTS AND DISCUSSION

Experiments were conducted for three different orientations such as horizontal, verticallydownwards, and vertically upwards.For each orientation experiments were conducted for three different mass flow rate (2.29 g/s, 2.71g/s and 3.31g/s).

4.1 Time temperature profile

Figure 2 shows the time temperature profile obtained from experiment conducted by horizontally placed test section for a mass flow rate of 2.29 g/s. Thermocouples were connected on the surface of the valve at three different location such as 106 mm, 118.5 mm,and 131 mm from the inlet. At each location three thermocouples were connected at 120 degree apart. The temperature time plot obtained from the thermocouple connected on the surface of the valve body also shows three region. They are a region with constant temperature gradient, region with temperature drops gradually and constant temperature region. The first region mainly represent the film boiling region 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 the figure it can be inferred that the time required to cover film boiling region is more for the valve body. Time covered during transition is less compared to film boiling and once attaining transition the entire system will chill-down quickly. One of the main reason for the slow chill-down of valve body is due to the presence of the longer film boiling regime (more than 95%) this is in agreement with the published results [10].

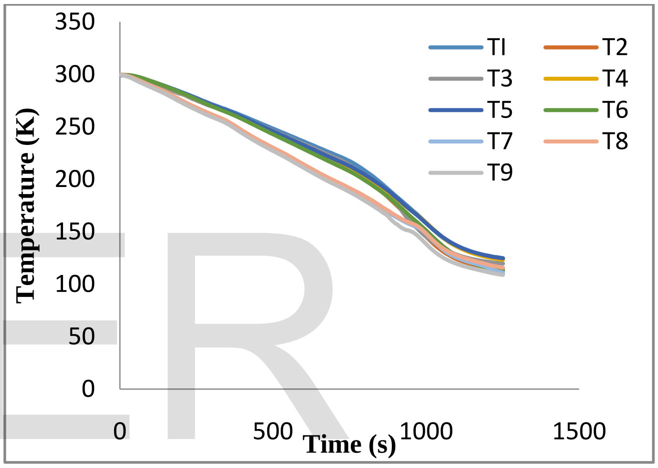

Fig. 2. Wall temperature time profile for 2.29g/s for horizontal flow.

4.2Comparison of Different orientations

Figure 3 shows the comparison of the time temperature plot obtained from experiments conducted for three different orientations for a mass flow rate of 3.31 g/s. From the fig.3., it is evident that the time taken for horizontal test section to attain chill-down is higher as compared to the other two orientations. This is because for the horizontal test section the film boiling regime will remain longer compared to the other two orientation of the test section. Another main observation from the figure is chill-down time for upward orientation of the test section is very much lower. This is because during the upward orientation buoyance assisted convection of the vapour phase will occurs and reduces the chill-downtime. In the case of downward orientation of the test section the buoyance force is fighting back and it is reducing the vapour phase velocity. This result shows close agreement with published results [13].

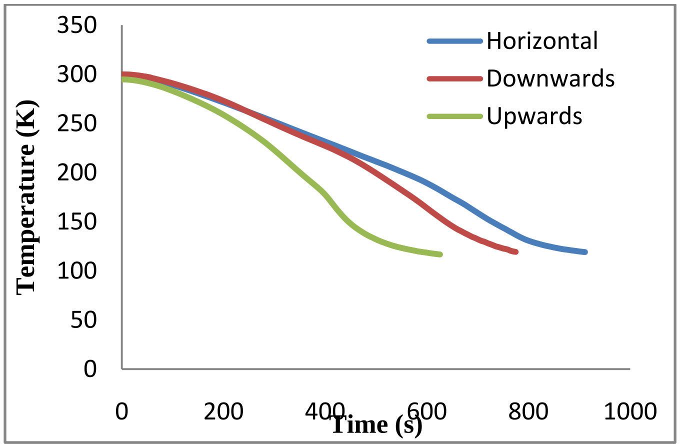

Fig. 3. Time temperature profile for three different orientation at 3.31 g/s.

4.3Comparison ofchill-down for different orientation

Figure 4 shows the variation of chill-down time with mass flow rate for horizontal, upward and downward orientation of the test section. This figure reveals that for all the three orientation, the chill-down time decreases with increase in mass flow rate. Another observation is for all the mass flow rate chill-down time is lower for upward orientation. Lower chill-down time also indicated that it requires less amount of cryogen for the chill-down process. That is the consumption of cryogen can be reduced if the orientation of the test section is vertically upward and there by the energy can be saved.

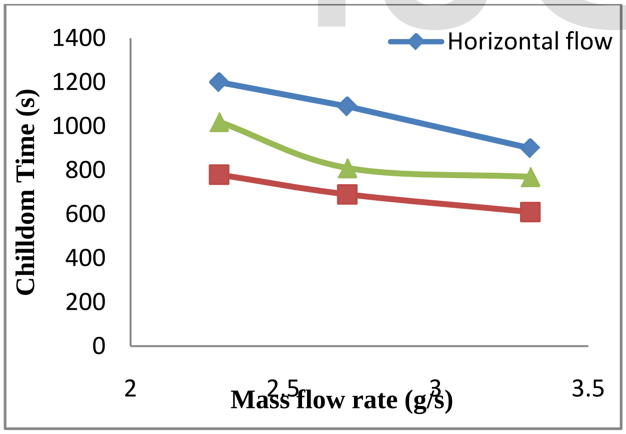

Fig. 4. Comparison of chill-down time with mass flow rate for different orientation.

At the mass flow rate of 2.29 g/s, for the vertically upward orientation, the chill-down time can be reduced to 35 % and 23.53 % when compared with horizontal and vertically downwards orientation. Similar results were obtained for the other two mass flow rates of 2.71 g/s and 3.31 g/s.

5CFD ANALYSIS

CFD analysis has been carried out to study chill-down time requirement of ball valve. The flow is assumed to be at unsteady state with multiphase characteristics. The fluid properties are constant. The valve geometry is designed by using Solid works. Then the fluid domain is created by importing the valve geometry to the Design Modeller of ANSYS FLUENT. Meshing of the geometry is created by using ANSYS Mesh software. Meshing is done with relevance center as fine and smoothing of high is provided. Velocity inlet is given as the inlet boundary condition and fluid temperature of 77.35 is assumed at the inlet that is fully saturated liquid nitrogen. The outlet boundary condition is taken as the pressure outlet and it is assumed to be the ambient atmospheric pressure condition. The wall heat flux is assumed as 350 W/m² . The turbulent intensity and hydraulic diameters provided are 4% and 0.005m respectively. The analysis part is carried by using ANSYS 14.5.Multiphase mixture model is used for the analysis.

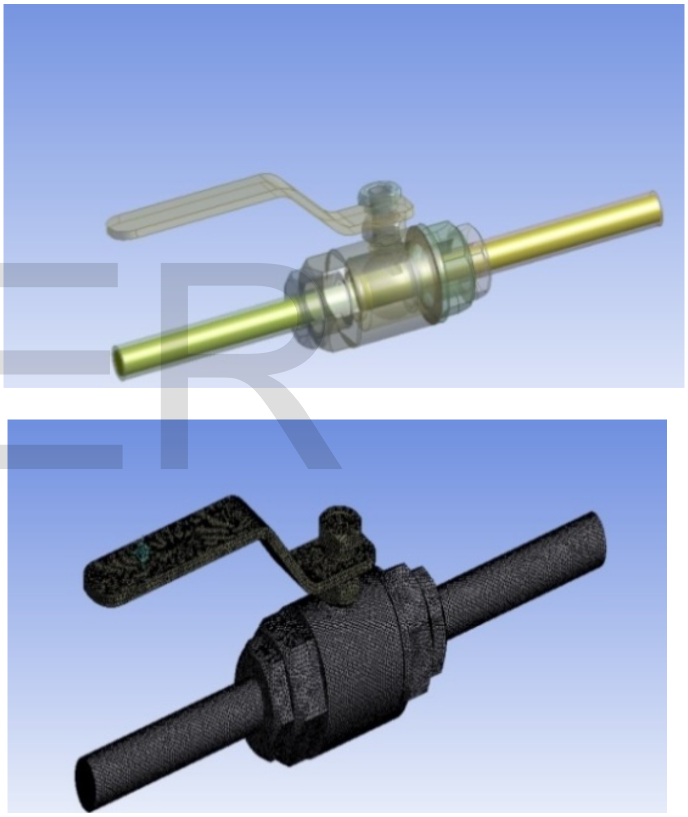

Fig.5. Meshed model of Valve geometry.

Two phase of nitrogen such as liquid and gaseous is also defined and the liquid nitrogen and gaseous nitrogen properties at the saturation temperature is given as the input conditions. Pressure based numerical solver is selected and the flow is considered to be turbulent and unsteady. Viscous model used here is K-epsilon model. All the walls are considered as stationary. The problem is defined as an unsteady problem so it is considered that the conditions will vary with time. Hybrid initialization is used for the initialization. Temperature of 300 K is patched to both solid and fluid domain. The volume fraction of gaseous nitrogen is patched to 1 that is the simulation is started by assuming the interior of the valve is initially filled with gaseous nitrogen. The analysis is done at a time step of 1 second.Figure 5 shows the meshed model ofvalve geometry.

5.1 Statictemperature contours at 2.29g/s

The temperature distribution of the ball valve at the mid plane fortime10 s (mass flow rate 2.29 g/s) is shown in Fig.7 (a). The temperature variation is occurred only at the inlet of the pipe. The outlet pipe and valve is still at the ambient condition. When the time proceeds, more and more liquid will flow through the test section and the wall temperature of the test section decreases.

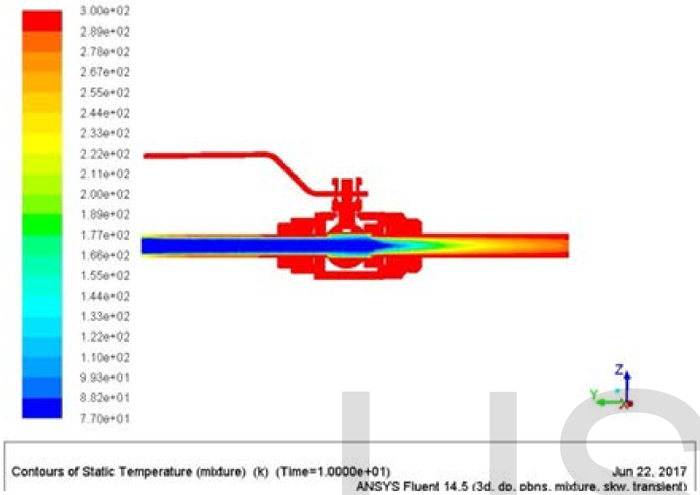

Fig.6. (a) Contour of static temperature at 10 sec.

Figure 6(a)-(d) describes the variation in static temperature for different time. From Fig.6. (c), it is clear thatat time 300s, the valve body attains a steady state temperature of 222 K, while reaching 600 s, the valve body is again cool down to 188 K.

5.2 Contours of volume fraction (liquid) at 2.29 g/s

At the start of the analysis only liquid phase is present near the inlet of the test section rest of the test section contain completely vapour. When the flow proceeds more and more liquid flow through the pipe. One main observation from these figures are there is always some vapour quantity present at the sections near to the outlet.

The Figure 7(a)-(b) shows the contours of volume fraction of liquid at different time for the mass flow rate condition 2.29 g/s.

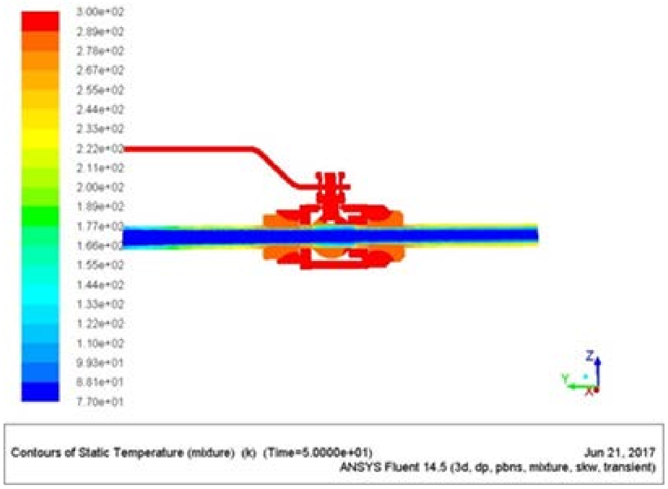

Fig. 6. (b) Contour of static temperature at 50 sec**.**

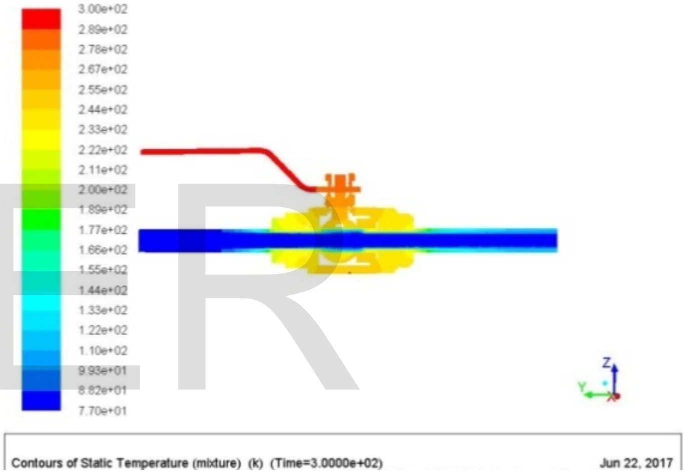

Fig.6. (c) Contour of static temperature at 300 sec

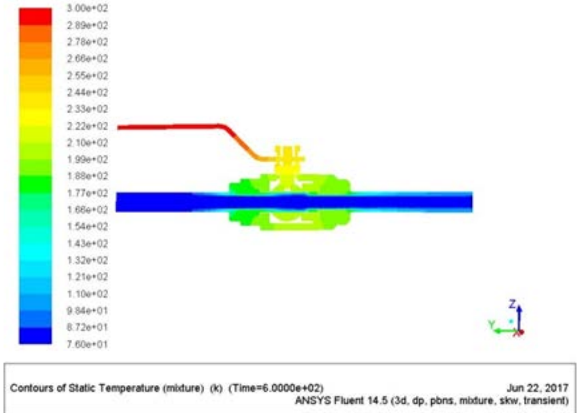

Fig.6. (d) Contour of static temperature at 600 sec.

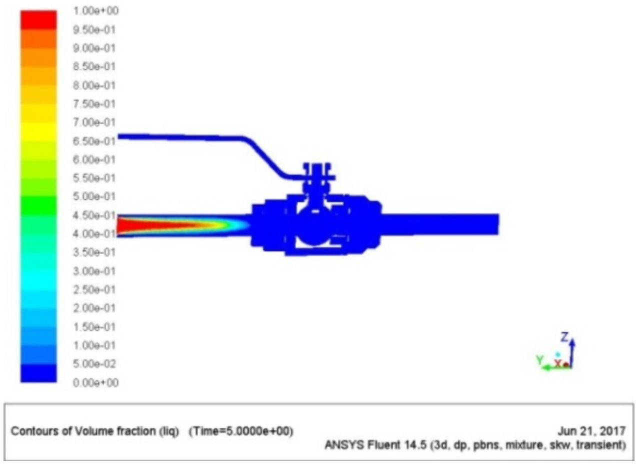

Fig.7. (a) Contour of volume fraction of liquid at 15 sec.

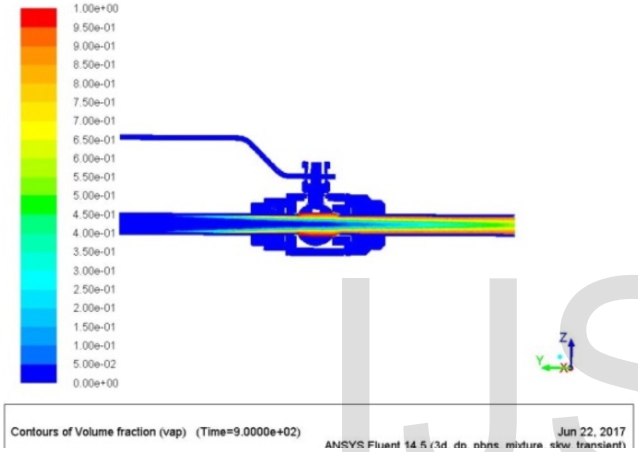

Fig.7. (b) Contour of volume fraction liquid at 900 sec.

5.3Comparison of Experimental and CFD results at 3.31 g/s

Figure 8shows the comparison of experimental and predicted wall temperature of the test section for a mass flow rate of 3.31 g/s. Experimental and computational value has close agreement up to 100 sections after that point the experimental value over predicts the computational value.

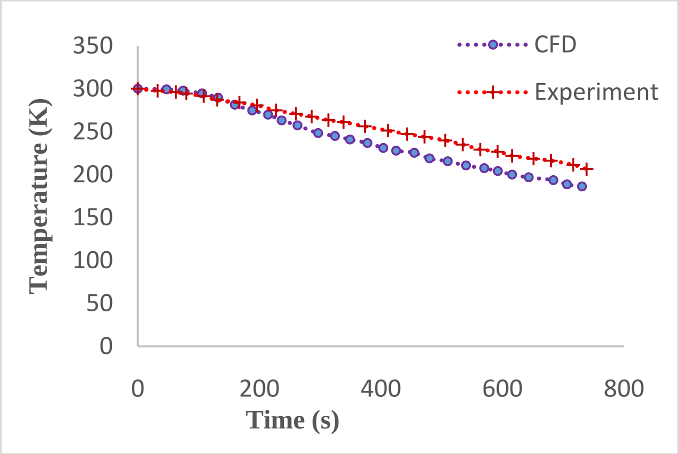

Fig.8. Comparison of experimental and CFD results.

6 CONCLUSION

The parametric effects of mass flow rate and flow direction on the chill-down time requirement in a standard port cryogenic ball valve was investigated. Experiments were done at various mass flow rate and found that chill-down time decreases with increase in mass flow rate. Effect of flow direction on the chill-down time reveals that the chill-down is lower for the upward flow orientation. Experimental and computational studies were performed to study the two phase characteristic in a cryogenic ball valve. ACFD model for studying the two phase flow characteristicsthrough the ball valve was modelled. Then the wall temperature measure and the wall temperature obtained from the analysis were compared

FUTURE WORK

The current study mainly based on the low mass flow rate conditions but many applications uses high mass flow rate condition thus high mass flow rate conditions has to be studied. Many literatures states that there may be an optimum mass flow rate for a particular flow for complete chill-down of the system with minimum expense of cryogenic fuel. This has to be discovered. The effect of various insulation on chill-down time requirement can also be studied.

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