Studies to Investigate the Effect of Feed Line Orientation on Chill-Down Performance of Cryogenic Feed Lines

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Abstract

In Cryogenic Systems, chilldown of transfer or feed lines to a temperature very close to that of the cryogen is to be achieved first prior to its admission at rated flow rate for steady state operation and this is achieved by admitting the cryogen at a low flow rate. This chilldown process is very complex and is highly sensitive to parameters like feed line orientation, distribution of thermal mass associated with the system, mass flux of the cryogen, heat in-leak etc. In the present study, experiments are conceived to address the influence of feed line orientation on chilldown performance. A set-up is realised employing a foam insulated test section and experiments are conducted using Liquid Nitrogen. Tests are performed in horizontal and different upward as well as downward orientation. Chill down performance is analysed using the measured surface temperature data. It is observed to be very sensitive to feed line orientation, faster with upward inclination and slower with downward orientation. Wall heat flux is estimated using experimental data and heat flux pattern for different feed line orientation is studied. Heat flux pattern at bottom locations is observed to be not affected significantly by feed line orientation. Whereas heat flux pattern at top locations is distinctly different in tests with upward orientation. CFD simulation is also done, as a typical case, for 45° downward inclination, using ANSYS software to capture the flow pattern and wall temperature profile. Flow structure is well captured and very good match is seen with the experimental data for the bottom wall temperature profile.

Keywords: *chilldown, inverse heat transfer technique, minimum heat flux, critical heat flux, feed line orientation.*

1. Introduction

In Cryogenic systems, feed or transfer line chilldown, is an important pre-requisite, to be achieved prior to admission of cryogen at rated condition. Time required to complete this chilldown, which is defined as “Chilldown time” is very strongly influenced by parameters like mass flux of cryogen, feed line orientation, its thermal mass, heat in-leak etc and an attempt is made here to study experimentally the effect of feed line orientation on chilldown performance.

Chilldown performance of cryogenic transfer lines has been a topic of extensive research for the last several decades since 1960s. JC Burke et al. [1] carried out experiments with horizontally held long transfer lines using Liquid Nitrogen (LN_2) to evaluate the chilldown time. Experiments were carried out by K Srinivasan et al. [2] and Durga Prasad et al. [3] with LN_2 using insulated short length test sections. It was concluded that for short transfer lines, contribution from forced convection is not significant. Experiments were performed by Jelliffee Jackson [4] to evaluate the chilldown time and heat transfer coefficient at the wall for different mass flux conditions. Chilldown time was reported to be less with higher mass flux. Influence of feed line orientation and mass flux on chilldown performance was studied by Jijo Johnson et al. [5]. Chilldown performance was reported to be improving upto 10° upward inclination and inferior for 15° upward inclination. Jesna Mohammmed et al. [6] studied the influence of mass flux on chilldown time and chilldown efficiency by conducting experiments with LN_2. Mass flux was reported to having a significant influence on the chill-down time and efficiency. Lingxue Jin et al. [7, 8] performed experiments using a stainless-steel test section with LAr, LOX and LN_2. Chilldown time was reported to be less with LN_2 compared to LAr.

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Influence of test section orientation on chilldown behaviour was studied extensively by SR Darr et al. [9,10] . Apart from horizontal and vertical directions, tests were done for different upward, and downward inclination (15°, 30°, 45° and 60 °) Chilldown was reported to be slower with downward inclination of test section compared to horizontal and faster with upward inclination. Jason Hartwig et al. [11] conducted experiments with LOX and Liquid Methane using 25.4mm and 114.3mm diameter lines. Stratification was not observed in smaller diameter transfer line, whereas in tests with larger diameter line, stratification and large temperature gradients were reported between top and bottom measurements. Venkatesh N et al. [12] conducted experiments with a SS test section of 30mm inner diameter, 1mm wall thickness and 2m length, with LN_2 as test medium to study the influence of feed line orientation and mass flux on chilldown performance. Wall temperature profile and heat flux pattern for different test section orientation were compared and certain findings with respect to influence of feed line orientation on chilldown performance were broughtout. Certain observations with respect to influence of feed line orientation on critical and minimum heat flux values were also reported.

As can be seen from available literature, only limited experiments are done to visualise and understand the flow structure prevailing during chilldown. Further, studies to understand the influence of feed line orientation are scarce. It is in this context that in the present work, experiments are devised to study the influence of feed line orientation on chilldown performance.

In the present study, experiments are conducted to study the influence of feed line orientation, with test section held at different upward and downward inclination upto 45° with respect to horizontal. Apart from this, CFD analysis using ANSYS is also done for 45° downward orientation and results are compared with experimental data. Details of the test set-up, experiments carried out, results and findings of the present study are covered in the subsequent sections.

2. Experimental Study

A test set up is conceived with the required measurements and realised to conduct experiments and understand the influence of feed line orientation on chilldown performance. Details of the experimental set-up, measurements made, test procedure, test matrix etc. are covered in the subsequent sections.

2.1 *Test Setup*

A photograph of the set up employed is shown in Figure 1. The set-up consists of stainless-steel test section of 39mm inner diameter, and 1.5mm wall thickness, and 2 m length provided with 28 mm thick polyisocynurate foam insulation. During tests, LN_2 is fed to the test section from a 380 litres dewar and a calibrated orifice of diameter 2.73 mm provided at the inlet to test section is used to control the LN_2 flow rate to the test section. A 50 litre GN2 cylinder and a pressure regulator are used to pressurize the dewar and maintain the required pressure at test section inlet during the experiments. In tests with varying feed line orientation, desired orientation of test section is achieved using a pre-formed spool piece of approximately 100mm length provided at the inlet to the test section.

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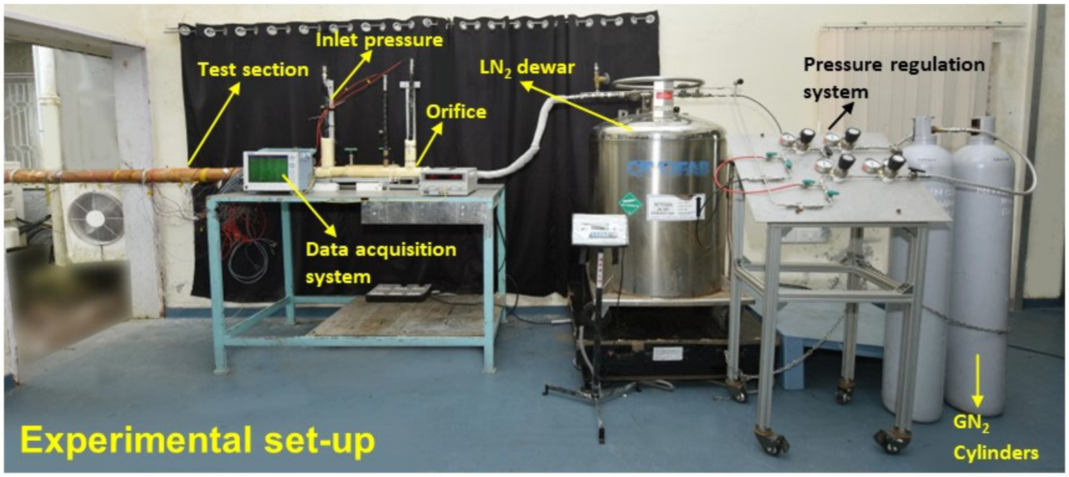

Figure 1: Photograph of test set-up

2.2 *TEST INSTRUMENTATION*

A schematic showing the details of test instrumentation is shown in Figure 2. The experimental set-up is instrumented with three pressure sensors (P1, P2 and P3), two RTDs and 8 thermocouples. Pressure sensors are of strain gauge type, 0-5bar range and have an accuracy ±0.7% of the full-scale reading. Sensor P1 measures the orifice inlet pressure, P2 the orifice outlet pressure and pressure at inlet to the test section is measured using P3. Thermocouples, 2nos. each are provided at 4 stations along the length of test section to measure the test section outer wall temperature. They are of T type and have an accuracy of ±~1.5K for the measured temperature range. Two 100Ω Platinum RTDs (TF1 and TF2) are used to measure the fluid temperature at two stations.

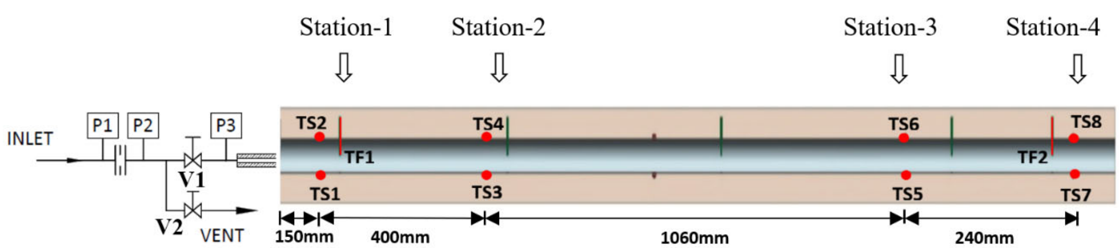

Figure 2: Instrumentation schematic for tests with varying feed line orientation

Temperature and pressure values read by these sensors are acquired using a `Yokogawa' data logger with a sampling rate of 1Hz.

2.3 *TEST MATRIX*

Nineteen tests are performed with an inlet pressure of 0.35MPa (Abs) for different test section upward and downward orientation upto 45^o with respect to horizontal and mass flux simulated during the experiments is 60 kg/m^2-s. Experiments are repeated for selected orientations to confirm repeatability.

3. EXPERIMENTAL RESULTS AND DISCUSSION

A set of nineteen experiments are carried out covering a test section orientation of horizontal position, and upward, and downward inclination of 10^o, 20^o, 30^o, and 45^o with respect to

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horizontal. Wall temperature data measured during the experiments and inner wall heat flux values estimated by inverse heat flux technique are analysed in detail to understand the pattern of their variation with respect to feed line orientation. Most of the observations are in line with the ones reported by Venkatesh N et al. [12] based on experiments performed with test section of 30mm inner diameter. Salient findings of the present study are broughtout in the subsequent sections.

3.1 *WALL TEMPERATURE PROFILE*

In tests with horizontal and downward inclination, the bottom wall temperature profile shows signature of all the three boiling regimes as in pool boiling, whereas top region is cooled only by vapour. In tests with upward inclination, pattern observed in surface temperature measurement at bottom location is almost similar to tests with horizontal and downward inclination. Whereas temperature profile of top location is significantly different and shows signature of liquid wetting. The observations reported above are clearly reflected in Figure-3, wherein as a typical case, the temperature profile observed in tests with horizontal position, 45^o downward and 45^o upward orientation are shown.

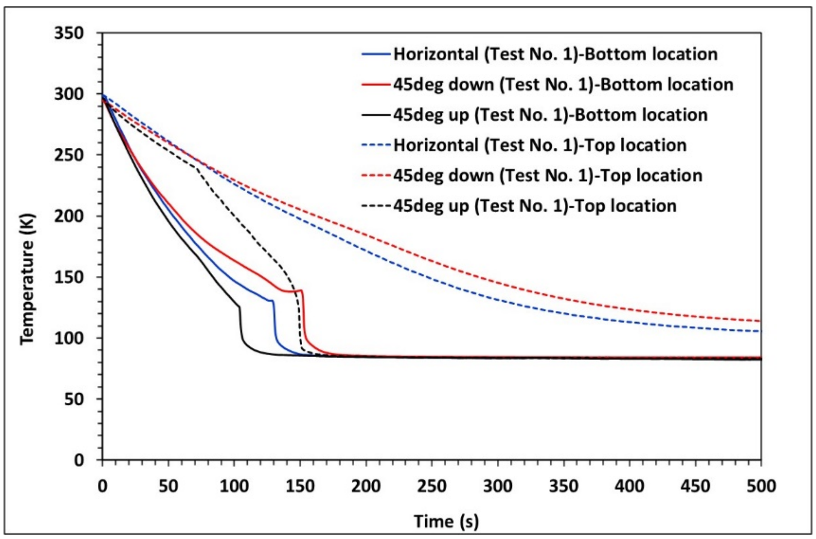

Figure 3: Temperature profile at station-3 during test in horizontal position, 45^o upward and downward orientation

Average of bottom and top temperature measurements is taken to estimate the average temperature at station 3. Profile of average temperature at Station 3, indicates that chilldown performance is inferior with downward inclination and improves significantly with upward inclination.

3.2 *HEAT FLUX COMPARISON FOR DIFFERENT ORIENTATION*

Heat flux at test section inner wall, both top and bottom locations, is estimated by Inverse Heat Transfer technique. The observations with regard to heat flux pattern are almost similar to the ones reported by Venkatesh N et al. [12]. Heat flux pattern at bottom locations are almost similar in tests with horizontal position, upward and downward inclination. whereas heat flux at top location, shows a significant jump in heat flux, when the wall superheat falls below a critical value. This is attributed to wall wetting by the liquid. As a typical case, heat flux pattern observed at bottom and top locations in station 4 during tests in horizontal, 45^o upward and downward orientation are shown in Figure-4 to substantiate the above.

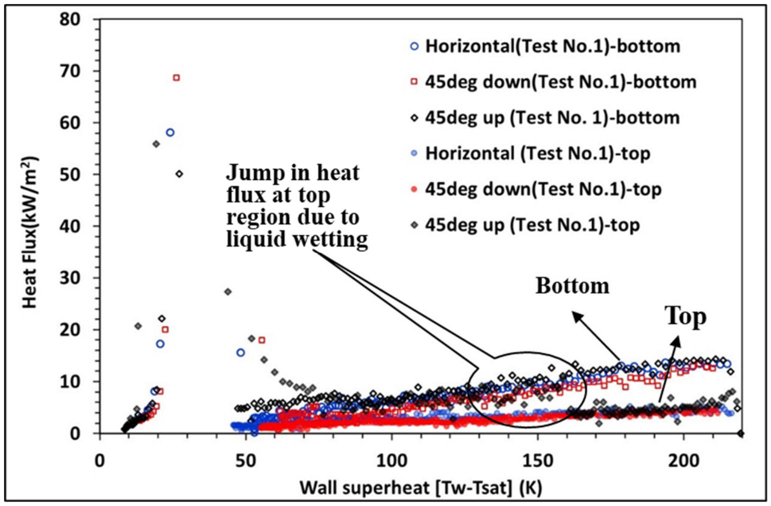

Figure 4: Heat flux pattern at bottom and top locations at Station 3 during tests in Horizontal position, 45° upward and downward orientation

Average minimum heat flux and critical heat flux are computed by taking the average of values estimated for Stations 2 and 3. Each data point in Figure 5 represents the average of critical heat flux observed at Stations 2 and 3 in a particular experiment conducted with a fixed test section orientation. Critical heat flux is found to increase with downward inclination of the test section and decrease with upward inclination. Each data point in Figure 6 represents the average of minimum heat flux observed at Stations 2 and 3 in a particular experiment done with a fixed test section orientation. Minimum heat flux is found to decrease with downward orientation of the test section, whereas reverse is the trend with upward orientation. These observations are very similar to the ones reported by Venkatesh N et al. [12] based on experiments with test section of 30mm inner diameter.

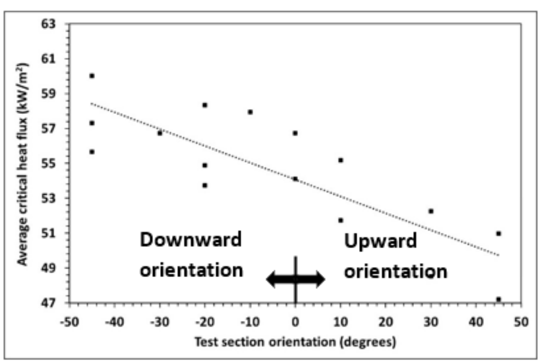

Figure 5: Comparison of average critical heat flux for different test section orientation

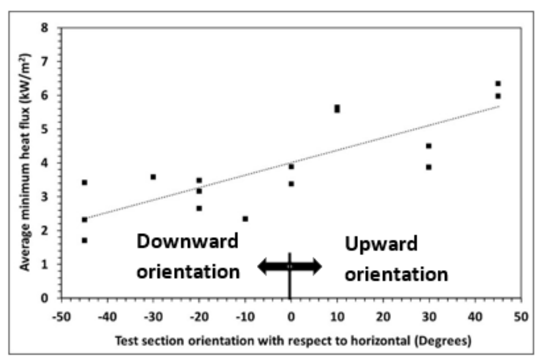

Figure 6: Comparison of average minimum heat flux for different test section orientation

4. CFD ANALYSIS

4.1 *COMPUTATIONAL DOMAIN AND BOUNDARY CONDITIONS*

The 3D computational domain of the feedline is shown in 7. The domain consists of the 2m long feedline with a small diameter line at the inlet. Foam insulation is also modeled over the feedline outerwall. The domain is meshed with hexahedral elements with finely spaced cells near the pipe inner wall to capture the flow gradients accurately. The total mesh count is 5.3lakhs with maximum skewness of 0.87.

Liquid nitrogen mass flow rate of 73.4g/s at the pipe inlet and ambient pressure of 101325Pa at the feedline outlet is specified as boundary conditions for the CFD analysis. The outer wall of the foam insulation is considered to be radiatively and convectively coupled to the ambient. The components of gravitational acceleration are specified to model the pipe oriented as 45^0 downwards. The domain is initialized with GN2 in the feedline and LN2 at 77K in the inlet pipe. The initial pressure in the domain is taken to be 101325Pa.

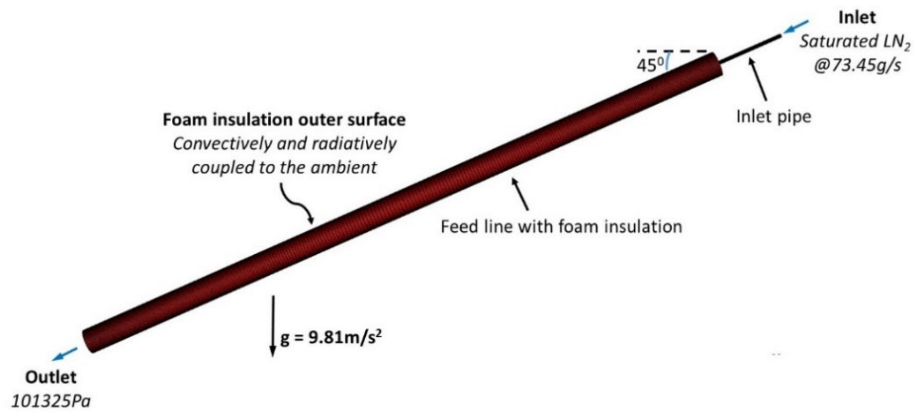

Figure 7: Computational domain of the Test section

4.2 *NUMERICAL METHODOLOGY*

The numerical simulations are carried out using ANSYS Fluent. The boiling of liquid nitrogen at the feedline wall during the chilldown process is modelled using Semi-mechanistic boiling framework in the Mixture model. The effective wall heat flux is modeled using Chen's correlation. The single-phase heat transfer coefficient is calculated from the liquid and vapor heat transfer coefficients weighted by the wetting fraction. The nucleate boiling heat transfer coefficient is calculated using the Zuber and Foster correlation given by Eq. (1) [].

$$h_{nb}=0.00122\ \frac{k_l^{0.79} cp_l^{0.45} \rho_l^{0.49}}{\sigma^{0.5} \mu_l^{0.29} L^{0.24} \rho_v^{0.24}} \left(P_{sat,T_w}-P_{sat,T_{sat}}\right)^{0.75} \left(T_w-T_{sat}\right)^{0.24} \quad .....(1)$$

where the k is the thermal conductivity, Cp is the specific heat, ρ is the density, σ is the surface tension, μ is the viscosity, T_w is the wall temperature, $P_{sat,Tw}$ is the saturation pressure at wall temperature and L is the latent heat of vaporization.

The turbulence is modeled using SST k-ω turbulence model. The pressure and velocity coupling is achieved using the Pressure-Implicit with Splitting of Operators (PISO) scheme. The discretization of the governing equations was carried out using second order upwind scheme in space. First order implicit scheme was used for time marching with a time step of $1x10^{-3}$s.

The two-phase flow was modelled by solving the momentum, continuity and energy equations for the mixture and the volume fraction equation for the liquid phase. The following governing equations were solved during the simulation:

$$\frac{\partial}{\partial t}(\rho_m)+\nabla.(\rho_m \mathbf{v_m})=0 \quad .....(2)$$

where, $\mathbf{v}_m$ is the mass-averaged velocity.

ρ_m is the mixture density and n is the number of phases. In the present simulation n=2.

$$\frac{\partial}{\partial t}(\rho_m \mathbf{v_m}) + \nabla.(\rho_m \mathbf{v_m} \mathbf{v_m}) = -\nabla p + \nabla.\left[\mu_m\left(\nabla \mathbf{v_m} + \nabla \mathbf{v_m}^T\right)\right] + \rho_m \mathbf{g} + \mathbf{F} \quad .....(3)$$

where F is a body force, and μ_m is the viscosity of the mixture,

The energy equation has the following form:

$$\frac{\partial}{\partial t}\sum_{k=1}^{n}(\alpha_k \rho_k E_k) + \nabla.\sum_{k=1}^{n}(\alpha_k \mathbf{v}_k(\rho_k E_k + p)) = \nabla.(k_{eff}\nabla T) + S_E \quad .....(4)$$

The liquid-vapor mass transfer is governed by the vapor transport equation

$$\frac{\partial}{\partial t}(\alpha_v \rho_v) + \nabla.(\alpha_v \rho_v \mathbf{v}_v) = \dot{m}_{l\to v} - \dot{m}_{v\to l} \quad .....(5)$$

where the subscripts v and l are for vapor and liquid phase respectively.

5. CFD Results and Discussion

As a typical result, wall temperature profile at a distance of 1060mm from inlet is compared with the experimental results [12] in Figure 8 and void fraction contour plot is shown in Figure 9. As can be seen, very good match is seen with the experimental results. Flow regime could be well captured, with bottom wall getting cooled by the liquid and top region only by vapour. A very good match is seen for the temperature profile at the bottom, though the fall rate of top wall temperature appears to be little slower compared to experimental data. More simulations are being done for other test section orientations for a one to one comparison and better understanding of the flow physics.

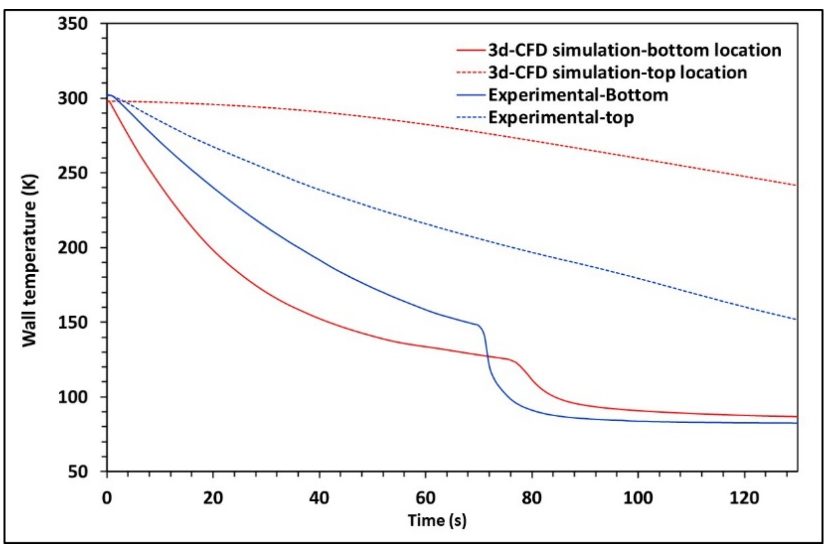

Figure 8: Comparison of wall temperature profile at 1060mm from inlet obtained through CFD analysis with experimental data

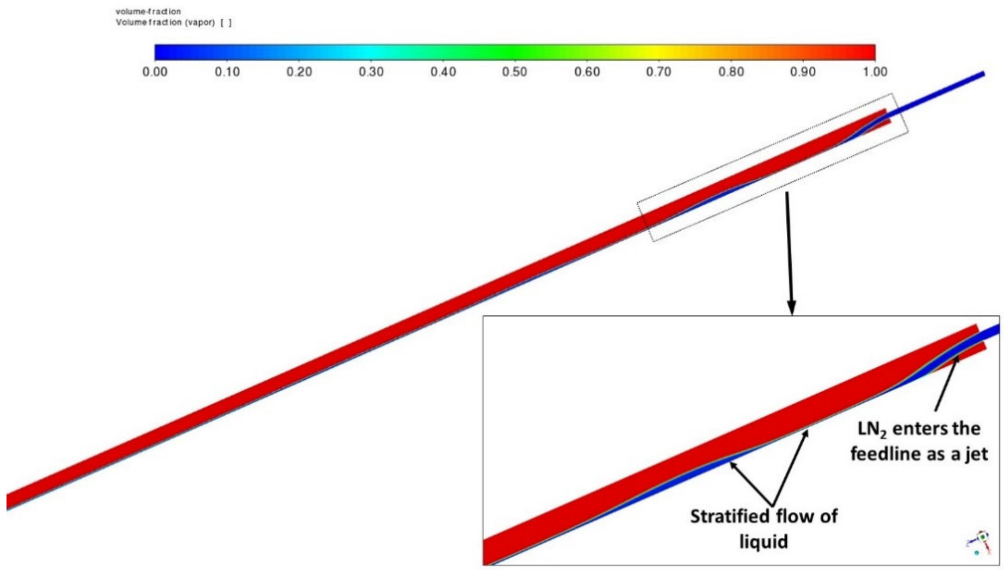

Figure 9: Void fraction contour obtained in CFD simulation

6. CONCLUSIONS

In the present study, experiments are performed employing a stainless steel test section insulated with poly-isocynurate foam using LN_2 as medium. Influence of feed line orientation on chilldown performance is studied. Major findings are:

- Bottom region goes through all the three regimes as in pool boiling in tests with horizontal and downward orientation, whereas top region is cooled only by vapour.
- In the test conditions simulated during the experiments, chilldown is slower with downward inclination compared to horizontal position, whereas chilldown improves significantly with upward orientation, mainly due to wetting of top wall by liquid.
- Pattern of variation of heat flux at bottom region of test section is not affected significantly by orientation. Heat flux pattern is significantly different for top wall, in tests with upward inclination. This is due to wetting of the top region of the test section by saturated liquid.
- Average critical heat flux values observed in the present study are higher with downward inclination and lower with upward inclination. Whereas the observation with minimum heat flux is reverse. This could be due to the flow structure prevailing in the test section and needs to be investigated further.
- CFD simulation done for 45^{o} downward orientation could capture the flow structure and wall temperature profile at bottom location very closely.

The findings of the present study will help to understand better the influence of feed line orientation on chilldown performance.

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ABBREVIATION

LN_2	Liquid Nitrogen
LAr	Liquid Argon
LOX	Liquid Oxygen
GN_2	Gaseous Nitrogen
Abs	Absolute

REFERENCES

1. JC Burke, Byrnes WR, Post AH, Arthur FER, Pressurised cool down of Cryogenic Transfer lines, Advances in cryogenic Engineering, 1960; Volume 4; pages 378-394.
2. K Srinivasan, V Seshagiri Rao and MV Krishnamurthy, Analytical and experimental investigation on cooldown of short cryogenic transfer lines. Cryogenics, September 1974; pages 489-494.
3. A Durga Prasad, K Srinivasan and MV Krishna Murthy, Cooldown of foam insulated cryogenic transfer lines, Cryogenics November 1974; pages 615-617.
4. Jelliffee Jackson, Transient heat transfer during chill down, Proceedings of HT-2005 ASME summer heat transfer conference paper, USA.
5. Jijo Johnson, SR Shine, Transient cryogenic chill down process in horizontal and inclined pipes, Cryogenics 71 (2015); pages 7-17.
6. Jesna Mohammed, Abdul Mohizin, KE Reby Roy, Experimental investigations on transient cryogenic chilldown of a short horizontal copper transfer line, Indian Academy of sciences, 202045:12.
7. Lingxue Jin, Hyokjin Cho, Sangkwon Jeong, Experimental investigation on line chilldown process by Liquid Argon, Cryogenics 97 (2019); pages 31-39.
8. Lingxue Jin, Jisung Lee, Sangkwon Jeong, Investigation of heat transfer in line chilldown process with various cryogenic fluids, Int Journal of heat and mass transfer; Volume 150 (2020); 119204.
9. SR Darr, Hong Hu, N Glikin, JW Hartwig, AK Majumdar, AC Leclair, JN Chung, An experimental study on terrestrial cryogenic transfer line chill down I. Effect of mass flux, equilibrium quality, and inlet sub-cooling, International Journal of Heat and Mass transfer, (2016); pages 1225-1242.
10. SR Darr, Hong Hu, N Glikin, JW Hartwig, AK Majumdar, AC Leclair, JN Chung, An experimental study on terrestrial cryogenic transfer line chill down II. Effect of flow direction with respect to gravity and new correlation set, International Journal of Heat and Mass transfer, 103(2016); pages 1243-1260.
11. Jason Hartwig, Peter Meyerhofer, Benjamin Stiegemeier, Robert Morehead; Liquid Methane and Liquid Oxygen horizontal chilldown experiments of a 2.54 and 11.43cm transfer line; Applied thermal Engineering; 205 (2022) 118042.
12. Venkatesh N, Deepak Kumar Agarwal, A Salih and S Sunil Kumar; Chilldown of Cryogenic feed lines- An insight into the influence of feed line orientation and mass flux; Journal of Cryogenics; 130 (2023) 103644; January, 2023.