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Comparison of Chilldown of Liquid Nitrogen Transfer Lines of Different Materials by Using Computational Fluid Dynamics

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Abstract: Even though the process of cryogenic chilldown is very complex, attempts are continuously being made to simulate the momentum and energy interactions accurately as in real case through CFD. One of the major reasons is the lack of reliable data and correlations that compass the parameters associated with cryogenic fluids. This work has taken the much needed first step in studying the effect of varying transfer line materials on their corresponding chilldown times. Chilldown in aluminium copper steel lines were investigated using validated computational fluid dynamics code (FLUENT 15.0). The time taken to completely chilldown o aluminiumis the fastest and requires minimum fluid mass compared to copper and steel . it is predicted through this computational technique that aluminium is the best material or chilldown as opposed to copper and steel

Keywords: Cryogenics, Chill down, Two phase flow, Heat transfer rate

I. INTRODUCTION

Cryogenic fluids have been used in various applications over the past century. One application that is continuously getting attention has been the use of cryogenic propellants for rocket propulsion. This interest is sparked by the fact that cryogenic propellants yield more energy and are more environmentally friendly, when compared to non-cryogenic propellants and the storage systems for these cryogenic propellants are lighter than those required for their non-cryogenic counterparts.

The operation of a cryogenic propulsion system requires cooling of transfer line before establishing a steady flow of cryogenic fluid between various system components. The process of cooling down the equipment with cryogenic fluid is known as a cryogenic chilldown process. Cryogenic transfer line chill down is a transient heat transfer problem that involves rapid heat exchange from a solid structure to a fluid with phase change. It is necessary to know how long it takes to chill down a given transfer line for satisfactory operation. When liquid cryogen, for example nitrogen, at saturation temperature (77.6 K at 1 atm.) begins flowing through a tube initially at ambient temperature (300 K) the liquid instantly vaporizes near the tube wall. Thus a cross-section of the flow will have an outer vapour ring with a saturated liquid core. As the flow moves downstream, the liquid core evaporates and the vapour becomes superheated. As the tube wall cools, the liquid core penetrates further and further downstream. Eventually, the tube becomes filled with liquid. Reduction in fluid density by vaporization causes the average flow velocity to increase significantly. Prediction of chilldown time requires modelling of these transient phenomena and understanding of how they affect heat transfer from the tube wall to the flowing cryogen. Transient heat transfer processes between the liquid and transfer line cause vaporization of the liquid, and this phase change can cause transient pressure and flow surges in the liquid. As the transfer line is cooled, these effects diminish until the liquid reaches a steady flow condition in the chilled transfer line. If these transient phenomena are not properly accounted for in the design process of a cryogenic system, it can lead to damage or failure of system components during operation. Although there is a substantial amount of data available for cryogenic boiling, none of them can be used to solve chilldown problem directly due to the difference in flow patterns between boiling and chilldown. It is believed that the transition boiling regime and the switch-over between nucleate boiling and single-phase convection contribute most to the complexity of the chilldown problem. Because of difficulties designing and conducting experiments, there is less chilldown data for cryogenic fluids compared to conventional fluids.

A. Two phase flow and heat transfer

Two-phase flow is the simplest case of multiphase flow, the latter being the simultaneous flow of different phases (states of matter): gas, liquid and solid. The nature of two-phase flow in spacecraft thermal control systems is single-component, meaning that the vapour and the liquid phase are of the same chemical substance. If the phases consist of different chemical substances, e.g. in airwater flows; the flow is called two-phase two-component flow. Flow-related (hydraulic) two-phase, single-component and two-component flows are described by the same mathematical model equations. Therefore results of calculations and experiments in one system can be used in the other, as long as they pertain to flow phenomena only, consequently there is no heat transfer.

Heat transfer in a two-phase two-component system has a relatively simple impact on the system behaviour only the physical (material) properties of the phases are temperature dependent. Two-phase single-component systems are far more complicated, because the heat transfer and the temperature cause (in addition to changes of the physical properties of the phases) mass exchanges between the phases, by evaporation, flashing and condensation. Hence complicated two-phase single component systems cannot be properly understood by using modelling and experimental results of simpler two-phase two-component systems. Two-phase single-component systems, like the liquid-vapour systems in spacecraft thermal control loops, require their own, very complicated mathematical modelling and dedicated two-phase single component experiments. Though liquid-vapour flow obeys all basic fluid mechanics laws, their constitutive equations are more numerous and more complicated than the equations for single-phase flows. The complications are due to the fact that inertia, viscosity and buoyancy effects can be attributed both to the liquid phase and vapour phase, and also due to the impact of surface tension.

B. Flow Patterns

In order to reliably predict the thermal transport associated with cryogenic chilldown, it is important to know the flow structure and temperature variations. It is useful to examine existing models for flow regime and heat transfer in two-phase flow.

1) *Horizontal Flow Regimes:* During the chilldown process, the vapour and liquid are flowing simultaneously inside the pipe. The resulting two-phase flow is more complex than single-phase flows. Apart from the inertia, viscous, and pressure forces experienced in single-phase flow, two-phase flows also experience interfacial tension forces, exchange of momentum, mass and energy between the liquid and vapour phases, as well as the wetting characteristics of the liquid on the pipe. The flow structure that the two-phase flow evolves into is referred to as flow regime and may take various forms depending on the flow rate of the various phases, fluid property, and pipe geometry and orientation. The two-phase flow regimes that are typically encountered for horizontal flow are illustrated in Fig. 1.1.

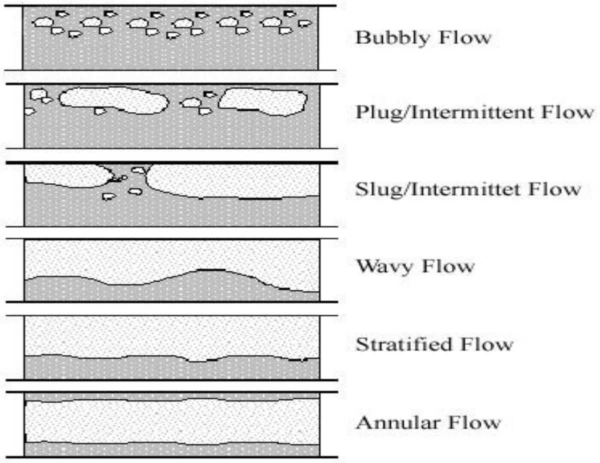

CHART 1: Schematic representation of flow regimes observed in horizontal two-phase flow

At very low vapour quality, bubbly flow is usually observed, with the bubbles residing in the upper portion of the pipe (as a result of buoyancy forces). As the quality is increased, the bubbles tend to coalesce producing larger plug-type bubbles, this is referred to as plug flow. At low mass flow rates and higher qualities, stratified flow is observed; as the flow rate and/or quality are increased the liquid-vapour interface becomes unstable (due to Helmholtz instability), resulting in stratified-wavy flow. At high liquid flow rates the amplitude of the waves may grow until the crest spans the cross-section of the pipe forming large vapour slugs. This is referred to as slug flow. At higher vapour velocities and moderate liquid flow rates the flow structure is observed to be annular, with liquid film covering the entire circumference of the pipe with an inner vapour core. If the vapour flow rate is very high and the vapour quality is also very high, it is possible for the liquid to be entrained in the vapour forming what is known as mist flow.

C. Definition Of Problem

Practical application of chilldown in rocket propulsion requires cryogenic fuel to be introduced into a turbo pump. A predetermined time gap is available for filling of the system. The entire chilldown should be completed within this stipulated time limit; otherwise it may cause the entry of gaseous nitrogen into the system hence causing damage. The vapour quality of the cryogen should be less than 6-7% for the ideal working of the turbo pump without cavitation effects.

Chilling effect is produced by passing the cryogenic fuel through the flow device. Maximum chilling effect should be produced with the minimum expense of cryogenic fluid. So the ideal mass flow rate required for complete chilldown with minimum expense of cryogen is a basic requirement in the design of a cryogenic propulsion system. The value of chilldown time will be different for different material transfer lines i.e., for example straight copper and steel. Hence a database of chilldown times for different material transfer lines is required for developing a cryogenic rocket propulsion system.

D. Objectives

To conduct a numerical analysis on fluid flow and heat transfer through selection of different material and hence to find out,

1) The quantity of fluid consumed during chilldown of straight pipes by varying transfer line material.
2) The time taken for complete chilldown.

II. LITERATURE REVIEW

Prediction of chill down time requires modelling of complex transient phenomena and understanding of how they affect heat transfer from the tube wall to the flowing cryogen.A brief discussion of the past developments in modelling and analysis of liquid nitrogen chilldown, multi-layer insulation, two phase phenomenon of boiling and evaporation and chilldown of transfer lines as a result of heat in leak is given in the present chapter.

A. Chilldown And Two Phase Flow

Reid Shaeffer *et al* [1] in their work “An experimental study on liquid nitrogen pipe chilldown and heat transfer with pulse flows” concluded that continuous flows with high Reynolds numbers are generally more efficient at transferring heat than other patterns or those of lower Reynolds numbers.

Jelliffe Kevin Jackson[2], in his work “Cryogenic two-phase flow during chilldown: flow transition and nucleate boiling heat transfer” deducted the heat transfer coefficient based on computed temperature values.He utilized the temperature history in conjunction with an inverse heat conduction procedure which allows the unsteady heat transfer coefficient on the interior of the pipe wall to be extracted.

Generalized Fluid System Simulation Program (GFSSP) is a robust general fluid system analyzer, based on the finite volume method, with the capability to handle phasechange, heat transfer, chemical reaction, rotational effects, and fluid transients in conjunction with subsystem flow models for pumps, valves, and various pipe fittings. GFSSP has been used to predict the chilldown of a cryogenic transfer line, based on transient heat transfer effects and neglecting fluid transient effects. [3] Recently, GFSSP’s capability has been extended to include fluid transient effects. [4]

N T Van Dresar[5] *et al* investigated transient behaviour of a small scale cryogenic transfer line. They found out that the optimum flow rate is about 3-5 times the flow rate necessary to balance the total heat inleak in a cryogenic transfer line.

Burke *et al.* [6] studied chill down of 60 ft., 100 ft. and 175 ft. long, 2 in. outer diameter (OD) stainless steel lines by flowing liquid nitrogen. A model to predict chill down time was developed by treating the entire line as a single control volume. This lumped system provides a simple estimate of chill down time but lacks accuracy due to its broad assumptions and averaging of fluid properties and flow rates over the chill down time.

Steward, *et al.* [7] modelled chill down numerically using a finite-difference formulation of the one-dimensional, unsteady mass, momentum and energy equations. The model results agree well with experimental results of chill down of a 200 ft. long, 0.625 in. inner diameter, 0.750 in outer diameter copper tube using liquid nitrogen and liquid hydrogen as the working fluids. Heat transfer coefficients were determined using superposition of single phase forced convection correlations and pool boiling correlations for both nucleate mid film boiling.

Cheng-feng tai[8], in his work “Cryogenic two-phase flow and phase-change heat transfer in Microgravity” focussed on developing the numerical techniques to simulate the two-phase flow and phase change phenomena for one of the major flow patterns in film boiling, the inverted annular flow. In this research, a numerical package for handling phase change and chilldown for cryogenic two-phase flow has been developed.

Alok Majumdar *et al.* [9] studied Numerical prediction of conjugate heat transfer in fluid network. They developed a conjugate heat transfer analysis and concluded that increasing the driving pressure and providing sub cooling decreases the chilldown time.

Yuan *et al.*[10] conducted cryogenic boiling and two-phase flow during pipe chilldown in earth and reduced gravity. The data from testing indicates that cryogenic liquid encounters three boiling regimes during line chilldown: film, transition, and nucleate boiling.

V.V.Klimenko *et al.* [11] studied channel orientation and geometry influence on heat transfer with two-phase forced flow of nitrogen and they concluded that gravity had more influence on a horizontal than a vertical pipe

Kawanami et al. [12] used liquid nitrogen as working fluid to investigate the heat transfer characteristics and flow pattern during the quenching of a vertical tube under both terrestrial and ten-second microgravity conditions. They claimed that the heat transfer under microgravity condition increased up to 20% compared to those in the normal gravity condition.

Jacobs [13] and Flynn[14] developed a method to quickly estimate the minimum and maximum amounts of liquid required to chilldown a cryogenic transfer line. Both the models equate the loss of internal energy of the transfer line to the cooling capacity of the cryogenic liquid.

B. Insulation

M. Chorowski, P. Grzegory, C. Parente, G. Riddone [16] in 2000 developed a mathematical model to describe the heat flux through MLI from 80 K to 4.2 K. The mathematical model enables prediction of MLI behaviour with regard to different MLI parameters, such as gas insulation pressure, number of layers and boundary temperatures. The calculated values have been compared to the experimental measurements carried out at CERN

J. A. Demko, J. E. Fesmire, S. D. Augustynowicz [17] in 2008 a design tool to determine the performance of insulation systems for comparative trade-off studies of different available material options was developed. The approach is to apply thermal analysis to standard shapes (plane walls, cylinders, spheres) that are relatively simple to characterize with a one-dimensional analytical or numerical model.

C. CFD Simulation

1) *Introduction To CFD:* Computational Fluid Dynamics (CFD) is one of the branches of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems that involve fluid flows. Computers are used to perform the millions of calculations required to simulate the interaction of fluids and gases with the complex surfaces used in engineering. CFD predicts what will happen, quantitatively, when fluid flow, often with the complications of

a) *Simultaneous* flow of heat
b) Mass transfer
c) Phase change
d) Chemical reaction
e) Mechanical movement
f) Stress and displacement of immersed solids

2) *CFD APPLICATIONS*

a) Aerodynamics of aircrafts and vehicles; lift and drag
b) Hydrodynamics of ships
c) Power plants; combustion in IC engines and gas turbines
d) Turbo machinery; flow inside rotating passages
e) Metrology; weather predictions
f) External and internal environment of buildings; wind loading

D. Geometry Model

In the present problem, the flow is assumed to be unsteady incompressible, so pressure based solver is used for the numerical analysis. The SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm is used as the solution method. This algorithm is essentially a guess-and-correct procedure for the calculation of pressure on the staggered grid arrangement.

To initiate the SIMPLE calculation process a pressure field is guessed and the discretized momentum equations are solved using the guessed pressure field to yield the velocity components. The correct pressure is obtained by adding a pressure correction to the guessed pressure field. To avoid the divergence problem a suitable under relaxation factor is considered during the iterative process.

The flow is assumed to be at unsteady state with multiphase characteristics. The fluid physical properties are constant. For this simulation, the flow is assumed to be incompressible and turbulent with constant fluid properties. One straight and four helical transfer lines with variable helical angles (20°, 25°, 30°, 35°) are modelled for analysis . The geometrical computational domains are shown below.

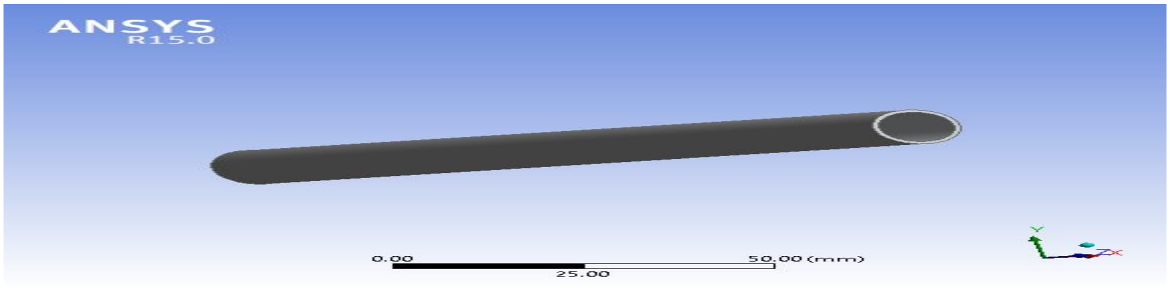

CHART 2: Straight tube

The pipe geometries in general are modelled using 2 domains: a solid domain and a fluid domain. The next step is to mesh the generated model. Meshing is carried out using Mesh software.

E. Boundary Conditions

Multi-Layer Insulation (MLI) at high vacuum has the maximum thermal insulating performance among the insulating materials. So vacuum jacketed MLI has to be used for insulating the transfer line chilldown. For effective insulation, vacuum of 10^{-4} Torr has to be provided. Aluminized Mylar with emissivity of $\epsilon = .05$ is selected as the best candidate for reflecting layer based on the mentioned criteria for the operating conditions. It has an aluminium coating of 400 Å on both sides of mylar film of 6 µm thickness. Similarly for the spacer, darcon netting is selected having conductance of 0.0851W/m^{2}K and a thickness of 0.025mm.

Emissivity of non-contacting layers are taken as$\epsilon 1 = .03$ and $\epsilon 2 = .05$

Equivalent Emittance, $E = 3.74*10^{-4}$

The heat flux as a result of radiation, Q_{rad} can be computed from above equation

$Q_{rad} = 0.1713$W/m^2

Apparent thermal Conductivity, $K_a = 2.84*10^{-3}$ W/Mk

The Reynolds number of the inlet is assumed to be 5000

We know $Re = \rho V D/\mu$, ρ = Density of liquid nitrogen = 808kg/L, Reynolds Number, Re = 5000, Diameter of pipe= 12.7mm, Absolute Viscosity of liquid nitrogen at 76K = $1.58 * 10^{-4}$Pa-s.

V. RESULT AND DISCUSSION

Chilldown on straight copper, aluminium and steel transfer lines have been investigated and the results are presented in the form of contours and graphs for different cases. Chilldown is said to be achieved when the volume fraction of liquid nitrogen obtained on the outlet is 1. The liquid nitrogen volume fraction and temperature along suitable faces are displayed as contours.

Chilldown Through Straight Copper Pipe

A. Temperature Contours

The temperature distributions of the copper pipe along a mid plane at different instants of time are shown below. It is evident that the outer wall is initially in thermal equilibrium with the ambient atmosphere. At the initial stage, which is at 0.01s, it can be seen that the interior of the pipe has started to cool down to near fluid temperatures. Further upstream of time it can be seen that the wall temperatures reduces significantly, ultimately filling the outlet of the pipe with liquid phase nitrogen at 65s. The temperature distribution at this instant show that the walls have cooled down to near fluid temperatures. At this stage the liquid nitrogen temperature is below its saturation value and hence it is assumed that steady state is achieved.

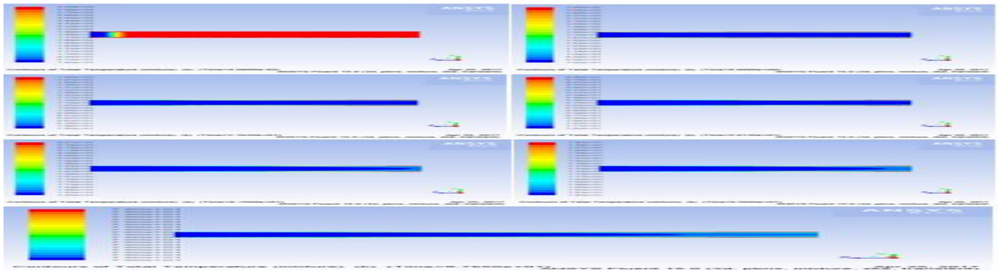

CHART 3:Distribution of temperature at the mid plane of a straight copper pipe for different intervals of time

B. Liquid nitrogen volume fraction Contours

The contours of volume fraction at the start of the analysis show that liquid nitrogen is present only at the near inlet regions. The liquid gets boiled off and flows in gaseous form in the other regions. When liquid nitrogen, at saturation temperature (77.6 K at 1 atm.) begins flowing through the tube initially at ambient temperature (300 K) the liquid instantly vaporizes near the tube wall. Thus a cross-section of the flow will have an outer vapour ring with a saturated liquid core. As the flow moves downstream, the liquid core evaporates and the vapour becomes superheated. As the tube wall cools, the liquid core penetrate further downstream eventually filling the tube with liquid.

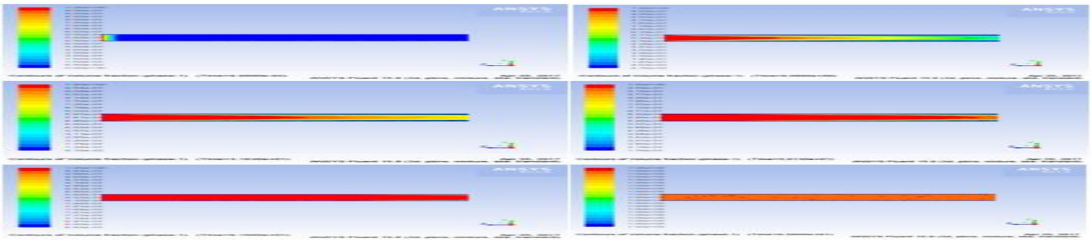

CHART 4: Distribution of volume fraction of liquid nitrogen at the mid plane of a straight copper pipe for different intervals of time.

It is observed from the Volume fraction- time plot that the outlet is filled completely with liquid nitrogen phase after 65s which is the required chilldown time for a straight pipe.

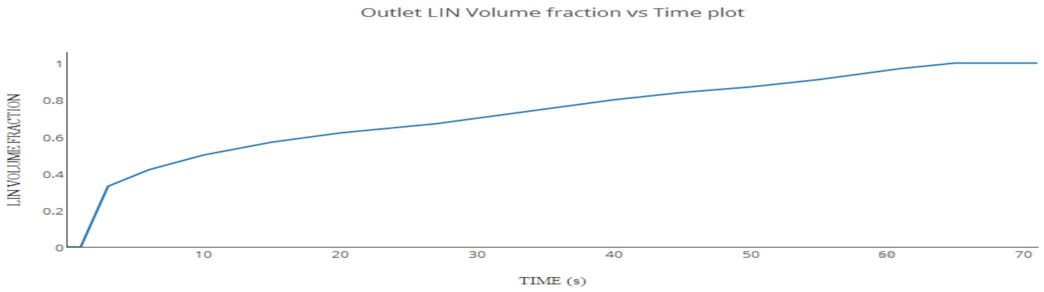

CHART 5: Variation of volume fraction of liquid nitrogen with time at the outlet of a straight copper pipe

In the flow time temperature graph, the temperature on the outlet part is seen to reduce swiftly from 300K to 150K in a time interval of 30s. This part characterizes the boiling regime in which there is maximum heat transfer. Further the temperature varies slowly from 150K to 76K in a time interval of around 35s implying the heat transfer is comparatively lower for this regime.

VI. CHILLDOWN THROUGH STEEL PIPE

A. Temperature Contours

The temperature distributions of the steel pipe along a mid plane at different instants of time are shown below. It is evident that the outer wall is initially in thermal equilibrium with the ambient atmosphere. At the initial stage, which is at 0.05s, it can be seen that the interior of the pipe has started to cool down to near fluid temperatures. Further upstream of time it can be seen that the wall temperatures reduce significantly, ultimately filling the outlet of the pipe with liquid phase nitrogen at 38.5s. The temperature distribution at this instant show that the wall has cooled down to near fluid temperature. At this stage the liquid nitrogen temperature is below its saturation value and hence we assume steady state is achieved.

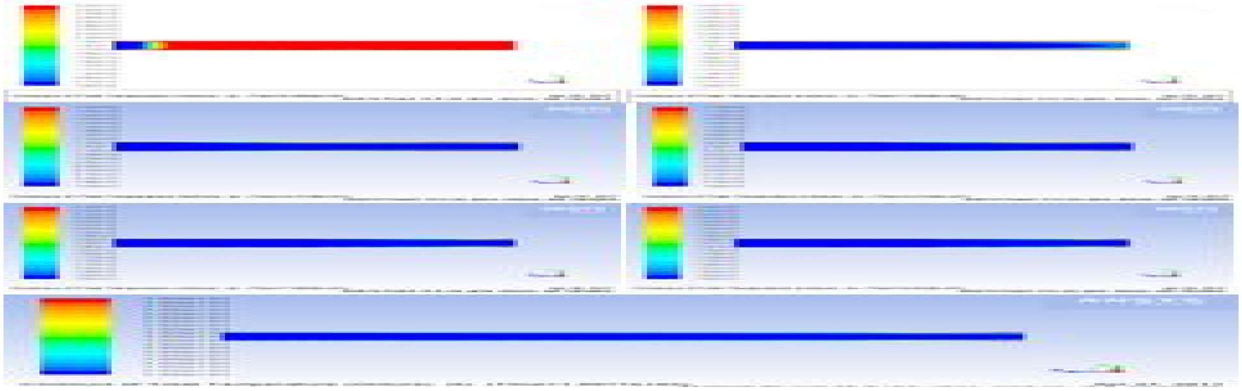

CHART 6: Distribution of temperature at the mid plane of a straight steel pipe for different intervals of time.

B. Liquid Nitrogen Volume Fraction Contours

The contours of volume fraction at the start of the analysis show that liquid nitrogen is present only at the near inlet regions. The liquid gets boiled off and flows in gaseous form in the other regions. When liquid nitrogen begins flowing through the tube initially at ambient temperature (300 K) the liquid instantly vaporizes near the tube wall. Thus a cross-section of the flow will have an outer vapour ring with a saturated liquid core.

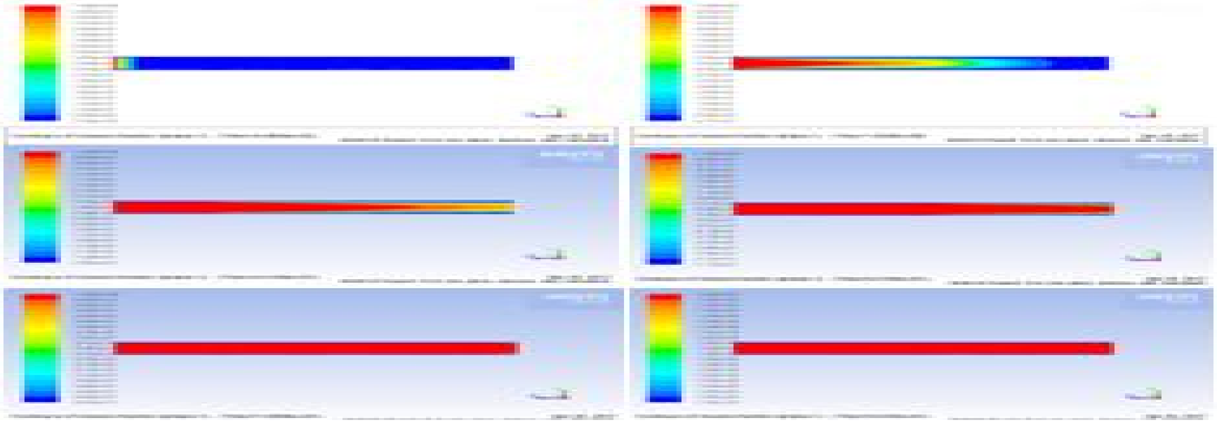

CHART 7: Distribution of volume fraction of liquid nitrogen at the mid plane of a straight steel pipe for different intervals of time.

It is observed from the Volume fraction- time plot that the outlet is filled completely with liquid nitrogen phase after 38.5swhich is the required chilldown time for a steel pipe

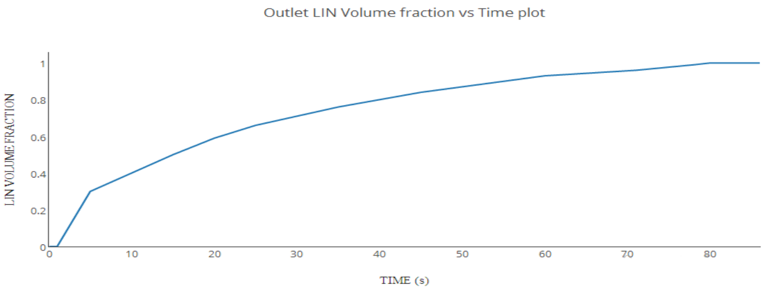

CHART 8: Variation of volume fraction of liquid nitrogen with time at the outlet of a straight steel pipe

In the flow time temperature graph, the temperature on the outlet part is seen to reduce swiftly from 300K to 150K in a time interval of 9s. This part characterizes the boiling regime in which there is maximum heat transfer. Further the temperature varies slowly from 150K to 76K in a time interval of around 29.5s implying the heat transfer is comparatively lower for this regime.

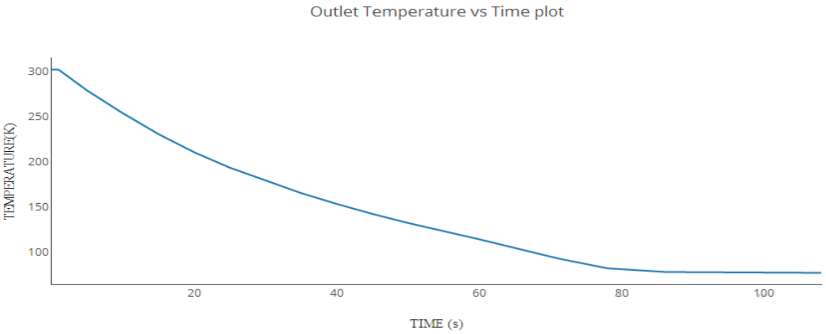

CHART 9: Variation of temperature with time at the outlet solid fluid interface of a straight steel transfer line

C. Comparison Of Various Materials

The variation of volume fraction of liquid nitrogen with time for all the material selected for study is shown in the figure 6.21. It can be observed that the required chilldown condition is attained only at a slower rate for a steel transfer line as compared to the aluminium and copper transfer line.

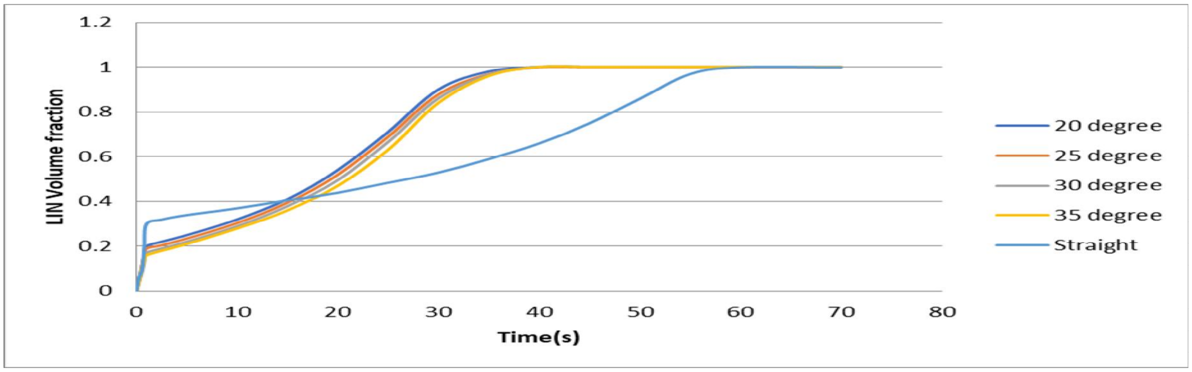

CHART 10: Variation of volume fraction of liquid nitrogen with time for various materials

The variation of temperature at the solid-fluid interface for all the material selected for study is shown in the figure 6.22. It is evident from the graph that the temperature reduces at a slower rate for the steel as compared to the aluminium and copper transfer lines.

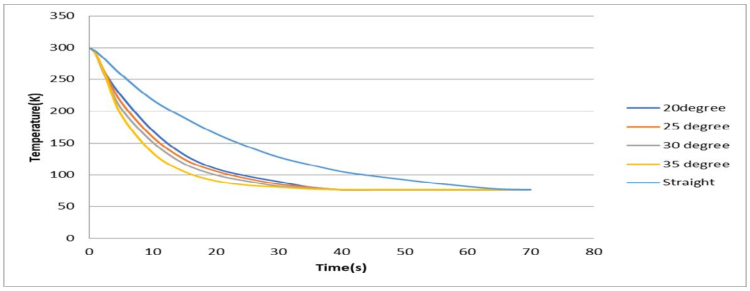

CHART 11: Variation of temperature at the solid-fluid interface with time for various materials

VII.CONCLUSION

Chilldown time and mass flow rates required for chilldown of different material transfer lines were found out using numerical methods. It was found that chilldown of aluminum is the fastest and requires minimum fluid mass when compared to copper and steel. It is predicted through this computational technique that aluminum is the best material for chilldown a opposed to copper and steel. It is concluded that future studies are required with improvements in the prediction scheme with detailed two phase correlations. The incorporation of microscopic level molecular calculations is suggested to bring down the difference in the computational and experimental results. Animation frames of contours of liquid nitrogen volume fraction are generated which gives a visual indication of how chilldown will take place. It is suggested to incorporate a method in FLUENT to predict the kind of flow which takes place during boiling.

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