CFD Investigations on the Liquid Nitrogen Chill down of Straight Transfer Lines and ITS Comparison with Helically Coiled Transfer Lines

K. Madhusoodanan Pillaia, Deepak J, K. E. Reby Royb

***Abstract:** Attempts are constantly being made to simulate the momentum and energy interactions involved in cryogenic chill-down process accurately as in real case through CFD. The main difficulty 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 geometries on their corresponding chill-down times. Chill-down in helical transfer lines were investigated using validated computational fluid dynamics code (FLUENT 15.0). The time taken to completely chill-down a straight as opposed to a helical transfer line, at constant heat flux, was compared in this study. Important flow quantities for multiphase system such as volume fraction distribution were plotted and displayed. It was found that centrifugal forces due to shape of helical transfer lines play an important role in the phase and temperature distribution in helical pipes. It was also observed that the time taken for complete chill-down of helical transfer lines were much smaller as opposed to a straight transfer lines. It is concluded that future studies are required with improvements in the prediction scheme with detailed two phase correlations.*

***Index Words:** Chill-down, Liquid Nitrogen, CFD analysis, Cryogenics, Helical Transfer lines, Two Phase flow, Flow boiling.*

I. INTRODUCTION

It is required to cool the transfer lines leading to a cryogenic propulsion system before establishing a steady flow of cryogenic fluid between various system components. The cooling of these types of equipment with cryogenic fluid is known as a cryogenic chill-down process. 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. Reid Shaeffer et al [1] in their work “An experimental study on liquid nitrogen pipe chill-down 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 chill-down: flow transition and nucleate boiling heat transfer” 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.

A Generalized Fluid System Simulation Program (GFSSP) developed by NASA has been used to predict the chill-down 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 and 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 stainless steel lines by flowing liquid nitrogen. They developed a model to predict chill down time by treating the entire line as a single control volume. Steward, et al. [7] modelled chill down numerically using a finite-difference formulation of the one-dimensional, unsteady mass, momentum and energy equations. Alok Majumdar et al. [8] studied Numerical prediction of conjugate heat transfer in fluid network and developed a conjugate heat transfer analysis and concluded that increasing the driving pressure and providing sub cooling decreases the chill-down time. V.V.Klimenko et al. [9] studied channel orientation and geometry influence on heat transfer with two-phase forced flow of nitrogen and concluded that gravity had more influence on a horizontal than a vertical pipe. Kawanami et al. [10] 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 claimed that the heat transfer under microgravity condition increased up to 20% compared to those in the normal gravity condition. Jacobs [11] and Flynn [12] developed a method to quickly estimate the minimum and maximum amounts of liquid required to chill-down a cryogenic transfer line. Previous works reported in literature dealt with chill-down in straight lines. The desirable condition should be the attainment of maximum chilling with the minimum expense of cryogenic fluid. So the ideal mass flow rate required for fastest chill-down with minimum expense of cryogen is a basic requirement in the design of a cryogenic propulsion system. This value of chill-down time will be different for different geometries of transfer lines.

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In the present work chill-down in a straight tube transfer line is compared with that of a helical tube transfer line using validated computational fluid dynamics code (FLUENT 15.0).

Abbreviations and Acronyms

ρ
Density(kg/m^3)
ρ_m Mixture density(kg/m^3)
V_m Mass averaged velocity (m/s)
N Number of phases
F Body force
μ_m Viscosity of the mixture
$V_{dr,k}$ Drift velocity for secondary phase
k_{eff} Effective conductivity
k_t Turbulent thermal conductivity
S_E Volumetric heat sources
h_k Sensible enthalpy for secondary phase
α_k Volume fraction for phase

II. CFD MODELLING

With the advancement and recent development of CFD codes, a full set of fluid dynamic and multiphase flow equations can be solved numerically. The current study used commercial CFD code, ANSYS FLUENT 15.0, to solve the balance equation set via domain discretization, using control volume approach. These equations are solved by converting the complex partial differential equations into simple algebraic equations. An implicit method for solving the mass, momentum, and energy equations is used in this study. The k-ε turbulence model with standard wall functions are used due to their proven accuracies in solving multiphase problems.

A. Geometry and Boundary Conditions

A cylindrical straight tube of diameter 12.7mm and length 139.7mm patched completely with gaseous nitrogen as shown in Figure 1 was used for part I of the simulation. The same straight tube twisted to form a helical tube with 90mm pitch and a single turn as shown in figure 2 was used for simulation part II. The inlet condition is given as fully saturated liquid nitrogen and the wall, interior and surrounding temperatures are assumed to be ambient. Initially the transfer line wall is exposed to ambient condition of 300K which is much above the saturation temperature at one atmosphere. Even though suitable insulation is provided, from numerical methods it can be concluded that a heat flux of 0.38 W/m2 is seen leaking into the geometry. Geometry is modelled using Design Modeller 15.0. Meshing is done with relevance centre as coarse, a relevance of 100 and a curvature normal angle of 1. Since the heat flux is given on the wall, the interface between the solid and liquid domain is of utmost importance. So the meshing is done in such a way that grid size near the boundary layer is smaller compared to the remaining modelled area. Grid independence study is carried out for both the geometries and the optimum number of elements is obtained.

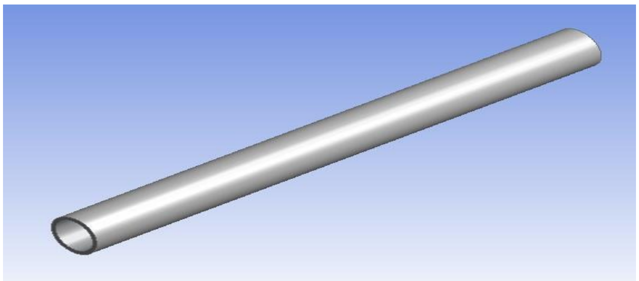

Fig.1 Straight tube transfer line

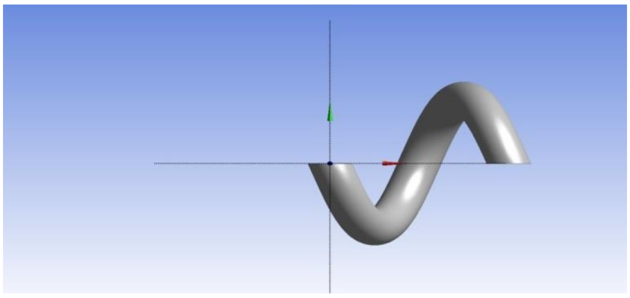

Fig 2 Helically coiled transfer line

B. Modelling Multi-Phase

The numerical simulations presented in this work are based on the ANSYS FLUENT mixture two fluid model. The modelling is based on mass-weighted averaged mass and momentum transport equations for all phases, gas and liquid. The mixture model is designed for two or more immiscible fluids in which both are treated as interpenetrating continua. In the mixture model, a single set of momentum equations is shared by the fluids, and the volume fraction of each of the fluids in each computational cell is tracked throughout the domain. One set of Navier-Stokes equations for the gas-liquid mixture together with two volume fraction equations and turbulence model equations are solved in this model. Transport equations are used to track the motion of liquid–vapour boundary and both the phases share a common velocity field. Mixture method in conjunction with evaporation– condensation mass transfer model has been used to simulate mass transfer by phase change. The liquid-vapour mass transfer is governed by the vapour transport equation.

C. Modelling assumptions

The flow is assumed to be transient, and the pressure based solver is used. Standard wall functions have been selected and the effect of drag, lift and slip interaction has not been investigated. Initially the interior of the pipe is assumed to be filled with nitrogen gas. straight tube. The temperature drop along the solid-fluid interface has been found out and plotted against time.

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D. Governing equations

The continuity equation can be expressed as

$$\frac{\partial}{\partial t}\left(\rho_m\right)+\nabla\cdot\left(\rho_m\vec{v}_m\right)=0$$

The momentum equation for the mixture can be expressed as

$$\frac{\partial}{\partial t}\left(\rho_m\vec{v}_m\right)+\nabla\cdot\left(\rho_m\vec{v}_m\vec{v}_m\right) = -\nabla p+\nabla\cdot\left[\mu_m\left(\nabla\vec{v}_m+\nabla\vec{v}_m^{T}\right)\right] + \rho_m\vec{g}+\vec{F}+\nabla\cdot\left(\sum_{k=1}^{n}\alpha_k\rho_k\vec{v}_{dr,k}\vec{v}_{dr,k}\right)$$

The energy equation for the mixture takes the following form

$$\frac{\partial}{\partial t}\sum_{k=1}^{n}\left(\alpha_k\rho_k E_k\right)+\nabla\cdot\sum_{k=1}^{n}\left(\alpha_k\vec{v}_k\left(\rho_k E_k+p\right)\right)=\nabla\cdot\left(k_{eff}\nabla T\right)+S_E$$

$$\frac{\partial}{\partial t}\sum_{k=1}^{n}\left(\alpha_k\rho_k E_k\right)+\nabla\cdot\sum_{k=1}^{n}\left(\alpha_k\vec{v}_k\left(\rho_k E_k+p\right)\right)=\nabla\cdot\left(k_{eff}\nabla T\right)+S_E$$

The volume fraction equation for secondary phase can be calculated from,

$$\frac{\partial}{\partial t}\left(\alpha_p\rho_p\right)+\nabla\cdot\left(\alpha_p\rho_p\vec{v}_m\right)=-\nabla\cdot\left(\alpha_p\rho_p\vec{v}_{dr,p}\right)+\sum_{q=1}^{n}\left(\dot{m}_{qp}-\dot{m}_{pq}\right)$$

where, energy transfer due to conduction,

$$E_k=h_k$$

E. Solution Strategy and Convergence

Chill-down due to voracious boiling of cryogen is a rapid transient problem. Transient analysis is carried out with a time step of 0.001 seconds. A first order upwind discretization scheme is used for the momentum equation, volume fraction, energy, turbulence kinetic energy and specific dissipation rate. First order implicit transient formulation is used. The convergence criterion is based on the residual value of the calculated variables, i.e., mass, velocity components, energy, turbulence kinetic energy, turbulence dissipation rate and volume fraction. In the present calculations, the threshold values are set to a ten thousandth of the initial residual value of each variable, except the residual value of energy which is a millionth. In pressure-velocity coupling, coupled pressure velocity coupling scheme is used. The coupled algorithm solves the momentum and pressure-based continuity equations together. Other solution strategies used are the reduction of under relaxation factors of momentum, the volume fraction, the turbulence kinetic energy and the turbulence dissipation rate.

III. CFD ANALYSIS AND RESULTS

A. Validation of the code

Chill-down of a straight tube liquid nitrogen transfer line investigated by Reid Shaeffer et al. [1] is used for validation. Liquid nitrogen is passed at a constant flow rate through the.

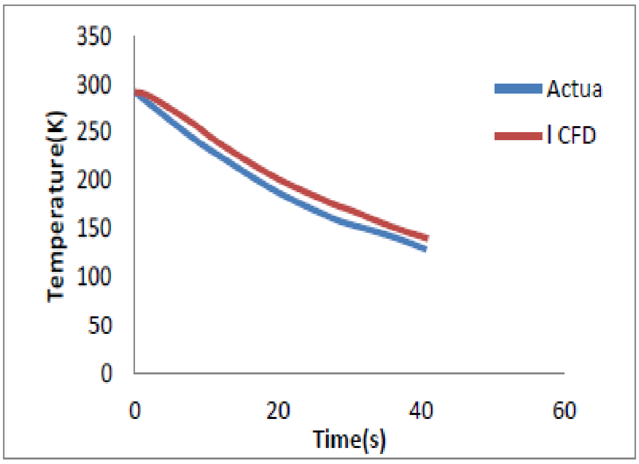

Fig 3 Variation of temperature with time along the solid-fluid interface

The results obtained from numerical and experimental calculations concluded that the code can be used for simulation of chill-down

IV. RESULTS AND DISCUSSION

Chill-down on straight and helical transfer lines have been investigated and the results are presented in the form of contours and graphs for different cases. Chill-down is said to be achieved when the volume fraction of liquid nitrogen obtained on the outlet is 1.

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Part I: Straight transfer lines

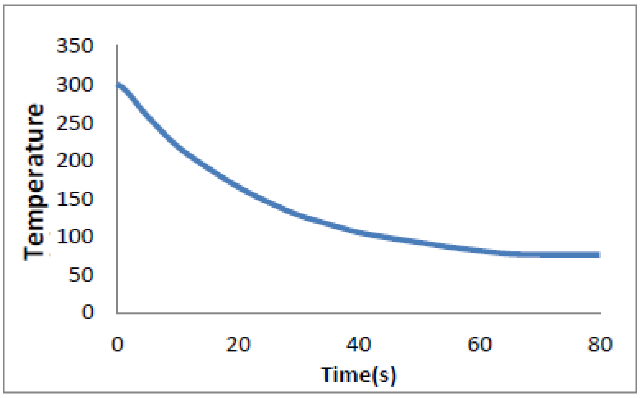

Fig 4 Variation of temperature with time at the solid fluid interface of a straight transfer line

In the flow time temperature graph, the temperature on the outlet is seen to reduce swiftly from 300K to 150K in a time interval of 22s. 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 40s implying the heat transfer is comparatively. lower for this regime.

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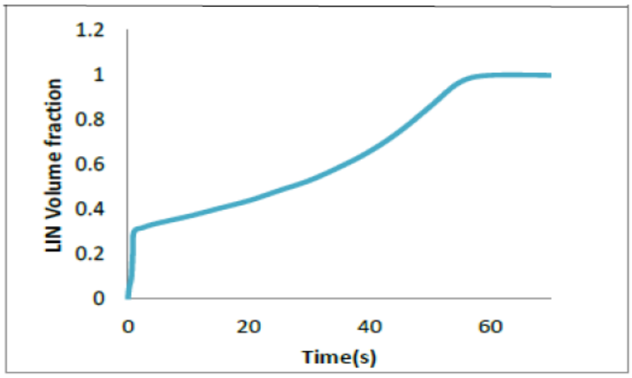

Fig 5 Variation of liquid nitrogen volume fraction with time at the solid fluid interface of a straight transfer line

From the above graph (fig 5), it is observed from the Volume fraction- time plot that the outlet is filled completely with liquid nitrogen phase after 63.5s which is the required chill-down time for a straight pipe.

The volume fraction of liquid nitrogen along suitable faces is displayed as contours.

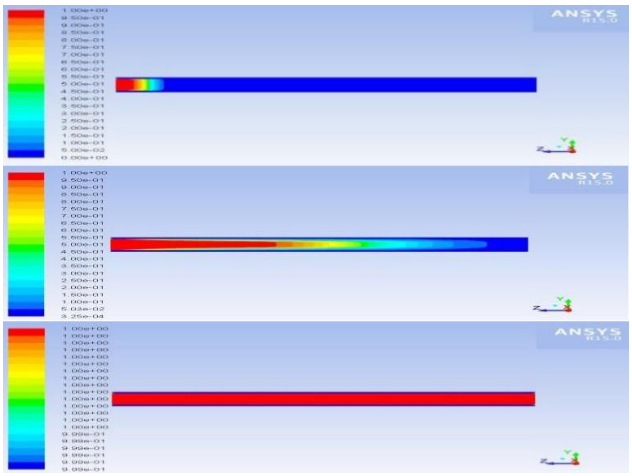

Fig 6 Distribution of volume fraction of liquid nitrogen at the midplane of a straight pipe for different intervals of time

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 liquid core penetrate further downstream eventually filling the tube with liquid.

Part II: Helically coiled transfer lines

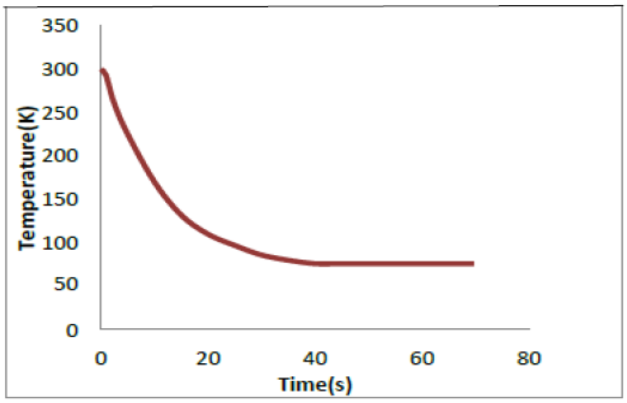

Fig 7 Variation of temperature with time at the solid fluid interface of a helically coiled transfer line

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 11s. 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 28s implying the heat transfer is comparatively lower for this regime. 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 vapor ring with a saturated liquid core. As the flow moves downstream, the liquid core evaporates and the vapor becomes superheated. As the tube wall cools, the.

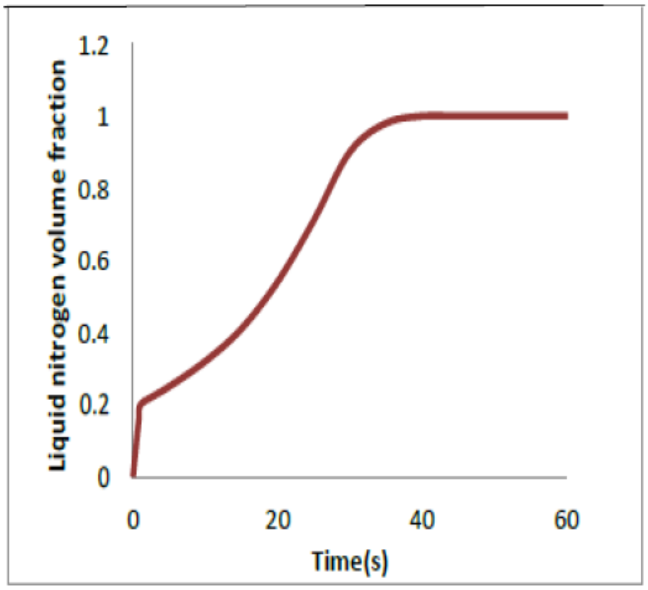

Fig 8 Variation of liquid nitrogen volume fraction with time at the solid fluid interface of a helically coiled transfer line

It is observed from the Volume fraction- time plot that the outlet is filled completely with liquid nitrogen after 39.2s which is the required chill-down time for the helically coiled transfer line. The volume fraction of liquid nitrogen along suitable faces is displayed as 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 vapor ring with a saturated liquid core. As the flow moves downstream, due to curvature of the tube, turbulence is created which enhances mixing of the 2 phases which in turn increases heat transfer, eventually, filling the tube in a rate faster compared to the straight tube transfer line i.e., at 39.2s.

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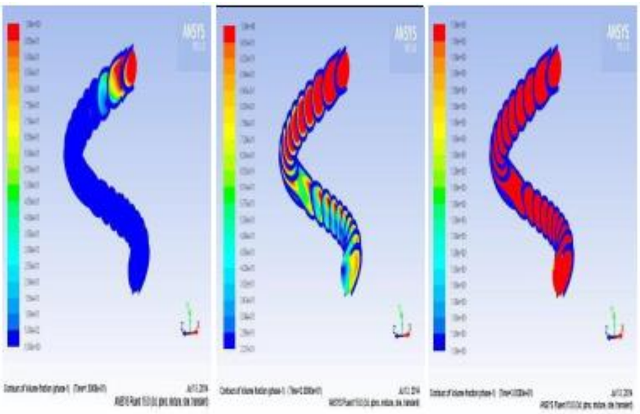

Fig 9 Distribution of volume fraction of liquid nitrogen on iso-surfaces created at different positions of a helically coiled transfer line at different intervals of time.

V. CONCLUSION AND SCOPE OF FUTURE WORK

Chill-down time is seen to reduce by 37.78% (23.8s) while using helically coiled transfer lines as opposed to a straight transfer line. 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 chill-down 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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