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Computational Study of Chill Down Process in Helical Cryogenic Transfer Line Internally Coated with Low Thermal Conductive Layer

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Abstract

The chill down of cryogenic transfer line is important for transporting cryogens from storage units such as cryogenic tanks or Dewar vessels prior to the actual operation of cryogenic systems. Any attempt to reduce chill down time of cryogenic transfer lines result in energy conservation, lowering overall performance costs and aiding in the efficient functioning of any cryogenic system. One of the methods to do so is coating the thin layer of low thermal conductive layer on the inner surface of a transfer line/piping along with proper selection of piping material. In the present research work, computational study of chill down process is carried out in a helical transfer line internally coated with low thermal conductive material of polytetraflouroethylene which belong to a family of Teflon carrying liquid nitrogen as cryogen. The effect of transfer line materials and change in dimensionless pitch ratio (axial pitch) in chill down time has been investigated. And, the effect of variation of inlet velocity on chill down process is also studied. From the computational study, it is observed that aluminium cools faster than steel and copper. For the specified model, the chilldown time of aluminum transferline is 96 seconds, copper is 134 seconds, and steel is 140 seconds. Also, it is discovered that changing the dimensionless pitch ratio by adjusting the axial pitch results in a minor variation in chill down time. Furthermore, the chill down time for a copper helical transfer line with an inlet velocity of 0.03 m/s is 134 seconds, 0.06 m/s is 78 seconds, and 0.09 m/s is 64 seconds, implying that increasing the inlet velocity of flow leads the cryogenic transfer line to chill down quickly.

Keywords

Helical transfer line, Cryogenics, Chill down time, Polytetraflouroethylene, dimensionless pitch ratio

1. Introduction

1.1 Background

The utilization and technical applications of cryogenic liquid has been extended day by day with the cutting edge innovation within the field of cryogenic engineering. Some of the application areas include the propulsion and aerospace systems, manufacturing and industries, cryo-surgery, cryo-coolers and refrigeration, food processing, cells preservations, cryo-liquid transportation, cooling of electrical and electronic components such as motors, semiconductors, superconducting magnets, computer hardware, etc.

The chill down of cryogenic transfer line is important for transporting cryogens from storage units such as cryogenic tanks or Dewar vessels prior to the actual operation of cryogenic systems. Chilldown process is defined as the process of cooling down transfer line/equipment with the cryogen flowing through it. The chilling down of a cryogenic transfer line is a transitory heat transfer problem that involves rapid heat transfer from a solid to a fluid, as well as phase transition, which can result in pressure and flow surges in the fluid [1]. For proper functioning of any cryogenic systems, it is important to know how long it takes to cool down a particular transfer line. Before creating a steady flow of cryogenic fluid in a cryogenic system, the transfer line must be chilled down. The time required for the chilldown of cryogenic transferline corresponds to when the inner surface temperature difference is less than 0.1 Ks-1[2]. If the transitory phenomenon of transfer line chill down is not properly considered, then it might cause a serious damage and even failure of the different components of cryogenic system during its operation.

When liquid cryogens comes into devices via pipes at ambient temperature, which is much higher than the cryogenic fluid temperature, it initially boils and evaporates. The phenomena of cryogenic fluids boiling cause a substantial increase in volume flow rate as well as pressure loss . From the chill down studies, it is inferred that an amount of 90 percent of the cryogen initial supplied to the transfer lines are consumed or rather wasted in the initial period of chill down where, film boiling dominates[3]. So, effective method has to be selected in order to reduce the chill down process time. As a result, several studies and efforts have been done to shorten the chill down time by different researchers. One of the methods is coating the thin layer of low thermal conductive layer on the inner surface of a transfer line/piping along with proper selection of piping material.

Cryogens, in straightforward understanding, are the liquefied forms of gaseous elements such as air, nitrogen, oxygen, and helium that are formed during liquefaction. Thus, liquid oxygen, liquid nitrogen, liquid helium, liquid hydrogen, liquid air is a few of the commonly used cryogen in the field of cryogenic engineering. Liquid nitrogen does have a number of favourable attributes, including non-corrosiveness, non-flammability, chemical stability, easy availability, ease of handling, as well as lower pricing making it excellent and popular choice amongst researchers for chill down investigations.

1.2 Related works

The experiment on straight transfer copper line [1] and straight stainless steel transfer line [2] carrying liquid nitrogen internally coated with polyurethane coating have been done. It is observed that there is rise in heat transfer coefficient and heat flux as well as reduction in chill down time as compared to uncoated tubes.The chill down phenomenon in helical coiled liquid nitrogen transfer line without internal coating is numerically investigated and it is observed that there is reduction in chill down time when a helical coiled transfer line was used as contradicted to a straight transfer line[4]. The experimental study is performed to compare the chill down phenomenon in helical and straight transfer line and the result was similar to that of the numerical investigation[5].

An experiment has been conducted to see the influence of inclination of straight transfer line in chill down phenomenon[6]. Different researchers have performed similar investigations in different cryogens like in liquid hydrogen propellant transfer line [7] and in transfer line transporting liquid argon[8].

The focus of this paper is to computationally investigate the chill down phenomenon on helical transfer line transporting liquid nitrogen internally coated with low thermal conductive layer of polyteterafllouroethylene to study the effect of transfer line materials. Also the effect change in dimensionless pitch ratio (axial pitch) and inlet velocity on chill down time is investigated on a copper helical transfer line.

2. Methodology

The literature review, which is the primary phase of the methodology, covers the vast majority of the study. Books, journals, papers, and articles are thoroughly researched and scrutinized throughout the research to acquire the essential background for the study, including knowledge on cryogenics, liquid nitrogen, the chill down process in a transfer line, and COMSOL multiphysics software, and heat transfer phenomena is gained. In addition, the essential assumptions and theories are recorded.

Secondly, the verification of the previously done experiment of similar phenomenon is carried out by computational study with the use COMSOL multiphysics software to use the same physics and algorithms for the model of this research study.

Next, the model is developed using the model wizard in COMSOL, where a numerical study is performed to determine the exact flow pattern and other parameters like chill down time which are needed for the research. According to the reviewed literature and field conditions, the necessary boundary conditions and flow parameters are determined [1][9][4]. The first phase of numerical analysis is Mathematical modeling, where the physical problem is defined and governing equation for each model is developed and required parameters are calculated. The physics for our problem is conjugate heat transfer in fluid and solid along with the turbulent flow in fluid. The multiphysics we added for the problem is the non-isothermal flow. The K-ε model of turbulent as it is more convenient and efficient for a phase change model of fluid flow in pipe [4].The outer surface of the helical transfer line is subjected to constant heat flux.

The general equation for fluid flow is solved by using Naviers' stroke equation along with the equation of conservation of mass which is given as

$$\rho\frac{\partial u}{\partial t}+\rho(u.\nabla)u=\nabla.[-pI+K]+F$$

$$\frac{\partial\rho}{\partial t}+\nabla.(\rho u)=0$$

The turbulence model that we used for computational study is K-ε model whose equation is given as

$$K=(\mu+\mu_T)(\nabla u+(\nabla u)^T)-\frac{2}{3}(\mu+\mu_T)(\nabla.u)I-\frac{2}{3}\rho KI$$

$$\rho\frac{\partial k}{\partial t}+\rho(u.\nabla)k=\nabla.[\mu+\frac{\mu_T}{\sigma k}]\nabla k+p_k-\rho\varepsilon$$

$$\rho\frac{\partial\varepsilon}{\partial t}+\rho(u.\nabla)\varepsilon=\nabla.[(\mu+\frac{\mu_T}{\sigma k})\nabla\varepsilon]+c_{\varepsilon1}\frac{\varepsilon}{k}P_k-c_{\varepsilon2}\rho\frac{\varepsilon^2}{K}$$

In the model there is a conjugate heat transfer where heat transfer takes place both in solid and liquid. The general equation for heat transfer in fluid is given as:

$$\rho C_p\frac{\partial T}{\partial t}+\rho C_p u.\nabla T+\nabla.q=Q+Q_p+Q_v$$

$$q=-k\nabla T$$

The general equation for heat transfer in solid is given as:

$$\rho C_p\frac{\partial T}{\partial t}+\rho C_p u.\nabla T+\nabla.q=Q+Q_t$$

$$q=-k\nabla T$$

Convective heat transfer occurs on the outer surface of the helical transfer line, which is solved by the equation given as

$$-n.q=q_0$$

$$q_o=h(T_e-T)$$

The numerical analysis is also divided into three stages. First, the influence of different transfer line materials on the chill down phenomena of a helical cryogenic transfer line is analyzed, and then the effect of changing the dimensionless pitch ratio by changing the axial pitch on the chill down phenomenon is studied and later on the effect of variation of inlet velocity in chill down time is also investigated.

3. Analysis in COMSOL Multiphysics

3.1 Geometric model of helical transfer line

The geometrical model of helical transfer line is drawn in graphic window of COMSOL multiphysics 5.6 with appropriate dimensions. The model comprise of two domains namely fluid domain in the centre and other solid domain along with the thin layer of low conductive material of Polytertraflouroethylene (PTFE).The geometric model for our study is shown in Figure 1.

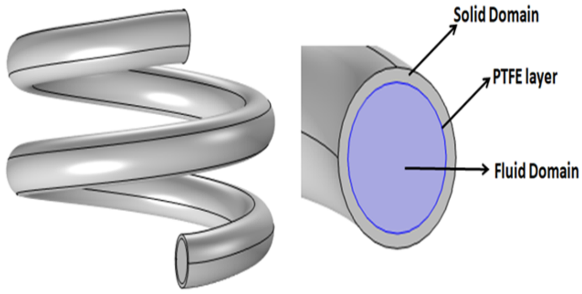

Figure 1: Geometric model of helical transfer line

The geometric description of the helical transfer line is given in Table 1.

Table 1: Geometry Description

Description	Values
Number of turns	2
Major radius	50 mm
Minor inner radius	5 mm
Minor outer radius	6 mm
Axial pitch	30 mm
Radial pitch	0
PTFE layer thickness	0.1 mm
Chirality	Right handed

The properties of low thermal conductive layer of polytetraflouroethylene are elisted in Table 2.

Table 2: Properties of polytetrafluroethylene(PTFE)

Description	Values
chemical formula	$(c_2F_4)_n$
Density	2000 Kg/m^3
Melting point	600F , 327°c
thermal conductivity	0.25 W/(m.k)

3.2 Mesh independence test

Mesh independence tests are performed on different meshes with physics-defined mesh sizes of 209390 (M1), 373368 (M2), 933088 (M3), and 1022393 (M4) elements, and chilldown time is calculated, which is shown in Table 3.

Table 3: Mesh independence test

Mesh set	Number of elements	Chilldown time(s)
M1	2,09,390	138
M2	3,73,368	135
M3	9,33,038	134
M4	10,22,393	134

The chill down time versus number of element graph is plotted which is shown in Figure 2 and it is observed that after a fine mesh of 933088 elements(M3), there is no change in the value of chill down time. Thus, from the mesh independence test, 933088 elements were chosen for analysis to reduce the computational cost and time.

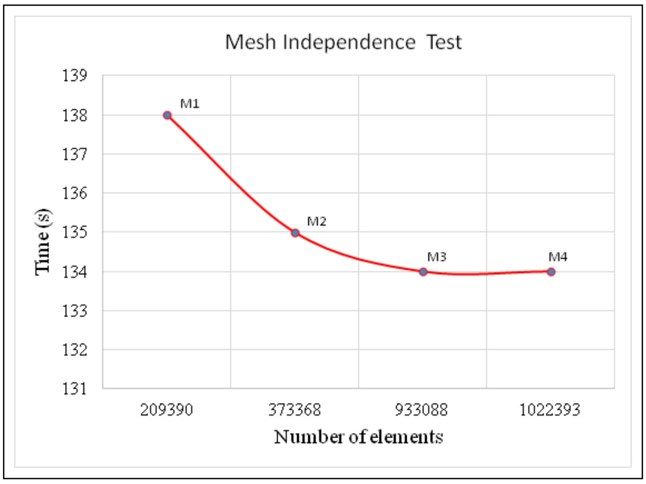

Figure 2: Mesh independence test

3.3 Setup

The model is run under multiphysics platform which is conjugate heat transfer with turbulent model along with non isothermal flow. The Conjugate Heat Transfer branch contains different versions of a multiphysics interface that couples heat transfer in solids and fluids with laminar or turbulent flow. In the Turbulent Flow, k-ε interface is selected for the fluid domain for it proven accuracies in two phase pipe flow [4]. Since the main aim of this study is to see the variation of surface temperature of wall over time, the Time Dependent study is used for our study. The initial conditions and boundary conditions required for the defined Physics is are employed. The inlet velocity is selected such that the Reynolds number falls within the turbulent zone for the investigation of the influence of transfer line materials, the effect of axial pitch variation, and the effect of inlet velocity variation on chill down time.The time dependent solver is solved in order to obtain the solution for the model from 0 sec to 150 sec with time step of 0.5 sec.The time discretization is transient with the time stepping method of implicit BDF. Once the solution has been converged, the result is post-processed, and various contours and graphs are generated to analyze the chilldown phenomena.

4. Results and discussions

4.1 Chill down of helical transfer line of different transfer line materials

The chill down curve of different transfer line materials of a helical transfer line namely copper,aluminium and steel internally coated with the layer of polytetraflouroelthylene is shown in Figure 3.

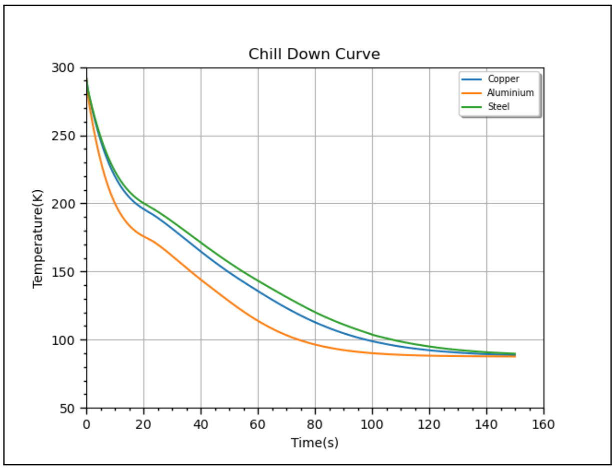

Figure 3: Chilldown curve of different transfer line materials

From the chill down curve in Figure 3, it has been observed that aluminium, copper and steel have a chill down time of 96 seconds, 134 seconds and 140 seconds respectively. Thus, the chill down of the transfer line occurs faster for the aluminium followed by copper and take longest time for the steel. Thermal conductivity and heat capacity at constant pressure is responsible for determining the cooling or heating process in a metal. Thus, among cooper, aluminum, and steel, aluminum would be the best cryogenic transfer line when only chill down time is considered.

The surface temperature contours of different transfer line materials is evaluated during post processing for different time interval. The comparison of temperature contours for time 30 sec and 120 sec for different line material is shown in Figure 4, 5 and 6.

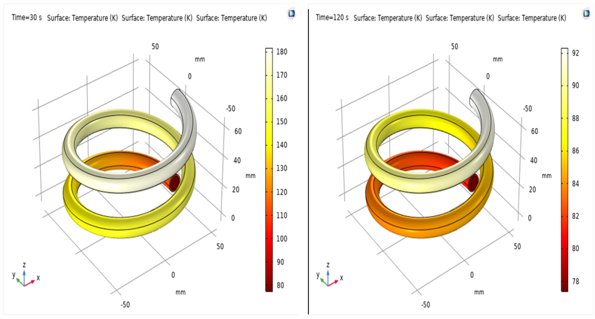

Figure 4: Surface temperature contour of copper at t=30 sec and t= 120sec

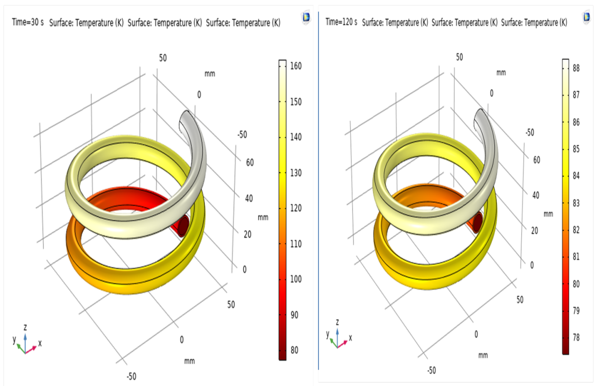

Figure 5: Surface temperature contour of aluminium at t= 30 sec and t= 120sec

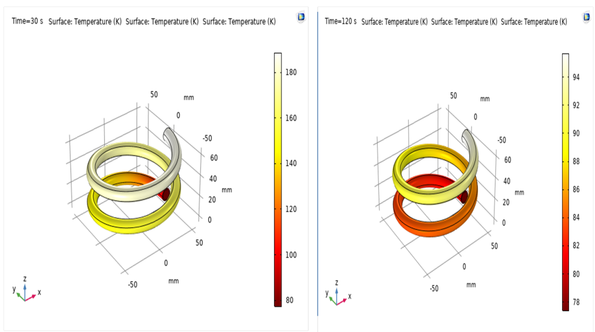

Figure 6: Surface temperature contour of steel at t= 30 sec and t= 120sec

From the temperature contour in Figure 4, 5 and 6, it is inferred that as the time progresses, the temperature of the transfer line progress towards an equilibrium temperature. It is because initially the liquid nitrogen is super heated due to wall temperature of transfer line and as the moves downstream with time, the liquid core penetrates further downstream, cooling the tube wall.

4.2 Chill down of copper helical transfer line of varying change in dimensionless pitch ratio (axial pitch)

By adjusting the axial pitch and modifying the dimensionless pitch ratio, a computational study of chill down for a copper helical transfer line is carried out. Axial pitches of 15mm, 30mm, and 50mm are investigated. Chill down graph for various dimensionless pitch ratios is shown in Figure 7.

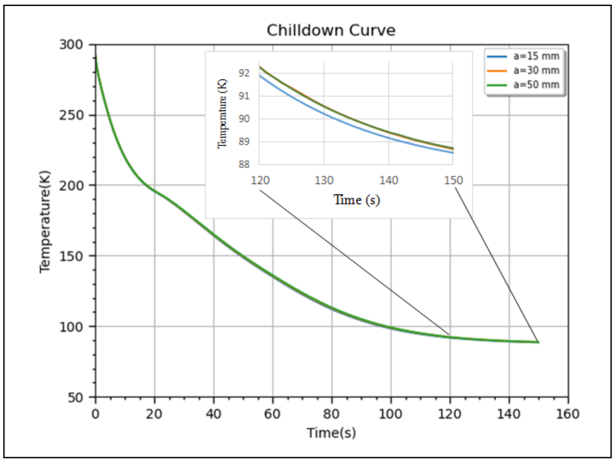

Figure 7: Variation of inner surface temperature with axial pitch of helical transfer line

From the graph, it can be observed that there is no significant change in the chill down curve as well as chill down time with change in axial pitch for this model. However, if the tabular data of graph is closely examined, it can be noticed that there is a slight temperature fluctuation. It might be due to the fact that the model that is being computed is of smaller scale. However, there might be significant consequences for practical transfer line prototypes with larger dimensions.

4.3 Chilldown of copper helical transfer line of varying inlet velocity

By changing the inlet velocity of flow, a computational study of chill down for a copper helical transfer line is carried out. The inlet velocities in a helical transfer line of 0.03 m/s, 0.06m/s and 0.09 m/s are investigated.The chill down graph for various inlet velocity conditions is shown in Figure 8.

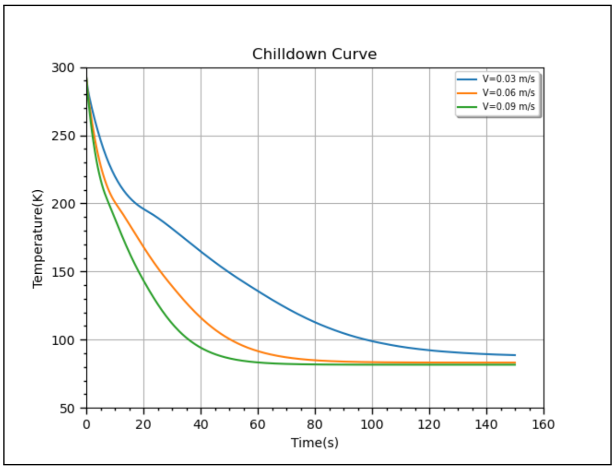

Figure 8: Variation of inner surface temperature with inlet velocity

The graph in Figure 8 shows that as the inlet velocity of flow increases, the chill down time for the helical transfer line decreases. The chill down time for V= 0.03 m/s is 134 seconds, whereas it is 78 seconds for V= 0.06 m/s and 64 seconds for V=0.09 m/s. The increase in velocity corresponds to an increase in the mass flow rate at the inlet. As a result, it can be deduced that as the mass flow rate increases, chill down occurs quickly.

4.4 Verification of Physics used

A circular tube with an internal diameter of 8mm and a thickness of 0.5 mm is modelled, and all of the needed parameters and boundary conditions are acquired from experimental based research paper entitled 'Experimental study on the effect of low conductivity coating on cryogenic transfer lines' [1]. The model is subjected to computational study in COMSOL multiphysics software.

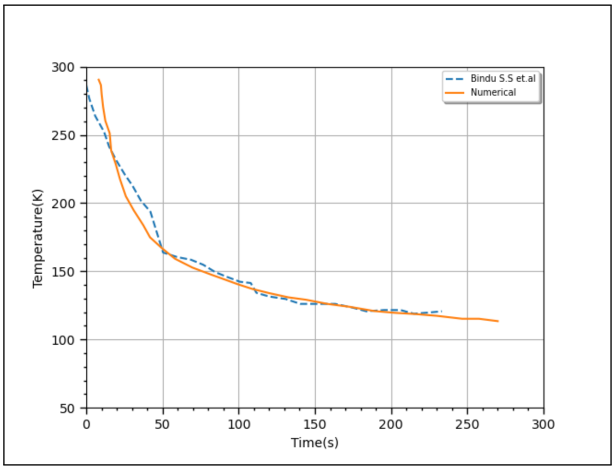

Figure 9: Verification of physics used

After the solution has converged, the temperature vs. time graph in the inner wall of the transfer line for the mass flow rate of 102 kg/m^{2}s is evaluated using post processing. The computational study's findings are compared to the experimental study's results of Bindu S.S et.al, and the comparison results are presented in Figure 9.

From the graph shown in Figure 9, it is noticed that numerical and experiment study yielded results that were virtually identical. As a result, the same algorithms and physics can be utilized to simulate comparable problems using COMSOL multiphysics software.

5. Conclusion

From the computational study of chill down of helical transfer line coated with low thermal conductivity layer of polytetrafluroethylene, it is found that chill down time of aluminum is less than that of copper and steel. For the model, the chill down time of aluminum transfer line is 96 seconds, copper is 134 seconds, and steel is 140 seconds. As a result, aluminum should be regarded as a transfer line material when chill down time is the only factor to consider when choosing a transfer line materials. Moreover, when the effect of change on axial pitch for a copper helical transfer line on chill down time is studied, it is found that there is no significant variation on the chill down time for the given model. Also, the variation of chill down time with change in inlet velocity in helical transfer line is studied. The chill down time changes dramatically as the inlet velocity rises. The chill down time for a copper helical transfer line with an inlet velocity of 0.03 m/s is 134seconds, 0.06 m/s is 78 seconds, and 0.09 m/s is 64 seconds. In addition, an increase in inlet velocity means in an increase in mass flow rate. If cryogen consumption is not a top priority, the increase of mass flow rate or inlet velocity of flow results in chilling the transfer line more quickly. As a result of the study, it can be deduced that the materials used in the transfer line, the dimensions of the helical transfer line, and the flow inlet velocity all have a significant role in the change of chill down time of a cryogenic transfer line during chill down phenomenon.

6. Recommendation

In order to get a better understanding of the chill down phenomena, an experimental examination of chill down of a helical transfer line coated with a low thermal conductivity layer of polytetraflouroethylene can be carried out for the same geometry on a cryogenic chill down test rig. Also, the impact of various interior coatings of transfer line on chill down time can be explored. Furthermore, other types of helical transfer lines, such as conical-helical transfer lines and other geometries, can be investigated.

Acknowledgments

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