ISSN 2229-5518

Experimental investigations on Helical and straight cryogenic transfer lines under different mass flux

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Abstract— The present study is concentrated on the chilldown time analysis of helical coils compared to straight tubes. Data presented in this paper is for the experiments conducted under terrestrial gravity conditions with different mass fluxes [66 Kg/m^2s, 86 Kg/m^2s and 102 Kg/m^2s] in horizontal copper line (7.9375 mm OD,0.8128 thick and 500 mm length) and a copper helical test section having helix angle 8^0 with horizontal axes under Polyurethane foam insulation. Both the sections were instrumented with temperature sensors, the readings of which were tracked in real-time using a data acquisition system. Temperature-time relationships were obtained. The results of the experiment indicated that, for a given mass flux, the transition during chilldown occurs earlier in helical transfer lines compared to straight tubes. This indicates the earlier occurrence of film boiling for the helical channels. Thus, the chilldown time can be reduced to a considerable extend there by reducing consumption of cryogen. The authors hereby suggest the application of helical geometry in cryogenic transfer lines wherever possible for the reduction of cryogen consumption during the initial stages of transfer process which can eventually result in energy savings.

Index Terms— Cryogenics, Chilldown, Liquid nitrogen, Helical transfer line, Cryogen saving

Nomenclature

G Mass flux, kg/m2.s-1

1. Introduction

From the time it started off as a scientific branch concerning with liquefaction of gases, the evolution of cryogenics has been instrumental to the extent that today we can find its applications over a wider horizon such as cryosprays, food preservation, space simulation chamber, cryonics, SQUID system using superconducting magnets etc. These applications demanded the transfer of cryogens from the storage unit to the location of its utilization. When the cryogen initially traverse through the transfer line which is in thermal equilibrium with the ambient, it gets evaporated until the transfer line is brought to a steady state temperature near the saturation temperature of the fluid so that subsequent flow would be in liquid phase. This initial phase of cryogenic transfer, where voracious evaporation occurs, is usually termed as chilldown or cooldown of cryogenic transfer lines. Nearly about 10 KWh of electricity is consumed during the process of production of one liter of liquid nitrogen. From chilldown studies it is inferred that an amount of 90% of the cryogen initially supplied to the transfer lines are consumed, or rather wasted in the initial period of chilldown where, film boiling dominates. Any initiative in the way of reducing chilldown time in cryogenic transfer lines can result in energy conservation and thereby reducing the cost of overall performance of any cryogenic system. Hence, optimization of chilldown parameters has been an area of research interest for decades.

2. Literature Review

The first remarkable work in this field dates back to 1960s when single phase convective heat transfer and film boiling were forecasted to be existing when Burke et al. [1] probed pressure chilldown of cryogenic transfer lines using liquid nitrogen as the cryogen. The visual inspection revealing the existence of flow patterns in two phase flow using liquid nitrogen and was observed by Bronson et al. in 1962[2]. His findings substantiated the fact that flow stratification led to the fluctuations in peripheral temperature. Chi and Vetere [3] in 1963, recorded transient wall temperature and associated it with the visual inspections to identify the regimes in flow transitions by employing liquid hydrogen flow through copper tubes. The classification of flow regimes into single phase convective boiling, film boiling and nucleate boiling were demonstrated by Chi[4] in 1965 by passing liquid hydrogen through aluminium transfer lines. He inferred that the film boiling consumes about 90% of the total chilldown time.

Sreenivasan et al. [5] through experiments in 1974 concluded that mass flow rate has no appreciable effect on chilldown time in short transfer lines. In 2007, Yuan et al. [6] studied the effect of low rates of flow, in cryogenic system chilldown. Later in 2009, he suggested terrestrial and microgravity numerical models. He also succeeded in associating the erstwhile results regarding visual inspections and peripheral temperature fluctuations and implied that liquid film-wall interaction was the driving force behind chilling of the bottom wall of transfer lines whereas, in the upper wall, forced convection of superheated vapor did the work. In 2012, Hu et al. [7] carried out experiments at low and high mass flow rates to find its impact on various flow patterns. He also studied the variation of heat flux and chilldown time when the flow was directed upward and downward through a vertical pipe and found out that while the former took more time to chilldown the pipe, the latter was having higher critical heat flux.

Study of chilldown in horizontal and inclined pipe was conducted both experimentally and numerically by Johnson et al. [8] in 2015. They employed inverse heat transfer technique to the transient chilldown period to presage heat flux and local heat transfer coefficient. Their results suggested the existence of an optimum upward line inclination that can minimize chilldown time. Darr et al. [9] in 2016 recognized that optimal design of cryogen transfer lines can be attained by identifying methods for minimizing cryogen consumption. They explained the effects of mass flux, pressure, flow direction, equilibrium quality and inlet subcooling in relation to gravity using liquid nitrogen through stainless steel test section. The data points obtained from their findings enabled them to arrive at a correlation for the heat transfer coefficient in straight transfer lines.

Evolution of diffusion pumps in the 1910s demanded the need for preventing the back stream of oil from the pump. This led to the development of liquid nitrogen cooled surface traps for condensing the back streaming of vapor. Helical geometries were often employed for cooling those surfaces. In 2002, D. G. Prabhajan et al. [10] compared helically coiled heat exchanger with straight tube heat exchanger using water as the exchange fluid and concluded that helical tube has got better heat transfer characteristics. They asserted that coil geometry and fluid flow rate plays significant roles in elevating the temperature of the fluid. Subhashini et.al. [11] in their review paper on the applications of curved geometries in process industries , demonstrates that helical geometries exhibit similar and sometimes better performance at lower energy consumption and reduced maintenance requirements over conventional configurations.

In spite of the aforementioned works which were limited to straight transfer lines, and heat transfer studies on helical transfer lines, lesser experimental data focusing on reduction of chilldown time using helical transfer lines are available. The objective of this paper is to experimentally compare the chilldown time needed for helical and straight cryogen transfer lines.

3. Experiment Setup

A systematic layout of the experimental setup can be shown in fig 1. The entire setup consists of three sections namely:

- Liquid nitrogen storage and supply system
- Test section
- Instrumentation and Data Acquisition system.

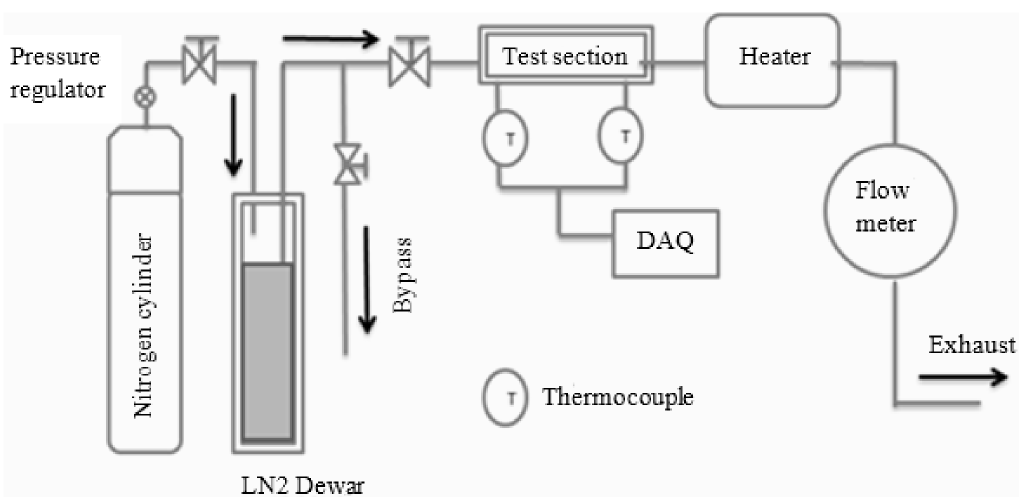


Fig.1. Layout of Experimental setup for chilldown studies.

Cryogen for this experimental study was Liquid nitrogen .It was selected because of its non-corrosive, relatively inexpensive, chemically inert, easily available, non-flammable characteristics and it does not pose any major hazards

. The liquid nitrogen was stored in IBP Co. Limited made TA-55, Dewar of capacity 55 L with static loss rate of 1.3 % per day. The Liquid nitrogen Dewar was pressurized u sing a nitrogen gas cylinder of 47 L capacity. The high pr essure nitrogen gas cylinder can supply gas at maximum pressure of 15 bar. The flow rate of liquid nitrogen was c ontrolled manually by controlling the Dewar pressure by employing a pressure regulator mounted on the nitroge n gas cylinder.

Copper tubes (specific heat capacity of 401 J/Kg K and thermal conductivity of 0.14 W/mK at 300 K) were selected for the study in regard with the low flow rates f rom the Dewar. Test section under consideration were 5/ 16" Copper tubes of 500 mm long for straight channel an d copper lines of helical geometries (7.9375 mm OD 0.81 28 mm Thick) with coil diameter of 116 mm. Coils with s ix helix angles viz. 40, 6 0,80,100,120 and 160 were studie d and the coil with 80 helix angle was considered for the present study. Liquid nitrogen was supplied to the test se ction through 1/2" SS 304 grade pipes and brass fittings. A bypass line was provided before the test section to byp ass the initial vapour produced during the initial cool do wn of the supply system. A transparent line provided at t he bypass line ensures a steady state of liquid being supp lied and only after that the line to the test section is open ed. Heat in leak at the inlet section was minimized by em ploying a combination of asbestos rope, nitrile rubber an d urethane modified poly-isocyanurate foam (thermal co nductivity of 0.14 W/mK).

The wall temperatures of each geometry was me asured by 18 thermocouples with three equidistant therm ocouples at each location at six equidistant points till a di stance of 360 mm (along the tube) from inlet employing T -type thermocouples. An insulation was provided with 1 60 mm as OD with urethane modified poly-isocyanurate foam to reduce the heat in leak at the section. Keysight 34 972A Data Acquisition / Data Logger Switch Unit was a dopted for logging data. Mass flux was measured by a si ngle phase mass flow measuring Rota meter at the exit li ne kept after a hot water bath maintained at 1000 C.

3.1 Experiment procedure

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

4. Results and Discussion

Experiments were conducted for both straight channel and for helical transfer line of helix angle 80 and coil diameter of 116 mm under three different mass flow rate (G), varying as 66 Kg/m^{2}s, 86 Kg/m^{2}s and 102 Kg/m^{2}s.

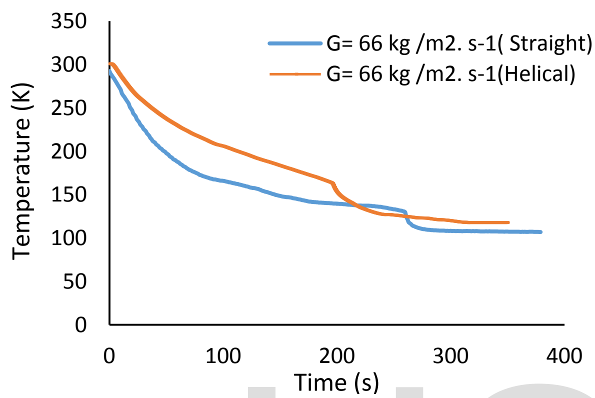
4.1 Time temperature profile of straight and helical transfer lines

Experimental results obtained for both straight and helical transfer lines are provided here. Wall temperature readings obtained were used for predicting the heat transfer and flow characteristics and was subjected to comparison.

Jackson et al. [12] proposed three different phases of chilldown phenomena, namely film boiling regime, where the flow structure can be either stratified flow or inverted annular film flow. Transition boiling regime, where a sudden drop in temperature is observed as liquid droplets begin to wet the wall. Nucleate boiling regime, where flow can be either bubbly or slug flow.

As observed from the works of researchers in this field, the present study also regards the initiation of transition regime as the basis for the comparison of chilldown parameters. This is because the temperature is found to be almost steady after the transition regime. Three regimes observed during previous studies of chilldown in straight tube was also observed in helical geometry. However, the observed chilldown transition temperature and time were different from the straight geometry.

In laminar flow, previous studies show that helical coils generally have superior heat transfer characteristics than straight channels. But this may not be true in turbulent flow to which our study belongs. This is also coincident with the results got through this work which suggest that in certain mass fluxes, coils with certain helix angles lagged behind straight channel in achieving chilldown. The variation may be due to the combined effect of added turbulence due to the curvature and the effect of body forces present in the system. Gravitational effect played a significant role in

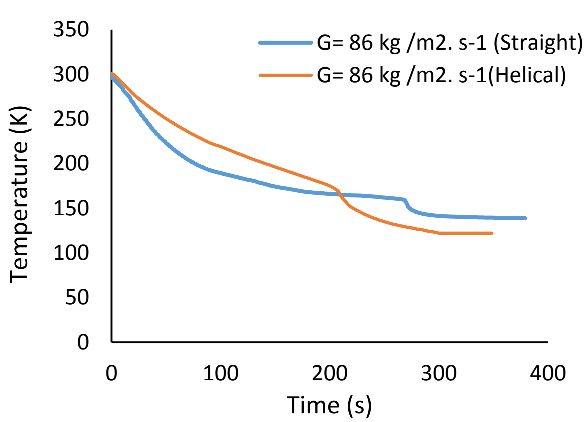


chilldown of a horizontal straight line. In case of straight geometry, the gravity forces and pressure force are perpendicular to each other. In the present scenario the pressure force changes the direction depending on the alignment of the helical coil. Pressure force was at a positive inclination with the horizontal during the first half turn and was in a negative inclination in the second half turn. The wall temperature time profile comparison for mass flux of 66 kg/m2.s-1, 86 kg/m2.s-1 and 102 kg/m2.s-1 are shown in Figs 2-4.

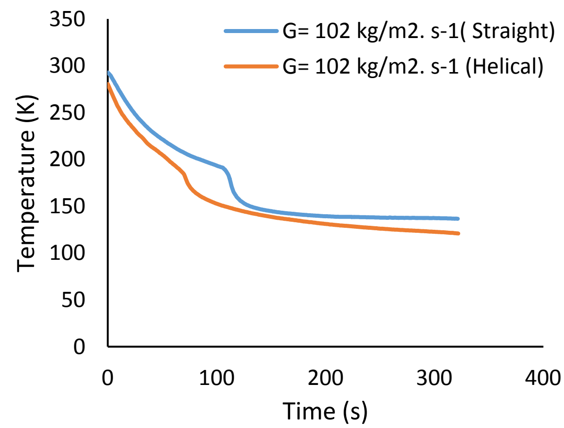
Fig.2. Wall temperature time profile comparison for mass flux of 66 kg/m2.s-1.

Fig. 3. Wall temperature time profile comparison for mass flux of 86 kg/m2.s-1.

The first region mainly represents the film boiling region and the flow structure can be inverted annular or stratified flow, the second region represent the transition regime and third one is the nucleate boiling regime, where either bubbly or slug flow can exist. From the



figures it is found that the time required to cover film boiling region in helical transfer lines is lesser than that needed in straight channel. The transfer line will reach



chilldown at a faster rate after attaining transition. Table1 shows the percentage variation of transition temperature for straight and helical channels under different mass fluxes.

Fig. 4. Wall temperature time profile comparison for mass flux of 102 kg/m2.s-1.

It is evident from the results that there is a direct relation between mass flux and occurrence of transition temperature. From these results, it can be inferred that helical coil have shorter chilldown time and also the time taken for transition to occur is less compared to straight channels.

TABLE.1.

PERCENTAGE VARIATION OF TRANSITION TEMPERATURE FOR STRAIGHT AND HELICAL CHANNELS UNDER DIFFERENT MASS FLUXES.

Geometry			
Mass flux (kg/m2.s-1)	Transition temperature for Straight channel	Transition temperature for Helical channel	% variation
66	259	196	24
86	289	208	28
102	109	71	34

4.2 Comparison of the effect of different mass flow rates on chilldown time

Fig. 5 shows the mean variation of temperature with time for coil with 80 helix angle mass fluxes 66 kg/ m2s, 86 kg/ m2s and 102 kg/ m2s. From the figure, it is evident that the transition from film boiling to nucleate boiling happen at higher wall temperatures with increase in mass flux. This may be due to the added turbulence caused by the secondary flow in helical pipe geometry resulting in the effective mixing of vapour and liquid phases in inverted annular film region and have uniform convective heat transfer around the wall surface.

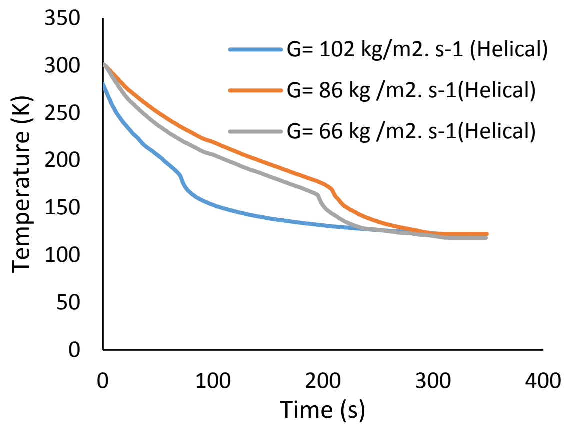


Fig. 5. Wall temperature time profile comparison of helical transfer line under different mass fluxes.

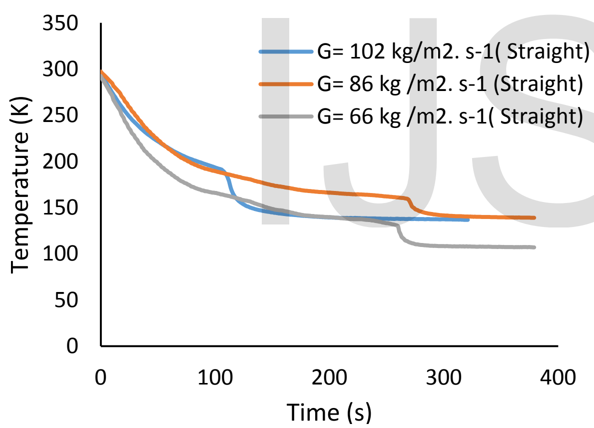


Fig. 6. Wall temperature time profile comparison of straight channel transfer line under different mass fluxes.

The wall temperature time profile comparison of straight channel transfer line under different mass fluxes is shown in fig.6.

5. Conclusion

This paper presents the results of an experimental study conducted on cryogenic chilldown of straight copper transfer line and helically coiled copper transfer line. For analyzing heat flow characteristics during chilldown process the transient temperatures for different mass flux conditions were measured. It was identified that the chilldown characteristics of copper transfer lines with a simple insulation like Polyurethane foam were similar to that of previously published studies on steel transfer lines. There is an inverse relation existing between the mass flux and chill down time for each geometry. Transition from film boiling to nucleate boiling occurred at higher wall temperature for both straight and helical channels, with increase in mass flux. It was seen that for a particular mass flux, transition occurs earlier in helical transfer lines than in straight channels. This results in cryogen saving ultimately creating opportunities for energy saving in an energy intensive scenario. The chilldown characteristics of helical transfer line was found to be different from the straight tube and it may be due to the variation in direction vectors of pressure force with positions in the helical transfer line. Unlike the temperature difference between upper and lower portion of the straight pipe, there is uniform distribution of wall temperatures at each sections in helical coils. This may be due to additional turbulence caused by the curvature. Future works on identifying the avenues for reduction in cryogen consumption by varying geometries can be investigated into.

Acknowledgment

Authors would like to acknowledge Space Technology Laboratory in TKM College for engineering for setting up the experimental setup. They would also like to express gratitude for Technical Education Quality Improvement Programme Phase-II (TEQIP-II) promoted by National Project Implementation Unit, MHRD, Government of India for their support.

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