Study on chilldown characteristics of a straight copper tube under pulsated cryogen flow

Jesna Mohammed, Resmi S.L, Muhammed Zakkeer M Hashim V, Bindu S.S

Abstract: Transfer line must be chilled down to the saturation temperature of the cryogen for uninterrupted fluid supply at use point. The process of cool down of related equipments with cryogenic fluid is known as cryogenic chilldown. In this paper, we have investigated the influence of variation in fluid flow pattern namely, pulsed and continuous flow of cryogenic fluid on the chilldown characteristics of a horizontal straight copper tube using liquid nitrogen under varying mass fluxes. To gain an understanding of how different flow patterns affect the efficiency of the chilldown process; different square wave pulse flow strategies were examined and compared with continuous cryogen flow pattern. Results from the different pulse rate experiments showed that, with increase in mass flux low off time pulse pattern reduces the chilldown time. Moreover, reduction in cryogen consumption for chilldown was observed in pulse flow pattern compared to continuous fluid supply.

Keywords: Chilldown, Cryogenic, Copper tube, Film boiling, Heat transfer, Liquid Nitrogen, Pulsating flow.

1. INTRODUCTION

Cryogenic fluids play an indispensable role for many space, medical and industrial applications such as metal processing, plate glass production, food processing, manufacture of MEMS, cryoresistive cables, high power electronic elements and so on. Proper transport, handling and storage of cryogenic fluids are some of the deciding parameters in their proper operation and performance. The complete understanding of N2 flow boiling heat transfer through channels is required for the design of these systems. Chilldown of the system components during initial applications is an inevitable part of cryogenic transport circuit. Owing to its low surface tension, low latent heat of vaporization and small liquid surface contact angle make these fluids different from conventional fluids. The intricate interaction between the two-phase flow and the boiling heat transfer results in the increased complexity of the chilldown process. However, the chilldown or quenching process which initiates cryogenic fluids transport has not been fully understood. The inherent threat during chilldown is that two-phase flows are unstable and can experience extreme flow and pressure fluctuations. The hardware may be subjected to extreme stresses due to thermal contraction and may not be able to sustain extreme pressure fluctuations from the cryogen. Efficiency of the chilldown process is also a significant concern since the cryogen used to chill down the system can no longer be used for propulsion or power generation. Therefore, chilldown must be accomplished with a minimum consumption of cryogen. An optimum flow rate exits that minimizes liquid consumption during the chilldown process. At higher flow rates, there is insufficient time for heat transfer from the liquid to the wall and inefficiencies result from the greater amount of incompletely vaporized liquid passing through the system. At lower flow rates, chilldown time and total ambient heat leak into the system increase, which raises liquid consumption. As a result, it is important to fully understand the thermo-fluid dynamics associated with the chilldown process and develop predictive models that reliably predict the flow patterns, pressure loss, heat transfer rates, and temperature history of the system. Chilldown in transfer lines are mainly affected by mass flow rate, initial wall superheat, liquid subcooling, gravity, material properties and orientation of the tube. Researches are still going on in analyzing the effects of various factors in this process. Difficulties in setting up experiments with cryogenic fluids provide less data in chilldown of cryogenic fluids. So far, chilldown effect is studied mainly with chilled water, FC 72 and occasionally with R113 and LN2.

Among the earlier researchers investigating LN2 flow boiling heat transfer in tubes Burke et al. [1] studied the pressure chill down of stainless-steel lines of different dimensions using liquid nitrogen. They anticipated the existence of single-phase convective heat transfer and film boiling. The findings of Bronson et al. [2] revealed the existence of flow patterns in two phase flow thereby authenticating the fact that fluctuations in peripheral temperature was a result of flow stratification. Later Laverty et.al. [3] explained that the plot of HTC along the axial direction had one peak and valley occurring at low vapor quality and the other peak much higher than the first. While, Yuan et al. [4] through their studies clearly

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demarked the three boiling regimes during line chilldown: film, transition, and nucleate boiling that cryogenic liquid encounters. Chilldown studies conducted on aluminium transfer lines by Chi et al. [5] reported that 90% of the chilldown time is dominated by film boiling with the maximum cryogen consumption. Studies on chilldown mechanism in short transfer lines made of Copper, Aluminium, Glass and Stainless Steel was conducted by Sreenivasan et al. [6] and they concluded that further works has to be done to predict the exact characteristics in chilldown physics. Dresar et al. [7] through their investigations on transient behavior of a small-scale cryogenic transfer line predicted that the optimum flow rate for chilldown of a cryogenic transfer line is about 3-5 times the flow rate necessary to balance the total heat in-leak. A procedure for predicting the transient heat transfer coefficient in a horizontal transfer line was provided Jackson et al. [8]. Increasing the supply pressure and providing sub cooled cryogen was suggested as a verified method to enhance heat transfer resulting in chilldown time reduction by Majumdar et al. [9] through a numerical package for chilldown. Klimenko et al. [10] investigated the effect of geometry and transfer line orientation on heat transfer with liquid nitrogen and concluded that these parameters greatly affect the low velocity cryogen transfer. Hartwig et al. [11] through cryogenic flow boiling experiments using Liquid Nitrogen and Liquid Hydrogen under high and low Reynolds Numbers concluded that rapid occurrence of chilldown at higher Reynolds Numbers was due to quick transition from vapor flow to annular liquid flow. Yuan et al. [12] through their chilldown studies under terrestrial and microgravity conditions associated their previous results concerning visual inspections and peripheral temperature fluctuations and inferred that the driving force behind chilling of the bottom wall of transfer lines was the interaction between liquid film and wall while, forced convection of superheated vapor ensured the effort on upper wall. Hong Hu et al. [13] by varying mass flux and flow direction in vertical pipes studied the effect of flow patterns on heat flux and chilldown time. They recognised that upward flow took more time to chilldown the pipe but, higher critical heat flux was encountered during downward flow. Effect of transfer line orientation on chilldown was investigated both experimentally and numerically by Johnson et al. [14]. Heat flux and local heat transfer coefficient was presaged by employing an inverse heat transfer technique to the transient chilldown period. The existence of an optimum upward line inclination that can minimize chilldown time was proposed by the authors. Darr et al. [15][16] documented the parametric effects of mass flux, pressure, flow direction, equilibrium quality and inlet sub cooling in relation to gravity on chilldown of transfer lines using liquid nitrogen through stainless steel test section. Using the enormous data points obtained from the study, they have proposed a correlation for the heat transfer coefficient in straight transfer lines. Shaeffer et al. [17] studied the effect of varying mass flux or Reynolds number in pulsating and continuous flow in LN2 transfer lines. The lowest chilldown efficiency, as low as 5-8% was identified for film boiling region whereas, highest chilldown efficiency is encountered for nucleate boiling region.

Very few literatures are available in chilldown in a copper transfer line. Copper tubes possess an advent of added flexibility in transfer lines but the increased parasitic heat influx due to high thermal conductivity limits its practicability in cryogenic systems and so are the studies on bare copper transfer lines. To design an effective transfer line for economic cryogenic transport, extensive studies that investigates effect of parameters like mass flux of cryogen, flow patterns, geometry, orientation of test section, and thermal mass of transfer line are to be performed. As a part of this extensive parametric investigations, the present work is concentrated on the study of copper transfer lines with simple insulation such as Polyurethane foam insulation under pulsed and continuous flow pattern of liquid nitrogen. Three different mass fluxes (86 kg/m²s, 102 kg/m²s & 125 kg/m²s) with three different pulse of 10 sec duty cycle (7sec on - 3sec off, 8sec on - 2sec off, 9sec on - 1 sec off) for each case was adopted. Similar chilldown trends in previous literatures were observed. Further sections of his paper discuss a typical chilldown process followed by experimental setup and procedure of experimentation. Results and discussion along with the methods of data reduction is elucidated.

1.1. Chilldown Process

Chilldown can be defined as the inverse process of boiling and can be explained by a boiling curve. Boiling occurs as a result of heating a liquid to its saturation or boiling point. The liquid will be converted into the vapor phase by extracting latent heat from the walls. Various regimes of the boiling curve are Film boiling, Transition boiling, Nucleate boiling and single-phase convection. Fig. 1 shows a typical boiling curve and the flow regimes.

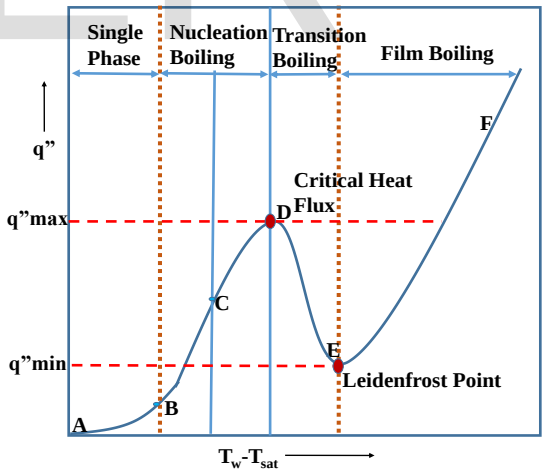


Fig. 1. Typical boiling curve and the flow regimes.

Quenching process begins in the film boiling regime of the boiling curve (Point F) and move towards Point E, then to Points D, C, B, and A. If the excess temperature (the difference between the inner wall surface temperature and the fluid saturation temperature) is very large then Film boiling occurs. As a result of film boiling the surface is not wetable by the liquid, causing a vapor blanket to veil the surface. The cooling of the tube wall causes the transfer of heat from the wall surface to the fluid. A further infusion of cryogen to the wall surface will continue to cool down the surface; finally allowing the liquid to initiate a direct contact with the surface that is known as re-wetting. This

moment of the first liquid contact is known as the quenching front, and can be said as the Leidenfrost point of the boiling curve. The Leidenfrost point is the point of the minimum heat flux in the film boiling regime, marking the onset of the transition boiling regime in a quenching process. During transition boiling, the heat transfer mode is intermittent as a results of this alternating liquid wetting and vapor drying on the wall surface takes place. Heat transfer is greatly increased by the presence of liquid contact. Due to the decrease in the wall superheat the heat flux increases due to more liquid-to-wall contact. Further cooling of the surface through the transition boiling regime will result in a local peak heat flux termed the critical heat flux (CHF). The CHF point represent the onset of the nucleate boiling regime and represents the maximum heat flux for the nucleate boiling regime. The chilldown process continues toward point A where boiling (phase change) eventually ceases and single liquid phase convection begins. To chilldown as quickly and efficiently as possible the film boiling regime must be minimized.

2. EXPERIMENTAL STUDIES

A systematic layout of the experimental setup is shown in Fig. 2.

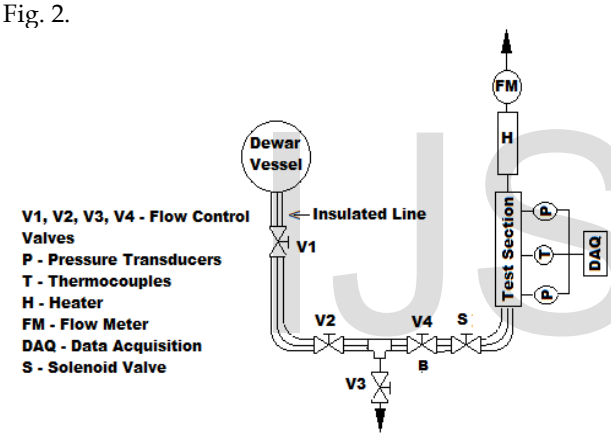


Fig. 2. Schematic diagram of the experimental setup.

It consists of 3 major segments as the unit for cryogen storage and supply, the test section under consideration and the peripheral instrumentation and data acquisition. The liquid nitrogen was stored in Duracyl 120LP' Dewar vessel manufactured by CHART Inc. (USA) having a capacity of 120 liters. A master valve is used to control the entire flow of cryogen to the system. A transparent bypass line is used after the master valve with a ball valve connection to make sure that the cryogen entering the test section is in liquid phase. A valve is provided at the entrance of the test section to avoid any gaseous flow through it when the bypassing is done.

Solenoid valve provided before the test section is depended for pulsating the flow of LN2 according to the experimental condition. The valve used for flow control was an AIRA solenoid valve rated for cryogenic use. The valve had an open/close response time of five to ten milliseconds. The valve is operated using the microcontroller board Arduino Uno based on microcontroller ATmega328P consisting of 14 digital input and output pins, 6 analogue inputs, a 16MHz quartz crystal, USB connection, power jack. It can be operated using a 5v power supply and it provides output based on the program which can be altered using a computer. The output signal is of 5v and 20mA.

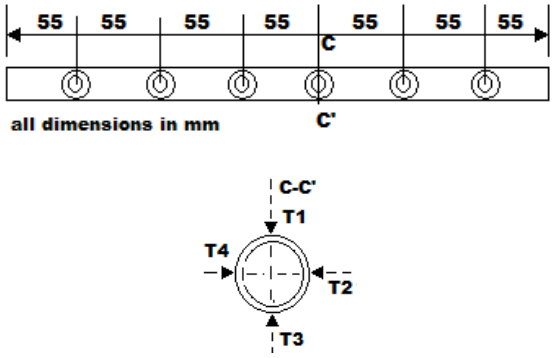


Fig. 3. Test section details.

An additional relay circuit to amplify and operate the solenoid valve using the signal from the microcontroller board was used. Test section is connected with thermocouples connected to the DAQ. Keysight 34972A Data Acquisition/ Data Logger Switch Unit was adopted for logging data. The cryogen exiting the test section is made to flow through a hot water bath maintained at 1000C to ensure the entry of single-phase fluid into the flow meter.

Test section under consideration is 5/16" (7.9375mm OD 0.8128 Thick) 500mm length straight OHFC copper (specific heat capacity of 401 J/kgK and thermal conductivity of 0.14 W/mK at 300K) tube. Fig. 2 provides the details of test section. Temperature measurements were recorded at six equidistant points till a distance of 330mm from inlet employing 4 T-type thermocouples at a specific cross section. An insulation was provided for the test section with 160mm as OD with urethane modified poly-isocyanurate foam (thermal conductivity of 0.14 W/mK) to reduce the heat inleak at the section. Heat inleak at the inlet section was minimized by employing a combination of asbestos rope and urethane modified poly-isocyanurate foam. Liquid nitrogen was supplied to the test section through 1/2" SS 304 grade pipes and brass fittings. A bypass line was provided before the test section to bypass the initial vapour produced during the initial cool down of the supply system. A transparent line provided at the bypass line ensures a steady state of liquid being supplied and only after that the line to the test section is opened.

2.1 Uncertainty Analysis

In the current experiment, the inverse heat conduction problem introduced by Burggraf et al. [18] needed to be solved in order to obtain the surface heat flux from the temperatures measured. Measurements in temperature, flow meter and Data Acquisition contributes to the uncertainties in the experiment setup. Temperature measurements have an uncertainty of ± 〖0.5〗 ^0C. Data Acquisition Systems have an accuracy of ±1^0C between -100^0C to 100^0C and ± 〖1.5〗 ^0C between -200^0C to -

100^0C. Mass flow rate have an accuracy of 0.5L/min.

3. RESULTS AND DISCUSSION

3.1 Temperature vs Time

Experimental results obtained for straight tube with different pulsed flow conditions are provided here. Effect of various pulse and cryogen mass flux were investigated. Wall temperature readings obtained were used for predicting the heat transfer and flow characteristics. Temperature measurement considered was at a distance of 300 mm from the inlet section at its cross-section.

Chilldown time is taken as the time taken by the average outer wall temperature to reach a steady value. Fig. 4 shows the variation of chilldown time with mass flux. It is observed that the mass flux has a significant influence on chilldown time. From the figure, it can be seen that at 86 kg/m²s 7-3 pulse has a chilldown time of 238.45 s, 8-2 pulse flow has a chilldown time of 222.3 s, 9-1 pulse flow has a chilldown time of 187.65 s and continuous flow has a chilldown time of 212s.

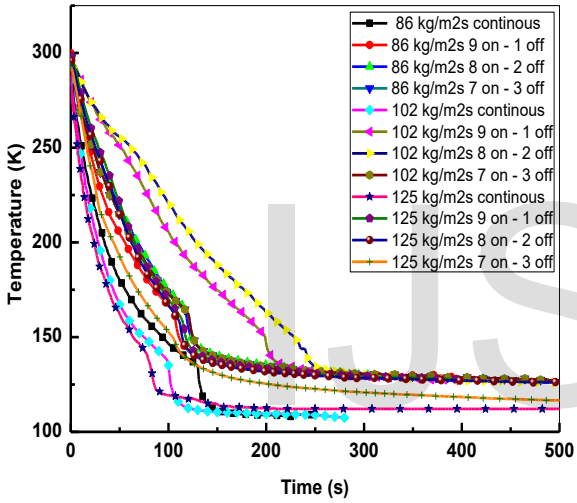


Fig. 4. Wall Temperature vs time for all flow conditions at 300 mm from inlet.

That is at low mass flux 9-1 pulse flow has minimum chilldown time. At 102 kg/m²s 7-3 pulse has a chilldown time of 273.46 s, 8-2 pulse flow has a chilldown time of 303.366 s, 9-1 pulse flow has a chilldown time of 285.439 s and continuous flow has a chilldown time of 260.93 s. At 125 kg/ m²s 7-3 pulse has a chilldown time of 121.35 s, 8-2 pulse flow has a chilldown time of 244.15 s, 9-1 pulse flow has a chilldown time of 270s and continuous flow has a chilldown time of 265.93 s. That is, as the mass flow rate increases chilldown time reduces in continuous flow patterns. It can be seen from the figure that continuous flow is the preferred flow pattern in terms of time. If not continuous flow, pulse patterns that result in short periods of valve inactivity are ideal.

3.2 Inner wall Temperature, Heat flux, Heat transfer Coefficient Evaluations

Analysis of Heat transfer characteristic is the most important part of the research. Physical explanations based on the comparison among the temperature profile, heat flux, heat transfer coefficient and critical heat flux (CHF) under various mass flow rates and flow conditions can be envisaged. Temperature profile indicates on in what manner LN2 quenches the tube walls and how fast the tube is cooled down. The analysis on heat flux and temperature will help to determine the heat transfer mechanisms during the chilldown process and serves for the comparison between chilldown of different experimental conditions being investigated. It is difficult to distinguish between the transition boiling and nucleation boiling regimes only from the temperature profile. As compared to the temperature profile, the heat flux profile can reveal more information regarding the heat transfer regimes, flow pattern development and other phenomena. In order to estimate the heat flux at the inner wall, an energy balance question is needed. This method has been used by several researchers.

However, in the present study outer wall temperature measurements were the only direct temperature measurements. In similar studies conducted by Reid Shaeffer e t al [17] and Hong Hu et al [13] used Burggraf correlations [18]. Burgraff's method is applicable to unsteady heat conduction with a single boundary condition. Burggraf developed a method that allows the estimation of the inner wall surface temperature by the measured outer wall temperature history through the solution of the inverse heat conduction problem (IHCP). The method uses lumped capacitance analysis and can produce accurate results with fewer terms. Inside wall temperature can be given by the correlation

$$T_i = T_0 + \left(\frac{r_0^2}{4\alpha}\left(\left(\frac{r_i}{r_0}\right)^2 - 1 - 2\ln\frac{r_i}{r_0}\right)\right)\frac{dT_0}{dT} + \left(\frac{1}{64\alpha^2}(r_i^4 - 5r_0^4)\ \frac{r_0^2 r_i^2}{8\alpha^2}\ln\frac{r_i}{r_0} - \frac{r_0^4}{16\alpha^2}\ln\frac{r_i}{r_0}\ \frac{r_0^2 r_i^2}{16\alpha^2}\right)\frac{d^2T_0}{dt^2} + \ldots.. \quad (1)$$

Inner wall surface heat can be calculated with the equation,

$$q_i'' = \rho c\left(\frac{r_i^2 - r_0^2}{2r_i}\right)\frac{dT_0}{dt} + \left(\frac{(\rho c)^2}{k}\left(\frac{r_i^3}{16} - \frac{r_0^4}{16r_i} - \frac{r_0^2 r_i}{4}\ln\frac{r_i}{r_0}\right)\right)\frac{d^2T_0}{dt^2} + \frac{(\rho c)^3}{k^2}\left(\frac{r_i^5}{384} - \frac{3r_0^4 r_i}{128} + \frac{3r_0^2 r_i^3}{128} - \frac{r_0^6}{384r_i} - \frac{r_0^2 r_i^3}{32}\ln\frac{r_i}{r_0} - \frac{r_0^4 r_i}{32}\ln\frac{r_i}{r_0}\right)\frac{d^3T_0}{dt^3} \quad (2)$$

Heat transfer coefficient can be found using the equation

$$h_i = \frac{q_i}{(T_i - T_{sat})} \quad (3)$$

In our present study, average temperature was used for finding the inner wall surface heat flux. Heat flux is plotted as a function of wall superheat of straight tube at different mass flux.

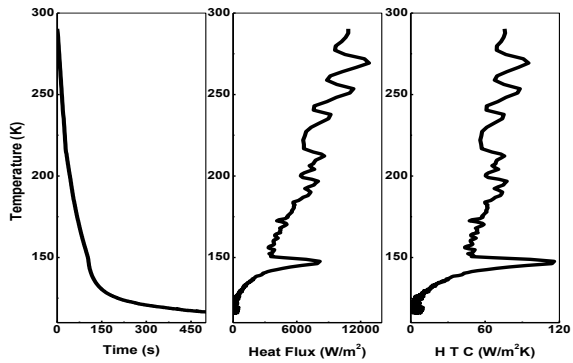


Fig. 5. Wall Temperature, Heat flux and Heat transfer coefficient at 125 kg/m^{2}s 7-3 pulse.

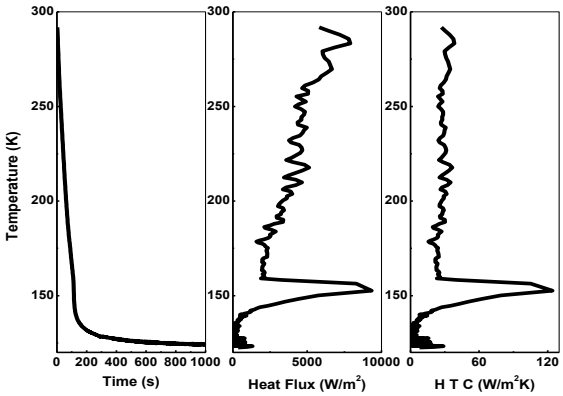


Fig. 6. Wall Temperature, Heat flux and Heat transfer coefficient 125 kg/m^{2}s 8-2 pulse.

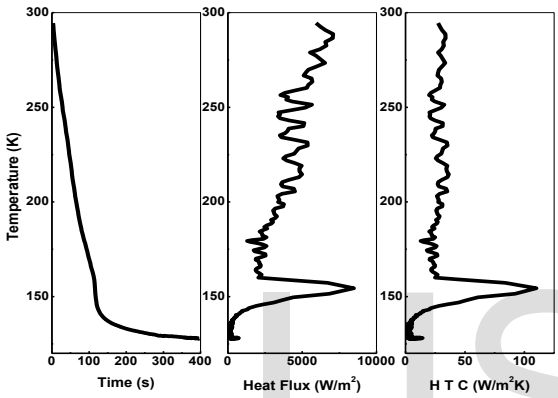


Fig. 7. Wall Temperature, Heat flux and Heat transfer coefficient at 125 kg/m^{2}s 9-1 pulse.

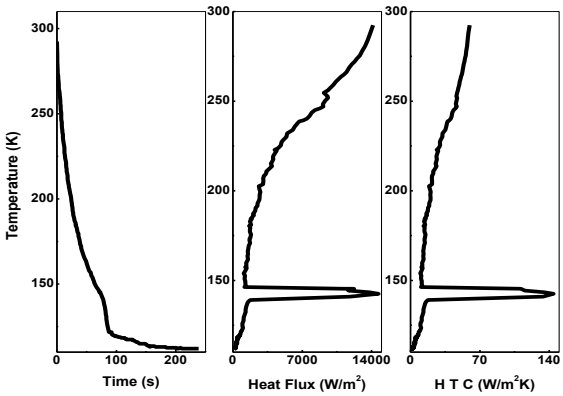


Fig. 8. Wall Temperature, Heat flux and Heat transfer coefficient at 125 kg/m^{2}s continuous flow.

The curve is similar to boiling curve in pool boiling conditions. Critical heat flux and Leidenfrost point are clearly identified and time for reaching these points are also determined. The variation of heat flux, heat transfer coefficient and chilldown time with respect to the wall superheat of test section for continuous and the three different pulsed flows considered for this study at a mass flux of 125 kg/m^{2}s is depicted in Fig. 5, 6, 7 and 8. From these figures, it is evident that the film boiling regime is completed at a higher wall temperature in all pulsed flow patterns compared to continuous mass flux supply. Moreover, the time taken for transition boiling regime is higher in pulsed

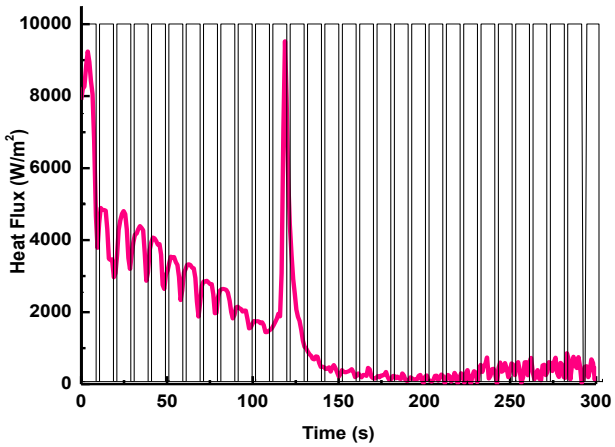


Fig. 9. Heat Flux vs time at 86 kg/m2s under 8 on-2 off pulsed flow.

flows while the chilldown time is shorter for continuous flows. When considering the heat transfer rates in the experimental conditions, it is clear that in the film boiling regime the average heat transfer rate for the continuous flow case is higher than that for pulse flow cases which explains why the chilldown time is longer for the pulse flow applications. It can be further concluded that the pulse flow is much less efficient in heat transfer due to the intermittent nature of the flow strength and intensity while the flow is constantly at its maximum strength for the continuous flow case. Regarding to the heat transfer coefficient profiles in Fig. 5, 6, 7 and 8, it is clear that the film boiling continues for longer time and the heat transfer coefficient is more stable under the continuous flow condition. Also, from the figures, it is clear that nucleation boiling heat transfer coefficient is almost one order of magnitude higher than that of the film boiling. The pattern of flow not only has an influence on the total time for chilldown, but the heat flux profile, critical heat flux and the heat transfer coefficient are all affected.

Fig. 9 depicts the variation of heat flux with respect to time for 86 kg/m^{2}s mass flux overlapped with the pulse of 8 sec on – 2 sec off. Notice the regular peaking of heat flux occurring when the valve is open initially till the onset of nucleate boiling. The mode of heat absorption during the initial period of chill down is depended on the quantity of fluid available whereas, after transition the heat transfer is not showing much dependence on the pulsating nature of supply.

3.3 Critical Heat flux

Both the critical heat flux and the critical heat flux temperature increase with increasing mass flux. The trend of increasing critical heat flux versus mass flux is due to the rate at which bubble nucleation sites are swept away. As the rate of bubble nucleation sites swept away is increases, critical heat flux increases [19][20]. This can be seen in the Fig. 10 that compares the critical Heat Flux temperature to the different mass flux and flow pattern adopted in the present study.

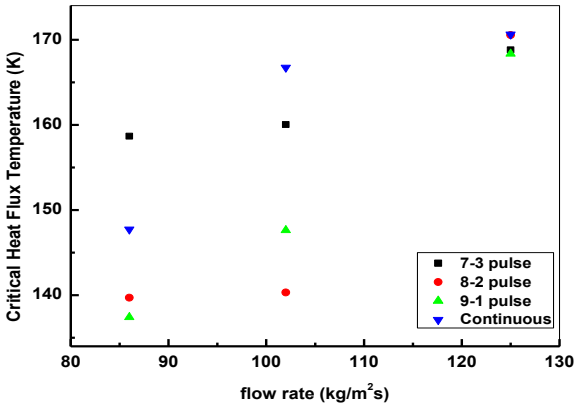
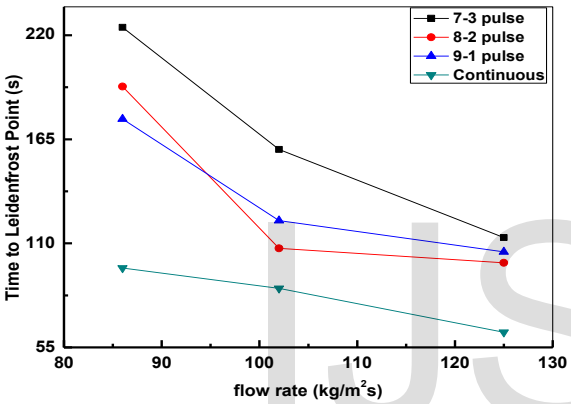
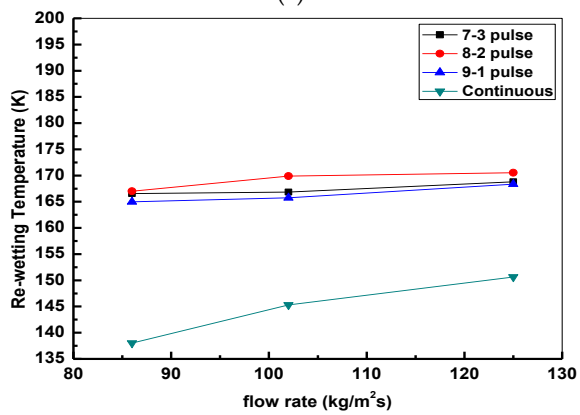


Fig.10. Critical Heat Flux for all flow patterns.

The rate at which bubble nucleation sites are swept away is proportional to the mass flux. The rate of bubble nucleation site movement is steady in continuous flow pattern whereas, they are intermittent in pulsed flows resulting in lower critical heat flux and temperatures.



(a)

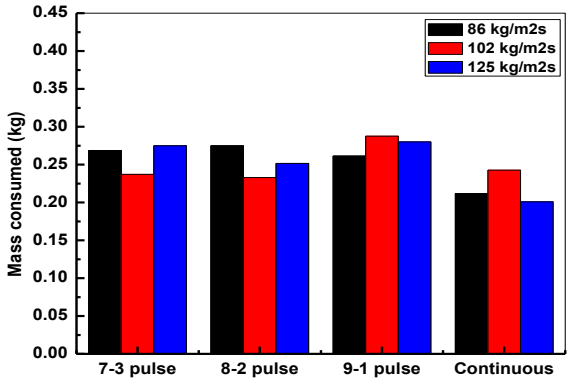


(b)

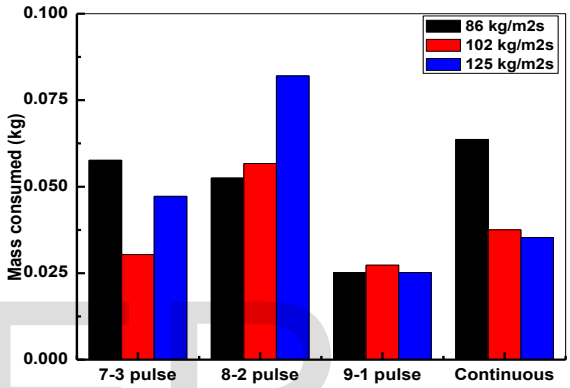
Fig.11. (a) Time taken to Leidenfrost temperature vs mass flux. (b) Re-wetting temperature vs mass flux..

3.4 Rewetting Temperature

The Leidenfrost temperature or Re-wetting temperature marks the onset of transition boiling when continuing from film boiling. The Leidenfrost point is identified by examining the boiling curve for each case. Fig. 11 (a) and (b) depicts the variation of re-wetting temperature and the time taken for the arrival of Leidenfrost temperature under different mass flux conditions. Leidenfrost temperature increases with the increase in mass flux. From Fig. 11 (b) it is worth noting that pulsed flow consistently achieved higher Leidenfrost temperatures than continuous flow patterns.



(a)



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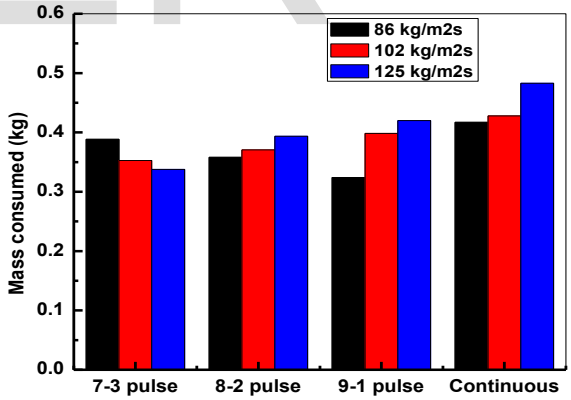

(c)

Fig.12. (a) Mass consumed during film boiling, (b) Mass consumed during transition boiling, (c) Total mass consumed during chilldown.

3.5 Mass of Cryogen Consumed

From previous research and publications, it is evident that higher mass flux usually leads to faster chilldown and also higher overall heat fluxes at the expense of more cryogen as a downside. Better use of cryogen can be accomplished with lower mass flow rate but will result in a longer chilldown time. Through the discussions in previous sections it is evident that continuous flow pattern is advisable for an earlier chilldown whereas, pulsed flow pattern has shorter transition boiling and nucleate boiling

period. It is clear from Fig. 11 (a) and (b) that film boiling ends earlier in continuous flows. When the performance of varied flow pattern is investigated into, total mass consumption for the process also has to be taken into consideration. Fig. 12 (a) depicts the mass consumed during film boiling under all mass flux conditions. It is evident that the minimum mass consumption is for continuous flow pattern. This is due to the earlier attainment of leidenfrost temperature. A different trend is observed during transition boiling as shown in Fig. 12 (b) where, mass consumption in near continuous flow pattern i.e.; with smaller valve inactivity period is the minimum in all cases considered. Finally, from Fig. 12 (c) we can arrive at a conclusion that total mass consumed during the entire chilldown period is the lesser in all pulsed flow pattern when compared to the respective continuous flow conditions. This gives an indication that not a particular flow pattern but rather a combination of patterns for a particular mass flux can drive in attaining both minimum chilldown time with the expense of lesser cryogen.

CONCLUSION

Heat transfer characteristics during chilldown under continuous and pulsed flow for three different mass flux were examined and the variation of heat flux and heat transfer coefficients with respect to wall superheat were much similar to pool boiling. Even having a higher leidenfrost temperature, the time for film boiling is longer for pulsed flows along with a faster completion of the other proceeding regimes. When concern is about mass reduction, pulse flow pattern with shorter off time for the valve is advisable. It is logical to use continuous flow rather than pulse flow when chilldown time is the only parameter to be satisfied. Results from the different pulse rate experiment shows that chilldown time is longer for high off time pulse in the case of low mass fluxes and vice versa.

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