Theoretical analysis and experimental investigation on performance of the thermal shield of accelerator cryomodules by thermo-siphon cooling of liquid nitrogen

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Abstract. Five beam line cryomodules with total 27 superconducting Radio Frequency (RF) cavities are installed and commissioned at IUAC to enhance the energy of heavy ion from 15 UD Pelletron. To reduce the heat load at 4.2 K, liquid nitrogen (LN2) cooled intermediate thermal shield is used for all these cryomodules. For three linac cryomodules, concept of forced flow LN2 cooling is used and for superbuncher and rebuncher, thermo-siphon cooling is incorporated. It is noticed that the shield temperature of superbuncher varies from 90 K to 110 K with respect to liquid nitrogen level. The temperature difference can’t be explained by using the basic concept of thermo-siphon with the heat load on up flow line. A simple thermo-siphon experimental setup is developed to simulate the thermal shield temperature profile. Mass flow rate of liquid nitrogen is measured with different heat load on up flow line for different liquid levels. It is noticed that small amount of heat load on down flow line have a significant effect on mass flow rate. The present paper will be investigating the data generated from the thermo-siphon experimental setup and a theoretical analysis will be presented here to validate the measured temperature profile of the cryomodule shield.

1. Introduction
For the heavy ion superconducting linear accelerator programme at IUAC, the radio frequency (97 MHz) superconducting quarter wave bulk niobium cavities are used as accelerating structure. In total 27 such cavities are distributed in five beam line cryomodules. The Super Buncher Cryomodule (SBC) and Re Buncher Cryomodule (RBC) with one and two cavities, respectively, are for bunching the beams and three linac cryomodules with 8 cavities each are used for accelerating heavy ions [1]. These cavities are operated at 4.2 K. For the present application, the stringent requirement of clean environment around cavity and a vacuum of better than $10^{-8}$ torr prevents the use of MLI insulation. A copper shield, cooled by liquid nitrogen, is used for the intermediate thermal shield between vacuum jacket at 300 K and cavities at 4.2 K. A thermo-siphon technique with liquid nitrogen as fluid is used for the shield cooling of SBC and RBC, where forced flow cooling is used for the shield of linac cryomodules. One pipe from the bottom of the LN2 vessel of SBC is anchored with a few thermal clamps to the bottom copper shield and finally enters at the top of nitrogen vessel. Figure 1 shows the schematic configuration of the superbuncher cryomodule and the thermal shield based on thermo-siphon flow of liquid nitrogen. Liquid nitrogen filling in the SBC is automated by using a pneumatic valve with feedback from the level indicator. The measured shield temperature along with the LN2 level in the vessel is shown in the figure 2.
It is noticed that the shield temperature is minimum (100 K) when the liquid level is 100% (35 cm.) and the temperature gradually increases till the level reaches to 8-10 cm. Further reduction of the LN2 level, the rise of the shield temperature is very fast. The shield temperature for this configuration depends on the total contact resistance of the clamps and the total heat transfer coefficient of two phase boiling liquid nitrogen and can be represented with the following equations (1,2,3).

\[ T_s = T_f + \left[ Q \left( \frac{1}{h_{tot}A_{C1}} + \frac{R_CA_C}{N} \right) \right] \]  

\[ h_{tot} = S.h_{nb} + F.h_{tp} \]  

\[ T_s = T_f + \left[ Q \left( R_1 + R_2 \right) \right] \]

Where \( T_s \) & \( T_f \) are the shield and fluid temperature (78 K) respectively. \( R_CA_C \) is the thermal contact resistance for each copper clamp, \( N \) is the total number of clamps and \( Q \) is the total heat load on the thermal shield. The total heat transfer coefficient (\( h_{tot} \)) is contributed by nucleate boiling heat transfer coefficient (\( h_{nb} \)) and two phase convective heat transfer coefficient (\( h_{tp} \)) along with suppression factor (\( S \)) and Chen factor (\( F \)) respectively [2]. \( R_1 \) and \( R_2 \) represent the thermal resistance contributed by fluid and clamp respectively. From this equation, we understand that shield temperature will depend on total heat transfer coefficient, which in turn varies with thermo-siphon liquid nitrogen mass flow rate (\( m \)) and the vapour quality (\( x \)) for a specific geometry. Preliminary calculation with a total heat load of 100 W for this geometry of SBC indicates a high mass flow rate (80-100 g/s), even when the liquid level reaches 20 % of the total. Calculation also shows an insignificant variation of mass flow rate occurs with the change of liquid level from 100% to 20 %. With higher mass flow rate and a measured of 100 W for liquid nitrogen, two phase flow is expected.
with low vapour quality at the end. With this kind of two phase flow, it is anticipated that the thermal resistance contributed by fluid flow ($R_1$) is much less compared to our earlier measurement [3] of the thermal contact resistance ($R_2$ = 0.8 K/W) of the clamps. Hence the variation of the shield temperature from 100 K to 110 K could not be explained based on the theory of basic thermo-siphon cooling.

To understand the above reasons, a simple thermo-siphon experiment was developed at IUAC. Experiments were carried out to generate a few sets of data on mass flow rate with variable parameters like load ($Q$), liquid nitrogen level etc. The experimental data are analyzed here to validate the measured shield temperature profile with liquid level.

2. Thermo-siphon experimental set up

A test set up was developed to simulate the proposed flow scheme for the thermal shield of the superbuncher cryomodules of linear accelerator and to understand some of the design parameters of proposed configuration like optimized position of thermal contact to have maximum flow, dependence of heat input and liquid level. The schematic process & instrumentation drawing of the test set up is shown in figure 3. The experimental set up along with inside assembly as shown in figure 4 is composed of a LN2 reservoir of 0.3 m high and 0.33 m diameter acting as a liquid-vapor phase separator, a vertically oriented U-tube of 16 mm inner diameter. Two heaters (100 W each) with variable heat input are fixed on the two arms of SS pipe through a copper clamp. Our attempt to measure the mass flow rate due to the thermo-siphon flow by using a venturi flow meter was not successful due to its range and vapor quality. Hence the mass flow rate was indirectly measured by monitoring the liquid nitrogen level with time. The value was corrected by subtracting the normal evaporation rate, which was measured by a dry gas flow meter. First arm (down flow line) of the U-tube was connected at the bottom of the phase separator vessel and other arm (up flow line) is open ended through a ball valve (V3) and also connected with the top of vessel by using a bypass valve (V4). The whole set up was housed in a vertical cylindrical cryostat of 0.5 m diameter and 1.5 m in height.

![Figure 3. Schematic drawing of experimental set up](image1)

![Figure 4. Thermo-siphon experimental set up and inside assembly](image2)

The whole loop, other than the heated section, is insulated with 20 layers of multilayer insulation, thus making it thermally adiabatic. Five calibrated silicone diodes temperature sensors (DT-470) are used to measure the temperature profile at different sections of the system as shown in figure 3. The
static heat load on this set up is measured by using the dry gas flow meter connected to the vent line and by opening the bypass valve and shown in figure 3. Both the heaters are calibrated by measuring the extra evaporated gas with respect to applied power. After the calibration of all the measuring instruments, the following sets of experimental data were generated.

2.1 Mass flow rate (m) with variable heat load (Q)
After filling the LN2 vessel, the system is stabilized by opening the bypass valve (V4) and vent valve (V2) and by closing the filling and drain valve (V1, V3). Once stabilized, the up flow line heater (Q) is put on with a specific power. After few minutes, once thermos-siphon flow is established, the drain valve is opened and bypass valve (V4) is closed. The open loop thermo-siphon flow is established and liquid nitrogen flows through the vent valve. The liquid nitrogen level is monitored with respect to time.

![Figure 5](image1.png)  
**Figure 5.** Measured LN2 level with time at various Q 

![Figure 6](image2.png)  
**Figure 6.** Calculated value of mass flow rate from level profile

The same experiment is repeated with different heat input. The liquid level profile with respect to time at different heat input on down flow pipe heater is shown in figure 5. The calculated average mass flow rate with level at different heat input is shown in figure 6.

2.2 Mass flow rate with fixed Q and variable q on down flow line.
A second set of experimental data was generated with a constant heat load (Q=75 W) on the up flow pipe line and an additional variable heat load (q) on the down flow line. It has been noticed that a small amount of heat load at the down flow line has a strong influence on the thermo-siphon mass flow rate. To have the information on the flow direction of the evaporated gas by the heat load (q) on down flow pipe, the flow meter was connected to the vent line. Figure 7 shows the measured liquid level profile with time at a fixed value of Q on the up flow line and with a variable heat load (q) on the down flow line. It is noticed that a small heat load on down flow line has a significant effect on the effective thermo-siphon mass flow rate. Flow meter reading also indicates that a fraction of the vapour generated by q flows upward direction in the down flow line and that reduces the driving force because of the low fluid density, corresponding to the up flow line height (h). The measured average mass flow rate with variable load q (1.5, 2, 5 and 7 watt) and fixed value of Q = 75 watt is shown in the figure 8.
3. Results and analysis

Analysis of the variation of shield temperature with time and liquid level helped us to incorporate modifications in the design of RBC to attain uniform shield temperature. Natural circulation is created in the vertical flow loop by the load from the shield. For a steady flow in the loop (shown in figure 9), the driving pressure ($\Delta p_d$) must be equal to the total system pressure drop [4,5] as in equation (4)

$$\Delta p_d = \Delta p_f + \Delta p_a$$

where $\Delta p_d$ is the driving force, and $\Delta p_f$ is the frictional pressure drop and $\Delta p_a$ is the acceleration pressure drop in the heated section.

By using the fundamental equation for the two phase frictional pressure drop and the acceleration pressure drop the mass flow rate corresponding to an ideal thermo-siphon loop as shown in figure 9 is well represented by equation (5).

$$g(H + h_1)(\rho_l - \rho_p) - gh_2\rho_p = m^2 \left[\frac{f_1}{2A_c^2D}\phi_1^2 + (H + h_1 + h_2)(1-x)^{1.75} \phi_1^2 \frac{f_1}{2A_c^2D}\phi_1^2 \right]$$

(5)

With the value of known parameters of H, h₁, h₂, L the mass flow rate is evaluated for different quality values by using equation (5). From the calculated value of m and input parameters of quality (x), Q is evaluated for each set of parameters of m and x. As the right type of mass flow meter was not available with us, the ideal close thermo-siphon loop (figure 9) is modified to open loop as shown in figure 10 and the mass flow rate is indirectly measured by using the rate of change in liquid level. So for a specific dimension of H = 0.3 - 0.1 m, h₁= 0.84 m, h₂=0.1 m, h₂ = 0.5 m, L (horizontal section length) = 0.3 m and the tube diameter D= 0.016 m, the calculated mass flow rate (m) of liquid nitrogen is plotted in figure 11 with respect to heat input (Q). With this open loop configuration, the measured mass flow rate is much less than the calculated mass flow rate (figure 11) for the ideal close loop.
The reason is two fold, first is the additional pressure drop at the end of loop with additional heat load from natural convection \( (Q_N) \) as shown in figure 10, and second is the possibility of minor heat input \( (q) \) on down flow line. To compensate for this additional pressure drop, calculations are repeated with increasing length of \( h_2 \) and are shown in figure 12. It is noticed that the measured mass flow rate agreed well with the theoretical value with an addition of equivalent length of \( h_2 = 5.0 \) m at various heat load \( (Q) \) on up flow line.

With this new hypothetical parameter of \( h_2 = 5.0 \) m, the calculation were repeated with the simultaneous heat load \( (q = Q) \) on down flow line. Here it is assumed that the vapour
generated in the down flow line moves in the upward direction and the density of two phase fluid on both arms across the length of \( h=0.84 \) remains same. In this case, available gravitational force is limited to the liquid height \( (H) \) in the reservoir. Further when the vapour moves in the upward direction in the down flow line, the buoyance force will oppose the free flow of liquid and this will further reduce the mass flow rate. All these measurements on this present set up, the liquid level in the reservoir varies continuously and hence it is difficult to have a correct mass flow rate under stabilized condition. To correct it, same experiment was repeated a no of times to have an average mass flow rate with a mean height of liquid reservoir. We have a plan on minor modification of the present experimental set up to maintain a constant liquid level and to have stabilized mass flow rate at a fixed value of the liquid height \( (H) \).

The calculated value of mass rate qualitatively agrees well within the range of measured data. It is also noticed that significant changes on mass flow rate occurs with liquid level \( (H) \) for this present case as shown in figure 13. With this low mass flow rate and higher vapour quality, it is expected that the two phase flow will be in the annular zone and the convective two phase heat transfer coefficient will be also the contributing parameter in addition to thermal contact resistance. Considering these and by using our earlier measured value of the thermal contact resistance \( (0.8 \text{ K/W}) \) for the copper clamp, the shield temperature is calculated with mass flow rate \( (1.0 \text{ to } 4.0 \text{ g/s}) \) at various vapour quality. The calculated shield temperature \( (T_s) \) variation as shown in figure 14 qualitatively agrees well the measured temperature. This paper gives a qualitative analysis on variation of the shield temperature and hence error bar is not incorporated. We would like carry out some more measurement to have an accurate quantitative analysis with error bar. Further a “P”- trap between the down flow line and the horizontal line will improve the mass flow rate.

**Figure 13.** Calculated mass flow rate at different liquid nitrogen level with \( h_2=0.5 \text{m} \)

**Figure 14.** The calculated shield temperature with vapour quality at different \( m \)
4. Conclusion
It is concluded that even a small amount of heat load in the down flow line causes a significant reduction on thermo-siphon mass flow rate. This reduction is prominent when the liquid nitrogen level is low. At low mass flow rate with high vapour quality, the thermal resistance by fluid flow is comparable with the thermal contact resistance by the copper clamps. Hence the shield temperature increases as the liquid level falls. It is recommended that for the future design of thermal shield the clamps can be avoided on the down flow line and can be added to the up flow line with parallel flow.

References
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