

Optimum Design of Liquid Helium Dewar with Vapour Cooled Shields

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The work presented aims to develop a numerical model which can be used to design a vapour shielded liquid helium (LHe) Dewar without LN₂ Shield. This model can compute the position of shields and the Net Evaporation Rate (NER) based on the capacity and number of vapour cooled shields (VCS) given by the user. The effect of neck dimensions on the heat in-leak is also given by this model. Heat in-leak design calculations are done using Finite Difference Method (FDM). A computer program is developed using MATLAB®. The results can be obtained either in graphical form or in terms of minimum NER and optimal positions of the VCS. The model is validated against available results in literature and additional results are discussed in detail. This program can be extended to estimate the neck dimensions and position of shields for any given capacity, number of shields and allowable boil-off rate.

Key words: Optimum Design, Liquid Helium Dewar, Vapour Cooled Shields, Finite Difference Method, Heat in-leak

INTRODUCTION

With helium supplies depleting at an alarming rate, it is essential to design helium storage systems with superior insulation performance. Vapour cooled radiation shielding is found to be the most effective method for minimizing the NER for a LHe storage Dewar. Due to high effectiveness, radiation shielding is the standard practise for most LHe Dewars.

Numerical and experimental investigations of heat in-leak into cryostats, Dewars and super-insulation (SI) have been performed by many authors [1-7].

Dewar design involves radiative, convective and conductive heat transfer

through various paths. In order to calculate this heat transfer using analytical techniques, exact equations and solution methodologies for all the processes are not available. Hence, using various simplifying assumptions [1], numerical computation [2] becomes essential for an optimum cryostat design.

In this paper, a solution methodology algorithm described by Goyal et al [1] is extended to calculate neck dimensions and optimum position of vapour cooled radiation shields (VCS) for minimum NER of LHe. The results are tabulated in a graphical manner wherever possible.

HEAT TRANSFER MODEL FOR A MULTI-VCS DEWAR

Vapour Cooled Shields

The VCS are, generally, 1mm – 2mm thick copper sheets that are attached at a particular point on the Dewar neck.

For LHe Dewars, it is an essential requirement to have good thermal contact between the helium boil-off vapour and the VCS. This is because the VCS intercept the radiation falling directly on the inner vessel (IV), and conduct this intercepted heat to the neck. This heat is then convected to the vapour element at the shield-neck joint (SNJ). Hence, the already vapourised helium gets heated up and is exhausted to the atmosphere. Thus, it reduces the total boil-off contained in the IV.

Numerical Model

A numerical model is developed for a multi-shielded LHe Dewar, which consists of one or more VCS attached directly to the Dewar neck. The neck is discretised into finite control volumes, and energy balance equations are solved for each control volume for steady state heat flow conditions [1, 10]. Figure 1 shows the heat transfer model adopted for the Dewar neck.

The following assumptions are made for the heat transfer calculations.

- Steady state conditions are assumed for the analysis.
- The neck material is taken as SS304L and the VCS material is taken as copper sheets of 1mm thickness.
- The neck, which is essentially a thin long circular tube, is characterised by constant heat flux, and flow of helium vapours through the neck is assumed to be a fully developed laminar flow [9].
- In this model, a constant emissivity value of 0.03 is used.
- For heat in-leak through SI; layer density (N) =33 layers/cm is assumed.
- It is assumed that total absorption of radiation occurs at the IV; hence funneling effect [5] is neglected.

- Perfect vacuum conditions are assumed in the current analysis [1].

Temperature Dependent Properties

The neck properties are significantly affected by the boundary conditions, i.e. temperatures of the IV and the outer vessel (OV). The temperature of the neck near to LHe, SNJs, sizes of IV, OV and neck are the main factors which determine the NER of the Dewar.

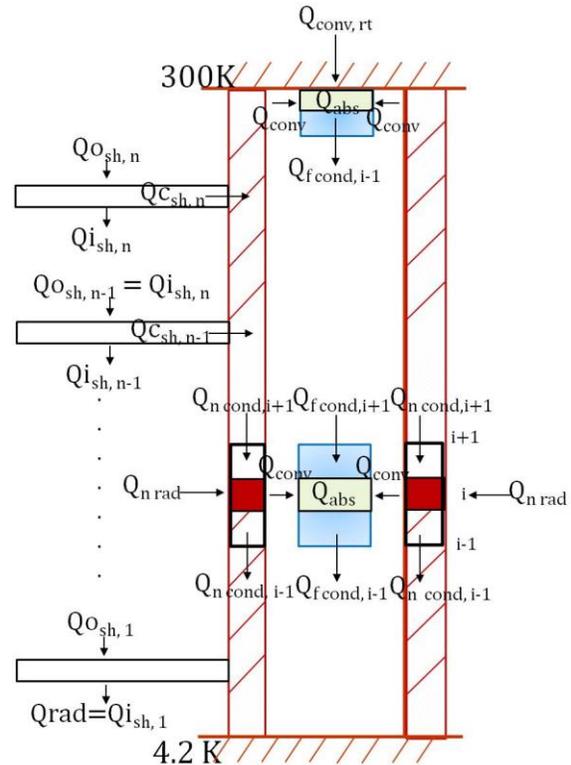


Figure 1. Heat Transfer Model for Multi-VCS Dewar

In the current analysis, temperature dependent thermal conductivity for SS304L and helium are used in the analysis.

Curve-fit equations are used for temperature dependent thermal conductivity (k_{He}) and specific heat capacity of helium at 1 bar pressure (C_{pHe}). Data points for these curve fit equations are taken from GASPAC (© COPYRIGHT Cryodata Inc.) dll [11]. Maximum error is $\pm 2.6\%$ for k_{He} and $\pm 1.65\%$ for C_{pHe} .

A logarithmic polynomial equation given by Marquardt et al [8] is used for temperature

dependent thermal conductivity of SS304L (k_{ss}).

Algorithm

The solution algorithm is given by the flowchart in Figure 2.

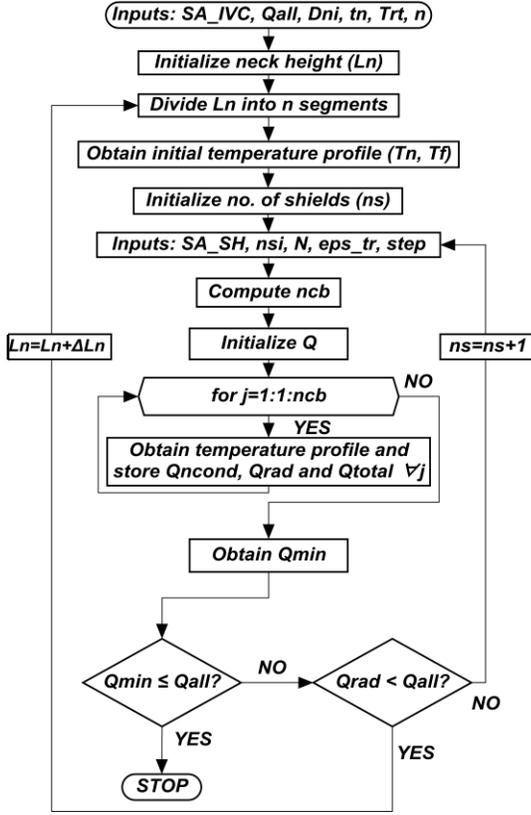


Figure 2. Flowchart for Optimised Neck Dimensions and Shield Positions

Heat Balance Equations [1]

The neck is discretised in axial direction. The heat balance equation for the i^{th} element of neck is given in Eqn. 1.

$$Q_{\text{ncond},i+1} + Q_{\text{nradi},i} = Q_{\text{conv},i} + Q_{\text{ncond},i-1} \quad (1)$$

Putting different 'Q' values appropriately and rearranging the above equation, an expression for the temperature of i^{th} element of neck is obtained as given in Eqn. 2.

$$T_{n,i} = \frac{\left\{ \frac{A_{\text{sn}}}{2} (h_i T_{f,i} + h_{i-1} T_{f,i-1} - h_{i-1} T_{n,i-1}) + \frac{A_{\text{cn}}}{d_x} (T_{n,i+1} k_{n,i} + T_{n,i-1} k_{n,i-1}) + E_{i+1} A_{\text{sn}} \right\}}{\left\{ \frac{h_i A_{\text{sn}}}{2} + \frac{A_{\text{cn}}}{d_x} (k_{n,i} + k_{n,i-1}) \right\}} \quad (2)$$

Similarly, the expression for i^{th} element of the fluid, final n^{th} element of the fluid as given by Goyal et al [1], are used for the heat balance of neck and vapour.

Eqns. 3 gives the expressions for the heat balance of shields [1].

$$Q_{o,sh,n} = Q_{i,sh,n} + Q_{c,sh,n} \quad (3)$$

This can be simplified to the expression given by Eqn. 4.

$$E_{c,sh,n} = \frac{E_{o,sh,n} A_{sh,n} - E_{i,sh,n} A_{sh,n-1}}{A_{\text{sn}}} \quad (4)$$

where $E_{i,sh,n} = E_{o,sh,n-1}$

Eqn. 5 gives the expression used for the convective heat transfer coefficient between the neck walls and the helium vapour [1].

$$h_{\text{conv},i} = \frac{\text{Nu} * k_{n,i}}{D_{ni}} \quad (5)$$

The net heat transferred to LHe is given by Eqn. 6.

$$Q_{\text{ncond},0} + Q_{\text{fcond},0} + Q_{\text{rad}} = Q_{\text{fg}} \quad (6)$$

This can be simplified to the expression given by Eqn. 7.

$$\frac{A_{\text{cn}}}{d_x} k_{n,0} (T_{n,1} - T_{n,0}) + \frac{A_{\text{cf}}}{d_x} k_{f,0} (T_{f,1} - T_{f,0}) + E_{1,i} A_i = m_f H_{\text{fg}} \quad (7)$$

The resulting ' m_f ' gives the mass flow rate of helium.

Using the above equations, the optimal number of shields and neck length are found using the flowchart given in Figure 2.

RESULTS AND DISCUSSIONS

Goyal et al [1] gave the results for up to two shields. The results from the current model are compared with these reported results and both are found to be in good agreement, as shown in Figure 3. The model is thus validated and hence can be used for multi-VCS cryostat design.

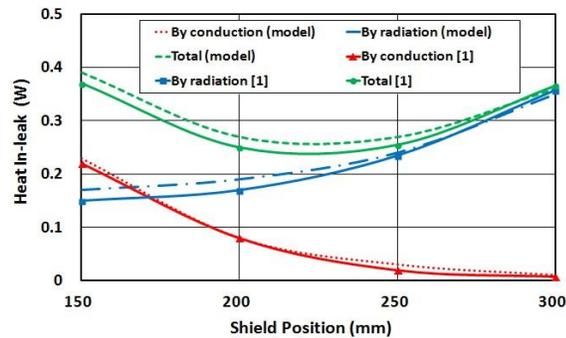


Figure 3. Heat in-leak LHe Dewar, Single VCS, 50 Layers of SI

Effect of Neck Dimensions

Neck diameter for experimental cryostats is generally dependent on the user requirements, based on instrumentation that are to be inserted through the cryostat neck. Figure 4 shows the variation of Q_{neck} Vs L/D ratio for neck lengths between 0.4m to 0.8m.

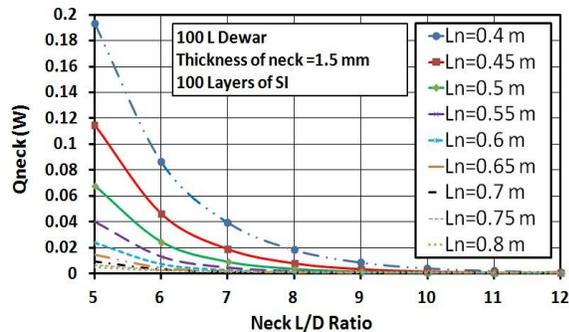


Figure 4. Qneck Vs. Neck L/D Ratio

For each of these L/D ratio combinations, Q_{IV} remains constant for a given capacity as it is entirely dependent on the surface area of the IV, and the temperature difference between the OV and IV.

From this graph, it can be seen that for shorter neck lengths, it is essential to have minimum possible neck diameters, i.e. larger L/D ratios in order to reduce the Q_{neck} . The neck IDs can be based on Figure 4.

For experimental cryostats that contain superconducting magnets immersed in a helium bath, it may be desirable for some users to have a wider neck diameter for additional instrumentation. In these cases, the neck heights can also be selected based on Figure 4.

If for a given capacity and neck height, Q_{neck} increases beyond Q_{all} , it can be reduced by either increasing the neck height (in case of helium Dewars), or by refrigerating the shield through external means (e.g. Cryo-cooler).

Figure 5 and 6 show the change in Q_{total} Vs Shield 1 and Shield 2 positions respectively. For a 100L LHe Dewar of neck height 500mm and neck diameter of 45mm, the optimal positions of both the shields are 110mm and 280mm from the IV respectively. The optimal position of both the shields given by the program is also marked in Figure 5.

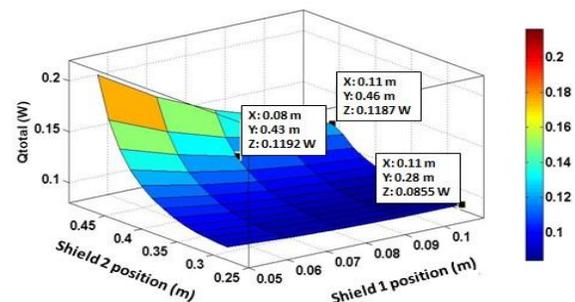


Figure 5. Q_{total} Vs Shield 1 and Shield 2 Position for 100L LHe Dewar, 100 Layers of SI

In case of a single shield, it may be noticed that the optimal shield position is near the centre of the neck, whereas in case of 2 shields, the shield positions for which Q_{total} is

minimum is near to $1/3^{\text{rd}}$ of the length and $2/3^{\text{rd}}$ of the length respectively.

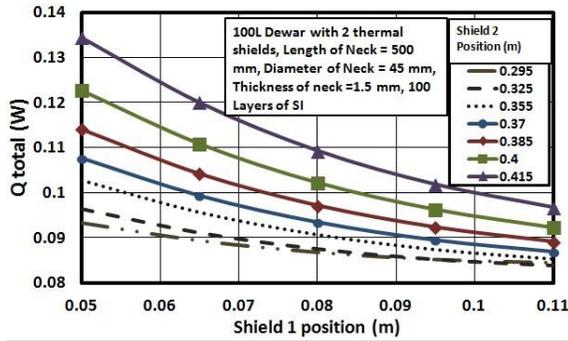


Figure 6. Q_{total} Vs Shield 1 Positions for different positions of Shield 2

From Figure 3, 5 and 6, it may be observed that for a given neck height L_n , the optimal shield position can be approximated to be at the length intervals of dsh from the IV, which is given by Eqn. 8.

$$dsh = \frac{L_n}{ns + 1} \quad (8)$$

Figure 7 shows the variation of Q_{neck} , Q_{IV} and Q_{total} Vs. no. of shields at optimal positions for a 100L dewar. We observe that the % decrease in Q_{IV} reduces when ns is increased. With further increase in ns , the curve becomes essentially a straight line with less than 0.5% decrease in Q_{IV} .

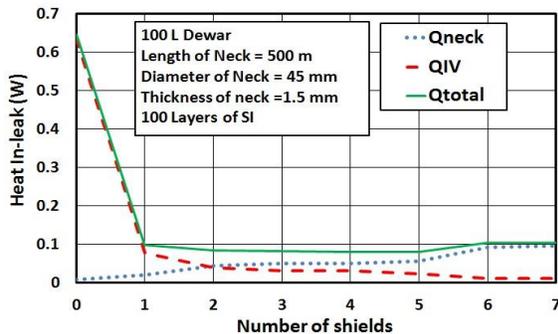


Figure 7. Q Vs. no. of shields for a 100 L Dewar

It may be noticed that, by addition of a single VCS at its optimal position, Q_{IV} reduces

drastically at the expense of marginal increase in Q_{neck} . This increase in Q_{neck} can be compensated or reduced either by moving the shields at the extremes, towards the centre (in case the shield positions are not optimized) or by increasing the neck height.

Figure 8 shows NER Vs. ns for Dewars of different capacities, i.e. 100L, 500L and 1000L with optimised neck lengths. It may be noted that, to obtain a NER of $\sim 1\text{-}2\%$ for a 100L Dewar, the number of shields required is more, whereas for higher capacities, fewer shields are needed.

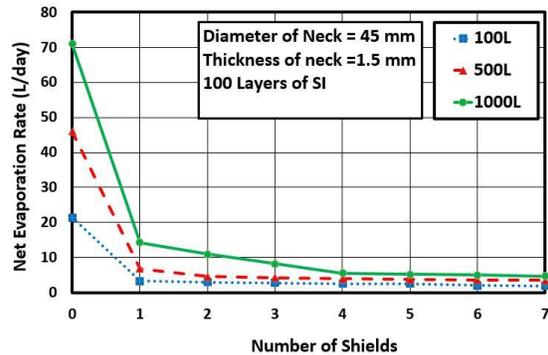


Figure 8. NER Vs. ns for Different Dewar Capacities with Optimized Neck Heights

CONCLUSION

The effects of neck dimensions, number of shields, and their optimal positions on the NER for a LHe Dewar are numerically investigated. A numerical model is developed for the optimal design of a multi-shielded Dewar using similar approach. This model can also be extended for design of experimental cryostats for NMR and MRI applications.

NOMENCLATURE

A_{cn}	Cross-sectional area of neck
A_{sn}	Surface area of discretized neck elements
LHe	Liquid helium
OV	Outer vessel
IV	Inner vessel
k	Thermal conductivity

Q	Heat in-leak (W)
Ln	Neck height
Dni	Neck diameter
tn	Thickness of neck
E	Radiation heat flux (through OV or shield)
SA_IVC	Surface area of inner vessel
SA_SH	Surface area of shields
h	Heat transfer coefficient
d _x	Height of neck and vapour element
dsh	Optimal positions of shields
SI	super-insulation
ncb	No. of combinations for shield positions (in case of multiple shields)
nsi	No. of layers of super-insulation
ns	No. of shields
Tn	Temperature of neck
Tf	Temperature of vapour
eps_tr	emissivity
N	Layer density of SI
NER	Net Evaporation Rate

Subscripts

He	Helium
ss	SS304L
ncond	Neck conduction
fcond	Fluid conduction
nrad	Neck radiation
sh	Shield
IV	Inner vessel
rt	Room temperature
i	Order of elements
j	Order of shields
abs	Absorption
min	minimum
rad	radiation
all	allowable

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