Experimental and analytical studies on a foam insulated rigid type transfer line for use with liquid nitrogen

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Abstract. The transfer line is one of the important components of any cryogenic system needed to transport the cryogenic fluid from one location to another. Towards our efforts to develop a long rigid-type transfer line for liquid nitrogen (LN2) to transfer this fluid from a 5000 litre capacity vertical storage tank to the Helium liquefier (Linde Model 1610) located at a distance of nearly 50 m, we designed and fabricated several units of straight section transfer lines of length ≈ 6.5 m and they were integrated to make the long length transfer line. Each unit was fabricated with 0.5 inch dia. copper inner tube supported by spacers within 2 inch dia. PVC outer tube. Each section was foam insulated after the necessary instrumentation for temperature measurements. The individual sub units were integrated together with a small bellow section in between to take care of thermal contraction during use. We present here the analytical and experimental studies of the cool down and mass flow characteristics of a single foam insulated unit. These experimental studies are representative results of the performances of the long length rigid foam insulated transfer line.

Keywords: transfer line, liquid nitrogen, foam insulation, heat transfer, cooldown, mass flow

1. Introduction
Vacuum insulated cryogenic transfer lines are widely used for both laboratory and industrial applications. Studies on cool down and mass flow characteristics of various types of transfer lines have been carried out by several researchers [1-7]. Estimation of cool down and time for mist flow conditions and the experimental studies on vacuum insulated lines were carried out by Chi[4]. The main problems encountered with vacuum insulated lines are selecting the vacuum level to be maintained in the inter-space between the inner pipe and the outer jacket and determining the outer jacket diameter for a particular flow condition. However, there are other types of transfer lines which are externally insulated and can be used for various applications. For example, rigid foam insulated type systems are popular for use with liquid nitrogen and liquid oxygen in view of their cost and ease of fabrication compared to those of vacuum insulated lines. Experimental and analytical studies on the cool down of foam insulated cryogenic transfer lines have been carried out by Durgaprasad et al.[7]. This paper presents the analytical and
experimental studies performed on a single section of the instrumented rigid foam insulated transfer line. These experimental studies give a better insight into the performance aspects of the complete transfer line.

2. Design and fabrication of the rigid foam insulated transfer line

The overall length of the complete transfer line is approximately 50 m inclusive of the straight part and some bends at the ends. The straight part is divided into multiple segments of \( \approx 6.5\) m each. The schematic of the single straight segment is shown in Figure 1.

![Schematic of single segment of the transfer line](image)

Figure 1: Schematic of single segment of the transfer line

Each segment is designed as follows. The inner pipe is made of copper tube of 12.7 mm O.D. and with a wall thickness of \( \approx 0.8\) mm. This has a length of \( \approx 6.5\) m. This is enclosed within a PVC tube of 50.8 mm O.D. and with a wall thickness of \( \approx 1.8\) mm. The length of the PVC tube is shorter by \( \approx 0.5\) m compared to that of the copper tube, so that the ends of the copper tube projects outside the PVC tube. The inner tube is centrally positioned within the outer PVC tube with the help of several rigid PUF spacers located at equal distances in the interspace of the transfer line. In this instrumented transfer line, the surface temperature of the copper tube is monitored by three Pt100 sensors. These are located at the inlet end, in the middle and at the outlet end respectively. The detailed dimensions and various other parameters are given in Table 1.

| S.No. | Dimensions/Parameters          | Nomenclature | Value (unit) |
|-------|-------------------------------|--------------|--------------|
| 1     | inner diameter of copper tube | \( d_{1i} \) | 11.1 (mm)    |
| 2     | outer diameter(O.D.) of copper tube | \( d_{1o} \) | 12.7 (mm)    |
| 3     | inner diameter of PVC jacket  | \( d_{2i} \) | 47.2 (mm)    |
| 4     | outer diameter of PVC jacket  | \( d_{2o} \) | 50.8 (mm)    |
| 5     | length of the section         | \( L \)      | 6.5 (m)      |
| 6     | ambient temperature           | \( T_a \)    | 300 (K)      |
| 7     | cryogenic fluid temperature   | \( T_f \)    | 77 (K)       |
| 8     | Avg. thermal conductivity of foam | \( k_{PUF} \) | \( \approx 25\) (mW/mK) |
| 9     | emissivity of copper (at 77K) | \( \epsilon_{1o} \) | 0.019         |
| 10    | emissivity of PVC (at 300K)   | \( \epsilon_{2i} \) | 0.85          |
The outer PVC jacket had suitable openings at appropriate locations to enable the application of foam insulation of the transfer line. The electrical connection leads from the sensors can be taken out of the PVC tube to enable monitoring of the temperatures at these locations. The foam insulation of appropriate density could be applied by filling the liquid of suitable chemicals in the inter-space of the transfer line. Carbon dioxide is used as the foaming gas in the above process. Either end of the inner copper pipe is prepared with suitable flare joints to enable connection to the adjacent segment.

Each segment is connected to the next segment, through an intermediate copper bellow of approximately 19 mm O.D. This enables to take care of the thermal contraction of the complete transfer line during its use. When the individual segments are integrated together, appropriate moving arrangements are provided in the outer PVC tube of the transfer line towards thermal contraction.

3. Steady state heat transfer through the transfer line
An estimate of the steady state heat load to the cryogenic fluid can be arrived at by considering the different modes of heat transfer that occur in the transfer line. Due to the high conductivity of copper, this heat load boils the cryogenic fluid by convection heat transfer. The heat loads by different processes are discussed below.

3.1. Heat transfer by solid conduction from the PUF insulation:
The average thermal conductivity of the PUF insulation used in the transfer line in the temperature range 300 K to 77 K is 0.025±0.002 W/ mK, by the data provided by the supplier. The steady state heat transfer by solid conduction \( Q_{SC}^{PUF} \) is given by the equation,

\[
Q_{SC}^{PUF} = \frac{2\pi L k_{PUF} (T_a - T_f)}{\ln\left(\frac{d_2}{d_1o}\right)}
\]  

Here \( L \) is the length of the foam section, \( k_{PUF} \) is the average thermal conductivity of the PUF insulation, \( T_a \) and \( T_f \) refer to the room temperature (≈ 300K) and the fluid temperature (≈ 77K due to the high conductivity of copper) of liquid nitrogen respectively. \( d_2 \) and \( d_1o \) refer to the inner diameter of the PVC tube and the outer diameter of the copper tube respectively. This value of \( Q_{SC}^{PUF} \) is estimated to be ≈ 166.67 Watts.

3.2. Heat transfer by gas conduction from the PUF insulation:
In the present transfer line test segment, the ends of the PUF insulation are closed with a suitable vapour barrier. Since the foaming gas is \( CO_2 \), it is expected that the vapour pressure of this gas decreases considerably when liquid nitrogen flows through the inner copper pipe. In view of this, it can be assumed that the heat transfer by gas conduction, \( Q_{gc} \) in the PUF insulation is negligible.

3.3. Heat transfer by radiation:
The steady state radiation heat load \( Q_r \) can be written as,

\[
Q_r = \varepsilon_{eff} \sigma (T_a^4 - T_f^4) A_{1o}
\]  

Here \( \varepsilon_{eff} \) is the effective emissivity of the two surfaces namely, the outer surface of the copper pipe and the inner surface of the PVC pipe. \( \sigma \) refers to the Stefan Boltzmann constant. This has the value 5.67 \times 10^{-8} \text{ W/(m}^2\text{K}^4). \( A_{1o} \) refers to the outer surface area of the inner copper tube. \( \varepsilon_{eff} \) can be defined as
\[ \epsilon_{eff} = \frac{\epsilon_{1o}\epsilon_{2i}}{\epsilon_{2i} + \epsilon_{1o}(1 - \epsilon_{2i})d_{2i}/d_{1o}} \]  

(3)

Here \( \epsilon_{1o} \) and \( \epsilon_{2i} \) refer to the emissivities of the outer surface of the copper tube and the inner surface of the PVC tube respectively. Similarly \( d_{1o} \) and \( d_{2i} \) refer to the outer diameter of the copper tube and inner diameter of the PVC tube. The steady state heat load for a single segment of the transfer line is given in Table 2.

Table 2: Steady state heat load through the single segment of the rigid foam insulated transfer line

| S.No. | Mode of heat transfer          | Nomenclature | Value (unit) |
|-------|-------------------------------|--------------|--------------|
| 1     | solid conduction through foam | \( Q_{SC}^{PUF} \) | 166.67(Watts) |
| 2     | gas conduction through foam   | \( Q_{GC}^{PUF} \) | \( \approx 0 \) (Watts) |
| 3     | radiation heat load           | \( Q_r \)    | 0.01(Watts)  |
|       | Total heat flow               | \( Q_T \)    | 166.68(Watts) |

4. Analytical model of cool down time of the single segment transfer line

The unsteady state heat transfer occurs during the cool down of the transfer line. The physical model along with the coordinates is shown in Figure 1. It is assumed that \( dz \) is the elemental length of the transfer line. The heat balance for this elemental length are given in reference [6] and they are reproduced here for a better understanding to the reader as given below.

\[
(q_{sc} + q_r)\pi d_{1o}dz - q_{conv}A\pi d_{1i}dz = \rho_1 C_1 \frac{\pi}{4} (d_{1o}^2 - d_{1i}^2)dz \left( \frac{dT_w}{dt} \right)
\]  

(4)

On rearranging the above equation we obtain,

\[
\frac{dT_w}{dt} = \frac{(q_{sc} + q_r)d_{1o} - h_1 d_{1i}(T_w - T_f)}{(\frac{\rho_1 C_1}{4})(d_{1o}^2 - d_{1i}^2)}
\]  

(5)

Here \( q_{sc} \) refer to the solid conduction heat load per unit area (heat flux) through the PUF insulation. \( q_r \) is the radiation heat flux from the ambient to the inner copper tube. \( q_{conv} \) refers to the convection heat flux from the copper pipe to the cryogenic fluid and is defined as,

\[
q_{conv} = h_1(T_w - T_f)
\]  

(6)

In the above equation \( h_1 \) refers to the convection heat transfer coefficient. Since all the property values are known, right hand side of equation (5) is a non-linear expression in \( T_w \) and represents an initial value problem with the following initial condition namely,

\[
T_w = T_a \quad at \quad t = 0
\]  

(7)

The correlations for boiling, forced convection and heat transfer coefficients used in the present analysis are taken from Srinivasan et al [8]. The variation of specific heat of copper with temperature and the emissivity values are taken from the reference [9]. Equation (5) is numerically solved by trapezoidal rule and the results of the analytical model are discussed along with the results of experimental studies.
5. Experimental Studies
Experiments have been performed to evaluate the performance of the single segment foam insulated transfer line both for its cool down as well for the mass flow characteristics. The schematic of the experimental arrangement is shown in Figure 2. The photograph of the experimental set up is shown in Figure 3.

![Figure 2: Schematic of the experimental set up for the cool down and mass flow studies of transfer line](image1)

Figure 2: Schematic of the experimental set up for the cool down and mass flow studies of transfer line

![Figure 3: Photograph of the experimental setup for the studies on transfer siphon](image2)

Figure 3: Photograph of the experimental setup for the studies on transfer siphon

The transfer line is connected between two storage dewars, one of which is the supply dewar, while the other is the receiver. The supply dewar filled with liquid nitrogen is pressurized to a known value and the liquid line valve is opened so that liquid nitrogen flows through the transfer line and gets collected in the receiver. It is ensured that the receiver dewar is initially empty but sufficiently cold so that it can be assumed that its cool down losses are negligible. The weight of
the receiving dewar is continuously monitored from the start of the liquid transfer, for different pressure settings of the supply dewar. The rate of change of the weight of the receiving dewar gives the mass flow rate through the transfer siphon. These experimental results are discussed below. Similarly during the cool down of the transfer line, the resistances of the PT100 sensors are continuously monitored to obtain the cool down of the transfer line with respect to time.

6. Results and Conclusions

6.1. Cool down characteristic of the transfer line
As discussed above, when the liquid nitrogen flow occurs through the transfer line, the temperatures at the locations where the Pt100 sensors are mounted are continuously monitored with respect to time from the start of the liquid nitrogen flow. The cool down behaviour of the transfer line is shown in Figure 4. T1, T2 and T3 are the temperatures measured at the locations 1, 2 and 3 as indicated in Figure 2. The uncertainty in the measurement of these temperatures is ±2K. The theoretical prediction of the analytical model is also plotted in the same figure. The analytical model predicts fairly well the cool down behaviour with time measured by the temperature sensors T1, T2 and T3.

![Figure 4: Cooldown curve for transfer line](image)

It is observed that the measured steady state temperatures follows the behaviour T1 > T2 > T3. This may be due to the fact that the vapour fraction in the liquid gradually increases with the liquid flow from the supply dewar to the receiver. This in turn modifies the heat transfer coefficients by the forced convection heat transfer [6-8]. Perhaps, only at very large mass flow rates, one can expect T1 \(\approx\) T2 \(\approx\) T3.

6.2. Mass flow characteristics of the transfer line:
The mass flow rate through the transfer line has been measured at different inlet pressures and the results are plotted in Figure 5. It is observed that the mass flow rate initially increases linearly with pressure for lower supply pressures and gradually decreases at higher supply pressures. This may be due to the fact that at larger inlet pressures, perhaps the pressure drop across the transfer
line reduces the flow rate through the line. Further experiments are in progress to verify the above.

![Mass Flow Rate vs Supply Dewar Pressure](image)

**Figure 5:** Mass flow characteristics of the single segment of Foam insulated transfer line

7. Conclusions
In this work, we discuss the development of a PUF insulated rigid liquid nitrogen transfer line of \( \approx 6.5 \) m length. This forms one of the several segments of the long length transfer line (\( \approx 50 \) m) needed for the transfer of this fluid from a large capacity storage tank directly to the helium liquefier (LINDE model 1610). The steady state heat load of this single segment has been theoretically evaluated. Also the cool down behaviour of the transfer line is analytically modeled. The experimental studies on the cool down and mass flow characteristics are carried out. The cool down behaviour compares well with the analytical model. The mass flow rates is found to increase with increasing supply dewar pressure. Now multiple units of this transfer line are being integrated to build the complete transfer line needed for the end application.

8. References
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