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Simulation and experimental research of heat leakage of cryogenic transfer lines

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Abstract. The heat leakage of cryogenic transfer lines directly influences the performance of large-scale helium refrigerator. In this paper, a thermal model of cryogenic transfer line considering numerical simulation of support coupled with MLI was established. To validate the model, test platform of cryogenic transfer lines with the merits of disassembly outer pipe and changeable easily multi-layer insulation has been built. The experimental results of heat leakage through overall length of cryogenic transfer lines, support and multi-layer insulation were obtained. The heat leakages of multi-layer insulation, a support and the overall leakage are 1.02 W/m, 0.44 W and 1.46 W/m from experimental data, respectively. The difference of heat leakage of MLI between experiment and simulation were less than 5%. The temperature distribution of support and MLI obtained in presented model in good agreement with experimental data. It is expected to reduce the overall heat leakage of cryogenic transfer lines further by optimizing structure of support based on the above thermal model and test platform in this paper.

1. Introduction

A large-scale helium refrigerator is continuous and energy intensive industrial process, which is widely used in superconducting systems, nuclear fusion engineering (e.g. Tokamak, Stellarator), and scientific researches (e.g. spallation neutron source) [1-3], etc. Cryogenic transfer line is one of key elements usually used to transfer liquid helium and supercritical helium in large-scale helium refrigerator, which connected with cold box, liquid helium Dewar, several cryogenic control valves and heat load. The heat leakage of cryogenic transfer lines directly influences the performance of large-scale helium refrigerator. So the design principle of cryogenic transfer line is to ensure cryogenic fluid transfer to every device at the lowest cooling loss. Multi-layer insulation (MLI) and Support device are two main effects to decrease the cooling loss significantly. On the one hand, MLI was applied around the circle tube to decrease heat convection, gas conduction and radiation to minimize the total heat leakage. On the other hand, it is concluded that the proportion of the heat leakage along the thermal bridges (supports) is 75% of the total heat leakage [4]. Support device is another main effect to decrease the heat leakage, which would be installed every other distance in the vacuum jacket to prevent thermal contact between two surfaces of two pipes in long-distance transportation. The support was generally made of Glass fiber reinforced plastic (G10) with high strength and low thermal conductivity.

Nomenclature		Subscripts	
T	Absolute temperature (K)	e	Effective
k	Thermal conductivity	i	MLI
Q	Heat flow	s	Support
q	Heat flux of MLI, W/m^2	t	Total
D_o	Inner diameters of test pipe, m	sr	Support radiation
l	Length of pipe, m	sc	Support conduction
δ	Thickness of MLI	h	Hot boundary
G_v	Flow rate of evaporated gas	c	Cold boundary
ρ	Density	g	Gas
h_{fg}	Latent heat of vaporization		

Therefore, to minimize cooling loss of cryogenic transfer line, researchers have made more efforts to reduce the heat leakage of support and MLI. In the analyzed XATL1 cryogenic transfer line, based on the MLI mathematical models proposed in [5-6], the heat loads ignoring heat leakage of support do not exceed 0.15 W/m for 4.5 K circuit and 1.5 W/m for 40/80 K circuit, respectively. By assuming that support are at a temperature of 4.5 K everywhere and conduction through support treated as one dimensional conduction with a liner temperature profile from 77 K to 4.5 K, the calculated heat transfer of a support is 0.0942 W [7]. In BEPCII (Beijing Electron Positron Collider II), numerical heat leakage of support structure was 0.446 W for 4.5 K and 0.388 W for 77 K cryogenic transfer line, respectively [8]. The above simulated results have ignored the radiation heat leakage of support and not been verified by experiment. Taking radiation and conduction through the support structure into account, the expected heat loads was 0.4 W/point for 4.5 K cryogenic transfer line applied in CERN [9]. The total heat leakage of cryogenic transfer line for different support constructions has been measured [10]. The lowest heat leakage of 0.73 W/m for cryogenic transfer line with the radiation shield fixed in support [11]. The total heat leakage of 4.5 K cryogenic transfer line of 0.98 W/m has been experimentally investigated [12].

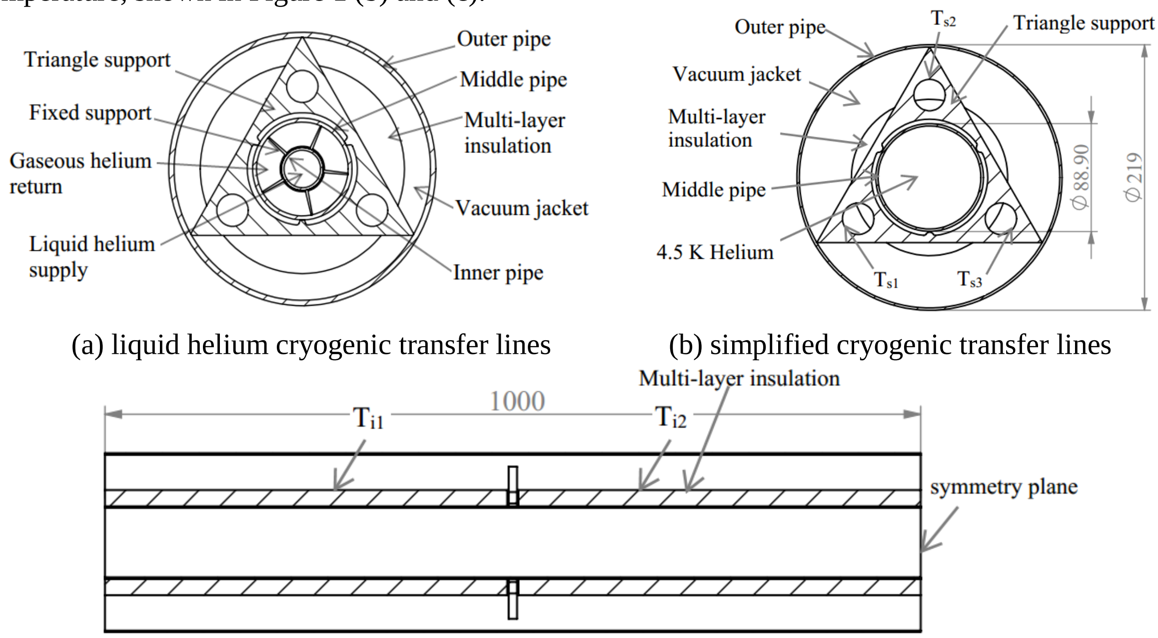
Generally, heat transfer in MLI involves radiation, solid conduction, residual gas conduction and convection. The published literatures were mainly focusing on heat flux, apparent thermal conductivity and vacuum level of MLI. The heat flux as a function of the number of MLI layers and of the overall vacuum level was proposed in [13], which was 0.64 W/m^2 with MLI to a painted surface from 300 K to 77 K. The thermal performance of MLI, consisting of double aluminized Mylar shields and nylon net supports was evaluated over the temperature range 300 K - 77 K, where the optimal number of 40 to 50 at a layer density of 25 layers cm^{-1} was proposed [14]. And the temperature distribution through the MLI indicates that effective thermal conductivity increases with the distance from the cold surface. Apparent thermal conductivity increased with the increase of the pressure level of MLI was experimentally investigated [15]. The benchmark thermal performance data of MLI was researched, including effective thermal conductivity and heat flux for the boundary temperatures 293 K and 77 K [16]. A new concept was proposed for the thermal insulation arrangement separating thermal insulation and the supporting structure in reference [17], which would improve evacuation conditions close to the cold wall. However, these simulations and experiments of MLI mentioned above were not coupled with support in cryogenic transfer lines and related measurements are required.

In most cases, the total heat leakage of cryogenic transfer lines is simulated or experimental measured and few references discuss the heat leakage proportion of support and MLI. Furthermore, there is lacking of easily assembled and accurate test platform of cryogenic transfer lines to verify the theoretical model and to obtain heat leakage proportion of support and MLI by experiments. Therefore, in this paper, a thermal model of cryogenic transfer line considering support coupled with MLI was established. Support coupled with MLI was simulated in model, considering support radiation with different walls. To validate the model, test platform of cryogenic transfer lines with the merits of easily disassemble outer pipe and changeable heat insulating material has been built. By the comparison of simulation and experiment, the optimized structure support and MLI would be studied and used in the liquid helium cryogenic transfer lines.

2. Thermal model of cryogenic transfer lines

A thermal model of cryogenic transfer lines is designed in Figure 1. A three-channel coaxial liquid helium pipe is shown in Figure 1 (a). The inner pipe supplies liquid helium. The space between the inner pipe and middle pipe transfers returned gaseous helium. MLI consisting of double aluminized Mylar shield and glass fiber paper is wrapped around the outer surface of middle pipe to reduce the heat leak of radiation. It would have a room as a vacuum jacket between MLI and outer pipe, which is evacuated to less than 5×10^{-5} torr [14] to reduce heat leak by convection and conduction in the residual gas. A triangle support made of G10 is installed between middle pipe and outer pipe to avoid a thermal bridge due to direct contact.

In most cases, the temperature of the liquid helium supply in the inner pipe equals to one of returned gaseous helium in the middle pipe. For simplicity and efficiency of thermal analysis, the liquid helium pipes could simplify as single cryogenic transfer lines used to simulate (see in Figure 1(b)). A 1m test pipe with a support arranged is used to simulate heat transfer, shown in Figure1 (c). Three points T_{s1}, T_{s2} and T_{s3} at the support and two other points T_{i1} and T_{i2} at MLI are located to monitor the local temperature, shown in Figure 1 (b) and (c).



(a) liquid helium cryogenic transfer lines (b) simplified cryogenic transfer lines

(d) 1 meter test pipe

Figure 1. Schematic drawings of the thermal model of cryogenic transfer lines

3. Simulation analysis of cryogenic transfer lines

In the simulation, the configurations of test pipe are the following. The test pipe is made of stainless steel 304. The nominal diameters of inner pipe and outer pipe are 219 mm and 88.9 mm, respectively. The MLI with the density of 25 layers cm^{-1} was wrapped around the outside of inner pipe. The boundary conditions are the following: ambient temperature is 293 K and liquid nitrogen temperature is 77 K. The free convective heat transfer coefficient is generally in the range of 5-25 W/(m K) and around 5-6 W/(m K) at static indoor condition. So, the free convective heat transfer coefficient was determined to be 5 W/(m K) [8, 12] in the simulations.

The apparent thermal conductivity of MLI is 0.279 mW/(m K) based on the experimental results. The emissivity of MLI with double aluminized Mylar shield, test pipe made of stainless steel 304 and

G10 support are 0.1, 0.25 and 0.5, respectively. Thermal conductivity of G10 and stainless steel 304 at different temperatures are shown in Figure 2.

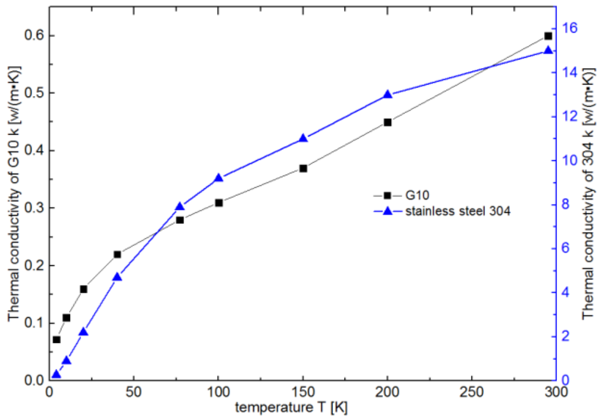
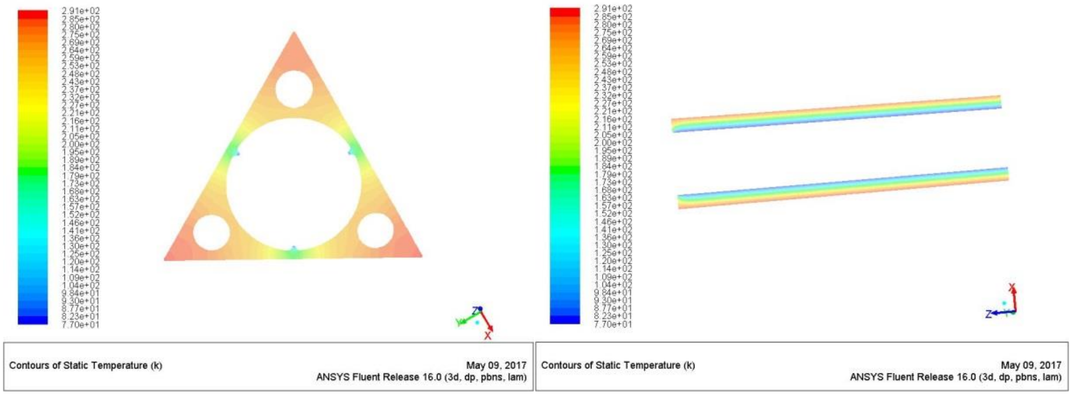


Figure 2. Thermal conductivity of G10 and stainless steel 304 at different temperatures

Numerical simulation of 1 m cryogenic transfer line was conducted by commercial software ANSYS. Temperature distribution of support, MLI and 1m cryogenic transfer line was analyzed carefully.



(a) support (b) MLI

Figure 3. Temperature contour of support (a) and MLI (b)

Figure 3 shows temperature contour of support and MLI. Triangle support has three uniform circle holes, which decrease the area of contact and increase the length of thermal bridge. From Figure 3(a), the highest temperature of triangle support is 291 K at the contact parts with the outer pipe, close to the ambient temperature. Three points T_{s1}, T_{s2} and T_{s3} at the triangle support are 275 K, 270 K and 275 K, respectively. Temperature T_{s2} is less than T_{s1} and T_{s3} because triangle support always has only two points to contact with and to bear the weight of the inner pipe. The temperature contour of support combining with the results in reference [18] shows that support not only has heat leak by conduction with outer pipe, but also has heat leak by radiation with walls of pipe.

From Figure 3(b), the average temperature of outmost layer of MLI is about 284 K. MLI has played a role of perfect radiation protection. As result of the Figure 3(b), temperature of MLI close to support is higher than temperature far from support in the same layer. The reason is that heat leakage of support due to conduction of support and radiation between different walls leads to higher temperature. The heat leakages of support will be discussed in the next part in detail.

4. The test platform of cryogenic transfer lines

To validate the thermal model, test platform of six-meters cryogenic transfer lines with the merits of easily disassemble outer pipe and changeable MLI has been built as shown in Figure 4. The picture of the test platform of cryogenic transfer lines is shown in Figure 5. The test platform mainly includes

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2-meters test pipes, guarded pipes, vent pipe, temperature sensors, data acquisition system, vacuum pump system and flow meter.

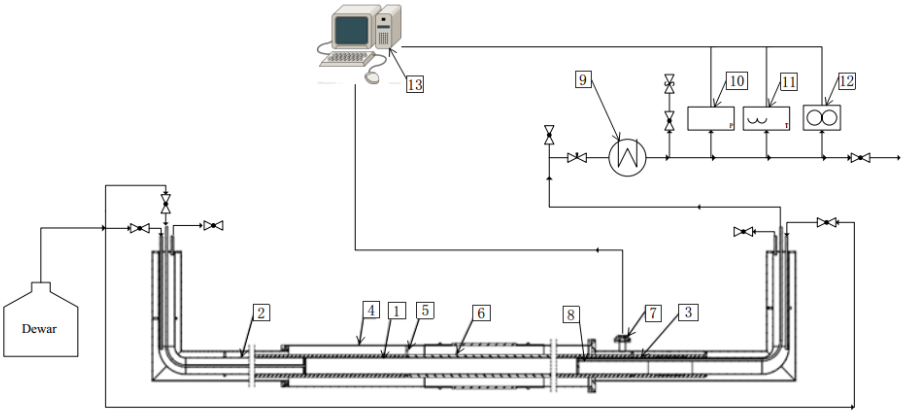
2-meters test pipe was filled with liquid nitrogen during the experiments. Two guarded pipes filling with liquid nitrogen were installed in both ends of two meters test pipe to maintain 77 K boundary condition. A vent pipe is put at the highest point of second guarded pipe to ensure the evaporated nitrogen gas expelling from test pipe to a gas flow meter. Through the test platform, heat leakage of support and MLI can be measured and researched for varisized pipes. The steady-state heat flow (Q_i) is the basis for calculating thermal properties including effective thermal conductivity (k_e) and heat flux (q) of MLI. In addition, the performance of different MLI and optimized support structure can be tested with this test platform. So the heat leak to test pipe is obtained from the flow rate of evaporated gas as following.

$$Q = G_v \rho_g h_{fg} \tag{1}$$

And the k_e and q can be calculated by Eqn. (2) and Eqn. (3):

$$k_e = \frac{Q_i \ln \frac{D_0 + 2\delta}{D_0}}{2\pi l (T_h - T_c)} \tag{2}$$

$$q = \frac{Q_i}{\pi l (D_0 + \delta)} \tag{3}$$



1-test pipe; 2-first guarded pipe;3-second guarded pipe;4-outer pipe; 5-support;6-MLI; 7-temperature sensors;8-vent pipe; 9-heater; 10-pressure probe; 11-temperature probe; 12-flow meter; 13-data acquisition system

Figure 4. Schematic drawings of test platform of cryogenic transfer lines

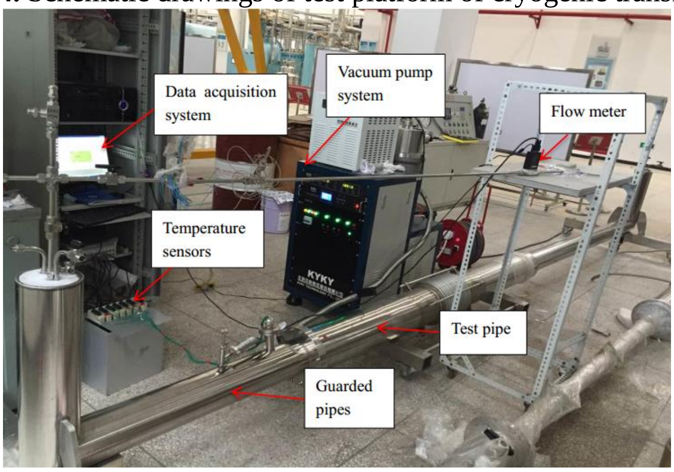


Figure 5. Picture of the test platform of cryogenic transfer lines

There are two key parameters: the flow rate of evaporated nitrogen gas and the temperature of support and MLI, which must be measured accurately within the scope of the testing accuracy. The volumetric flow rate of evaporated nitrogen gas is measured by a gas flow meter, which is directly proportional to the energy transmitted through the liquid nitrogen by the latent heat of vaporization (h_{fg}). The accuracy of the flow meter is 1% of the reading for a range of 0-2 L/min. The temperature of support and MLI is used to verify the efficiency of a cryogenic transfer line. All temperature values are acquired by four-wire platinum RTDs with the accuracy of ±0.1 K in the experiments.

5. Discussions and comparison

To obtain the heat leakage Q_i of MLI, Q_s of support and Q_t of cryogenic transfer line, two cases of experiment have been performed. Case 1) 2-meters test pipe with MLI installed two triangle supports, Case 2) 2-meters test pipe with MLI without any supports. Flow rate of evaporated nitrogen gas of two cases are measured (see in figure 6). At the same time, three temperature sensors are put at the support and four temperature sensors are put at the outmost layer of MLI (the sensors location see in Figure 1(b), (c)). Through these experimental data, the heat leakage and temperature of a support and MLI could be obtained. The experimental results are summarized as following.

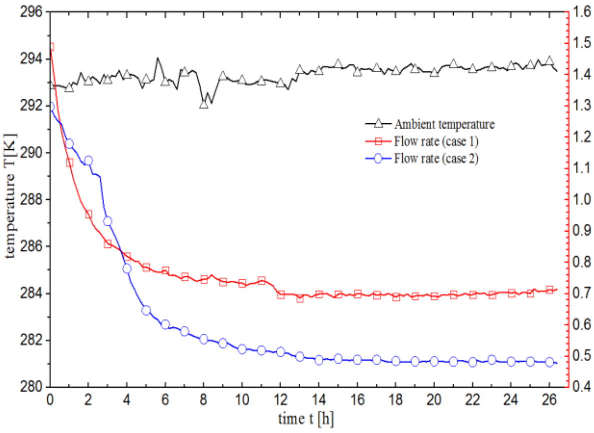


Figure 6. The time variations of flow rates of evaporated nitrogen gas of 2-meters test pipe

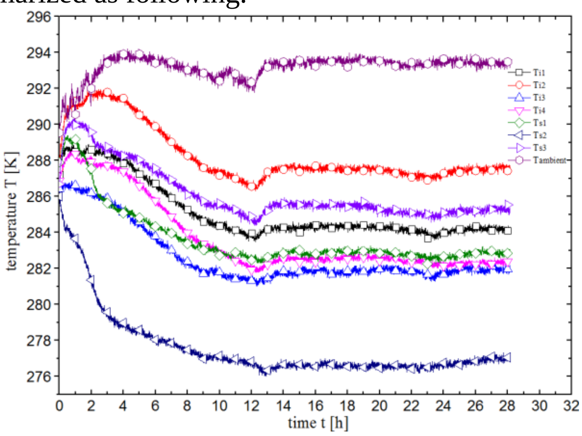


Figure 7. The time variation of temperature of MLI and support

Table 1. Heat leakage comparison of simulation and experiment

Type	Q_s(W)		Q_i(W/m)	Q_t (W/m)	Q(W/m^2)	k_e((mW/(m K)))
	Q_{sc}	Q_{sr}				
Simulation	0.05	0.64	0.97	1.66	2.41	0.266
Experiment	0.44±0.02		1.02±0.04	1.46±0.06	2.52±0.10	0.279±0.012

Table 2. Temperature comparison between simulation and experiment of support and MLI

Type	T_{i1}	T_{i2}	T_{i3}	T_{i4}	T_{s1}	T_{s2}	T_{s3}
Simulation	284	284	284	284	275	270	275
Experiment	284	287	282	282	283	277	285

Figure 6 shows that flow rate of evaporated nitrogen gas has been stable and fluctuated slightly after 12 hours. When ambient temperature is 293 K, the total flow rate of evaporated nitrogen gas is 0.700 L/min in Case 1 and 0.490 L/min in Case 2, respectively. Combining equation (1) with flow rate of evaporated nitrogen gas, the heat leakage of MLI and two supports for test pipe with diameter 88.9 mm have been obtained, seen in Table 1. As a result of experiment, the heat leakage Q_i of MLI, Q_s of support and Q_t of cryogenic transfer line are 1.02 W/m, 0.44 W and 1.46 W/m, respectively. By comparing the result of simulation and experiment, heat flux q_i of MLI is 2.52 W/m^2 and k_e is 0.279 mW/(m K). The deviations of heat leakage Q_i of MLI between experimental and simulation were less than 5%, which shows consistent and valid to data of MLI. For heat leakage Q_s of support, Q_{sr} due to heat radiation is 0.64 W/m, larger than Q_{sc} due to heat conduction. The results of support show that heat leakage of support is mainly caused by heat radiation effect. The simulated result of support is higher than experiments, which indicates parameters of support set in the simulation would be further optimized.

Figure 7 shows the time variation of temperature of MLI and support. According to temperature comparison of MLI shown in Table 2, the temperature of T_{i1}- T_{i4} between experiment and simulation shows remarkable consistency. The temperature of outermost layer of MLI is 284 K. The temperature difference of support between experimental and simulation is less than 10 K. T_{s2} is lower than T_{s1} and T_{s3} as the simulated results. The experimental value of support combining with simulation and reference [18] shows that support not only has heat leak by conduction with outer pipe, but also has heat leak by radiation with walls of pipe.

6. Summary

In the paper, a thermal model of cryogenic transfer line was established and heat leakage and temperature of MLI and support was acquired. Support coupled with MLI was simulated in model, taking into account support radiation with different walls. Moreover, test platform of cryogenic transfer lines with the merits of easily disassemble outer pipe and changeable MLI has been built. The heat leakages of MLI, a support and cryogenic transfer line are 1.02 W/m, a 0.44 W and 1.46 W/m from experiment data, respectively. Heat flux of MLI (q) is 2.52 W/m^2, k_e is 0.279 *m*W/(m K), the heat leakage deviations of MLI between experiment and simulation were less than 5%. The temperature distribution of support and MLI analyzed in presented model in good agreement with experimental data. Based on simulation and test system, cryogenic transfer lines will be further optimized, including structure of support and the performance of the MLI.

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