Simulation and experimental research of heat leakage of cryogenic transfer lines

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Background

A large-scale helium refrigerator is continuous and energy intensive industrial process, which is widely used in superconducting systems. Cryogenic transfer line is one of key elements usually used to transfer liquid helium and supercritical helium in the large-scale helium refrigerator. The heat leakage of cryogenic transfer lines directly influences the performance of the large-scale helium refrigerator. Therefore, the simulation and experimental research of heat leakage of cryogenic transfer lines is an important and vital issue for the design structure of the cryogenic transfer lines.

Objectives

- A thermal model of cryogenic transfer line considering temperature distribution and heat leakage of support and multi-layer insulation was established.
- To validate the model, the test platform of cryogenic transfer lines with the merits of disassembly outer pipe and changeable easily heat insulating material has been built.

Conclusion

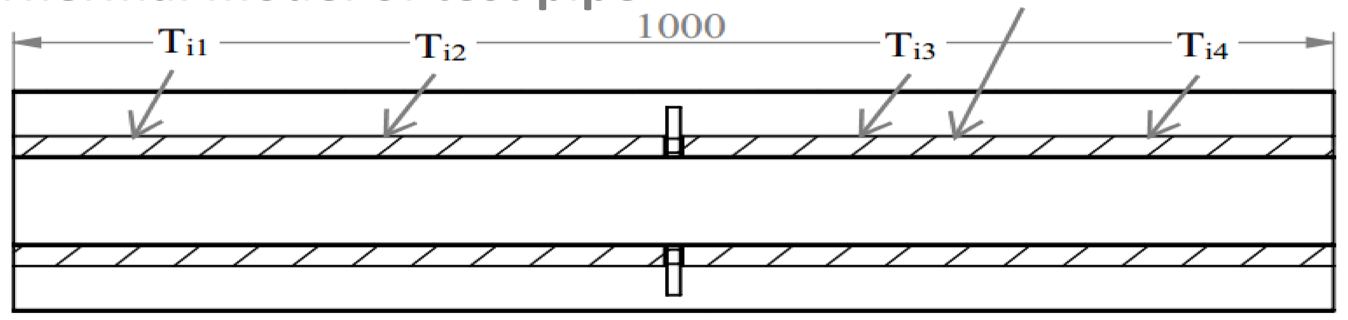
- In this paper, the thermal model of cryogenic transfer line was established and the heat leakage and temperature of the multi-layer insulation and support was acquired.
- Moreover, the test platform of cryogenic transfer lines with the merits of disassemble easily outer pipe and changeable easily heat insulating material has been built. The heat leakages of multi-layer insulation, a support and the overall leakage are 1.02W/m, a 0.44W and 1.46W/m from the experiment data, respectively.
- The deviations of the heat leakage of multi-layer insulation between the experiment and simulation were less than 5%, which verified the theoretical model reasonable. Based on the simulation and test system, the cryogenic transfer lines will be further optimized, including the structure of support and the performance of the multi-layer insulation.

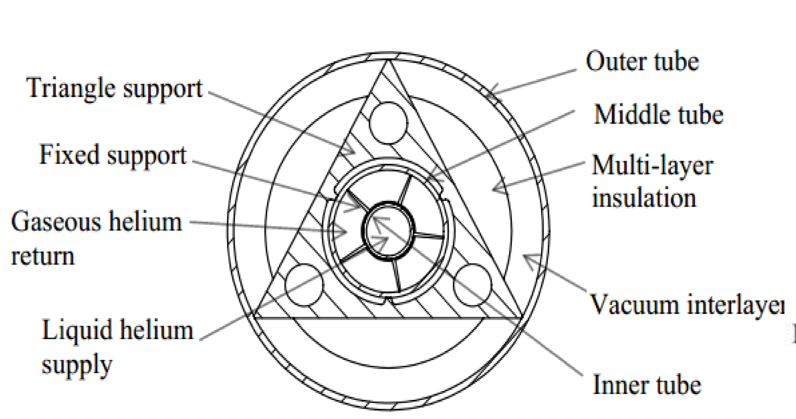
Methods

Simulation

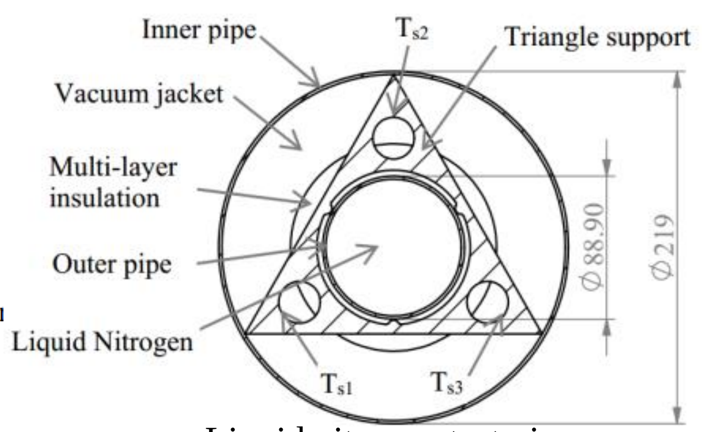
- To protect inner pipe from the outer pipe, the triangle support made of Glass fiber reinforced plastic (FRP) is installed between the two pipes.
- Because of the temperature between the liquid helium supply and gaseous helium return closely, the liquid helium pipes can simplify as the liquid nitrogen test pipes. A 1m liquid nitrogen test pipe with a support arranged is used to simulate.
- The real application boundary condition were chosen as following: ambient temperature is 293K (20℃), convection coefficient is $5\ W/(m^2 \cdot K)$. The wall temperature of liquid nitrogen middle transmission is 77K.

Thermal model of test pipe

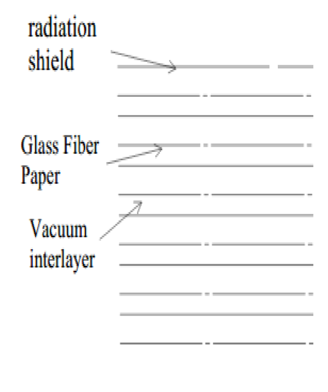




Liquid helium pipes



Liquid nitrogen test pipes



Multi-layer insulation

Experiment

1). three temperature test points of the support;
2). four temperature test points of the outmost layer of MLI;
3). the mass flow rate of the gas nitrogen of different experiments.

The steady-state heat flow (Q_i) is the basis for calculating the thermal properties including effective thermal conductivity (k_e) and heat flux (q) of multi-layer insulation.
The k_e and q can be calculated by Eqn.

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

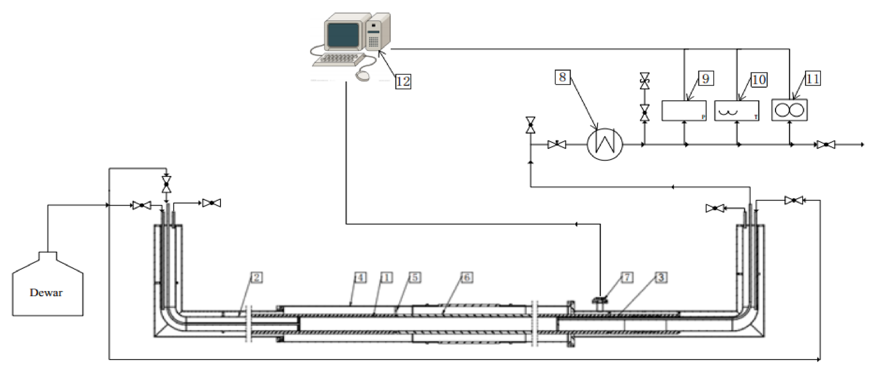
$$q = \frac{Q_i}{\pi l(D_0+\delta)}$$

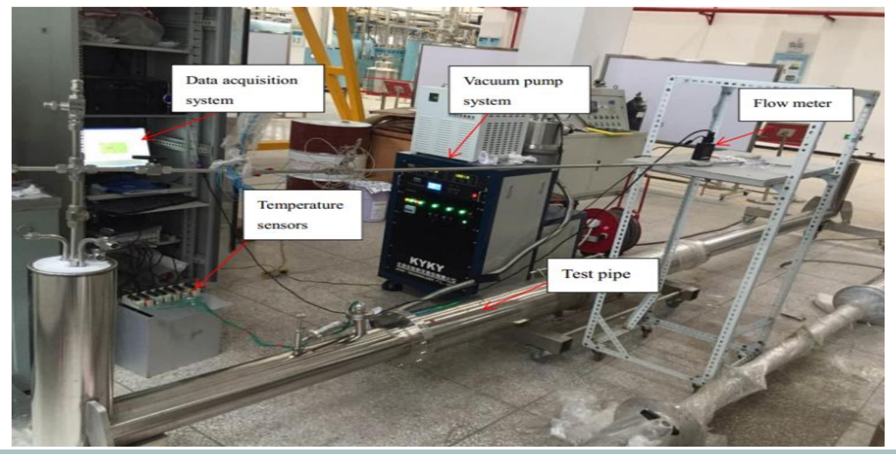
The test platform

The test platform with the merits of disassembly outer pipe and changeable easily heat insulating material includes the following aspects: test pipes, temperature sensors, data acquisition system, vacuum pump system and flow meters.

According to this test platform, lots of researches can be conducted as following:

- the heat leakage of cryogenic transfer lines with different size,
- heat leakage proportion of support and multi-layer insulation
- the performance of different multi-layer insulation and the optimized structure of support.





Results

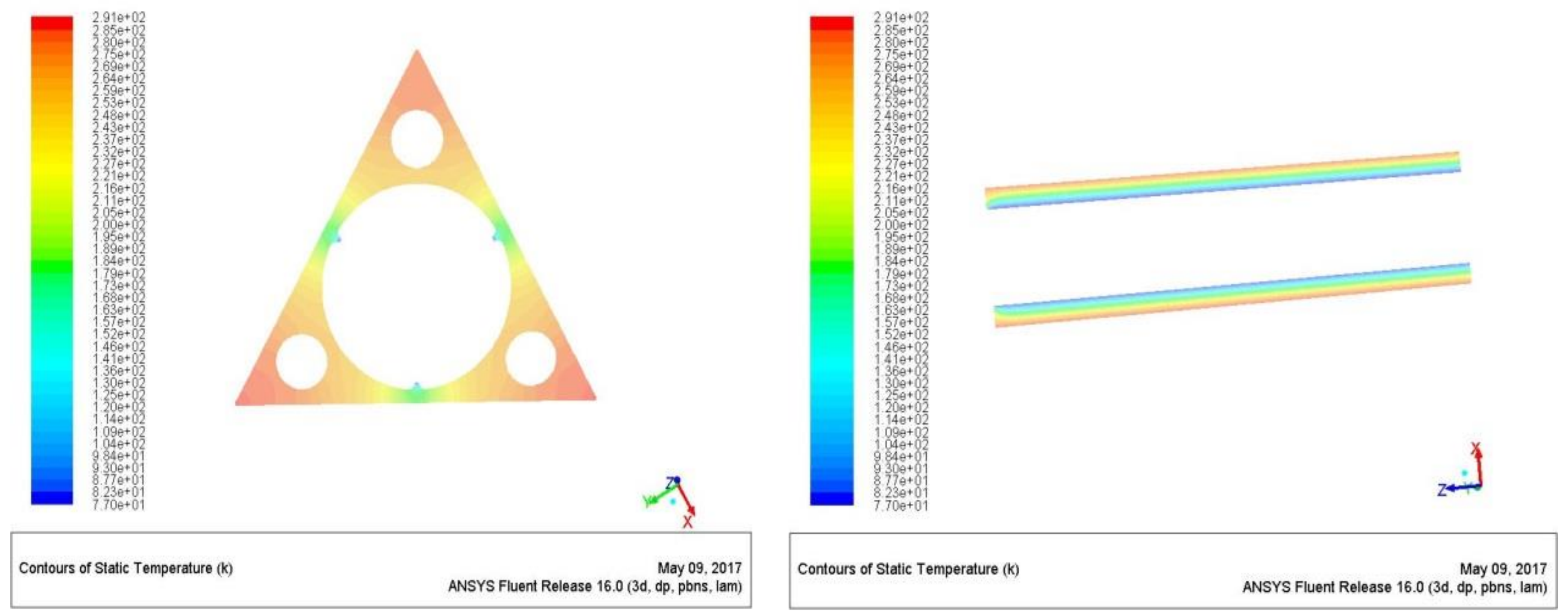


Figure 1. Temperature contour of support (a) and multi-layer insulation (b)

- The support not only conducts with wall in the different pipes, but also has radiation heat transfer with wall. The temperature of the contact segment in the outside is 291K, so it will not have frosting condition.
- The triangle support always only two points to bear the weight of inner pipe. So the highest point will not contact with the outer pipe. The T_{s2} about 270K is less than the T_{s1} and T_{s3} about 275K.
- The temperature of outmost layer of MLI is higher than about 280K. The average of the T_i is about 284K;

Table 1. Heat leakage comparison of the pipe with diameter 88.9mm

Type	Q_s(W)		Q_l(W/m)	Q_t(W/m)	Q(W/m²)	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±0.02	1.46±0.02	2.52±0.02	0.279±0.006

Table 2. Temperature comparison of the support and insulation

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

- The deviations of the heat leakage of multi-layer insulation between the experimental and simulation were less than 5%.
- The temperature of T_i between the experiment and simulation were shown remarkable consistency. And the experiment temperature of outermost layer of MLI is 284K.

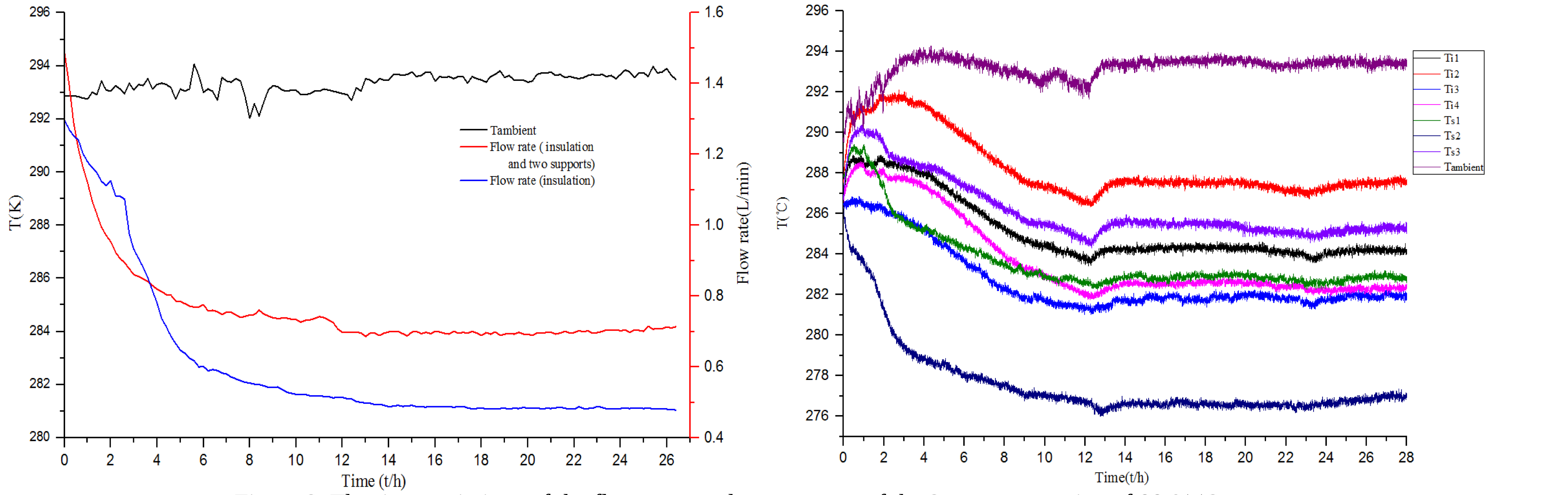


Figure 2. The time variations of the flow rates and temperature of the 2-meters test pipe of 88.9×2mm

- The flow rate and temperature have been stable and fluctuated slightly after 12 hours. The total flow rate of multi-layer insulation and two supports is 0.700L/min, while the multi-layer insulation is 0.490L/min.
- The temperature of support from previous research is much lower than the results of simulation and experiment, because the support radiation has not been considered. The factors of support radiation deserve consideration because the temperature of support surface was lower than the wall of outer pipe and insulation.
- The difference of temperature of the support between the experimental and simulation is less than 10K. And the T_{s2} is lower than the other two points due to the top of the point don't touch with the outer pipe.

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