Characteristics Analysis of Thermal Resistance of Cryogenic Pipeline in Vacuum Environment

Wang Zijuan, Ding Wenjing, Liu Ran

Abstract—If an unsteady heat transfer or heat impulse happens in part of the cryogenic pipeline system of large space environment simulation equipment while running in vacuum environment, it will lead to abnormal flow of the cryogenic fluid in the pipeline. When the situation gets worse, the cryogenic fluid in the pipeline will have phase change and a gas block which results in the malfunction of the cryogenic pipeline system. Referring to the structural parameter of a typical cryogenic pipeline system and the basic equation, an analytical model and a calculation model for cryogenic pipeline system can be built. The various factors which influence the thermal resistance of a cryogenic pipeline system can be analyzed and calculated by using the qualitative analysis relation deduced for thermal resistance of pipeline. The research conclusion could provide theoretical support for the design and operation of a cryogenic pipeline system

Keywords—pipeline, vacuum, vapor quality

I. INTRODUCTION

LARGE space environment simulation equipment is used to simulate cold and dark space conditions [1]. Usually the simulation equipment needs to be equipped with a complicated cryogenic pipeline which is a liquid nitrogen cooling system used to provide a cold environment. A pipeline running process normally includes precooling and single-phase closed-cycle. If an unsteady heat transfer or heat impulse happens in part of the system, it will lead to abnormal flow of the cryogenic fluid in the pipeline. When the situation gets worse, the cryogenic fluid in the pipeline will have phase change which means two-phase flow. This will make a serious impact on the performance of the cryogenic pipeline system.

In traditional calculations of the flow in a cryogenic pipeline system, the interaction of heat transfer and flow is not taken into full consideration. Therefore some calculation results do not accord with the facts. In this thesis, an analytical model and a calculation model for cryogenic pipeline system can be built referring to the structural parameter of a typical cryogenic pipeline system. With the qualitative analysis relation deduced for a cryogenic pipeline system, the thermal resistance in the process of precooling and single-phase closed-cycle can be calculated and the influence on thermal resistance of a cryogenic pipeline system from the vapor quality of fluid and heat load of the system.

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II. ANALYTICAL MODEL

Take some large vacuum equipment for example, a cryogenic pipeline system is shown in Fig.1 and Fig.2. A pipeline has a horizontal cylinder structure. Both the left half and the right half consist of I ,II ,III three parts. Part II and part III cover the upper half of the cylinder. Each part covers an area of 45 degree sector. Part I shows heat sink that covers an area of 68 degree sector of the lower part of the cylinder.
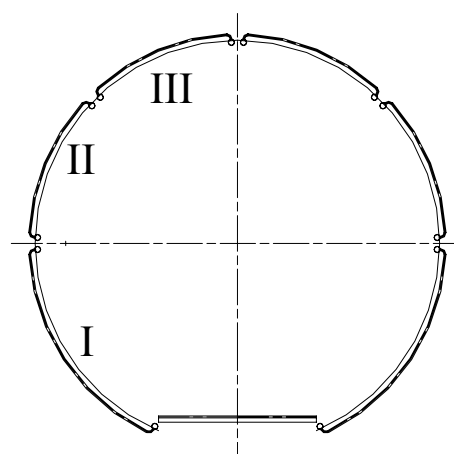

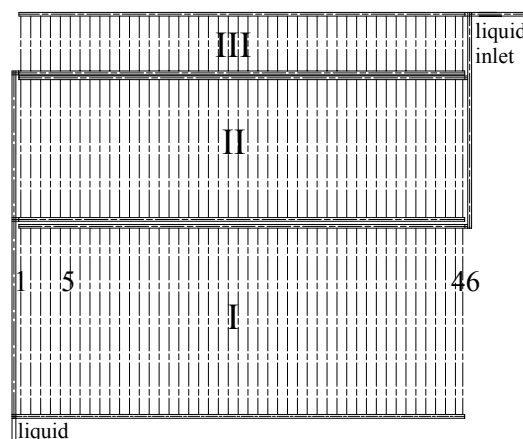Fig. 1 General Drawing of the Structure of a Pipeline

Fig. 2 Schematic of the Layout of a Pipeline

This pipeline is a bilateral symmetry structure. Only the left half of the pipeline including part I II III is calculated as shown in Fig. 3.

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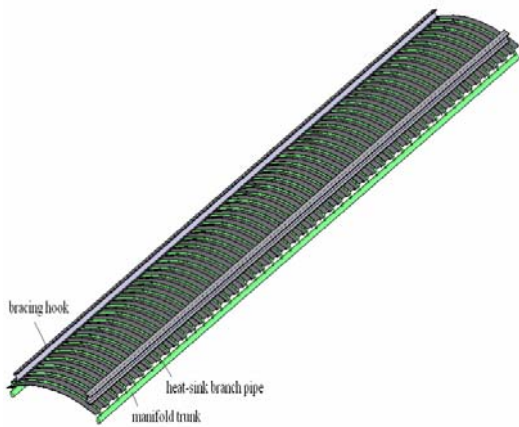International Journal of Mechanical and Mechatronics Engineering
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Fig. 3 Schematic of the Structure of a Pipeline

These three parts share the same liquid inlet and liquid outlet. Each heat-sink branch pipe is numbered 1 2 3 ……46 in succession from the gate to the end. Inlet and outlet is connected in Z shape, inlet is under the outlet. A branch pipe's DN is 18 mm and a manifold trunk's DN is 70mm. In part II, header pipe of fluid inlet's DN is 70mm, nozzle of fluid inlet's DN is 40mm. In part III, header pipe of liquid inlet's DN is 70mm, nozzle of liquid inlet's DN is 30mm.
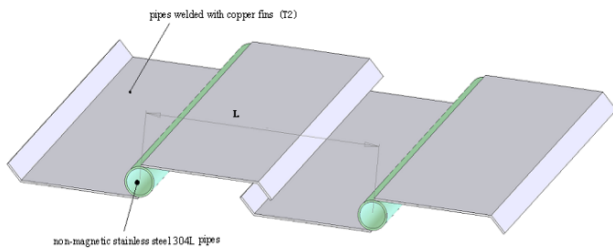

Fig. 4 Schematic of the Structure of a Branch Pipe

The pipeline is made of stainless steel welded with copper fine using liquid nitrogen to cool down. (As shown in Fig.4) In proper running condition, the flow rate of liquid nitrogen is 32m³/h, maximum heat load is 400W/m2, the temperature of inlet liquid nitrogen is 83K, pressure is 5 bar. In precooling condition, the maximum flow rate of liquid nitrogen is 8m³/h, the temperature of inlet liquid nitrogen is 83K, pressure is 5 bar. The flow chart of a feed liquid system is shown in Fig. 5.
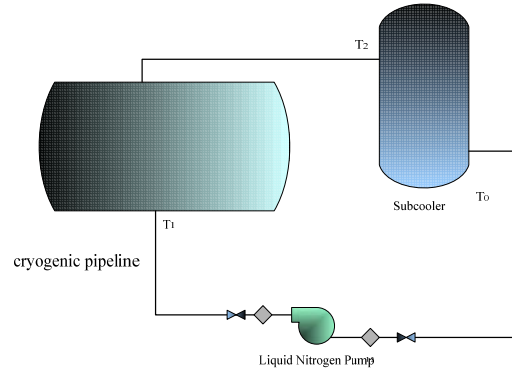

Fig. 5 Flow Chart of a Feed Liquid System

III. CALCULATION MODEL

Mathematic model needs the following hypotheses:

1) The flow is one-dimension non-coherent constant flow.
2) There is heat balance between two phases: vapor and liquid.
3) Suppose that two-phase flow should be single-phase flow of average nature.
4) Define equivalent resistance in the system: flow reduction caused by heat-transfer in cryogenic system equalizes the flow reduction caused by friction force in non-heating condition.Technical papers submitted for publication must advance the state of knowledge and must cite relevant prior work.

Suppose that the two-phase medium pressure should be P0 and the temperature should be T0 before entering the system. The system parameter of the inlet and outlet of the pipeline should be denoted by subscript 1 and 2, so the system could get the following formulas.

Law of conservation of mass:

$$\rho_1 V_{1m} = \rho_2 V_{2m} \tag{1}$$

Law of conservation of momentum:

$$p_{1m} + \rho_{1f} V_{1m}^2 = p_2 + \rho_{2m} V_{2m}^2 + \Delta p_m \tag{2}$$

Law of energy conservation:

$$c_p T_{1m} + \frac{V_{1m}^2}{2} = c_p T_{2m} + \frac{V_{2m}^2}{2} \tag{3}$$

Equation of state:

$$\frac{p_{1m}}{\rho_{1m} R T_{1m}} = Z_{1m} \quad ; \quad \frac{p_{2m}}{\rho_{2m} R T_{2m}} = Z_{2m} \tag{4}$$

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In the formulas:

Δp_m—friction force reduction caused by viscidity in equivalent system

V — flow rate of passage mass, let U=Um

P_1, T_1, ρ_1 — pressure, flow rate, temperature, density in inlet

P_2, T_2, ρ_2 — pressure, flow rate, temperature, density in outlet.

Cryogenic two-phase flow density and compressibility factor could be expressed by the following formulas[2]:

$$\rho^{-1} = x\rho_g^{-1} + (1-x)\rho_l^{-1} \qquad (5)$$

$$Z = xZ_g + (1-x)Z_l \qquad (6)$$

In the formulas:

ρ_g— the density of gas-phase cryogenic fluid

ρ_l— the density of liquid-phase cryogenic fluid

x— flow vapor quality of homogeneous phase fluid

Z_g— the compressibility factor of gas-phase cryogenic fluid

Z_l— the compressibility factor of liquid-phase cryogenic fluid

The calculation formula of vapor quality in thermodynamics could use the test formula 7[2]:

$$x_e(z_d) = \begin{array}{l} -0.0022\dfrac{qDC_{pl}}{r\lambda_L}, Pe < 70000 \\[2mm] -154\dfrac{q}{G_r}, Pe > 70000 \end{array} \qquad (7)$$

The calculation formula of distribution of vapor quality could use the test formula 8[2]:

$$x(z) = x_e(z) - x_e(z_d)\exp\left[\frac{x_e(z)}{x_e(z_d)} - 1\right] \qquad (8)$$

In the formula:

xe (zd) —thermodynamics balance of vapor quality in bubble separation spot

Therefore the outlet temperature and resistance of equivalent system could be expressed with the following formulas:

$$\frac{T_{2m}}{T_2} \approx \frac{1}{1+\dfrac{q'}{C_P T_0}} \qquad (9)$$

TABLE I
CALCULATED DATA OF THERMAL RESISTANCE OF THE PIPELINE

	200W/m²	300W/m²	400W/m²	500W/m²
Part I	0.0408	0.078	0.103	0.145
Part II	0.042	0.08	0.115	0.148
Part III	0.043	0.082	0.117	0.151

TABLE II
CALCULATED DATA OF FLOW DISTRIBUTION OF THE PIPELINE

Number	Total Flow (Kg/s)	Max Temperature (K)
I	2.576	92.15
II	2.184	91.97
III	2.111	92.22

$$\Delta p = \left(1 - \frac{Z_{2m}}{Z_2}\frac{1}{1+\dfrac{q'}{c_p T_0}}\right)(p_0 - p_2) \qquad (10)$$

IV. CALCULATION RESULT AND ANALYSIS

A. Single-phase Closed-cycle Operating Condition

When the pipeline is working in single-phase closed-cycle operating condition, there is single-phase over-cooling liquid nitrogen inside the pipe. Let vapor quality x=1, $\rho=\rho l$, Z=Z1. According to the formulas mentioned above, we could deduce the analytic relation of thermal resistance in the pipeline while working in single-phase closed-cycle operating condition. (See formula 11).According to formula 10, the measurement of thermal resistance in the pipeline is mainly related to total pressure difference of the system, heat load and heat condition of gas. The calculated data of thermal resistance of the pipeline's three parts I II III is shown in Table 1. The calculated data of flow distribution when heat load is 400W/m2 is shown in Table II.

It can be read from the tables above, the situation of a pipeline structure whose main pipe of inlet and main pipe of outlet are connected with each other is similar with that of a normal parallel pipeline structure. Each parallel pipeline's total pressure difference is similar and equal to the loss-in-head of main pipe of parallel start-stop point. Because the heat sink's resistance of each part differs, the flow distribution of each part's pipe is different. The flow distribution of three parts' pipes is shown in Fig.6.
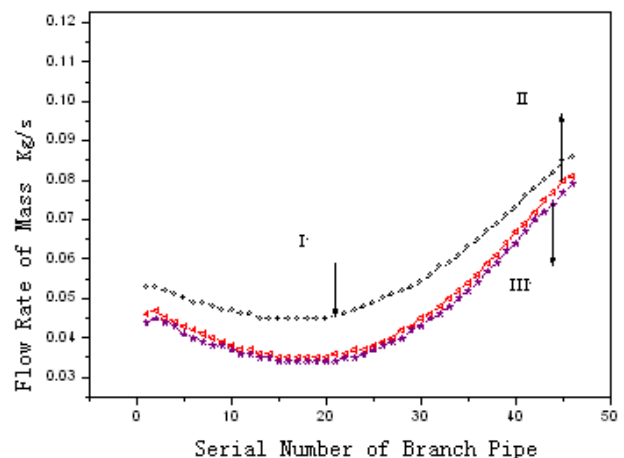

Fig. 6 Schematic of Flow Distribution of a Pipeline

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B. References

When the pipeline is in precooling operating condition, the fluid in the pipe is in two-phase-flow state and the liquid-phase share is gradually increasing with the decrease of precooling temperature. The thermal resistance is related to the fluid's flow state in the pipe and the pipeline's structure. As per the formulas above, we could deduce an analytic relation of the pipeline's thermal resistance in precooling operating condition. (As shown in formula 11.

$$\Delta P = \left[1 - \frac{xZ_{2gm} + x(1-x)Z_{2lm}}{xZ_g + (1-x)Z_l} \frac{1}{1 + \frac{q'}{C_pT_0}} \right] (P_0 - P_2) \qquad (11)$$

According to formula 11, at the first stage of precooling, the main load of the system is the thermal capacitance in the pipeline and a large amount of saturation liquid nitrogen entering the pipeline evaporates quickly so that the fluid in the pipe flows at a high speed. The flow and resistance of the system is mainly determined by compressibility factor and total pressure difference. In a pipeline system whose main pipe's section is the same as the branch pipe's section, the thermal resistance of a pipeline which has a larger thermal capacitance is bigger than that of a pipeline which has a comparatively minor thermal capacitance. Meanwhile, flow distribution of the pipeline whose thermal capacitance is larger reduces in precooling stage. However, the precooling stage lasts longer. In order to intervene the exterior flow distribution, some measures such as adding adjusting valves or regulating the aperture of the feed-liquid pipe should be used as to keep the uniformity of the pipeline system's flow distribution.

The pipeline's cooling curve without interventions of the exterior flow distribution is shown in Fig.7. The pipeline's cooling curve with interventions of the exterior flow distribution is shown in Fig. 8.
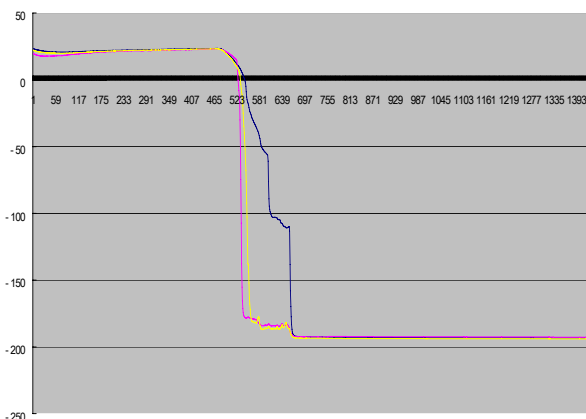

Fig. 7 The Pipeline's Cooling Test Curve without Interventions of the Exterior Flow Distribution
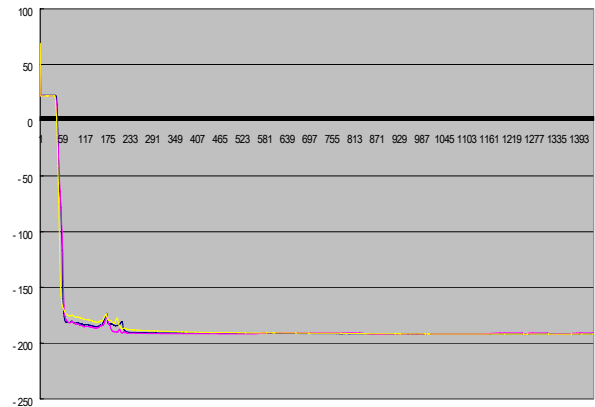

Fig .8 The Pipeline's Cooling Test Curve without Interventions of the Exterior Flow Distribution

C. Analysis and Discussion

From the calculation result of the thermal resistance of the pipeline in precooling and single-phase closed-cycle operating condition, we could find out that the thermal resistance of cryogenic two-phase flow in the stage of convective boiling is closely related to compressibility factor of the two-phase flow (Z), the heating level of reaction system ($\frac{q'}{C_pT_0}$) and the total pressure difference in the system. Thermal resistance and its trend of development are determined by these three factors' specific function in the process of flow and heat transfer. When the heating level of the system is low, the system's flow and resistance is mainly decided by compressibility factor and total pressure difference. At this moment, resistance is closely related with the vapor content in two-phase flow, the total pressure difference in the system and the types of cryogenic fluid. When the heating level of the system is comparatively high, the system's resistance is largely affected by heating. At this moment, besides the increase of the proportion of vapor phase, the change of resistance caused by heating is obvious. The interrelationship of resistance and system is nonlinear. When the heating level is high, the liquid in the cryogenic pipe is highly evaporated so that the thermal resistance and vapor quality is closely related.

V. SOME COMMON MISTAKES

In this thesis, vapor quality and heating level of the system are used to illustrate the heating situation of the pipeline and their influence on the condition of the fluid flow in the pipe is analyzed. By the analysis of the thermal resistance in cryogenic pipeline, it could assumed that when a large amount of heat exchange exists in the cryogenic pipeline system, the thermal resistance's parameter as one of the main parameters affecting the system's performance should be calculated according to the specific situations. The analytic methods used in this thesis focus on the calculation of thermal resistance of the system and analysis of the influence of thermal resistance. These methods also provide a theoretical support for the design and operation of a cryogenic pipeline system.

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