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Pipeline Design and Thermal Stress Analysis of a 10kW@20K Helium Refrigerator

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Abstract. This paper is based on the devices and pipeline in the horizontal cryogenic cold-box of a 10kW@20K helium refrigerator developed by Technical Institute of Physics and Chemistry, Chinese Academy of Sciences. Four devices, six valves, supporting components and pipe lines are positioned in the cold-box. At operating state, the temperature of these devices and pipeline is far below the room temperature, and the lowest temperature is 14K. Due to different material and temperature, the shrinkage of devices and pipes is different. Finite element analysis software SOLIDWORKS SIMULATION was used to numerically simulate the thermal stress and deformation. The results show that the thermal stress of pipe A is a little large. So we should change the pipe route or use a bellows expansion joint. Bellows expansion joints should also be used in the pipes connected to three of the six valves to protect them by decreasing the deformation. At last, the effect of diameter, thickness and bend radius on the thermal stress was analyzed. The results show that the thermal stress of the pipes increases with the increase of the diameter and the decrease of the bend radius.

Keywords: Pipeline, Thermal stress, Cold box, SOLIDWORKS SIMULATION, Numerical simulation

INTRODUCTION

A 10kW@20K helium refrigerator has been developed by Technical Institute of Physics and Chemistry, Chinese Academy of Sciences. The cold loss is a significant factor which influences the performance of a helium refrigerator. There are three modes of cold loss for the cryogenic parts. The first mode is conduction and convection which occurs across the residual gas. It can be neglected by putting the cryogenic parts into a high vacuum cold-box. The second mode is thermal radiation which could be reduced greatly by using at least 25-layers Mylar film coated with high reflectance aluminum. The third mode is conduction occurs across the supporting components.

There are four low temperature devices and six cryogenic valves in the horizontal cold-box of this helium refrigerator. The devices and valves are connected with pipes following the Piping & Instrument Diagram (PID). All the parts in the cold-box cool down after the refrigerator starts. Because of different material, thermal expansion coefficient and operating temperature, the deformation of parts is different. The devices and pipes could be ruptured to break the vacuum as a result of large thermal stress. In addition, the valves could be out of action due to large deformation. Therefore, the thermal stress and deformation of parts in the cold-box should be numerically simulated and analyzed as a whole for safety. Finite element analysis software SOLIDWORKS SIMULATION [1] was used in this paper. On the basis of the analysis, an improved design of pipeline was developed to reduce stress, and a solution was proposed to decrease the deformation of the valves.

ESTABLISHMENT OF PHYSICAL AND MATHEMATICS MODEL

The physical model based on parts in the cold-box was established (see Figure 1). At equilibrium state, the stress of the parts is equivalent to the external force. The differential equations of equilibrium [2, 3] are expressed as:

$$\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + F_x = 0 \quad (1)$$

$$\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + F_y = 0 \quad (2)$$

$$\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_z}{\partial z} + F_z = 0 \quad (3)$$

The stress- strain equation at assumption of isotropy is expressed as:

$$\varepsilon_x = \frac{\partial u}{\partial x}, \varepsilon_y = \frac{\partial v}{\partial y}, \varepsilon_z = \frac{\partial w}{\partial z} \quad (4)$$

Also, the stress and strain follow the Hooke's law expressed as:

$$\varepsilon_x = \frac{1}{E} [\sigma_x - \nu(\sigma_y + \sigma_z)] + aT \quad (5)$$

$$\varepsilon_y = \frac{1}{E} [\sigma_y - \nu(\sigma_z + \sigma_x)] + aT \quad (6)$$

$$\varepsilon_z = \frac{1}{E} [\sigma_z - \nu(\sigma_x + \sigma_y)] + aT \quad (7)$$

where aT is the thermal strain, σ is the stress, ε is the strain, ν is Poisson's ratio, and τ is the shear stress.

MATERIAL, BOUNDARY CONDITIONS, ALLOWABLE STRESS AND DEFORMATION

Device i, device ii and device iii are made of 3003-O aluminum alloy. The material of device iv, pipes and supports is 316L stainless steel. The heat insulation plates are made of Bakelite.

At first, the model of parts in cold-box was established in SOLIDWORKS SIMULATION and the material as above was set. The pipes, valves, supports and device iv were simplified to thin-shell elements to decrease the mesh size. The temperature boundary condition was set according to the PID. The end of the bayonet pipe and valves were set at room temperature. The temperature of the parts in the cold-box was numerically simulated. Then the temperature distribution acted as an applied load when the thermal stress and deformation were numerically simulated.

In this paper, the pipes, valves and devices are research objects which should be far away from the restriction set as a boundary condition. The stress and deformation of supports had been numerically simulated in previous jobs which would not be analyzed in this paper [4]. Therefore, the restriction could be set at the supports. Besides, the restriction also would be set at the joint between cold-box and parts.

To ensure the reliability of valves, the maximum deformation should not exceed the allowable deformation. It can be expressed as:

$$\delta \leq [\delta] = 3\text{mm} \quad (8)$$

If the safety factor is set to 1, the maximum von mises stress could not exceed the allowable stress. It can be expressed as:

$$\sigma_{\text{vonmises}} = \sqrt{0.5 [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]} \quad (9)$$

$$\sigma_{\text{vonmises}} \leq [\sigma] \quad (10)$$

where $[\sigma]$ is the allowable stress at operating temperature.

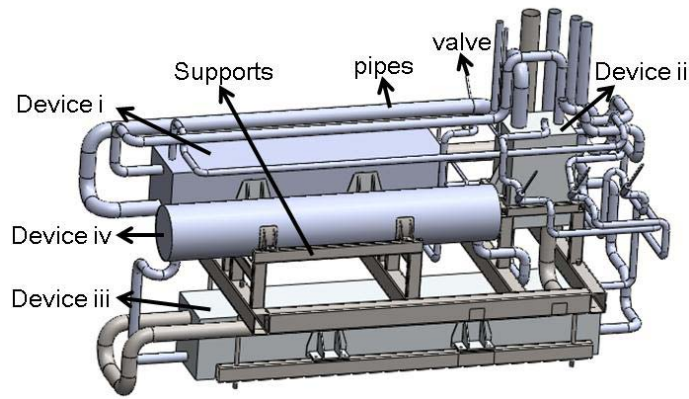


FIGURE 1. Physical model of parts in cold-box

RESULTS AND ANALYSIS OF THERMAL STRESS AND DEFORMATION

Temperature and Thermal Stress Distribution of Parts in the Cold-box

The temperature distribution of the parts in the cold-box is shown in Figure 2, and the thermal stress distribution is shown in Figure 3. As mentioned above, the restriction was set at the supports, and the stress at this point could not reflect the truth. As research objects of this paper, pipes, valves and devices show the true stress and the maximum thermal stress could be probed. The resulting thermal stress in the pipes is shown in Table 1. As you can see from Table 1, the maximum thermal stress of pipe A is 200MPa, which is a little large. It doesn't exceed the allowable stress at 80K (about 400MPa), but it should be improved for safety.

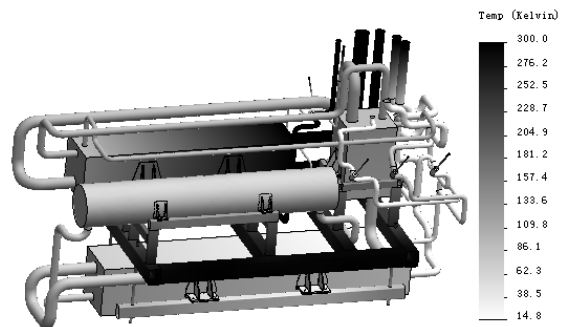


FIGURE 2. Temperature distribution of parts in the cold-box

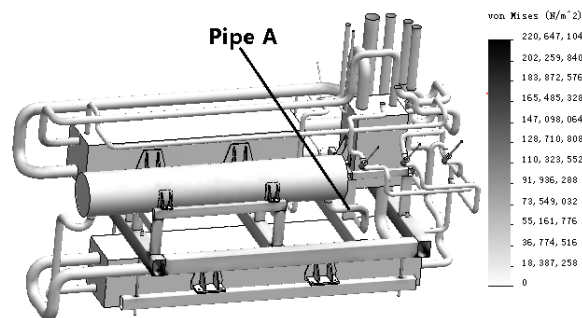


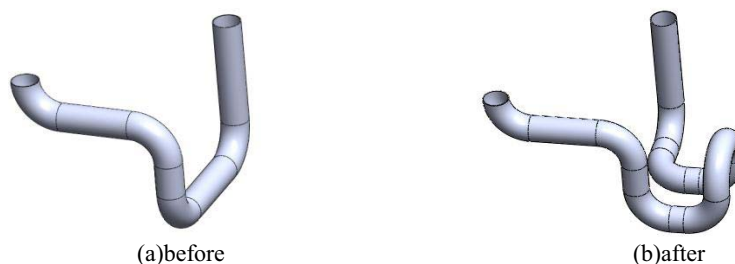
FIGURE 3. Thermal stress distribution of parts in the cold-box

TABLE 1. Maximum thermal stress of pipes

Component	Maximum thermal stress
Pipe A	200 MPa
Pipe B	134 MPa
Pipe C	101 MPa
Pipe D	72.4 MPa
Pipe E	35.3 MPa
Pipe F	104 MPa
Pipe G	135 MPa
Pipe H	123 MPa

TABLE 2. Thermal stress change of pipe A

Pipe A	Maximum thermal stress
Before	200 MPa
After	178 MPa

**FIGURE 4.** Thermal stress distribution of parts in the cold-box

Solutions for Decreasing Thermal Stress

There are two solutions generally used to decrease thermal stresses. Bellows expansion joints can be used as a flexible part or pipe route should be changed. The change of route is shown in Figure 4. As you can see from Table 2, the maximum thermal stress decreased from 200MPa to 178MPa by changing the pipe route.

Deformation Distribution of Parts in Cold-box and Solution

Thermal stress is an important parameter for the parts in the cold-box. Besides, deformation is another key parameter for valves. The deformation distribution of parts in the cold-box magnified 42 times is shown in Figure 5, and the original position is indicated by shading. According to the results, the deformation of valve 3, valve 4 and valve 5 exceeded the allowable value and should be reduced. The only solution is to use bellows expansion joints. When the pipes cool down and start to shrink, the bellows expansion joints will decrease the shrinkage of the pipes with the deformation of the bellows to protect the valves.

TABLE 3. Maximum deformation of valves

Component	Maximum deformation
Valve 1	2 mm
Valve 2	2.5 mm
Valve 3	4.3 mm
Valve 4	4.4 mm
Valve 5	3.5 mm
Valve 6	1.1 mm

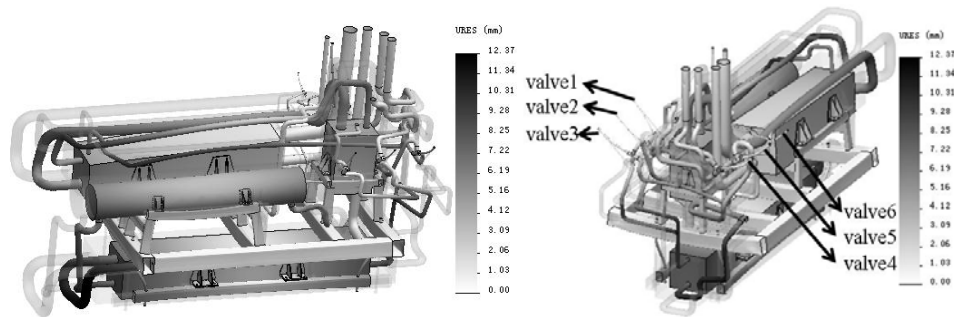


FIGURE 5. Deformation distribution of parts in cold-box (magnified 42 times)

TABLE 4. Effect of diameter, thickness and bend radius of pipes

Parameters	Maximum thermal tress
Diameter(89mm)	178 MPa
Diameter(109mm)	213 MPa
Thickness(2mm)	178 MPa
Thickness(4mm)	175 MPa
Bend radius(114mm)	153MPa
Bend radius(80mm)	178 MPa

Effect of Diameter, Thickness and Bend Radius of Pipes

Diameter, thickness and bend radius are basic parameters for pipes [5]. The effect of these parameters on thermal stress should be discussed. For pipe A, the results are shown in Table 4. The thermal stress increases with the increase of the diameter and the decrease of the bend radius. The thickness makes no difference to thermal stress.

The diameter and thickness generally are set by PID. The bend radius is the only parameter to improve the design of the pipeline. According to the result, the bend radius should be increased if there is enough space.

CONCLUSION

Finite element analysis software SOLIDWORKS SIMULATION was used to numerically simulate the thermal stress and deformation of parts in the cold-box. The results show that the thermal stress of one pipe is a little large, and the pipe route should be changed or a bellows expansion joint should be used. The bellows expansion joints should also be used in the pipes connected to three of the six valves to protect them by decreasing the deformation. At last, the effect of diameter, thickness and bend radius on the thermal stress was analyzed. The results show that the thermal stress of pipe increases with the increase of the diameter and the decrease of the bend radius.

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