DESIGN OF A HELIUM PHASE SEPARATOR WITH CONDENSER

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Abstract

This paper presents the design of a helium phase separator with volume of 100 litres. A condenser using a cryocooler for cooling is built into the phase separator to save liquid helium consumption during the test period. The heat loss to the 4.2 K inner vessel is confined within 1W due to the limited 1.5W cooling capacity from the cryocooler. Analysis of mechanical strength and heat load is illustrated.

INTRODUCTION

After long distance transfer the heat loss will bring inevitable two-phase flow with considerable pressure gradient due to the low latent heat of liquid helium. This situation deteriorates the transfer efficiency, especially for a cryostat that is not continuously filled with liquid helium. A helium phase separator placed at the upstream side of the cryostat can solve this problem. In addition to reduce the gas phase during transferring liquid helium, the phase separator needs to keep a stable transfer pressure. Furthermore, to provide versatile function a sample port for experiment study is built into the phase separator.

CONFIGURATION

Figure 1 shows the components of the phase separator, where an inner vessel with a volume of 100 litres is hanged on the outer vessel via four sustaining rods, and a thermal shield is placed in between the two vessels to reduce the heat from thermal radiation. Three cryogenic valves are used for the filling and the extracting of liquid helium, and the pressure regulation respectively. A cryocooler with two stages of cold head provides the cooling for the thermal shield and the condenser. To connect to the thermal shield, the cryocooler needs to extend into the space between the outer vessel and the inner vessel.

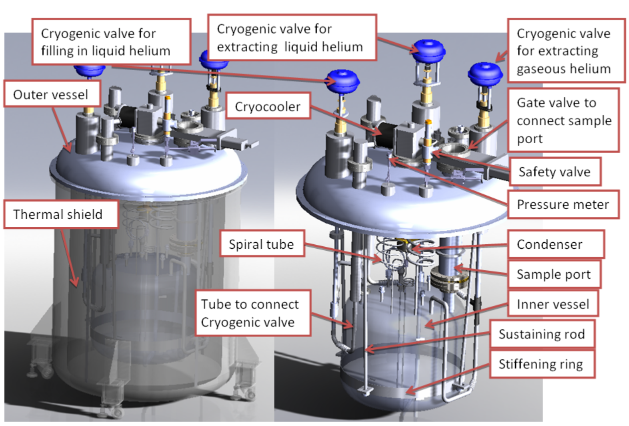

Figure 1: Components of the phase separator.

The first stage of cryocooler is indirectly connected to the thermal shield via flanges and screws. This connection enables the removal of cryocooler for maintenance. The first stage provide 32K thermal anchor to reduce the heat into the inner vessel. The second stage of cryocooler contacts directly to the condenser, which includes a plurality of surface, to condense the vaporized helium gas into liquid helium and thus reduce the consumption of liquid helium.

The sample port with a diameter of 100 mm is designed as a device to place experimental samples at cryogenic temperature. There are two ways to cool down the sample: one is utilizing the cryocooler to cool down the sample to a temperature near 4.5K without liquid helium; the other is utilizing liquid helium to obtain the temperature near 4.2K.

A problem encountered in the design of phase separator is the thermal stress resulting from contraction upon cooling the inner vessel from room temperature to 4.2K. To reduce the thermal stress, spiral tubes and bellows are adopted for the linkage between the outer vessel and the inner vessel, as Fig. 2 shows.

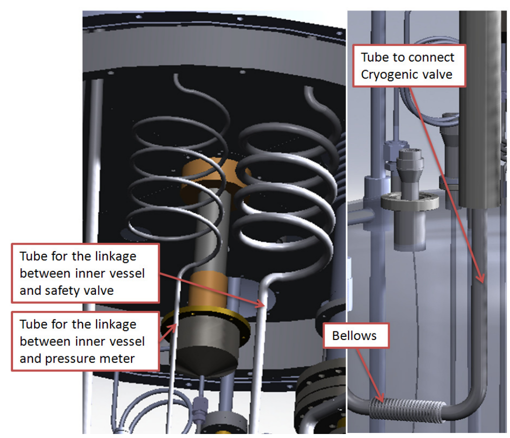

Figure 2: Spiral tubes and prolongation of tubes.

COMPONENT DESIGN

Inner Vessel

All structure of the vessel with shapes resembling curved plates is referred to as shell. The inner vessel is comprised of a cylinder shell, two torispherical heads, and a stiffening ring for connection of the sustaining rods. The inner vessel must be durable enough to withstand the internal pressure, the weight of the liquid helium, and the bending stresses from the sustaining rods. To design an inner vessel storing 100-liter liquid helium with suitable height, the inside diameter of head is constrained in the range from 300mm to 600mm. The design internal absolute pressure is 601.33 kPa under the condition of vacuum in between the inner vessel and the outer vessel. Alloy 316L stainless steel is selected as the material for the inner vessel.

Parameters of the vessel are characterized in Fig. 3, where the parameters H and D are chosen in accordance with the volume of inner vessel. The parameter h is determined based on the cold head length of the cryocooler and the required maintenance space between the outer vessel and the thermal shield. There are membrane stress distributed over the inner vessel and the sustaining rods due to the inner pressure and the total weight of inner vessel, in which 70% volume is filled with liquid helium. Relations among the parameters and the membrane stress can be found in references [1][2][3]. The design process requires iterations for determining the parameters and confirming the membrane stress being lower than the allowable stress, as Fig. 4 shows.

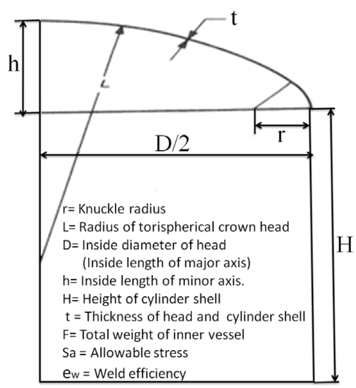

Figure 3: Parameters of the vessel design.

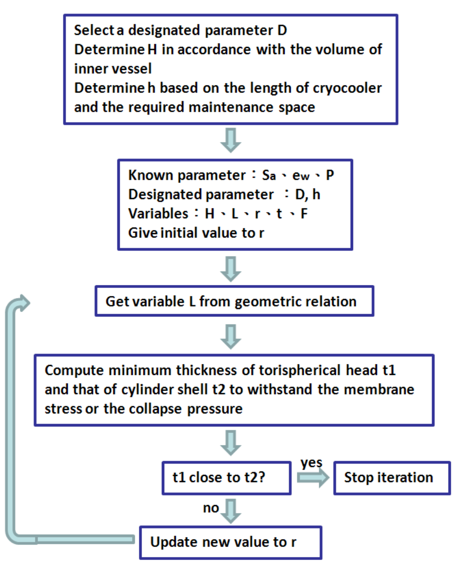

Figure 4: Design process of the vessel.

Outer Vessel

The outer vessel has similar structure as that of the inner vessel except that there is an external absolute pressure 101.33 kPa and no internal pressure. Alloy 304 stainless steel is selected as the material for the outer vessel. Design of the outer vessel needs to check the failure from elastic instability, which can be calculated from the ASME code [3]. Table 1 presents the results for the inner vessel and the outer vessel.

Sustaining Rods

The inner vessel is suspended by four G10 sustaining rods with outer diameter 16mm and inner diameter 13mm. To provide the suspension force in both vertical and horizontal directions, the sustaining rods shall be installed with a deviation from vertical position to an angle of 5 degree. Each rod sustains the inner vessel with 91.24N load. Because of the slanted installation of sustaining rods, bending moment should be utilized to calculate the tension stress of each rod. The maximum stress is 24.64 MPa and occurs at the edge in contact with the outer vessel.

Table 1: Parameters of Inner Vessel and Outer Vessel

Parameters	**Inner vessel**	**Outer vessel**
Pressure difference P (kPa)	601.33	101.33
Radius of torispherical crown head L (mm)	1441	2000
Inside diameter of head D (mm)	555	950
Inside length of minor axis h (mm)	100	150
Height of cylinder shell H (mm)	300	1000
Knuckler radius r (mm)	86.46	115.36
Thickness of head and cylinder t (mm)	1.93	2.34

Thermal Shield

With the aim of developing a thermal shield with reliable structure and high performance, two ways were studied: one is material choice and the other is the method to sustain the thermal shield. We select the OFHC copper material to capitalize on its excellent thermal conductivity during cryogenic temperature. A framework comprised of battens with 2mm thickness sustains the whole weight and keeps insignificant deformation of the thermal shield. The OFHC copper sheet with 0.2mm thickness is attached along the edge of the framework by Laser beam welding. This sustaining method ensures that the thermal shield has sufficient elasticity to absorb contraction upon cooling the inner vessel from room temperature to 4.2K. Figure 5 presents the design of the thermal shield.

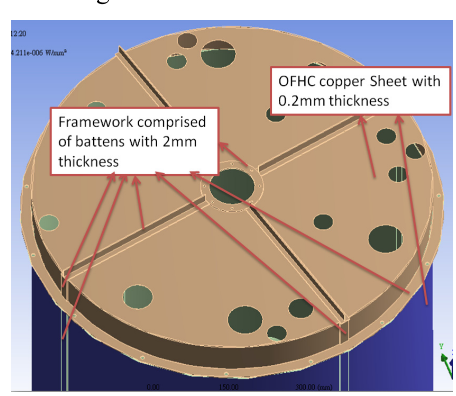

Figure 5: Structure of thermal shield.

Condenser

Figure 6 depicts the condenser design. The condenser is composed of an array of 16 vertical fins, with height of 40 mm and diameter of 65mm, on an OFHC plate with diameter of 137 mm. The shape of condenser's fin is similar to Taylor [4] and the heat transfer coefficient of the condenser fin can be calculated using the semi-empirical equations [5]. A condenser-cover is vacuum-brazed with the OFHC plate to form a confined chamber which separates the helium from the vacuum area of the outer vessel. The bottom of the cover is designed with funnel shape and therefore the condensed liquid helium can flow smoothly back to the inner vessel. Returning flow pipe and guided pipe are the flow channels for liquid and gas helium, respectively. VCR connector is adopted on the flow channel to let the condenser demountable.

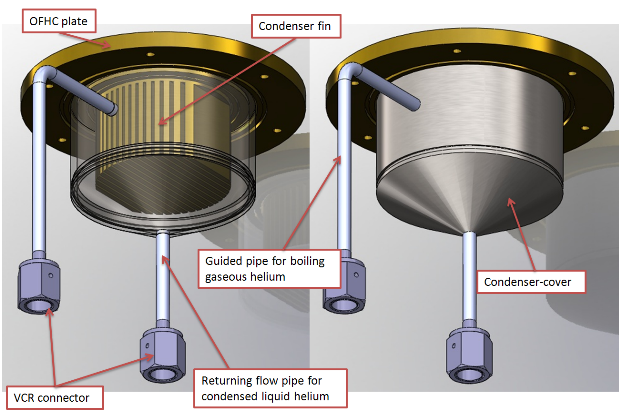

Figure 6: Details of the condenser.

HEAT LOAD

Considerable efforts are taken to reduce heat loss from outer vessel into inner vessel via thermal conduction or thermal radiation. The phase separator is characterized by prolongation of tubes for installing cryogenic valves, safety valve, and pressure meter, as depicted in Fig. 2, to effectively limit the heat conduction passing through those devices and reaching the inner vessel. The heat-bridge at penetrations of the outer vessel for the cryogenic valves and the thermal anchor on the thermal shield, the cryogenic valves, and the sample port are another effective means to reduce the heat loss from thermal conduction. Multilayer superinsulation is wrapped around the thermal shield, the outer surface of the inner vessel, and the tubes for liquid helium and gaseous helium to reduce the heat into the phase separator via thermal radiation.

Simulation result for the heat load on the first and second stages of the cryocooler are shown in Table 2 and Table 3. The first stage provides thermal anchor with a heat load of 13W at temperature 32K, which is determined from the loading curve of the cryocooler. Because the remaining cooling capacity at the second stage is limited to 1.3W at 4.2K, heat loss to the inner vessel must be reduced as low as possible to ensure that the second stage could provide sufficient cooling power for condensation of the helium gas. The heat loss from each tube of cryogenic valves could be reduced to below 0.05W, and that of the sample port could merely be diminished below 0.4W due to its wide cross-section. The total heat load at the second stage of cryocooler is near 0.6W, which includes the thermal radiation heat of 0.03W evaluated using the empirical heat-flux data of the superinsulation material.

Table 2: Heat Load to the First Stage of Cryocooler

Component	**Heat loss (W)**
Conduction of cryogenic valves and sample port	2.043
Thermal radiation (300K to 32K)	10.913
Total heat loss	12.956

Table 3: Heat Load to the Second Stage of Cryocooler

Component	**Heat loss (W)**
Inlet port for filling liquid He	0.044
Outlet port for extracting liquid He	0.033
Outlet port for extracting gas He	0.021
Safety valve	0.055
Pressure meter	0.023
Sample port	0.366
Sustaining rods	0.011
Thermal radiation (32K to 4.2K)	0.029
Total heat loss	0.582

CONCLUSION

A process of developing a new type of phase separator with multifunction is presented. Mechanical stress is verified to avoid the failure from elastic instability and the damage of material. The phase separator is designed to have heat loss within 13 W at 32 K and 0.6 W at 4.2 K, which allows the condenser to function properly with cooling from the cryocooler.

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