Thermal design and optimization of high-pressure helium heat exchanger

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Abstract. Helium at a temperature of 20K and high pressure is widely used as a gas source for cryogenic products. In the past, helium was usually cooled by liquid hydrogen immersion. This method needs to consume lots of liquid hydrogen and has poor safety. The cooling time is also too long. This paper designs a high-pressure helium heat exchanger to obtain and store helium with 20K at 35MPa required by a certain system. The heat exchanger can not only meet the gas requirements but also can control the cooling time within 48 hours.

1. Introduction

The pressurized delivery system is one of the key technologies. Helium is usually used as the working medium for the pressurized delivery system, due to its small molecular weight [1,2]. The valves, pipelines, and systems involved in the cryogenic helium pressurized delivery system must meet the liquid hydrogen temperature zone (20K), so higher technical requirement is imposed on the entire system [1,3]. This requires that during the system design experiment, the performance of the system needs to be tested in the temperature region of liquid hydrogen, such as the valve airtightness test, the screening test, the vibration test, etc.

In the past, the method for obtaining helium in the temperature region of liquid hydrogen was usually to introduce high-pressure helium into a heat exchanger immersed in liquid hydrogen. Due to the small heat exchange temperature difference when the heat exchange reaches a stable condition, and the limitation of heat exchange time, the high-pressure helium gas cannot reach 20K [4]. This method cannot meet the real working condition of the simulation of the cryogenic helium pressurized delivery system. Besides, because this method uses a large amount of hydrogen, which is a flammable and explosive medium, the experiment is highly dangerous. This caused some scientific research institution not to have the qualification to use liquid hydrogen, and some experiments such as the vibration experiment cannot be completed under this condition [5].

Now there are helium cryocoolers that have a cooling temperature of 20K and operate stably. So, in this paper, a high-pressure helium heat exchanger is designed, which uses the helium cryocoolers as the cold source to cool the high-pressure helium. This method no longer uses hydrogen and is safer. At the same time, the heat exchanger can meet the requirements of more liquid hydrogen temperature zone experiments with helium as the working medium.
2. Working parameters and structures of the high-pressure helium heat exchanger

2.1. Working parameters
A principal diagram of the high-pressure helium heat exchanger is shown in Figure 1. The room temperature helium from the gas distribution station is pre-cooled to 80K by liquid nitrogen and then charged into the storage tank of the high-pressure helium heat exchanger. The cold helium of cryocoolers flows through the heat exchanger tubes in the high-pressure helium heat exchanger to cool the helium in the storage tank. Finally, the temperature of the helium in the storage tank reaches 20K and the pressure reaches 35MPa. In particular, to meet the time requirements of the actual experiment in this design, it is necessary to ensure that the entire cooling time does not exceed 48 hours.

![Figure 1. Principle diagram of the high-pressure helium heat exchanger.](image)

1. Cryocoolers; 2. A high-pressure helium storage tank; 3. Heat exchanger tubes; 4. Pre-cooling system; 5. 300K helium tubes; 6. Related experimental platform.

2.2. Structure
The structure of the high-pressure helium heat exchanger is shown in Figure 2. The storage tank volume is 70L, and the tank body is made of stainless steel S30408. The storage tank installed in vacuum to reduce heat leakage. The cold helium heat exchanger tubes are straight copper tubes with a total of 64, and the effective heat exchanger length of the tube is 1m. The outer diameter of a single tube is 14mm, and its wall thickness is 3.5mm.

Because the temperature of the helium entering the storage tank is 80K and the heat capacity of the storage tank is relatively large, the storage tank body needs to be pre-cooled from room temperature to 80K to prevent the helium from being heated by the tank body. The liquid nitrogen jacket structure is added outside the storage tank, and the tank body is immersed in liquid nitrogen to cool it down to 80K. Then the liquid nitrogen is drained after precooling and the jacket structure is kept under vacuum.
3. Analysis of heat transfer principle

3.1. Liquid nitrogen pre-cooled storage tank body
The tank is immersed in liquid nitrogen at a temperature of 80K, which brings one-dimensional non-steady-state heat conduction. The heat transfer between the tank wall surface and liquid nitrogen is convective. Liquid nitrogen temperature remains at 80K. That is, the heat transfer coefficient between the outer wall surface of the storage tank and the liquid nitrogen surface is infinite, and the Biot number \((B_i)\) is infinite, so the temperature of the outer wall surface of the tank approached the temperature of the liquid nitrogen(80K).

3.2. Process of decreasing temperature and increasing pressure of helium
The heat exchange form of the high-pressure helium heat exchanger is an overall natural convection heat transfer accompanied by local forced convection on the outside of heat exchanger tubes, heat conduction inside the heat exchange tube wall, and forced convection on the inside of heat exchanger tubes.

3.2.1. Heat exchanger between high-pressure and low-pressure helium. The helium on the high-pressure helium side and the wall surface of the heat exchanger tube exchange heat with a temperature difference \(T_h-T_{hw}\), and the heat exchanger capacity is \(Q_h\) expressed in Equation (1).

\[
Q_h = h_h(T_h - T_{hw}) A_h
\]  
(1)

where \(h_h\) is the heat transfer coefficient on high-pressure helium side, \(T_h\) is high-pressure helium temperature, \(T_{hw}\) is outer wall temperature of heat transfer tube, and \(A_h\) is the surface area of the outer wall of the heat transfer tube.

Because the heat transfer on the outside of the heat transfer tube is an overall natural convection heat transfer accompanied by local forced convection, the mixed convection heat transfer coefficient in 80K to 20K temperature zone is currently in the research blank. According to experience, the value of \(h_h\) should be between 5 and 10. For conservation reasons, \(h_h\) can be 5.

**Figure 2.** Structures of the high-pressure helium heat exchanger.
1. Storage tank; 2. The liquid nitrogen jacket structure; 3. Vacuum shell; 4. Helium inlet and outlet pipe; 5. Vacuum interface; 6. The cold helium heat exchanger tubes; 7. Safety valve interface; 8. Cold helium inlet of cryocoolers; 9. Pressure sensor interface; 10. Cold helium outlet of cryocoolers.
The heat transfer of the heat transfer tube wall is to transfer heat from the high-pressure helium sidewall surface to the low-pressure helium sidewall surface, and the heat exchanger capacity \( Q_w \) is expressed in Equation (2).

\[
Q_w = \frac{\lambda_w \cdot 2 \cdot l}{\ln(d_o/d_i)} (T_{hw} - T_{lw})
\]

where \( \lambda_w \) is the thermal conductivity of heat exchange tube, \( l \) is effective to heat exchange length of heat exchange tube, \( d_o \) and \( d_i \) are the outer and inner diameters of the heat transfer tube, and \( T_{lw} \) is the inner wall temperature of the heat transfer tube.

The helium on the low-pressure helium side and the wall surface of the heat exchanger tube exchange heat with a temperature different \( T_{lw} - T_i \), and the heat exchanger capacity is \( Q_l \) expressed in Equation (3).

\[
Q_l = h_l (T_{lw} - T_i) A_l
\]

where \( h_l \) is the heat transfer coefficient on the low-pressure helium side, \( T_i \) is low-pressure helium temperature, and \( A_l \) is the surface area of the inner wall of the heat exchanger tube.

Since the low-pressure helium side is forced convection in the tube, \( h_l \) can be calculated by Equation (4).

\[
h_l = \frac{N_u \cdot \lambda_w}{d_i}
\]

where \( N_u \) is the Nusselt number. For laminar flows, \( N_u \) is can be calculated by Equation (5), and for turbulent flows, \( N_u \) can be calculated by Equation (6) (Dittus-Boelter correlation)

\[
N_u = 4.364 \quad (5)
\]

\[
N_u = 0.023 \cdot Re^{0.8} \cdot Pr^{0.4} \quad (6)
\]

where \( Re \) is the Reynolds number, \( Pr \) is the Prandtl number.

According to the heat balance, the heat \( Q_h \) from the high-pressure helium to the outer wall of the heat exchange tube is equal to the heat \( Q_w \) of the heat exchange tube, equal to the heat \( Q_l \) absorbed by the low-pressure helium on the inner wall of the heat exchanger tube, and equal to the heat \( Q \) released when the temperature of the high-pressure helium decreases.

\[
Q = Q_h = Q_w = Q_l
\]

\[
Q = m \cdot c \cdot \Delta T
\]

\[
Q = K \cdot A_h \cdot (T_h - T_i)
\]

where \( m \) is high-pressure helium mass, \( c \) is the specific heat capacity of helium, \( \Delta T \) is the temperature change of high-pressure helium, and \( K \) expressed in Equation (10) is the heat transfer coefficient based on the area outside the heat transfer tube.

\[
\frac{1}{K} = \frac{d_o}{h_l d_i} \cdot \frac{d_o}{2 \lambda_w} \ln \left( \frac{d_o}{d_i} \right) + \frac{1}{h_l}
\]

3.2.2. Heat exchanger between high-pressure helium and storage tank body. The heat transfer between the high-pressure helium and the tank body is natural convection. When the temperature of the tank body is higher than the high-pressure helium temperature, the high-pressure helium cools the tank body. The temperature of the tank body decreases and the temperature of the high-pressure helium increases. When the temperature of the tank is lower than the high-pressure helium, the tank heats the high-pressure helium. The temperature of the tank increases, and the temperature of the high-pressure helium decreases.

Take the temperature of the tank body lower than that of high-pressure helium as an example, and the balance of heat transfer is shown in Equation 11.

\[
Q_T = M \cdot \int_{T_{lw}}^{T_{hw}} C_T \cdot dT = m \cdot c \cdot (T_h - T_i) \quad (11)
\]

where \( M \) is the total mass of the tank, \( C_T \) is the specific heat capacity of the tank, \( T_{lw} \) is the temperature of the tank after it has been cooled, and \( T_h \) is the temperature of the high-pressure after it has been warmed.
4. Calculation of heat exchange time of heat exchanger

4.1. Heat exchange time for liquid pre-cooled storage tank body
For the liquid nitrogen pre-cooled storage tank body calculated is the heat transfer time of the upper and lower end caps and sidewalls of the storage tank from 300K to 80K. The calculation method is a simulation by a computer. The simulation software is Solidworks Simulation®. This software is a design analysis software based on finite element analysis (FEA).

The computer simulation results are shown in Figure 3. The ordinate is the temperature of the tank, and the abscissa is the cooling time. The time required for the tank to be pre-cooled from room temperature (300K) to 80K by liquid nitrogen is 3 hours.

![Figure 3. The process of tank cooling by liquid nitrogen.](image)

4.2. Heat exchange time for helium to decrease temperature and increase pressure process
To ensure the stable operation of the helium filling and cooling process, a set of inflatable strategies are developed. The inflation process is shown in Table 1. After pre-cooling with liquid nitrogen, the tank body was stable at 80K. Firstly, fill the tank with helium at 5 MPa and 80K. When the low-pressure helium of the cryocoolers reaches 50K, it will exchange heat with the high-pressure helium in the tank. When the high-pressure helium temperature reaches 20K, the first phase ends. Then fill the tank with 80K hot helium until the pressure in the tank reaches 10MPa. At this time, the temperature of the helium in the tank and the tank body first increased and then gradually decreased. When the temperature reached 20K, the second stage was ended. Follow this inflation strategy until the final helium state in the tank reaches 20K at 35 MPa. Table 2 shows the calculation results.

| Process | Initial state | End state | Process | Initial state | End state |
|---------|---------------|-----------|---------|---------------|-----------|
| 1       | 5MPa@80K      | 20K@1.1445MPa | 7       | 35MPa         | 20K@29.959 MPa |
| 2       | 10MPa         | 20K@3.0729MPa | 8       | 35MPa         | 20K@32.938 MPa |
| 3       | 15MPa         | 20K@6.0557MPa | 9       | 35MPa         | 20K@34.220 MPa |
| 4       | 20MPa         | 20K@10.623MPa | 10      | 35MPa         | 20K@34.730 MPa |
| 5       | 25MPa         | 20K@16.807MPa | 11      | 35MPa         | 20K@34.929 MPa |
| 6       | 30MPa         | 20K@23.518MPa | 12      | 35MPa         | 20K@35.006 MPa |
Table 2. Heat exchange time for helium to decrease temperature and increase pressure process

| Process | Charge Quality(kg) | Time(h)  |
|---------|--------------------|----------|
| 1       | 1.9399             | 19.3019  |
| 2       | 2.9167             | 3.0983   |
| 3       | 3.0843             | 3.4294   |
| 4       | 2.7126             | 3.4586   |
| 5       | 2.0884             | 3.1803   |
| 6       | 1.5150             | 2.7739   |
| 7       | 1.1004             | 2.4383   |
| 8       | 0.4330             | 1.4769   |
| 9       | 0.1747             | 0.7753   |
| 10      | 0.0677             | 0.3519   |
| 11      | 0.0261             | 0.1358   |
| 12      | 0.0101             | 0.0525   |
| Total   | 16.0689            | 40.4731  |

5. Summary
The high-pressure helium heat exchanger can be used to obtain and store helium with 20K at 35MPa required by a certain aviation system. The cooling time is 43.5 hours. This time includes the time for the entire heat exchanger to be pre-cooled from room temperature (300K) to 80K and the time for the high-pressure helium and the storage tank to be cooled and pressurized to 20K at 35MPa. Cooling and pressurizing times are acceptable within 48 hours. Therefore, the high-pressure helium heat exchanger meets the design requirements.

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