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Design and cooling of BESIII beryllium beam pipe

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Abstract

The beryllium beam pipe was restructured according to the requirements of the upgraded BESIII (Beijing Spectrometer) experiment. SMO-1 (sparking machining oil no. 1) was selected as the coolant for the central beryllium beam pipe. The cooling gap width of the beryllium beam pipe was calculated, the influence of concentrated heat load on the wall temperature of the beryllium beam pipe was studied, and the optimal velocity of the SMO-1 in the gap was determined at the maximum heat load. A cooling system for the beam pipe was developed to control the outer wall temperature of the beam pipe. The cooling system is reported in this paper with regard to the following two aspects: the layouts and the automation. The performance of the cooling system was tested on the beam pipe model with trim size. The test results show that the design of the beryllium beam pipe is reasonable and that the cooling system achieves the BESIII experimental aim. The cooling system has already passed the acceptance test and has been installed in position. It will be put into practice for the BESIII experiment in 2008.

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Keywords: BESIII; Beryllium beam pipe; Cooling system; Automation

1. Introduction

A new BESIII experiment will be executed on the upgraded BEPCII (Beijing electron positron collider). The single storage ring of accelerator has become double rings after being upgraded, and the luminosity is $1 \times 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-2}$, which is about 100 times higher than before. The BESIII was restructured to match the new physics research with a data acquisition life of 10 years; it will operate with an energy of 2–5 GeV for the precision study of τ-charm physics and continue to lead the world [1,2].

As a part of an ultrahigh vacuum storage ring of the accelerator, the beam pipe is located in the center of the BESIII and the electron and positron collide at the central region of the beam pipe when they reach the desired energy. When the BEPCII operates, the high frequency cavity will cause the high order module (HOM) on the inner wall of the beam pipe and the positron and electron running at the speed of light may produce synchrotron radiation (SR) on the inner wall, which results in a heat load on the inner wall of the beam pipe [3]. The working temperature of the MDC nearest to the beam pipe is restricted to 293.15 ± 1 K (relative to the ambient temperature of 293.15 K) to prevent wire breakage. The maximum distance between the MDC and the beam pipe is 29.3 mm, so the beam pipe should be cooled to control the influence of the outer wall temperature on the MDC.

The beam pipe consists of two extension copper pipes and a central beryllium beam pipe. The BESIII physics research aims at discovering the new phenomena produced by the collision decay of an electron and a positron. The thickness of the beryllium beam pipe should be minimized to reduce multi-scattering and to improve the particles' momentum resolution. Conversely, the thickness of the extension copper pipes should be maximized as much as possible in the limited space to shield the secondary particles [4].

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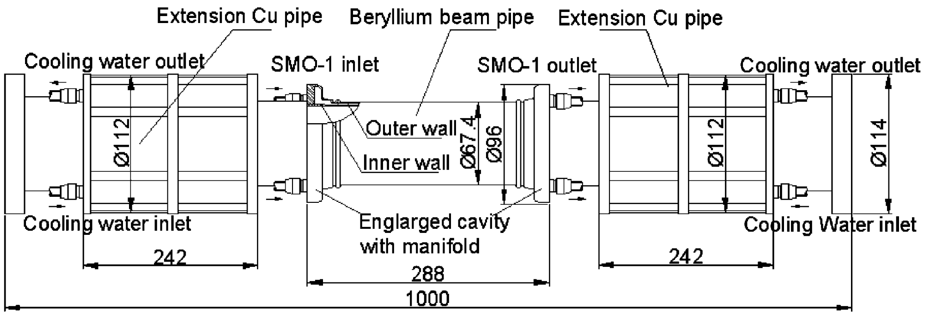

Fig. 1. Structure sketch of the beam pipe.

Based on the requirements of the BESIII experiment, the cooling gap of the beryllium beam pipe was designed, and the cooling system was developed.

2. Work conditions of the beam pipe

2.1. *Structure of the beam pipe*

The structure of the beam pipe with a total length of 1000 mm and an inner diameter of Φ63 mm is shown in Fig. 1.

The beryllium beam pipe is composed of an inner beryllium pipe, an outer beryllium pipe, and two enlarged cavities with manifolds. The narrow cooling gap with a length of 227 mm between the inner and the outer beryllium beam pipes with thicknesses of 0.8 and 0.6 mm, respectively, is divided into six average parts by six ribs along the circumference. The maximum inlet pressure of coolant is 500 kPa gauge pressure when the safety factor is 2.

2.2. *Heat loads*

Based on the results of physical simulation, the HOM is uniformly distributed on the inner wall of the beam pipe with a maximum of 600 W, and the SR is on the inner wall as a zonal distribution with a maximum of 100 W. The maximum value of HOM on the beryllium beam pipe is 200 W. The maximum value of SR on the beryllium beam pipe is about 24 W, with a zonal width of about 2 mm. These heat loads vary with the BEPCII operating state.

2.3. *Restriction of inner wall temperature*

Because of the heat loads on the inner wall and the cooling liquid in the cooling gap, there must be thermal stress on the inner and outer walls of the beryllium beam pipe. The conditions of the calculation for the restriction of the inner wall temperature by FEM (finite element method) are as follows: 100 kPa pressure in the cooling gap, an initial temperature of 293.15 K on the inner and outer walls, and the fixation of two ends of the beryllium beam pipe. The physical properties of the beryllium are shown in Table 1, which was used in the calculation. The results of the calculation indicate that the maximum temperature of the inner wall can reach 308.15 K with a safety factor of 2.

Table 1
Be physical properties

Property	Value
Density (kg/m^3)	1844
Specific heat capacity ($J/(kg \cdot K)$)	1925
Thermal conductivity ($W/(m \cdot K)$)	216
Coefficient of thermal expansion at 293.15 ($\times 10^{-6}$/K)	11.5
Poisson's ratio	0.12
Yield strength (MPa)	240

Table 2
Thermal physical properties of SMO-1 and water

Property	SMO-1[a]	Water
Density (kg/m^3)	810	998.2
Specific heat capacity ($J/(kg \cdot K)$)	1517	4183
Thermal conductivity ($W/(m \cdot K)$)	0.165	0.599
Kinematic viscosity ($10^{-6}\,m^2/s$)	2.29	1.006
Flash point (K)	345.15	

[a] Measured by the Physics Chemistry Laboratory of East China University of Science and Technology.

3. The cooling of the beryllium beam pipe

3.1. *Coolant*

Water may cause corrosion of beryllium easily under radiation [5]; thus SMO-1 was chosen as the coolant for the beryllium beam pipe for its lower viscosity, lower density, and higher specific heat capacity. Moreover, SMO-1 has higher flash point, a lower volatility and does not corrode to some metals such as stainless steel, copper and brass. Table 2 compares the thermal properties of SMO-1 and water. The specific heat capacity and thermal conductivity of SMO-1 are lower than water, and its kinematic viscosity is higher than water, which is no benefit for the cooling of the beryllium beam pipe.

A corrosion experiment was carried out with a powder metallurgy beryllium plate with dimensions of $\Phi 50 \times 0.8$ mm dipped in SMO-1. A magnetic force stirrer with a constant temperature was used to simulate the erosion of SMO-1. Prior to the experiment, the SMO-1 was cleaned with high purity nitrogen to remove the impure gases, silica gel was put into the oil to dehydrate it, and the experimental vessel was airproofed using vaseline. The test lasted 15 months and the beryllium plate was weighed every 3 months. Based on the testing results, the predicted depth of corrosion is 19.9 μm over a period of 10 years, which has little impact on the intensity of the beryllium beam pipe.

3.2. Calculation of cooling gap width

Conversation of energy and FEM were used to calculate the cooling gap width of the beryllium beam pipe. In order to simplify the calculation, the influence of ribs and the two enlarged cavities with manifolds on the temperature and pressure were ignored.

The equivalent diameter of the cooling gap can be calculated by the following formula:

$$d_{\mathrm{e}} = \frac{4A}{U} = 2\delta, \tag{1}$$

where A is the section area of the cooling gap, U is the wetted perimeter of the cooling gap, and δ is the cooling gap width.

The temperature difference between the inlet and outlet of the SMO-1 should be less than 2 K to maintain the temperature difference of the outer wall within a range of 2 K. Consequently, the temperature of the MDC caused by the beryllium beam pipe must be 293.15 ± 1 K when the inlet temperature of the SMO-1 is 292.15 K. The energy conservation equation is expressed as:

$$\dot{Q} = \rho w A C_{\mathrm{p}} \Delta T, \tag{2}$$

where $\dot{Q}$ is the heat load on the inner wall, C_{p} is the specific heat capacity of SMO-1, and w is the velocity of SMO-1. When the HOM heat load is 200 W, the following can be obtained from Eqs. (1) and (2):

$$w \geqslant \frac{1}{2493.8\delta}. \tag{3}$$

Reynolds number:

$$Re = \frac{w d_{\mathrm{e}}}{v}, \tag{4}$$

where v is the kinematic viscosity of the SMO-1. From Eqs. (1), (3) and (4), the following can be obtained:

$$Re \geqslant 350.$$

Based on the Reynolds number, the cooling gap width was selected by the accurate calculation of FEM using the ANSYS software.

The physical properties of the beryllium and the SMO-1 are shown in Tables 1 and 2. The conditions of calculation were: the SMO-1 flows through the gap with $Re = 350$, an inlet temperature of 292.15 K, an HOM heat load of 200 W, and the assumption that the outer wall is adiabatic to simplify the calculation. The cooling gap width varied from 0.4 to 1.8 mm. The results of the calculation are shown in Fig. 2.

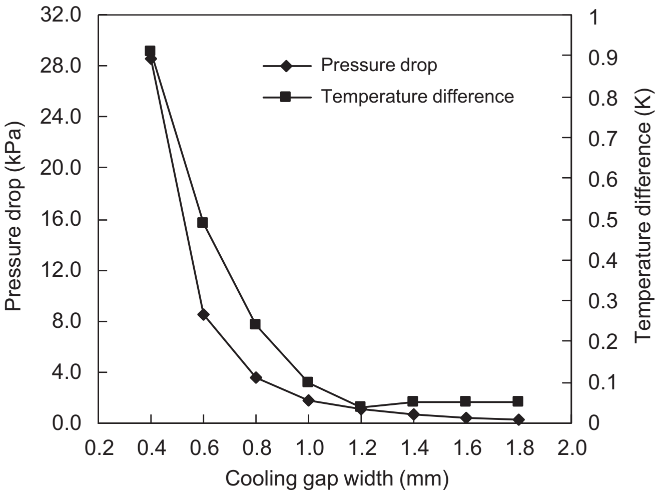

Fig. 2. Pressure drop and temperature difference on the outer wall of beryllium beam pipe with different cooling gap widths.

The temperature difference of the outer wall was less than 1 K with gap widths ranging from 0.4 to 1.8 mm. If the temperature precision of SMO-1 was less than ± 0.5 K, the outer wall temperature difference would be less than 2 K. The maximum temperature on the inner wall was 302.35 K. The pressure drop between the inlet and outlet of the beryllium beam pipe decreased as the cooling gap width increased. Until the width was 0.8 mm, the curve of pressure drop became flat. Considering the physical and safety requirements for the beryllium beam pipe, the optimal gap width of 0.8 mm was selected.

3.3. Influence of SR

The maximum heat flux of HOM on the beryllium beam pipe was 4450 W/m^2. However, the maximum heat flux of SR is 52,860 W/m^2, which is more than 10 times more than that of the HOM.

The conditions of calculation using ANSYS were as follows: a cooling gap width of 0.8 mm, a SR heat load of 24 W, an HOM heat load of 200 W, an adiabatic outer wall, $Re = 350$, and an inlet temperature of 292.15 K for SMO-1. The calculated result for the temperature distribution along the SR central line is shown in Fig. 3.

Obviously, the influence of the SR on the temperature of the outer wall was weak. The maximum temperature on the outer wall was 292.5 K, and the average temperature on the outer wall was 292.2 K. The maximum temperature on the inner wall, which was near the outlet, was 306.4 K. The average temperature on the inner wall was 299.3 K. Because the thermal conductivity of beryllium is about 1300 times as much as that of SMO-1, the SR heat load was

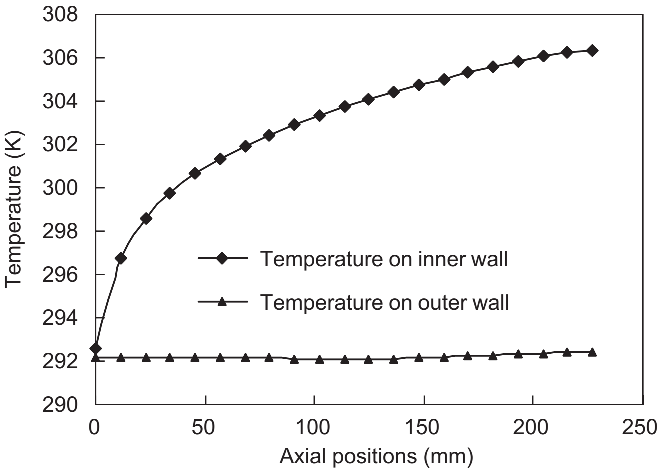

Fig. 3. Temperature distribution along the SR central line.

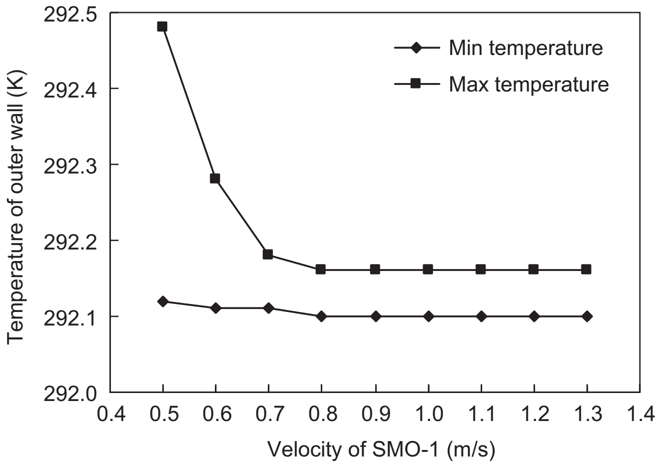

Fig. 4. Temperature on the outer wall of the beryllium beam pipe with different velocities.

mainly transferred through the inner wall, which did not cause the temperature to rise acutely.

3.4. *Optimal velocity of SMO-1*

The results of ANSYS analysis at the maximum of HOM and SR with the velocity of SMO-1 from 0.5 to 1.3 m/s ($Re = 350$–908) is shown in Fig. 4. The temperature of the outer wall decreased as the velocity increased. After the velocity reached 0.8 m/s, the temperature became stable. However, the pressure drop continued to increase with increasing velocity. Therefore, a velocity of 0.8 m/s (corresponding flow rate of 7.9 L/min) was selected as the working velocity to balance the outer wall temperature and pressure drop. At this velocity, the temperature difference of the outer wall was less than 0.1 K, the average temperature of inner wall was 297.25 K, the maximum temperature was 305.15 K, which was in the SR region close to the SMO-1 outlet, and the average temperature of the SR region was 301.85 K.

4. Design of the cooling system

4.1. *Layouts of the cooling system*

The cooling system for the beam pipe is composed of two circulation subsystems: the first and the second. The first circulation cooling subsystem consists of the extension copper pipes cooling circuit as well as the beryllium beam pipe cooling circuit, the flowcharts of which are similar. The two first circulation cooling subsystems shared the same second circulation cooling subsystem, which is composed of two refrigerators.

4.1.1. *First circulation cooling subsystem*

The cooling system for the beam pipe is located in the shielded basement north of the BESIII. The length of the metal pipes is about 20 m between the BESIII and the cooling system. The polyurethane pipes, TUH series pipes and TUS series pipes (manufactured by SMC Co., Ltd.) were selected as the coolant ducts in the BESIII where neutron and gamma-ray radiation exist, because of their better resistance to electron and gamma-ray radiation [6,7].

The two kinds of polyurethane pipes were irradiated by the equivalent of 10 years' worth of absorbed doses in BESIII. The total gamma-ray doses were 10^4 Gy and the total neutron doses were $4.068 \times 10^{18}\,\mathrm{m}^{-2}$. The pipes were bent in the radiation experiment. The radiation resistance of the irradiated and non-irradiated samples were studied by the pressure test, FTIR (Fourier transform infra-red), and thermal analysis. The safe pressure of the two kinds of pipes hardly changed after being radiated by gamma-rays. The safe pressure of TUH polyurethane pipe hardly changed after being irradiated by neutrons, but the TUS polyurethane pipe ruptured after being irradiated by neutrons. The thermal stability of TUH is better than that of TUS. Therefore, the TUH series pipe ($\Phi 8 \times 1.1$ mm) was selected as the coolant duct and had a length of 6 m.

The flow rate of SMO-1 was increased to 12 L/min to enlarge the adjustable range for the initial design of the beryllium beam pipe cooling circuit. The total head loss with the flow rate of 12 L/min was over 100 kPa, so the pumps must work at the inlet end of the beryllium beam pipe to avoid cavitation. The flowchart of the beryllium beam pipe cooling circuit is shown in Fig. 5.

The first circulation cooling subsystem is sealed by elastic air chambers, which can make the subsystem clean and safe, and maintain a constant pressure. The flow rate is adjusted by bypass valves. The vane pumps driven by magnetic force with motors of 750 W, the maximum outlet pressure of which is 0.7 MPa and the maximum flow rate is 19 L/min, were selected to supply the cooling liquid. All the power units had spare units in the cooling system. The 20 μm filters were installed on the duct before the pumps to satisfy the requirement of the pumps.

The temperature sensors used in the cooling system were grade A armoured platinum RTDs (resistance temperature detectors) of 100 Ω [8]. These kinds of RTDs also are used

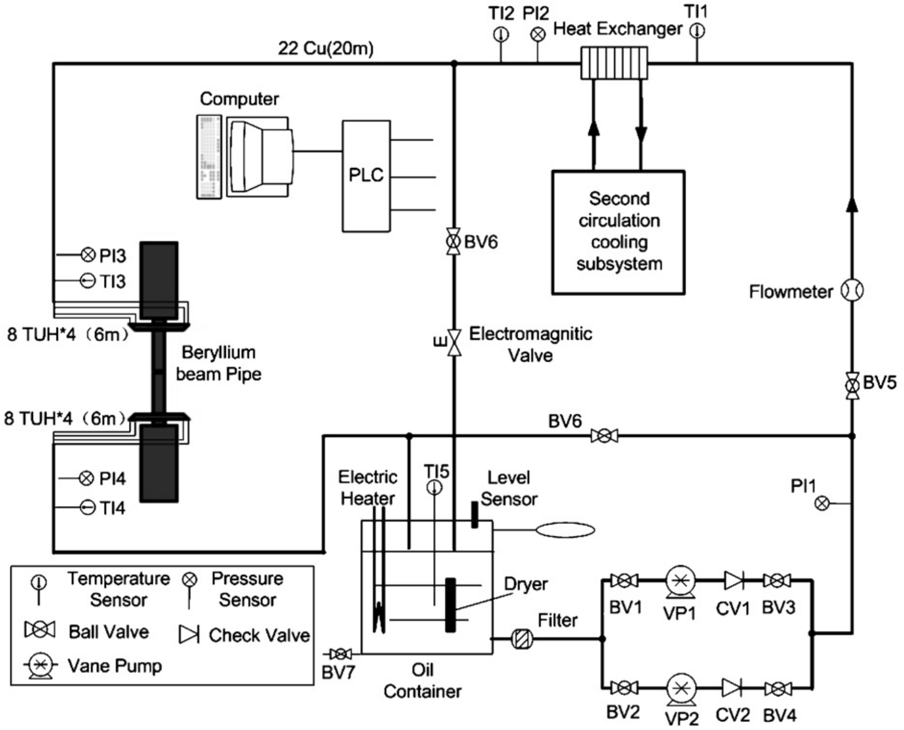

Fig. 5. Flowchart of the beryllium beam pipe cooling circuit.

on the outer wall of beam pipe to measure the temperature. The pressure of the cooling system was measured by MS-2 sensors with a measuring range of 0–0.3 MPa. The flow rate was measured by LWGY-10 series 0.2–1.2 m^3/h turbine flow rate sensors, and the level of cooling liquid in the containers was measured by Honeywell 983-180E ultrasonic level sensors. Some of these sensors can display locally and all the sensors can transmit remotely.

4.1.2. Second circulation cooling subsystem

The second circulation cooling subsystem takes the heat load away from the first circulation cooling subsystem using two plate heat exchangers. The flowchart of the second circulation cooling subsystem is shown in Fig. 6. The two refrigerators of this subsystem share the same water container and backup each other, so the spare one can work immediately to supply the cooling water of appropriate temperature when the working one is in trouble, which avoids fluctuation of the temperature.

The refrigeration capacity of the refrigerators is more than the heat load of the cooling system. The hot gas bypass valve and the PID control are used in this system to maintain the outlet temperature of the cool water at the set value in a temperature range of 283.15–298.15 K with a precision of ± 0.1 K, even if the heat load is variable.

4.1.3. Temperature and pressure control

The scheme of fixing the flow rate and compensating the heat load in the cooling system is implemented according to the restriction of the temperature and the pressure for the beryllium beam pipe.

The temperature and flow rate of cooling water, which flows into the heat exchangers from the second circulation cooling subsystem, is fixed. Also, the flow rate of SMO-1, which can remove the maximum heat load of the beryllium beam pipe, is fixed. An electrical heater is put into the oil container to compensate for the decrease of the heat load and to maintain the inlet temperature of the SMO-1. According to the operating state, the inlet temperature of the SMO-1 for the beryllium beam pipe can be adjusted by changing the set value of the outlet temperature of the cool water from the second circulation cooling subsystem.

In order to make the beryllium beam pipe safe, the inlet pressure of the beryllium beam pipe is inspected in real time. After the inlet pressure exceeds a dangerous value, the by-pass electromagnetic valve is opened by PLC to relieve the pressure. The vane pumps driven by magnetic force have their own mechanical safe valves, which can be set to protect the cooling system.

4.2. Automation

The reliability of the cooling system is ensured by its automation which is composed of the process control system and the remote monitoring and control systems.

4.2.1. Process control system

Two PLCs of S7-200 series (manufactured by SIEMENS Industrial Automation Co., Ltd.) were used instead of a single PLC of S7-300 series in order to reduce the cost of this cooling system. These have 28 digital input signals and 20 digital output signals in their CPUs and extend six

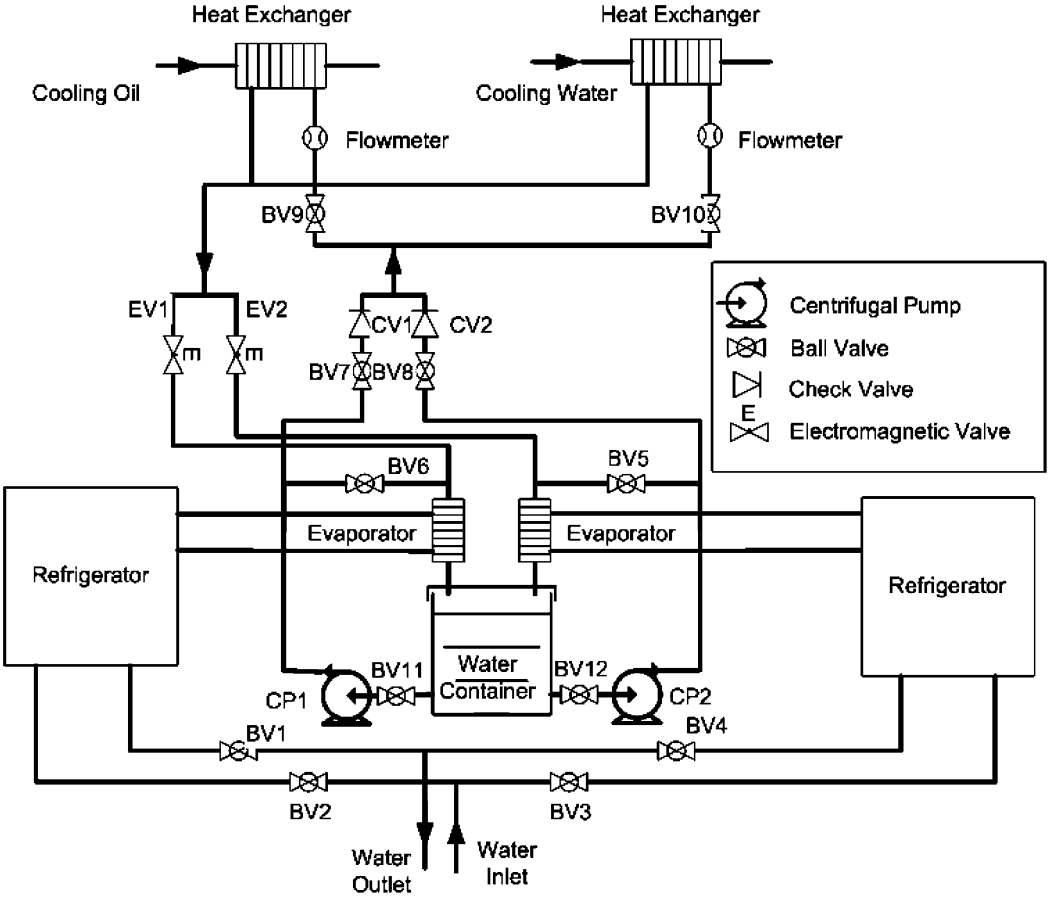

Fig. 6. Flowchart of the second circulation cooling subsystem.

four-channel analog input modules and four four-channel analog input and one-channel analog output modules. PROFIBUS wire was used to connect the two PLCs for communication, with one as the master station and the other as the slave station; PPI cable was used to connect the PLCs and the computer. The PLCs were programmed using the ladder logic language.

The working and spare power units were interlocked and switched by the PLCs. The acquired data in PLCs were compared with set values to protect the cooling system and to alarm synchronously. The cooling system has the function set up for automation and as well as manual switching operation.

4.2.2. Remote monitoring and control system

The human–computer interaction interface for monitoring and control runs on the remote computer, which was developed based on the configuration software Controx2000 (developed by Huafu Huitong Technology Ltd.) and which could be operated easily.

When the two PLCs were connected to the computer, the computer was also a master station, so they formed a complex multi-station, which made the communication between PLCs and Controx2000 difficult and complex. A new communication protocol needed to be compiled to resolve this problem, which enhanced the difficulty of development and maintenance. PC Access, which is offered by SIEMENS for S7-200 series PLC as the OPC (OLE for process control) Server and can be supported by the Controx2000 as the Client, was used to settle this problem.

The monitoring and control system can give sound alarms when the acquired data exceed the safe ranges. The acquired data and the alarm items are stored in the computer for 1-year period, and the main parameters are stored for 1 min intervals. This system also restricts the access of different users, and records the operation of every user. Some limit values and set values of the parameters can be set by the operators in this system, including the upper limit values of total running time of the power units. When the cooling system is operating normally, the closure of the remote monitoring and control systems does not affect the running of the process control system.

4.2.3. Communication with center control system

The cooling system for the beam pipe must communicate with the center control system as a subsystem of the BESIII. The communication signals are classified into two I/O signals transferred by ON or OFF and many network signals. When the outer wall temperature of the beam pipe is over the safe value or this system does not work normally, the top class I/O signal is sent to the center control system for cutting off the beam. When the cooling system is ready for the injecting beam after receiving a starting command, a normal I/O signal is sent to the center control system.

The network signals are transferred by the OPC Server, which is also supported by the LabView on the center control system. The center control system can read the data from the OPC Sever by network at any time.

5. Result of test

The cooling system plant for the beam pipe is shown in Fig. 7. This plant was connected to the beam pipe model with a trim size for testing. Because the thermal conductivity and the specific heat capacity of aluminum are lower than beryllium, the beryllium was replaced by aluminum to reduce the test cost in the beam pipe model. Thus, the aluminum beam pipe of the beam pipe model was mainly tested in this paper.

The heat load of HOM on the inner wall of the aluminum beam pipe was simulated by a film electric heater. The outer wall was covered with heat insulator and the temperature test points on the outer wall were located on the center line of the cooling gap.

The result of comparisons of experimental and theoretical values is shown in Fig. 8. The experimental value of the temperature on the inner wall was less than 296.5 K and the experimental value on the outer wall was less than 292.6 K, between which the maximum difference is 0.64 K. The error of the pressure drop was 35.1% according to the test. This error was caused by ignoring the influence of the enlarged cavities with manifold in calculation. However, the experimental value of pressure drop is 9.32 kPa, which is acceptable.

The performance of the cooling system was also tested in this paper. The results of the test prove that the function of control and protection are viable. The adjusting range and control precision for the parameters of beryllium beam pipe cooling circuit are as follows:

Fig. 7. Cooling system plant for the beam pipe.

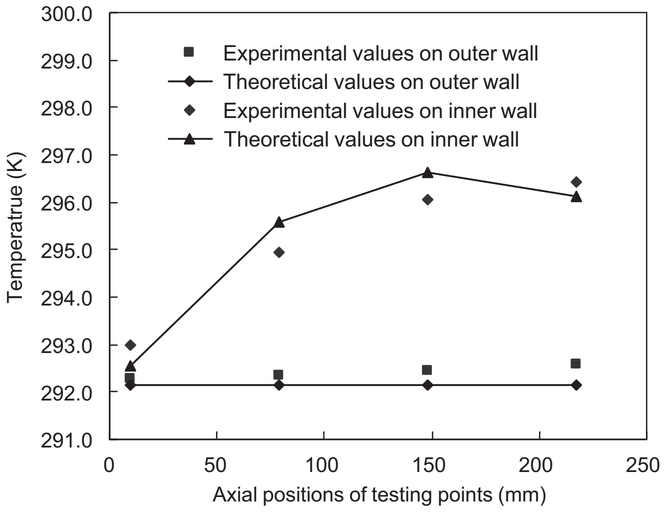

Fig. 8. Temperature comparison between the experimental values and the theoretical values at a velocity of 0.81 m/s and an inlet temperature of 292.15 K.

(1) The adjusting range of the inlet temperature is from 285.15 to 298.15 K with a precision of ±0.3 K.
(2) The flow rate of the SMO-1 can be adjusted from 4 to 15 L/min. When the SMO-1 flows at 15 L/min, it can remove 800 W of uniform heat load.

6. Conclusions

The cooling gap with width of 0.8 mm for the beryllium beam pipe was calculated, the optimal velocity of 0.8 m/s for SMO-1 was selected and the influence of HOM and local SR heat load on the temperature of the inner and outer wall was studied. The results of tests of the beam pipe model prove that the design of the cooling gap for beryllium beam pipe is reasonable. The manufacture of the beam pipe for BESIII experiment is underway.

The cooling system for the beam pipe was developed, and the performance of the cooling system was tested. The test results show that the function and reliability of the cooling system for the beam pipe achieve the design goal and working requirements. This system can take the heat load of HOM and SR away in time, and maintain the temperature and pressure in a safe range. Combining with the two PLCs and a computer, the cooling system can operate safely for a long time. The cooling system has a reasonable structure and comprehensive protection, which can be installed, used, and maintained easily. The cooling system has already passed the acceptance test and has been installed. It will work for the first phase operation as part of an accelerator in this fall and will operate as part of the BESIII subsystem in 2008.

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