Coolant choice for the central beryllium pipe of the BESIII beam pipe*

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Abstract In order to take away much more heat on the BESIII beam pipe to guarantee the normal particle detection, EDM-1 (oil No.1 for electric discharge machining), with good thermal and flow properties was selected as the candidate coolant for the central beryllium pipe of the BESIII beam pipe. Its cooling character was studied and dynamic corrosion experiment was undertaken to examine its corrosion on beryllium. The experiment results show that EDM-1 would corrode the beryllium 19.9 μm in the depth in 10 years, which is weak and can be neglected. Finite element simulation and experiment research were taken to check the cooling capacity of EDM-1. The results show that EDM-1 can meet the cooling requirement of the central beryllium pipe. Now EDM-1 is being used to cool the central beryllium pipe of the BESIII beam pipe.

Key words beam pipe, cooling, BESIII, BEPCII

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1 Introduction

The Beijing Electron Positron Collider (BEPCII [1]) and its detector, the Beijing Spectrometer (BESIII [2]) have been constructed, with a luminosity of 0.3×10^{33} cm^{-2}·s^{-1} at a center of mass energy of 1.89 GeV, which the design life of is 10 years [3]. The BESIII beam pipe is located in the center of the BESIII and installed in the BESIII drift chamber (DC). As shown in Fig. 1, the BESIII beam pipe consists of three components, the central beryllium pipe, the left extended copper pipe and the right extended copper pipe. The left extended copper pipes and the right extended copper pipe have symmetric structures, and are welded to the two ends of the central beryllium pipe [4].

After being accelerated and focused, the electrons and positrons collide in the BESIII beam pipe. Particles produced in the collisions pass through the BESIII beam pipe and are detected by BESIII. There will be much more heat and no more than 750 W [5][3)] on the inner surface of the BESIII beam pipe. The heat is mainly from synchrotron radiation (SR) and high order mode (HOM), which varies with the mounting precision of magnets, the controlling precision and the character of the beam. The simulation calculation shows that the heat of SR is less than 150 W and distributes in a width of 2 mm along the z-axis, while that of HOM is less than 600 W and distributes uniformly. As one of the detectors of BESIII, the DC's particle detection is affected seriously by temperature, according to the requirements of the BESIII physical experiment, suitable coolant must be chosen to take away the heat of the BESIII beam pipe in time to maintain the inner surface temperature of the DC inner cylinder at 20 ℃±2 ℃.

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3) ZHOU Neng-Feng. The power of synchrotron radiation on the beam pipe of interaction region. Communication report. Institute of High Energy Physics, 2004 (in Chinese)

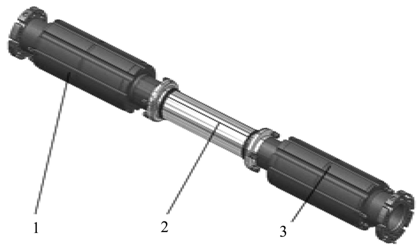

Fig. 1. Basic structure of the BESIII beam pipe. 1-Left extended copper pipe; 2-Central beryllium pipe; 3-Right extended copper pipe

Water is widely used to cool copper in industry because of its high specific heat capacity and thermal conductivity and non-corrosion to copper. In order to prevent the formation of scale and achieve the quite ideal cooling effect, the more pure water, the de-ionized water (DW) is chosen as the coolant of the two extended copper pipes [6]. However, the coolant for the central beryllium pipe is still needed for studying. Fig. 2 shows the structure of the central beryllium pipe. It consists of the outer layer, the inner layer and two enlarged transition cavities, by which the cooling channels with the height of 0.8 mm are bounded. The hatching in Fig. 2 is the region in which coolant flows. There are four inlets or outlets in each enlarged transition cavity. The cooling polyurethane hose with the dimension of $\phi 8\times 1.1$ mm is used in the central beryllium pipe.

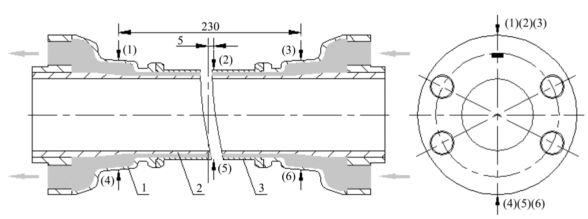

Fig. 2. Schematic drawing of the central pipe of the BESIII beam pipe. 1-The enlarged transition cavity; 2-The inner beryllium layer; 3-The outer beryllium layer; (1)–(6) The measuring point

In the BES I detector[1)], the heat produced in the beam pipe was small and could be carried away by air, which has no effect on the BES I physical experiments. So no coolant is needed to cool the BES I beam pipe. In the experiment of CLEO, the beryllium beam pipe of the detector of CESR, Cornell University is cooled by PF$^{\rm TM}$-200IG, a complex combination of normal paraffin, with a good thermal property. The result of the experiment shows that the corrosion of PF$^{\rm TM}$-200IG on beryllium is weak and can be neglected [7]. SVD1.4, one of the beryllium beam pipes in Belle, is cooled by helium gas, but the other beam pipe is cooled by PF-n, which has properties that are similar to those of PF$^{\rm TM}$-200IG. Corrosion experiment of PF-n on beryllium was done in which a beryllium plate, 13 g, was immerged in PF-n. The weight decreases by 2 mg after 18 months, which indicates that PF-n has corroded the beryllium faintly[2)].

So, the coolant of the central beryllium pipe must be chosen cautiously to ensure the proper operation of the BESIII beam pipe.

2 Choosing the coolant

Several factors are taken into account in choosing the coolant for the central beryllium pipe as follows: (1) Good thermal property. The coolant must take away the heat in time to maintain the inner surface temperature of the DC inner cylinder at 20 ℃$\pm$2 ℃. (2) Weak corrosive effect. The design life of the BESIII beam pipe is 10 years, in which the coolant can't corrode the beryllium badly so as not to affect the proper operation of the BESIII beam pipe. (3) Easy obtainment. A large amount of coolant is needed in 10 years, so the coolant must be obtained easily.

Water is an ideal coolant in industry. But the combination of oxygen gas and water vapor can corrode the beryllium [8]. So water is excluded as the coolant of the central beryllium pipe. Although PF-n and PF$^{\rm TM}$-200IG are chemically compatible with beryllium, they can't be obtained easily. No.1 oil for electron discharge machining (EDM-1) is produced by China Petroleum and Chemical Corporation and can be bought easily in China. It has good thermal and flow properties and a high flash point. It is a kind of nontoxic coolant with small smog and low odor. So there will be no undesirable environmental or personal hazards in handling it. Helium gas is a kind of inert gas with a high specific heat capacity and is used to cool the beryllium beam pipe of Belle. Therefore EDM-1 and helium gas become the candidate coolants of the central beryllium pipe.

2.1 Cooling capability

The properties of EDM-1, PFTM-200IG, helium gas and DW (deionized water) are listed in Table 1,

1) LIU W. The design of the BES I beam pipe[R]. Science and Technology Documents of Institute of High Energy Physics of Chinese Academy of Science, No. 02.13.6-32-3, 1989: 18-36 (in Chinese)

2) Toru Tsuboyama. The corrosion of paraffin on beryllium, private communication

whose data of EDM-1 were measured by the Physics Chemistry Laboratory of East China University of Science and Technology[1)].

Hypothetically, helium gas is in normal atmospheric pressure (300 K, 0.1 MPa).

Table 1. Properties of EDM-1 compared with de-ionized water and PF^{TM}-200IG

property	EDM-1	helium gas [9]	DW [10]
density /(kg/m^3)	810	0.1604	998.2
specific heat capacity/ (J/kg·K)	1517	5193	4183
thermal conductivity/ (W/m·K)	0.165	155.97	0.599
kinematic viscosity/ (10^{-6}m^2/s)	2.29	124.25	0.89
flash point/K	345	–	–

The thermal conductivity, specific heat capacity and density of EDM-1 are 27.5%, 36.3% and 79% of those of DW respectively. According to the principle of energy conservation, a formula is given by

$$Q = C_{\rm p} \cdot V \cdot \rho \cdot A_{\rm c} \cdot \Delta T, \tag{1}$$

where Q is the heat flow in W; $C_{\rm p}$ is the specific heat capacity of the coolant in J/kg·K; V is the velocity of the coolant in m/s; ρ is the density of the coolant in kg/m^3; $A_{\rm c}$ is the effective cross sectional area of the coolant in m^2; and ΔT is the temperature difference of the inlet and outlet in ℃. When V, $A_{\rm c}$ and ΔT are constant, different coolants will take away different heat.

As far as EDM-1 and DW are concerned, the ratio of the heat taken away can be described as the equation,

$$\frac{Q_{\rm EDM-1}}{Q_{\rm DW}} = \frac{C_{\rm pEDM-1} \cdot \rho_{\rm EDM-1}}{C_{\rm pDW} \cdot \rho_{\rm DW}} = 0.294.$$

That is, the cooling capability of EDM-1 is 29.4% of that of DW. Analogously, the cooling capability of helium gas is 0.05% of that of DW. The cooling capability of EDM-1 is much stronger than that of helium gas.

2.2 Velocity of coolant

Despite the low cooling capability, helium gas has no corrosion on beryllium. So it is necessary to consider the feasibility of helium gas to cool the central beryllium pipe. The velocities of EDM-1 and helium gas in the polyurethane hose are calculated to verify their feasibility.

In Eq. (1), $A_{\rm c} = n \times \pi \frac{d^2}{4} = \frac{\pi n d^2}{4}$, where d is the inner diameter of the cooling tube, and n is the number of the cooling tubes. Then Eq. (1) can be modified as $V = \frac{4Q}{C_{\rm p} \cdot \Delta T \cdot \rho \cdot \pi n d^2}$ to calculate the velocities of coolant in the polyurethane hose, where Q is supposed as the maximum value, one third of the whole heat, 250 W; n=4; d=0.0058 m. As the temperature of the inner surface of the DC inner cylinder must be controlled in the narrow range of 20 ℃±2 ℃, the temperature difference of the inlet and the outlet, ΔT must be as small as possible. When ΔT=0.5 ℃ and ΔT=2 ℃, the inlet velocities of helium gas are 5680 m/s and 1420 m/s respectively, which are much higher than the acoustic speed in helium gas, 1019 m/s. So helium gas can't be used as the coolant of the central beryllium pipe, while those of EDM-1 are 3.85 m/s and 0.963 m/s, which are common for liquid in engineering and can be achieved easily.

3 Corrosion of EDM-1 on beryllium

EDM-1 is described by the manufacturer as noncorrosive to metals such as copper, aluminum and stainless steel. The content of EDM-1 is investigated by the Research Institute of Petroleum Processing and Great Wall Lubricating Oil Application Research Center Limited Corporation[2,3)]. The results show that the contents of S, Cl and P in EDM-1 are 40 mg/L, 0.37 mg/L and 0.002% respectively. All the elements of S, Cl and P may be harmful to beryllium. Motivated by the type of metal used to construct the BESIII beam pipe, we undertook an experiment to examine the corrosion of EDM-1 on beryllium.

3.1 Method

Weight-loss method is adopted to study the corrosion of EDM-1 on beryllium. The experiment equipments are shown in Fig. 3. A beryllium plate with dimensions ϕ50 mm × 0.8 mm is supported by the supporting plank immersed absolutely in the EDM-1, which is contained in a glass basin. The glass basin is on the thermostatic magnetic stirrer. EDM-1 flows

1) The Physics Chemistry Laboratory of East China University of Science and Technology. The thermo physical property measuring report of EDM-1. Shanghai, 2004 (in Chinese)

2) The Research Institute of Petroleum Processing. The analysis report of EDM-1. Beijing, 2005 (in Chinese)

3) Great Wall Lubricating Oil Application Research Center Limited Corporation. The measuring report of EDM-1. Beijing, 2005 (in Chinese)

with the rotating of the magnetic bead. The EDM-1 velocity can be adjusted by the stirrer. So EDM-1 with constant temperature washes the surface of the beryllium plate to simulate the corrosion of EDM-1 on the beryllium metal. The beryllium plate is weighed for each period of time with the electronic balance. The glass thermometer can display the temperature of EDM-1 more clearly.

Nitrogen must be insufflated in EDM-1 to drive out the oxygen and silicon gel is put in EDM-1 to absorb the water. The glass basin is sealed by geoline. The temperature of EDM-1 is set at 32 K. Acetone and ethanol are used to wash the beryllium plate before weighing it. Nitrogen and geoline are also needed after every weighing.

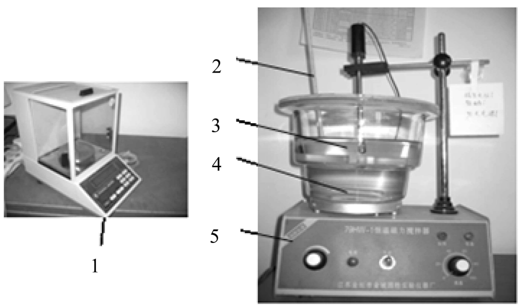

Fig. 3. Equipment of corrosion experiment. 1-Electronic balance; 2-Glass thermometer;3-Glass basin; 4-Magnetic bead; 5-Thermostatic magnetic stirrer

3.2 Results and analysis

The corrosion results of the weight-loss method are estimated by comparing the weigh before and after the corrosion. The corrosion rate can be described as [11]

$$V_{-\mathrm{w}} = \frac{W_1 - W_0}{At}, \tag{2}$$

where $V_{-\mathrm{w}}$ is the corrosion rate in kg/m^2·h; W_0 is the weight before the corrosion in kg; W_1 is the weight after the corrosion in kg; A is the corrosion area in m^2; and t is the corrosion time in h.

The corrosion depth in the predicted time can be calculated by

$$h = \frac{V_{-\mathrm{w}}T}{\rho}, \tag{3}$$

where h is the corrosion depth in m; ρ is the density of the test plate in 1844 kg/m^3; and T is the predicted corrosion time in h. As the design life of the BESIII beam pipe is 10 years, T in Eq. (3) is set as 87600 h. Table 2 lists the corrosion rate and the corrosion depth at that rate in 10 years.

It can be seen from Table 2 that the corrosion rate, 4.18×10^{-7}kg/(m^2·h) in initial stage, becomes small with the lapse of time and stabilizes at 1.54×10^{-7}kg/(m^2·h) at last. The results can be explained as follows. At the beginning of the corrosion, the compact beryllium is oxidized by harmful elements such as O, S, P, Cl in EDM-1 and the film of thin oxide is generated on the surface of the beryllium plate. Washed by EDM-1, the oxide film spalls from the plate and the corrosion rate is higher then. Simultaneously, the concentration of the harmful elements decreases. Subsequently, the rate of oxidation reaction falls gradually and the corrosion rate decreases and stabilizes at last.

Table 2. Corrosion rate and depth of EDM-1 on beryllium

corrosion time/h	weight/ kg	corrosion rate/ (kg/(m^2·h))	corrosion depth in 10 years/m
0	2.961×10^{-3}	–	–
2362	2.957×10^{-3}	4.18×10^{-7}	1.99×10^{-5}
9846	2.954×10^{-3}	1.75×10^{-7}	8.29×10^{-6}
11184	2.954×10^{-3}	1.54×10^{-7}	7.34×10^{-6}

According to the stable rate of 1.54×10^{-7} kg/(m^2·h), the corrosion depth will only be 7.31 μm in 10 years and accounts for 1.22% of the smallest thickness (600 μm) of the central pipe. Even at the fast corrosion rate, 4.18×10^{-7} kg/(m^2·h), the corrosion depth will only be 19.9 μm in 10 years and accounts for 3.32% of 600 μm. The safety factor of the BESIII beam pipe is higher than 3, so the small corrosion depth has almost no effect on the global safety and can be neglected. EDM-1 is chemically compatible with beryllium.

4 Cooling results

4.1 Finite element analysis

The software of ANSYS is used to check the cooling effect of EDM-1 on the central beryllium pipe. Since the BESIII beam pipe is symmetric about its axis, the finite element analysis is done by establishing a 1/2 three-dimensional volume model. In establishing the model from −90 degrees to 90 degrees, different volumes are endowed with different material characteristics. The type of element is fluid 142.

There is heat of 600 W distributing uniformly on the inner surface of the beam pipe and 150 W distributing in a width of 2 mm on 90 degrees position along the z-axis. The coolants of the central beryllium and the extended copper pipes are EDM-1 and DW. The inlet temperature of EDM-1 is 18.4 ℃ and that of DW is 18.6 ℃. Both of the two fluxes are 8 L/min. It is assumed that the two ends and the outer wall of the BESIII beam pipe are on heat-insulation boundary condition. The temperature nephogram of the out wall of the central beryllium pipe is shown in Fig. 4.

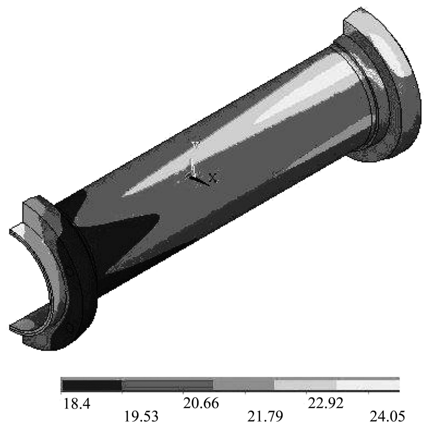

Fig. 4. The temperature nephogram of the central beryllium pipe.

The main temperature of the outer wall is in the range of 18.4–21.8 ℃, which satisfies the temperature requirement of DC.

4.2 Experimental research

Experiment is necessary to verify the calculation values. So a model with the scale of 1:1 was made as shown in Fig. 5. As the beryllium is expensive, the inner and outer beryllium layers are made of corrosion resisting aluminum alloy to reduce the experiment cost.

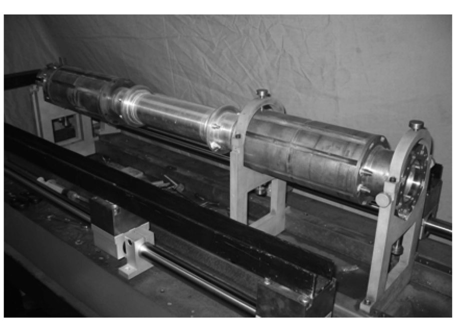

Fig. 5. Model of the BESIII beam pipe.

In the experiment, the central beryllium pipe and the extended copper pipes are cooled by EDM-1 and DW respectively. Quartz heater and electric heating tape are used to simulate HOM and SR. The outer wall temperatures are measured by the PT100 temperature sensors. The distribution of 6 measuring points is shown in Fig. 2, in which (1), (2) and (3) are on 90 degrees position corresponding to the site of SR, and (4), (5) and (6) are on −90 degrees position. The whole measurement error is 5.03% and the position error of the measuring point is ±5 mm.

Two experiments, A and B, are taken.

Experiment A: (a) The heat of HOM and SR are 600 W and 150 W respectively. (b)The inlet temperature of EDM-1 is 18.4 K and that of DW is 18.6 K. Both of the two fluxes are 8 L/min.

On the same condition, the temperature field is calculated by the previous finite element model in which the material characteristics of inner and outer beryllium layers are endowed with those of the corrosion resisting aluminum alloy. The calculation values of the outer wall temperatures are extracted to be compared with the experiment values as shown in Fig. 6.

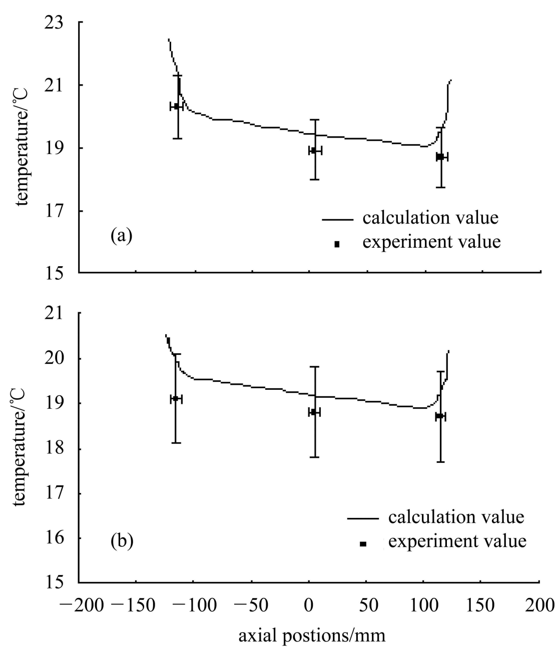

Fig. 6. Comparison of calculation and experiment temperatures on condition A. (a) 90 degrees position; (b) −90 degrees position.

Comparing the calculation values with the experiment values in Fig. 6, the least error, maximal error, average error and mean square root are 1.48%, 4.14%, 2.52% and 2.68% respectively, which are all less than 5.03%.

Experiment B: (a) The heat of HOM and SR is 600 W and 0 W respectively. (b) The inlet temperature of EDM-1 is 18.7 ℃ and that of DW is 18.6 ℃. Both of the two fluxes are 8 L/min.

The temperature field is calculated by the finite element method under the same condition. The calculation and experiment values are compared in Fig. 7.

Comparing the calculation values with the experiment values in Fig. 7, the least error, maximal error, average error and mean square root are 1.13%, 3.28%, 2.40% and 2.50% respectively, which are all less than 5.03%.

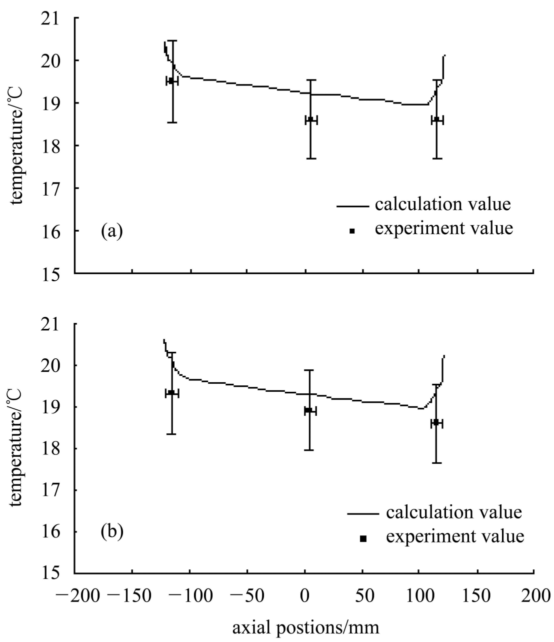

Fig. 7. Comparison of calculation and experiment temperatures on condition B. (a) 90 degrees position; (b) −90 degrees position.

It can be seen from Fig. 6 and Fig. 7 that the temperature calculated or measured, is not symmetric, and higher in "−" side than "+" side. This is because the coolant flows from "+" side to "−" side as shown in Fig. 2. It also can be seen that the calculation values are higher than the experiment values. The important reason is that the outer wall can't be on heat-insulation condition entirely in experiment. But the calculation value is coincidental with the experiment and the whole average error and mean square root are all less than the whole measurement error, which proves that the experiment is credible and the finite element model is proper. Therefore as the coolant of the beryllium beam pipe, EDM-1 can meet the cooling requirement.

5 Conclusions

The experiment and finite elements analyses have been done to choose a suitable coolant for the central beryllium pipe of the BESIII beam pipe. The results show that EDM-1 is chemically compatible with beryllium and it can meet the cooling requirements of the BESIII physical experiment. Conclusions can be drawn that EDM-1 is an ideal coolant for the central beryllium pipe. EDM-1 is being used in the coolant system of the BESIII beam pipe.

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