Analysis on the Pump Selection in the Reconstruction of the Cooling Water System at Chinese High Magnetic Field Laboratory

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Abstract—**Chinese High Magnetic Field Laboratory (CHMFL) will build a resistive magnet with steady magnetic field strength of 42 Tesla which will set a new record for a single resistive magnet. As one of the important auxiliary systems, the cooling water system needs to be fully upgraded to meet the higher cooling requirements of the magnet and the power system. In this paper, the reconstruction scheme of cooling water system is introduced firstly, then the parameters selection of the chilled water pumps and high-pressure pure water pumps are emphatically analyzed. The data fitting method and the applied fluid technology software ATF Fathom were used to analyze and check the selection of chilled water pump. After these pumps are in place, the effectiveness of the above analysis scheme has been verified through testing, which can provide a reference for the reconstruction of pumps in other systems. For the high-pressure pure water pump, the solution focuses on improving the overall cooling capacity of the pump group and also improving the system stability. Based on the large-circulation-flow magnet of CHMFL, tests were conducted on the parallel operation capability of the new and old pumps, and the system characteristic curve and pump performance curve are analyzed and researched. The result shows that the pump parameters selection is reasonable and the magnet cooling circulation capacity is effectively improved.**

Index Terms—**42 Tesla resistive magnet, pump, data fitting, AFT Fathom**

I. Introduction

Chinese High Magnetic Field Laboratory (CHMFL) was completed in 2017 and has been running so far, providing scientific research support for more than 170 units and more than 3,000 projects around the world, and promoting the output of a large number of high-level results with major international influence[1]. CHMFL will build a new resistive magnet with 42 Tesla magnetic field strength. The cooling water system is primarily used to remove the heat generated by the resistance magnet due to the consumption of a large amount of electrical energy, to maintain the properties of the magnet material. Therefore, the cooling water system that matches the power supply is one of the necessary technical equipment systems to ensure the normal operation of the resistive magnet in CHMFL. After the completion of the magnet, the peak heat load of the magnet and power system is nearly 40 MW, and this heat will be taken away by the cooling water system.

The cooling water system consists of the refrigeration and cooling circulation system, the deionized water-cooling circulation system (pure water circulation) and the control system. Its schematic diagram is shown in Fig 1 (Tank: chilled water storage tank; Pump 1: chilled water pump; Pump 2: high-pressure pure water pump; Exchanger: heat exchanger; Magnet: Resistive magnet; Pure water system: deionized water preparation and purification system; Power system: 28 MW power supply system). On the left side is the refrigeration and cooling circulation system, which includes the preparation, storage and supply of chilled water, the chilled water pumps and the plate heat exchangers. On the right side is the deionized water-cooling circulation system, where the high-pressure pumps supply the low-temperature deionized water for the resistive magnet to remove the heat generated by the magnet excitation, and then the heat exchanger takes away the heat through the 6 ℃ low-temperature chilled water on the other side. In order to meet the cooling requirements of the new resistive magnet, the existing cooling water system needs to a completely improved.

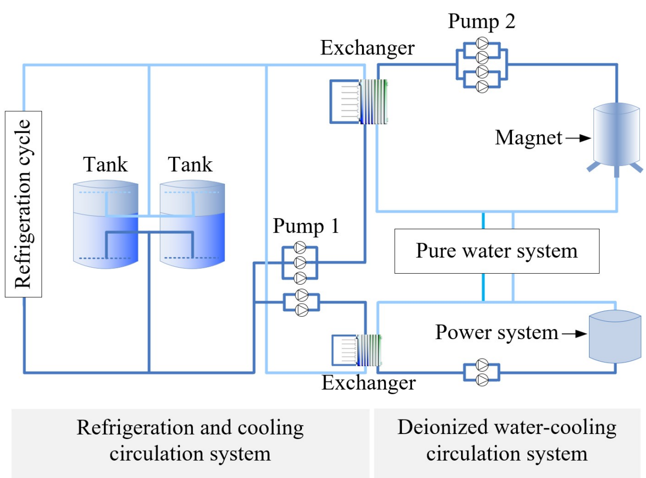

Fig 1. Schematic diagram of cooling water system of CHMFL

The power consumption of the 42T resistive magnet

Manuscript received January 22, 2024; revised June 18, 2024.

This work was supported by Youth Innovation Promotion Association of CAS (Grant No. 2021448). (A portion of this work was supported by Hefei Comprehensive National Science Center and the High Magnetic Field Laboratory of Anhui Province.)

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operation in the future is estimated to be approximately 35.5 MW, while the current maximum cooling capacity of the water-cooling system does not exceed 28 MW. This upgrade requires comprehensive performance enhancements in the key areas such as the magnet cooling circulation flow rate, chilled water supply, and heat exchange capacity. According to the design parameters of the magnet, its circulating cooling water flow rate needs to be increased to approximately 1200 m^3/h. This will be achieved primarily by using the existing high-pressure pure water pump in parallel with a newly added pure water pump with appropriate parameters. After adding the new pump, it can serve as a backup pump for the existing magnet, enhancing the overall operational stability of the system. Because of limitations in the space of pump room and the inability to carry out large-scale pipeline modifications, the demand for higher chilled water supply flow rate for the new magnet cooling could only be achieved by replacing these pumps, so a detailed calculation and analysis of the chilled water supply pump parameters was required. The heat transfer area was increased by connecting a new plate heat exchanger in parallel. This paper will focus on the improvement of the pump performance based on this renovation, and the related analysis process and scheme can provide a reference for other similar renovation projects.

II. Reconstruction Scheme

The current cooling water system of CHMFL has three chilled water supply pumps with flow rate of 500 m^3/h and a head of 40 m. When these three pumps are operated in parallel, the maximum flow rate is about 1435 m^3/h, which is insufficient to meet the cooling requirements of the new 42 MW resistive magnet. Considering the large flow loss of multiple pumps in parallel and the limited space in the pump room, the final decision is to replace all these three pumps.

The new resistive magnet cooling requires pure water flow rate of about 1200 m^3/h, and the current four high-pressure pure water pumps running in parallel cannot meet this requirement, so it is necessary to add new pumps Four existing high-pressure pure water pumps have flow rate of 280 m^3/h and head of 300 m. Through calculation and analysis, two new pumps with flow rate of 350 m^3/h and head of 300 m are determined, based on the following reasons:

(1) Four high-pressure pure water pumps have been in operation for over 10 years, resulting in a high failure rate due to long-term operation. When multiple high-power resistive magnets and 45.22 T hybrid magnet are running, all four pumps must participate in operation without backup pumps, so there is a risk to system stability. In future, the two new high-pressure pure pumps will be used in conjunction with the existing pumps, with the new pump as the main, and the old pump as the auxiliary mode to provide circulating pure water for all resistive magnets.

(2) After the completion of the 42 T resistive magnet, there is a possibility of changes in circulating flow rate caused by magnet calculation or assembly error. The two new pumps and four old pumps can operate in parallel in multiple modes. In the extreme case, all six pumps can be put into the magnet cooling cycle to ensure the security and stability operation of the new magnet.

In addition, the power system has added a set of equipment with a power of 14 MW to meet the requirement of the 42 T resistive magnet, resulting in a heat load of approximately 1.5 MW. To address this, a new set of power supply cooling circulation has been also added. In summary, the reconstruction scheme of the cooling water system is shown in Fig 2 (Pump 1: new chilled water pump; Pump 3: new high-pressure pure water pump; Exchanger 2: new heat exchanger; Magnet 2: 42T resistive magnet; Power system 2: new 14MW power supply system. The remaining names and definitions are shown in Fig 1).

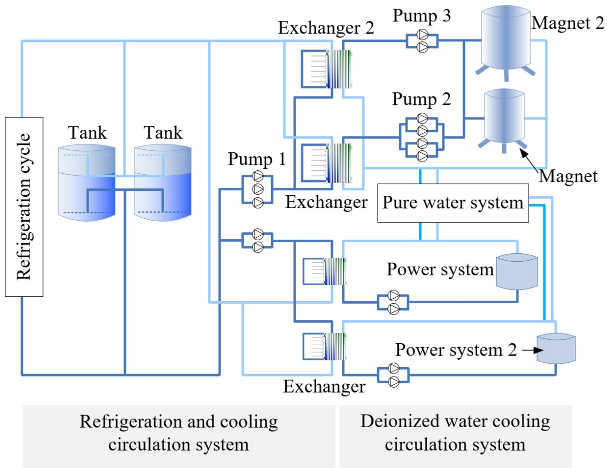

Fig 2. The transformation scheme of cooling water system

III. Chilled Water Pump Analysis and Selection

A. Data fitting method

The flow rate and head of the pump can be selected by analyzing the system resistance parameters and combining with the pump selection provided by the supplier. In this section, fitting analysis and prediction will be made based on the measured pressure and flow rate parameters of the current cooling water system pipeline combined with the system reconstruction scheme, and then the fluid software AFT Fathom will be applied for verification. The pressure difference and flow rate at the inlet and outlet of the original chilled water pump are shown in the following table.

TABLE I
THE MEASURED VALUE OF THE ORIGINAL CHILLED WATER PUMP

	Flow rate (m^3/h)	Pressure difference (Pa)
1	846	91667
2	1148	193333
3	1293	255000
4	1409	303333
5	1435	321667

The pressure difference and flow rate in TABLE I are fitted and the resulting trend line is shown in Fig 3. The equation of the fitted curve is as follow.

$$y = 0.1685x^2 + 2.1597x - 30750 \quad (1)$$

The above fitting equation can predict the pressure difference of the pumps under the existing system pipeline at the flow rate of 1500~2000 m^3/h, as shown in TABLE II.

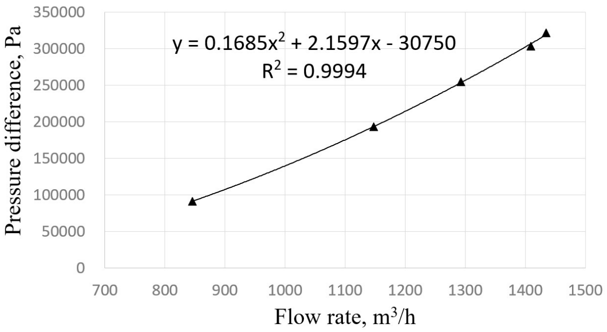

Fig 3. Characteristic curve of chilled water circulation pipe

TABLE II
PREDICTION OF PRESSURE DIFFERENCE AFTER CHILLED WATER FLOW INCREASE

	Flow rate (m^3/h)	Pressure difference ΔP (Pa)
1	1500	351615
2	1600	404066
3	1700	459886
4	1800	519078
5	1900	581638

After the reconstruction, a new plate heat exchanger will be added. Its pressure drop on the chilled water side is close to the existing exchanger. In addition, relevant parallel pipelines will be added, which will cause changes in the flow resistance of the system. According to the theory of fluid mechanics[2][3], the resistance curve equation of pipe network is：

$$\Delta P = SQ^2 \tag{2}$$

S——Pipeline resistance characteristic coefficient，kg/m^7；

Q——Total flow rate，m^3/s.

The operation data of the existing plate heat exchanger is shown in TABLE III.

TABLE III
PLATE HEAT EXCHANGER MEASURED VALUE

	Flow rate(m^3/h)	Pressure difference ΔP_1 (Pa)
1	846	55000
2	1148	86000
3	1293	101000
4	1409	115000
5	1435	121000

According to TABLE III, the plate impedance under different flow rates can be calculated, and its average value is 827366 kg/m^7. Assuming that the circulating flow rate of the chilled water allocated to the two plate exchangers after system reconstruction is equal and the system resistance coefficient remains unchanged. The total pressure difference of the new system is set as ΔP_N, and the pressure difference of the single plate heat exchanger in the original system is ΔP_1, and the pressure difference of two plate heat exchangers in parallel is ΔP_2. The relationship between these three pressure difference parameters and the total pressure difference of the original system ΔP can be expressed as:

$$\Delta P_N = \Delta P - \Delta P_1 + \Delta P_2 \tag{3}$$

Thus, the values of ΔP_1, ΔP_2 and ΔP_N under different flow rates can be calculated, As shown in TABLE IV.

Generally, a certain safety factor should be considered in the project, and the selection of head is usually amplified by 1.2 times [4]. According to the maximum cooling flow rate of 2000 m^3/h and its corresponding pressure drop of 0.456 MPa, an estimate is made. Combined with the parallel flow loss of the pumps and the selection provided by the supplier, the parameters of the chilled water supply pumps can be preliminarily determined as the flow rate of 680 m³/h and the head of 55 m.

TABLE IV
PRESSURE DIFFERENCE CALCULATION OF SYSTEM AND PLATE HEAT EXCHANGER

Flow rate, m³/h	ΔP_1	ΔP_2	ΔP_N
1500	143640	35910	243885
1600	163430	40858	281493
1700	184497	46124	321513
1800	206841	51710	363946
1900	230462	57616	408792
2000	255360	63840	456049

B. Analysis by AFT Fathom

AFT Fathom is a powerful applied fluid technology analysis software that can be used to calculate the pressure drop and flow distribution in incompressible fluid and low-speed gas networks, and is now widely used in the chemical, petrochemical, power and other industries. In addition, this software can accurately simulate the interaction of various components in the system, and tightly integrate the characteristics, analysis, software of equipment and system schematic diagram, which greatly improves the user's system engineering quality, thereby reducing costs and improving efficiency and piping system reliability [5].

In this section, AFT Fathom 11 will be used to model the circulating loop of the cooling water system and check the pump analysis results in Section 2.1. The model is shown in Fig 4.

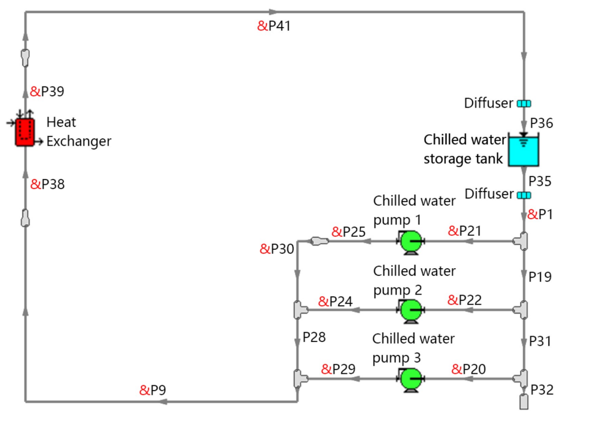

Fig 4. Chilled water circulation pipeline model

AFT Fathom allows for the configuration of various parameters in the model, including equipment resistance, local resistance, friction loss, and absolute roughness of pipe walls within the pipe network. The relevant parameter settings are explained as follows:

(1) The pressure loss data of the plate heat exchanger is set according to the measured flow rate of 1435 m^3/h in Fig 3. AFT fathom can fit the pressure loss curve of the plate according to the set data;

(2) The chilled water storage tank of the cooling water system is a cylindrical water tank with a height of 10 m and a diameter of 21 m. It uses naturally stratified technology and octagonal diffuser. Both the upper and lower water diffuser have resistance which is 5 m according to the analysis;

(3) The friction between the fluid and the pipe wall during flow within a pipeline results in energy loss, known as friction loss, which can be expressed as head loss or pressure loss along the pipeline. A calculation segment refers to a section of cold or hot water pipeline with constant flow rate and pipe diameter. The formula for calculating the friction loss in a given segment is as follows:

$$\Delta P_m = \lambda \cdot \frac{l}{d} \cdot \frac{\rho v^2}{2} \tag{4}$$

In this formula, ΔP_m represents the friction loss in the calculation segment, measured in Pa; λ is the friction coefficient; l is the length of the calculation segment, measured in meters; d is the diameter of pipeline in the calculation segment, measured in meters; ρ is the density of the fluid in the calculation segment, measured in kg/m^3; and v is the velocity of the fluid in the calculation segment, measured in m/s.

The friction coefficient is related to the flow state of the fluid and the surface roughness of the pipe wall. Specifically,

$$\lambda = f(R_e, K/d) \tag{5}$$

where R_e is the Reynolds number, $R_e = vd/\upsilon = \rho vd/\mu$; ν is the kinematic viscosity of water, measured in m^2/s; μ is the dynamic viscosity of water, measured in Pa·s; and K represents the absolute roughness of the pipe wall, measured in meters. The absolute roughness is influenced by factors such as the usage of the pipeline (corrosion and scale deposition on the pipe wall caused by the fluid) and the duration of pipe usage. The cooling water system of CHMFL has been in operation for more than 10 years since it was completed. The chilled water pipe of the system is made of carbon steel. According to the "Air Conditioning System Design Manual"[4], the absolute roughness of the pipe of the cooling water system is taken as 0.5 mm;

(4) According to engineering experience, the ratio of local resistance to the on-way resistance h_d/h_f is generally between 1 and 1.5 for small residential buildings, between 0.5 and 1 for large high-rise buildings, between 0.2 and 0.6 for long distance pipeline (central cooling) [6] [7]. Therefore, h_d/h_f is set to 0.8 for this system.

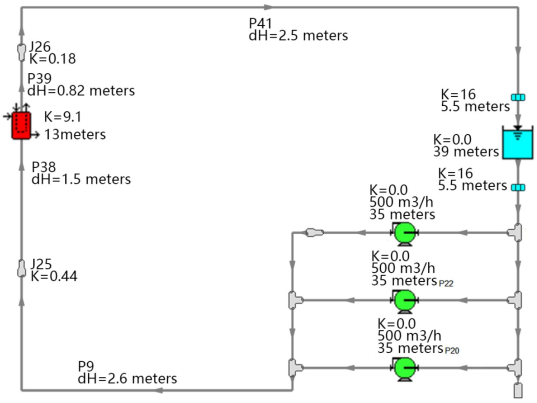

Fig 5. Calculation result of pipeline before reconstruction

In addition, various pipe fittings in the system can be added and set in the pipe model of AFT Fathom. For example, the system water return pipeline consists of two 90° elbows, two 135° elbows and two manual butterfly valves, which can be set in detail on the "Fittings & Losses" property page of the pipe. After all the equipment, pipes and pipe fittings are set according to the actual situation, the simulation results are shown in Fig 5. The model analysis head of chilled water pump is 35 m, and the actual pump head of the pump is 40 m, which is about 1.15 times of the model analysis. The result verifies the reliability of the model.

After the reconstruction of the cooling water system, a new plate heat exchanger and some pipes were added. The flow rate of the chilled water pump was changed to 680 m^3/h. These changes were added to the above model and the head of the chilled water supply pumps were reanalyzed and verified. Because of the plate heat exchanger is changed from one to two in parallel, the pipeline structure has also changed, so the parameters of the new plate heat exchanger and pipeline need to be set in the model. The calculation results are shown in Fig 6, the head of the new chilled water pump is 44 m.

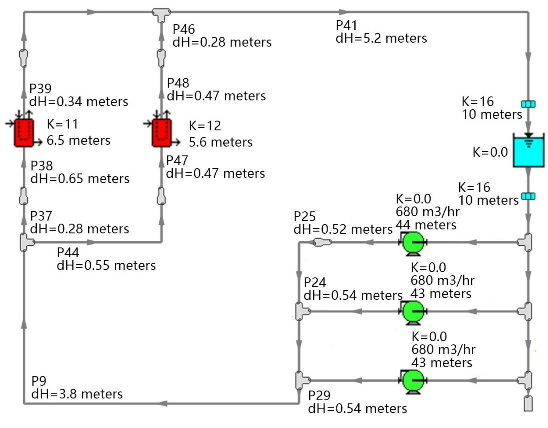

Fig 6. Calculation results of pipeline after reconstruction

Amplify the model calculation results of AFT Fathom by 1.2 times, and it can be concluded that the head of the pump selection is 52.8m. This result is close to the calculated value in Section 2.1. According to the selection provided by the pump supplier, the parameters of the new chilled water pump can be determined as a flow rate of 680 m^3/h and a head of 55 m.

IV. Analysis and Selection of the High-Pressure Pure Water Pump

The reconstruction of the high-pressure pure water pump is to increase the cooling circulation capacity of the magnet by adding two pumps with the same head and slightly higher flow rate, so as to better ensure the operation of the 42T resistive magnet. At the same time, the existing magnet will also have backup pumps during operation, which can improve the stability of the system. Since the 42 T resistive magnet has not been built, this section will analyze the capacity improvement of the new pumps and the characteristics of the pipeline network after reconstruction based on the existing large-circulation flow rate magnet. The parallel operation flow rate of water pumps is not a simple superposition of flow rates, it is related to the characteristic curve of the pipeline network of the system [8] ~ [11]. There are 5 resistive magnets (WM1~WM5) and a hybrid magnet (HWM11) in CHMFL. The operating flow rate of HWM11 and WM3 needs to be provided by four water pumps in parallel, which is similar to the situation of the 42 T resistive magnet. Then, some relevant analysis of these high-pressure pure water pumps was conducted based on the operation of these two magnets.

Both new and old water pumps are variable frequency pumps. For different magnets, these water pumps can automatically adjust the operating frequency to maintain the pressure difference between the magnet inlet and outlet to 25 bar, and the frequency of the magnet operation process is unchanged. According to the proportional law of centrifugal pump, the characteristic curve of the water pump is related to the rotational speed [12~14]. When the speed changes from n_1 to n_2, the approximate relationship between the flow rate Q and the head H of pump is:

$$\frac{Q_2}{Q_1}=\frac{n_2}{n_1} \quad , \quad \frac{H_2}{H_1}=\left(\frac{n_2}{n_1}\right)^2 \tag{6}$$

When the rotational speed change is less than 20%, the efficiency is considered unchanged. In this case, the error of the results calculated in this formula is not large [11]. The characteristic curve of the centrifugal pump is usually measured at 50 Hz. According to the formula (6), the characteristic curve within the range of 20% of the speed changes can be obtained. The intersection point of the system characteristic curve and the pump characteristic curve is the working point of the pump parallel operation, from which the working point of the single pump in operation can also be obtained. For HWM11, when the four old pumps provide circulating flow rate, the frequency is 48 Hz. According to formula (6), the rated flow of the pump at this time is 268.8 m^3/h, and the rated head is 276.48 m.

TABLE V
OPERATING DATA OF HWM11

	Flow rate(m^3/h)	Head(m)
1	430	42
2	687.7	104.8
3	840.3	159.4
4	958.1	212.9
5	1083	268.4

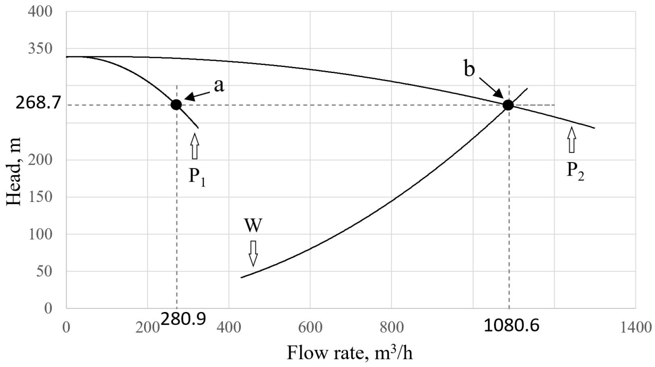

Fig 7. System characteristic curve of HWM11

TABLE V shows the operating data of HWM11 when four high-pressure pure water pumps rise from 25 Hz to 48 Hz. In Fig 7, P_1 is the characteristic curve of a single pump at 48 Hz, P_2 is the characteristic curve of four pumps running in parallel at 48 Hz, and W is the system characteristic curve fitted by the data in TABLE V. The intersection b (1080.6, 268.7) of curve W and P_2 is the working point of the four old pumps when HWM11 is running, and the intersection a (280.9, 268.7) of curve P_1 is the working point of the single pump at this time.

Taking WM3 as an example, the frequency at which four old pumps provide the experimental flow rate is 48 Hz. TABLE VI is the operation data based on WM3. In Fig 8, P_1 is the characteristic curve of a single pump at 48 Hz, P_2 is the characteristic curve of four pumps running in parallel at 48 Hz, and W is the system characteristic curve fitted by the data in TABLE VI. The intersection b (1019.7,277) of curve W and P_2 is the working point of the four old pumps when WM3 is running, and the intersection a (265,277) of curve P_1 is the working point of the single pump at this time.

TABLE VI
WM3 OPERATION DATA OF WM3

	Flow rate(m^3/h)	Head(m)
1	446.8	63.4
2	611.8	108
3	715.6	146.3
4	814.2	190
5	872.1	208.7
6	909	238.8
7	958.7	259.8
8	1010	270.5

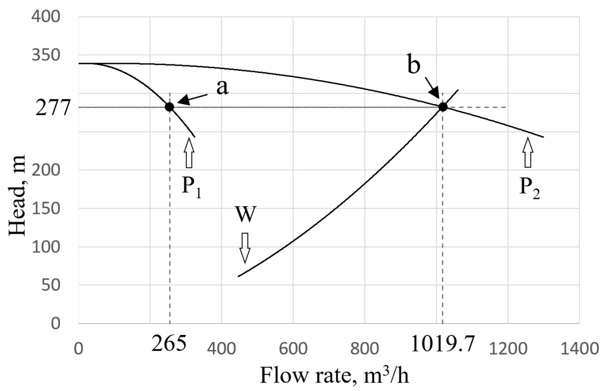

Fig 8. System characteristic curve of WM3

V. Analysis and Measurement

A. Chilled water supply pump

After the transformation, three chilled water pumps were replaced by new pumps with a flow rate of 680 m^3/h and a lift of 55 m, and a plate heat exchanger was added. Then, a balance valve is used to ensure that the flow rate of chilled water distributed to the two exchangers is basically the same. The measured results are shown in TABLE VII.

After the reconstruction, the maximum flow rate of the chilled water pump can reach to 2073 m^3/h, which can meet the cooling demand of the new resistive magnet. The pressure drops of the original heat exchange measured at the maximum flow rate is 0.069 MPa. And according to formula (2) and formula (3), it can be known that the pressure drop value ΔP_2 is 0.0686 MPa when the cooling flow rate is 2073 m^3/h. These two results are basically consistent, which verifies the validity of the above analysis method.

TABLE VII
CHILLED WATER FLOW RATE AFTER RECONSTRUCTION

Flow rate, m^3/h	Old heat exchanger	New heat exchanger	Total Flow
30Hz	653	590	1243
45Hz	970	890	1860
50Hz	1087	986	2073

B. High-pressure pure water pump

The new high-pressure pure water pump has a flow rate of 350 m^3/h and a head of 300 m. The new and old pumps were tested on WM3 in the "2+2" parallel mode. When the pressure difference reached to 25 bar, the frequency of four pumps was 46.5 Hz. The test results are shown in TABLE VIII.

TABLE VIII
"2+2" MODE OPERATION DATA OF WM3

	Flow rate, m^3/h	Head, m
1	502	65.4
2	674	113.1
3	767	154.1
4	874	201.4
5	929	221.4
6	936	232
7	960	242.7
8	1001	253.6
9	1009	264.7
10	1027	270.2

The fitted system curve W is shown in Fig 9. P_1 is the characteristic curve based on the old pump, P_2 is the characteristic curve by the new pump, and P_3 is the characteristic curve of two new pumps and two old pumps operate in parallel. The intersection point a (1037,271) of curve W and P_3 is the working point when 4 pumps are connected in parallel. Point b (218,271) and point c (292,271) are the working points of the old pump and the new pump at this time. The addition of new pumps reduced the operating frequency of the four pumps from 48 Hz to 46.5 Hz when WM3 reached the experimental conditions. The margin of the pump set has been improved. After the reconstruction, the characteristic curve of the pipeline network has changed. Curve W_1 is the system curve when the 4 old pumps provide flow for WM3 before the transformation, and the curve W is obviously shifted to the right relative to W_1, so the flow rate of the same head will be greater. The new resistive magnet has not been built yet, so accurate test data and system characteristic curve cannot be obtained. However, according to the parallel operation data of the old and new high-pressure pure water pumps, the performance of the current pump set has been significantly improved, which can meet the cooling needs of the new magnet. The addition of two new pumps can provide backup pumps for the operation of existing resistive magnets, and the system stability will be significantly improved.

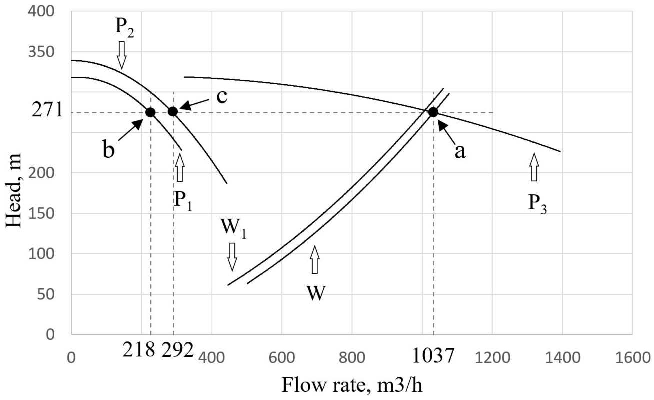

Fig 9. System characteristic curve of "2+2" mode of WM3

VI. Conclusion

The new-built 42 T resistive magnet of CHMFL will consume approximately 35.5 MW of electrical power during operation, and the heat needs to be dissipated by cooling water system. Since the maximum cooling capacity of the existing water system in the device is 28 MW, corresponding upgrades and modifications must be carried out to better support the resistive magnet in creating new records of steady-state field strength in the future. This article analyzes the magnet cooling cycle and the enhancement of the cooling capacity of the system, and the following are the conclusions.

(1) Several analysis methods are proposed to determine the parameters of the water pumps in the process of cooling water system reconstruction, and each method can also be mutually verified. The results prove that these methods are accurate and effective. Firstly, the data fitting method is employed, which uses the measured data of the circulation pipeline and plate heat exchanger before renovation as the basis. By fitting the data, the pipeline characteristic curve is drawn, and the pressure drop of the circulation pipeline after increasing the flow rate and paralleling the plate heat exchangers is predicted. This initially determines the parameters of the new chilled water pumps. Furthermore, AFT Fathom is used to perform a complete modeling the circulation pipeline of the original system, accurately restored the influence of equipment, elbows, tees and valves

on the pipeline resistance. This further verifies the parameters of the chilled water pumps.

(2) Two new high-pressure pure water pumps are added and operated in parallel with the existing pumps to meet the cooling needs of the new resistive magnet. Since the new resistive magnet has not been installed yet, relevant analyses are conducted based on the hybrid magnet HWM11 and the resistive magnet WM3, which have similar circulation flow rates to the new resistive magnet. Based on the actual measurements, it is found that the WM3 can reach to the operational state of the original four pumps at 48 Hz in "2+2" mode at 46.5 Hz. The system characteristic curve has shifted to the right obviously compared to before, which means that after the system reconstruction, a larger flow rate can be achieved when the pump head is fixed.

(3) The replacement of the chilled water supply pumps not only satisfies the cooling requirements of the new magnet but also enables the existing magnets to operate in a mode of two pumps in use and one as a backup. The relevant scheme effectively enhances the stability of the water-cooling system in the future.

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