Design of component cooling water system for Comprehensive Research Facilities in Support of CFETR

Weibao Li[1,2], Jiansheng Hu[1,2], Lei Yang[1,2], Bin Guo[1,4], Lili Zhu[1], Jinxuan Zhou[1,2], Zhe Liu[1,2], Lidong Yao[1,2] and Qianglin Xu[3]

[1]Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China
[2]University of Science and Technology of China, Hefei, China
[3]Anhui Jianzhu University, Hefei, China

[4]E-mail: guobin@ipp.ac.cn

Abstract. Comprehensive Research Facilities in Support of CFETR is aimed to demonstrate a comprehensive research platform with the highest parameters and the most complete functions in the field of magnetic confinement. The cooling water system is an integral part of a comprehensive research platform. The cooling water system includes component cooling water system (CCWS), chilled water system (CHWS) and heat removal system (HRS). The component cooling water system is mainly responsible for transferring the heat load generated by each subsystem during the operation, preventing the system from overheating. This paper presents the thermal hydraulic design of CCWS for Comprehensive Research Facilities in Support of CFETR. Through the development of the thermal hydraulic model of the CCWS, the AFT Fathom code is used to calculate the key thermal hydraulic parameters and predict the thermal hydraulic behaviour. Based on the results of thermal hydraulic analysis, the key thermal hydraulic parameters have been plotted to evaluate the capability of CCWS, such as the required pump head, inlet pressure, flow rate, inlet and outlet temperature and pressure drop of the customer. This paper will provide design guidance for the construction of component cooling water system (CCWS) for Comprehensive Research Facilities in Support of CFETR.

1. Introduction

Comprehensive Research Facilities in Support of CFETR is a comprehensive research platform which serves for Chinese fusion reactor science and technology research. Multiple research systems are contained, such as include power supply system (PWS), cryogenic system (CGS), lower hybrid current driven (LHCD), Electron-cyclotron-resonance heating (ECRH), host vacuum vessel system (HVVS), vacuum vessel system (VVS) and integration of several cooling system (ISCS). These research systems are also called subsystem of Comprehensive Research Facilities in Support of CFETR in the following. During the subsystems operation, more than 56.6 MW of head load will be generated which need to be removed. Therefore, the cooling water system is necessary to remove the thermal power generated by the subsystems, the component cooling water system (CCWS), the chilled water system (CHWS) and the heat removal system (HRS) are include in the cooling system. As the most important and complex part of the cooling water system, the CCWS is discussed in this paper.

The component cooling water system (CCWS) has the function to transfer the thermal power to the heat rejection system (HRS) with required flow rate and temperature, which can ensure the stable operation of the subsystems. Hence, it is necessary to design the component cooling water system (CCWS) to supply cooling water with certain pressure, temperature and flow for subsystems.

Presently, many researchers have been made on the thermal hydraulic analysis of the component cooling performance itself. In References [1-4], water-cooled divertor which are focus on the thermal performance of the divertor itself have been analyzed. However the external cooling water system is usually be neglected, such as CCWS. So, this paper presents a method for the CCWS process design and developing the thermal-hydraulic model to predict the behavior of the system.

In this paper, the CCWS description of the requirement and process design are presented firstly. Secondly, thermal-hydraulic analysis theory and pressure loss model is discussed. Thirdly, thermal hydraulic model analysis is introduced to determine pump-head and other thermal-hydraulic parameters. The discussion and conclusion are showed in the end.

2. CCWS description of the requirement and process design

Numerous clients are included in each subsystem thereby the large number of clients are labeled by the uniform rule. Letter S, L, and N are applied to description of the clients, respectively represent the system serial number, cooling loop serial number, and clients serial number. For example, S1-LHCD-L1-N1 represents the first client is located in the cooing loop 1 of LHCD system which is also named first system [5].

According to requirement of each subsystem, as shown in the Table 1, it is obvious that the overall heat load is 56.6MW, and the total cooling water mass flow is about 2176.43 kg/s. In addition, the requirement of inlet pressure, temperature for some clients is different, as well as the cooling water conductivity. Also, the 5 independent cooling loops are requested on the GCS system. Taking these factors into account, the clients with similar requirement are designed in a same cooling loop, thereby 32 clients are designed to be 17 cooling loops. However, the each cooling loop has the same function so that the schematic of all cooling loops can be illustrated in Fig. 1.

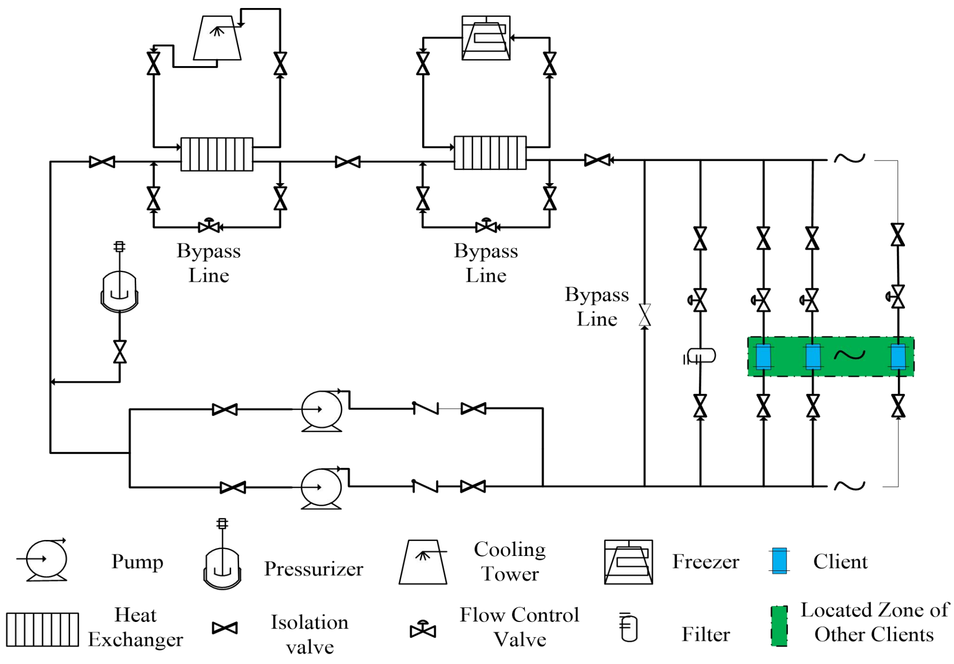

Figure 1. Schematic of cooling loop.

To satisfy the requirement of different clients, some branches in parallel are designed to feed each client. The clients put in the green zone can be replaced to other clients. Flow control valve are installed in the downstream of the clients so that the mass flow and inlet pressure of the clients can be controlled at the specific level. Isolation valve is located at the inlet and outlet of each client to isolate the clients when the clients are in maintenance. Bypass line of the clients is designed to protect the clients form exceeding the requirement. Similarly, the bypass line of the heat exchanger has the same function to satisfy the temperature. To avoid the conductivity is lower than the requirement of clients, filter is placed in parallel of branches. Pressurizer is at the main returned head, is also at the upstream of the pump to ensure that the coolant does not vaporize, which will guarantee the system safely. The pumps are located in parallel to decrease chance of system breakdown [6].

Table 1. Equipment water cooling system client.

Named	Flow rate (kg/s)	Max pressure loss (Mpa)	Max heat load (kW)	Conductivity (μs/cm)	Inlet temperature (°C)
S1-LHCD-L1-N1	66.67	0.6	44500	< 0.3	≤ 28
S1-LHCD-L1-N2	16.67	0.8	195	< 0.3	≤ 28
S1-LHCD-L1-N3	5.56	0.8	100	< 0.3	≤ 28
S1-LHCD-L2-N4	27.78	1	210	< 0.3	≤ 28
S1-LHCD-L2-N5	22.22	1	500	< 0.3	≤ 28
S1-LHCD-L3-N6	13.89	1.8	220	< 0.3	≤ 28
S2-ECRH-L1-N1	41.67	0.8	150	< 0.1	≤ 30
S2-ECRH-L1-N2	250	0.6	12000	< 0.3	≤ 30
S2-ECRH-L1-N3	5.56	0.6	120	< 0.3	≤ 15
S3-VVS-L1-N1	8.33	0.5	400	≤1	≤ 20
S4-CGS-L1-N1	277.78	0.55	3	< 20	≤ 33
S4-CGS-L2-N2	333.33	0.55	0.25	< 20	≤ 33
S4-CGS-L3-N3	111.11	0.55	1	< 20	≤ 33
S4-CGS-L4-N4	55.56	0.55	0.5	< 20	≤ 33
S4-CGS-L5-N5	27.78	0.55	0.2	< 20	≤ 33
S5-PWS-L1-N1	27.78	0.6	500	< 1	≤ 32
S5-PWS-L1-N2	111.11	0.6	2500	< 1	≤ 32
S5-PWS-L2-N1	1.39	1	14	< 1	≤ 32
S5-PWS-L2-N2	41.67	0.6	1400	< 1	≤ 32
S5-PWS-L2-N3	77.78	0.6	4300	< 1	≤ 32
S5-PWS-L2-N4	88.89	0.5	7200	< 1	≤ 32
S5-PWS-L2-N5	133.33	0.5	6000	< 1	≤ 32
S5-PWS-L3-N1	138.89	0.5	4450	< 10	≤ 32
S5-PWS-L3-N2	55.56	0.6	1500	< 10	≤ 32
S5-PWS-L3-N3	8.33	1	100	< 10	≤ 32
S6-ISCS-L1-N1	5.56	0.5	300	< 1	≤ 35
S6-ISCS-L1-N2	27.78	0.7	2000	< 1	≤ 35
S6-ISCS-L1-N3	27.78	0.5	2000	< 1	≤ 35
S6-ISCS-L1-N4	27.78	0.5	1000	< 1	≤ 35
S6-ISCS-L1-N5	27.78	0.6	1000	< 1	≤ 35
S6-ISCS-L1-N6	83.33	0.5	3000	< 1	≤ 35
S6-HVVS-L1-N1	27.78	0.5	1000	< 1	≤ 32

3. Thermal hydraulic analysis theory

During the progress of flow with incompressible fluid, the fluid is required to lose mechanical energy to compensate for the energy is consumed by the friction loss between the fluid and the solid wall, and the fluid when the local flow boundary changes abruptly. In the engineering design calculation, the energy loss is divided into two categories: the resistance loss ΔP along the path and the local resistance loss ΔP_S. Through the calculation of the pressure loss, system sizing parameters for the pump, pipe, control valve and other fittings can be determined [7,8].

The pressure loss of the pipeline can be calculated by the Darcy formula, referring to (1):

$$\Delta P = \rho g \left(f \frac{L}{D} \frac{v^2}{2g} \right) \tag{1}$$

Where f is the pressure loss coefficient, ρ is the fluid density, g is the gravitational acceleration, L is the pipe length, D is the pipe diameter, and v is the fluid velocity. If the tube is laminar flow (Re < 2000), f can be calculated by equation (2).

$$f = \frac{64}{\mathrm{Re}} \tag{2}$$

If it is turbulent (Re > 4000), it can be calculated by Colebrook equation (3), where ε is the absolute surface roughness of the pipe:

$$\frac{1}{\sqrt{f}} = -2 \log \left[\frac{\varepsilon}{3.7D} + \frac{2.51}{\mathrm{Re}\sqrt{f}} \right] \tag{3}$$

Local resistance loss of components in the model is calculated by local pressure loss formula (4), ξ is the local drag coefficient:

$$\Delta P_s = \xi \frac{\rho v^2}{2} \tag{4}$$

The conservation of pressure between the two components in the cooling water loop is described by the Bernoulli equation (5):

$$P_1 + \frac{\rho v_1^{\,2}}{2} + \rho g Z_1 = P_2 + \frac{\rho v_2^{\,2}}{2} + \rho g Z_2 + \Delta P_s \tag{5}$$

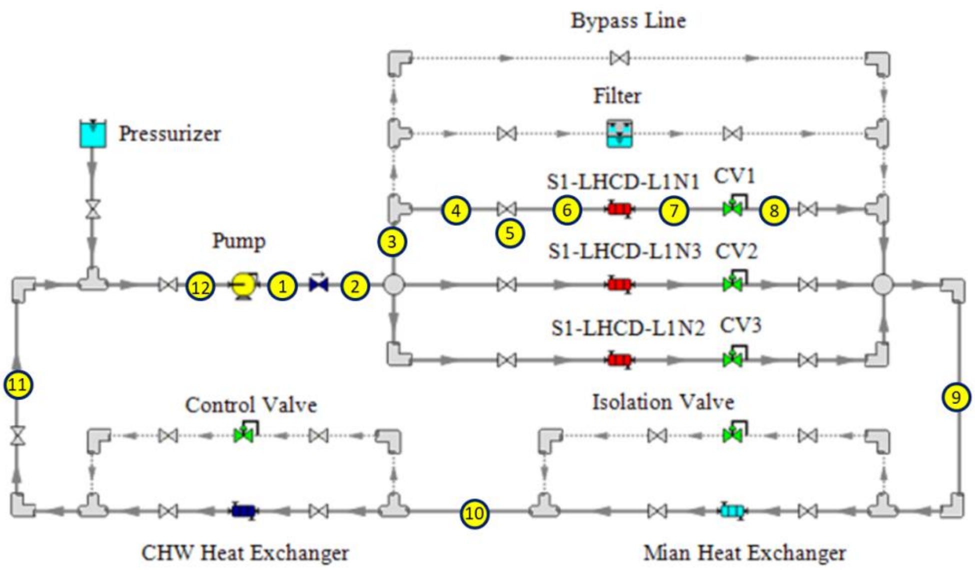

Figure 2. Thermal hydraulic analysis model of the LHCD cooling loop 1 (circle with yellow present pressure reference point).

4. Thermal hydraulic simulation analysis

For steady-state operating conditions, the AFT Fathom code is used to determine the fitting parameters for each cooling loop, including pressure distribution throughout the piping system, flow rate and cooling water temperature changes [9]. Due to all cooling loop model being too large to shows here, only the cooling loop 1 is given in Fig. 2 as an example. In the model, clients are modeled as heat exchanger in red to reject heat power to the coolant flowing through it. Valve in green is control valve at the downstream of the client to keep the flow and pressure. Once the component is stay in maintenance, valve in gray is isolation valve to isolate the component. Heat exchanger in Cambridge blue represents main heat exchanger located at the main returned head Heat exchanger in dark blue represents CHW heat exchanger which can make the coolant temperature lower [10].

4.1. Simulation results

The output file calculated by Fathom code is mainly showing pump head, the inlet pressure of the client, the inlet and outlet temperature.

a) Pump. Pump sizing is determined by the head result of the system provided by the Fathom code.

Table 2. Pump minimum requirement.

Subsystem	name	Mass Flow (kg/s)	dH (meter)	Total power (KW)	NPSHa (meter)
LHCD	L1	88.9	99.99	87.1	11.74
	L2	50.00	119.95	58.78	11.74
	L3	13.90	193.10	26.28	11.18
ECRH	L1	41.50	96.02	39.21	11.05
	L2	249.90	75.95	186.09	10.95
	L3	5.55	70.30	3.83	11.62
VVS	L1	8.30	55.00	4.48	11.94
CGS	L1	276.77	67.51	183.11	11.95
	L2	332.12	70.76	230.31	11.68
	L3	110.71	72.48	78.63	11.67
	L4	55.35	69.49	37.70	11.68
	L5	27.68	71.48	19.39	11.67
PWS	L1	138.9	75	102.1	11.73
	L2	343.1	130	437.1	11.68
	L3	202.8	120	238.5	11.72
ISCS	L4	199.30	90	175.8	11.72
HVVS	L5	27.68	60	16.27	11.77

Table 2 is mainly showing pump minimum requirement, 20% margin on the minimum required pump head should be included when specifying these pumps. Therefore, the required pump parameters are provided as Table 3.

b) Pressure. Fig. 3 shows the scatter plot of client inlet pressure and client demand pressure. In this figure, the vertical axis represents the pressure value, and the horizontal axis represents the number of clients. The blue points represent simulation result and the red points represent the minimum requirement of the clients. Clearly, inlet pressure of the clients simulated is much larger than the minimum requirement. And the maximum pressure is 19.85 bar, the minimum pressure is 6.49 bar.

Through the simulation, the branch in parallel with pressure drop has been calculated as the critical path to decide system total pressure drop. Once the critical path is determined, 12 points taken as shown in the Fig. 2 are the pressure reference points. Fig. 4, Fig. 5, and Fig. 6 present the critical path pressure curves for the seven cooling subsystems. In these figures, the vertical axis represents the pressure value, and the horizontal axis represents reference points. Obviously, maximum pressure drop happens between the inlet and outlet of clients, and minimum pressure is larger than the NHPs of the pump shown as Table 3.

Table 3. Pump requirement.

Subsystem	name	Mass Flow (kg/s)	dH (meter)	Total power (KW)	NPSHa (meter)
LHCD	L1	88.9	124.99	108.88	11.74
	L2	50.00	149.94	73.48	11.74
	L3	13.90	241.38	32.85	11.18
ECRH	L1	41.50	120.03	49.01	11.05
	L2	249.90	94.94	232.62	10.95
	L3	5.55	87.88	4.79	11.62
VVS	L1	8.30	68.75	5.6	11.94
CGS	L1	276.77	84.39	228.89	11.95
	L2	332.12	88.45	287.89	11.68
	L3	110.71	90.6	98.29	11.67
	L4	55.35	86.86	47.13	11.68
	L5	27.68	89.35	24.24	11.67
PWS	L1	276.80	93.75	102.1	11.73
	L2	311.10	162.5	437.1	11.68
	L3	257.4	150	238.5	11.72
ISCS	L1	199.30	112.5	175.8	11.72
HVVS	L1	27.68	75	20.3375	11.77

c) Temperature. Figure 7 shows the scatter plot of client inlet temperature, outlet temperature, and client requirement temperature. In this figure, the vertical axis represents the temperature value, and the horizontal axis represents the number of clients. The blue points and red points respectively represent client inlet and outlet calculation temperature, and the pink points represent the requirement temperature of the clients. Clearly, inlet temperature of the client is lower than the required maximum temperature, which has satisfied the requirement of the clients. Also, the maximum outlet temperature simulated is 51.46 °C, the minimum outlet temperature simulated is 28.64 °C.

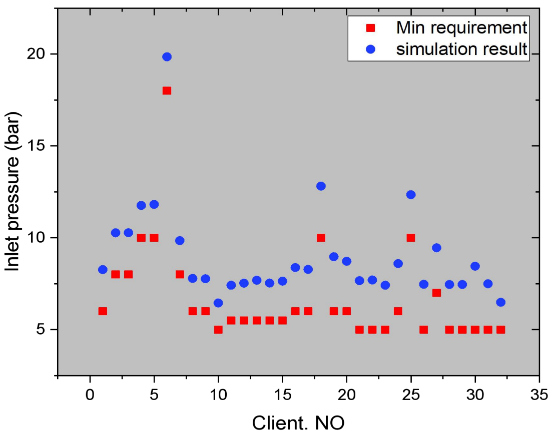

Figure 3. Inlet pressure of clients.

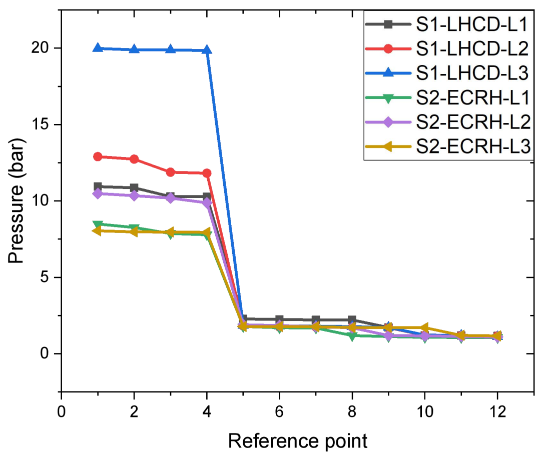

Figure 4. The critical path pressure distribution of S1 and S2.

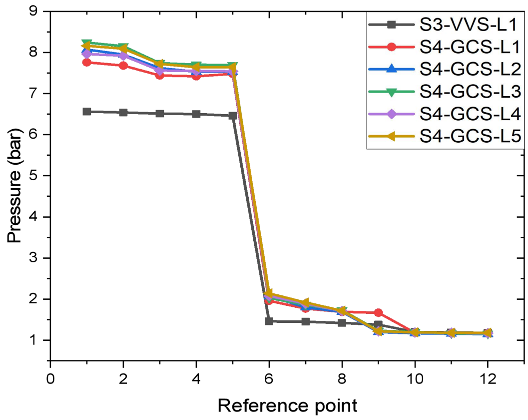

Figure 5. The critical path pressure distribution of S3 and S4.

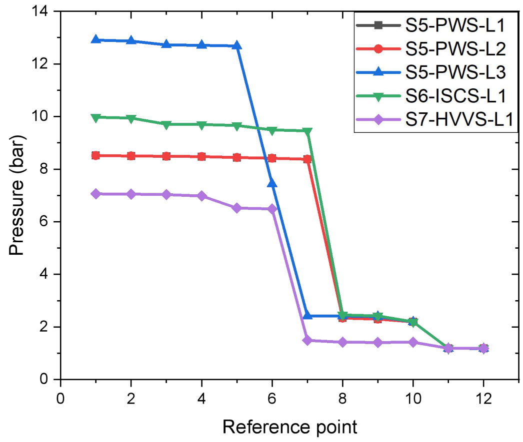

Figure 6. The critical path pressure distribution of S5, S6 and S7.

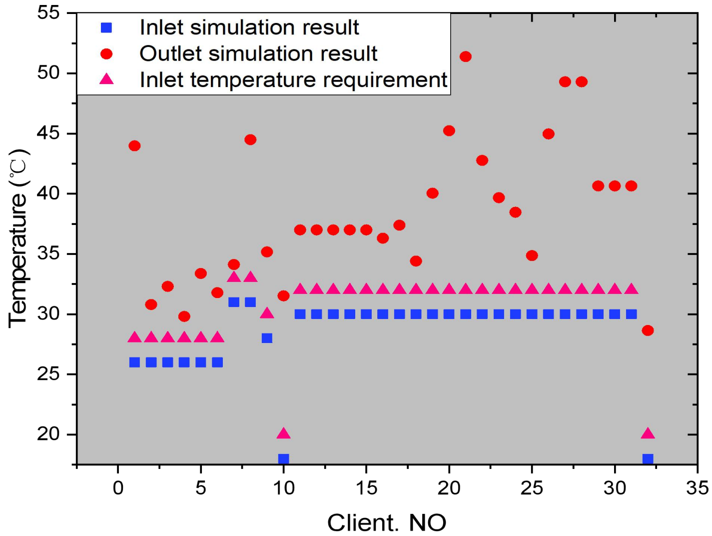

Figure 7. Temperature distribution of inlet and outlet of different clients.

5. Discussion

Comparing Fig. 4, Fig. 5, Fig. 6, it is clear that different clients required different pressure loss will cause the different pressure distribution through the flow path, therefore multiply cooling loop is necessary to be designed to satisfy different client requirement. The size of pump selected in the table 3 can meet all system head requirement. Also, the maximum pressure loss of the client S1-LHCD-L3N6 is 18 bar.

The Fig. 3 indicated that the inlet pressure can meet the requirement of the clients, and the largest pressure is 19.85 bar at the inlet of the S1-LHCD- L3N6. Meanwhile, the Fig. 7 indicated that the temperature distribution of the client inlet can also satisfy the requirement of the clients, and the highest temperature 51.46 °C is distributed at the branch pipe of S5-PWS-L2-N2.

6. Conclusion

The AFT fathom code is used to design the cooling water system for Comprehensive Research Facilities in Support of CFETR. The thermal-hydraulic analysis results indicate that cooling water system designed can satisfy the thermal-hydraulic parameter of all clients, such as pressure, temperature, which can provide guarantee for safety operation. The design methodology introduced in this paper can be a good reference for design the cooling water system in the future, thereby providing a solid guarantee for the stable operation of the fusion device.

Acknowledgments
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