Preliminary Design of ITER Component Cooling Water System and Heat Rejection System

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Abstract—**Being an experimental facility, the entire fusion power of ITER Tokamak needs to be rejected to the atmosphere with the help of Cooling Water System. The heat generated in the Tokamak is 847 MW whereas that of auxiliary heating systems and supporting systems is approximately 300 MW. The heat generated in the Tokamak is transferred through Tokamak Cooling Water System (TCWS) to Component Cooling Water System (CCWS) and then to the Heat Rejection System (HRS). The HRS which acts as the heat sink finally rejects the heat to the atmosphere. As ITER Tokamak will operate in a cyclical manner during various scenarios, the real challenge lies in providing an optimized HRS design which can accommodate the short duration pulses, when the incoming heat is approximately 1150 MW and also the comparatively longer dwell periods, when heat input is a small fraction of that. A significant challenge in the design of CCWS is that the system must remove the intermittent pulse-triggered heat loads along with the normal continuous auxiliary systems heat loads, while maintaining stable cooling water temperatures, pressures and flows through the Tokamak and the components of plant auxiliary systems. This paper describes the optimized CCWS design which meets the system requirements and seamlessly transfers the heat generated in the Tokamak, components of auxiliary and supporting systems to HRS. This paper also highlights the challenges encountered during the preliminary design and describes the development of a viable optimized HRS design solution which is capable of rejecting the heat to the atmosphere and maintaining the basin temperature within prescribed limit.**

Keywords—heat rejection; cooling water system; Tokamak; ITER

I. INTRODUCTION

ITER machine is being constructed to demonstrate the technical feasibility of the nuclear fusion energy conversion, at plant scale, from high temperature Deuterium-Tritium plasma using the Tokamak magnetic confinement arrangement and with a power amplification of at least 10 [1]. Fusion power shall be generated in ITER machine in which burning plasma at temperatures in excess of 150,000,000 °C will be confined within a vacuum vessel by magnetic fields. The enormous amount of heat generated by the Tokamak and its auxiliary systems will be removed by the cooling water system, consisting of TCWS, CCWS, Chilled Water System (CHWS) and HRS.

Being an experimental facility, ITER Tokamak will operate in a pulsed manner. High levels of fusion power (total thermal load from plasma up to 847 MW in the inductive operation scenario) will be generated during repeated plasma pulses of 500 seconds of plasma burn followed by 1300 seconds of dwell period (in the inductive scenario). Moreover, the heat generated by auxiliary heating systems and supporting systems is approximately 300 MW. The total heat generated is released to the atmosphere with the aid of one or more sub-loops of cooling water system. The CCWS is responsible for providing the components with cooling water at pre-defined temperature, pressure, flow rate and quality and transferring the heat rejected by the components to HRS. The HRS rejects the received heat to the atmosphere with the help of induced draft Cooling Tower (CT).

This paper describes the major challenges encountered during preliminary design and the design modifications carried out as part of system design and optimization of CCWS and HRS in order to achieve a viable design.

II. DESIGN CHALLENGES

A. *CCWS*

The main challenge of CCWS design is to maintain coolant temperatures, pressures, flow rates and water chemistry to meet needs of the components as well as to be controllable and adjustable to allow operation at different heat loads and flow rates. As the pressure differentials across the components served by the common loop vary significantly, it is challenging to make available cooling water with required supply pressure at the component locations. Moreover, an interesting challenge lies in cooling components of varying metallurgies like copper, aluminum and stainless steel. Other challenging factors are the need to provide high flow rates with correspondingly low differential temperatures to many of the components and the requirement of very low conductivity water by few of the components.

B. *HRS*

The pulsed nature of ITER machine operation as depicted in Fig.1 presents a distinct challenge to the design of the HRS.

HRS must reject the heat loads of auxiliary plants plus large, intermittent heat loads from Tokamak pulse operations, while maintaining stable CT basin water temperature to meet the needs of cooling water system components [1].

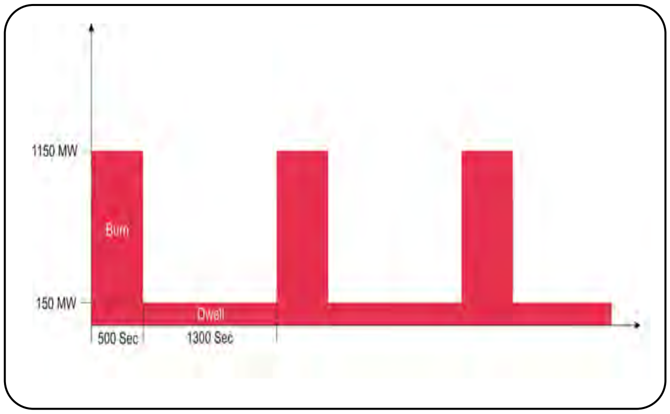

Fig. 1. Heat load variation during inductive operation

The major challenge of HRS design is to provide an optimum design solution to meet a very high peak heat load of about 1150 MW with an average heat removal capacity for the CT within the constraints.

III. THE PRELIMINARY DESIGN

A. CCWS

The original conceptual scheme of CCWS was with only two CCWS sub-loops namely CCWS-1 and CCWS-2 with former cooling primarily the TCWS and latter catering to the requirements of all remaining auxiliary and supporting system components of ITER machine. CCWS-1 provides a secondary confinement function (safety classified) in case of leak from a TCWS heat exchanger within the piping up to the closest isolation valves.

TABLE I. HEAT LOAD AND FLOW RATES OF CCWS SUB-LOOPS

Sub-loop	**Heat load (MW)**	**Flow rate (kg/s)**
CCWS-1	981.6	5824
CCWS-2A	40.1	902
CCWS-2B	27.5	1097
CCWS-2C	5.9	158
CCWS-2D	90.3	2142

During the preliminary design, it was realized that the wetted metal parts of auxiliary systems vary as copper, aluminum and stainless steel. Moreover, few of the components require cooling water with more stringent conductivity. As the system components differ on requirements, the new solution adopted during preliminary design for the CCWS was to introduce several sub-loops (CCWS-2A, CCWS-2B, CCWS-2C and CCWS-2D) instead of original single one (CCWS-2), to meet requirements of the components regarding water chemistry and wetted material. The heat load and flow rates of each of the sub-loop are listed in Table-I. The heat load of CCWS-1 varies cyclically whereas those of remaining sub-loops remain fairly constant.

According to the adopted design, CCWS-2A and CCWS-2B sub-loops cool the systems whose wetted components are made of copper and aluminum respectively and the quality of water has been selected accordingly in these sub-loops. The sub-loop CCWS-2C supports the components of stainless steel construction with very stringent conductivity requirement. The sub-loops CCWS-1 and CCWS-2D support the systems requiring demineralized water. Table-II shows the water quality requirements of all the sub-loops of CCWS.

TABLE II. WATER QUALITY REQUIREMENTS OF CCWS SUB-LOOPS

Sub-loops	**pH at 25 °C**	**Water conductivity at 25 °C (µS/cm)**	**Dissolved oxygen concentration (µg/kg)**
CCWS-1	6.5 – 9.5	≤ 50	NA
CCWS-2A	6.5 – 7.5	≤ 1.0	≤ 50
CCWS-2B	6.5 – 7.5	≤ 1.0	NA
CCWS-2C	6.5 – 7.5	≤ 0.3	NA
CCWS-2D	6.5 – 9.5	≤ 50	NA

Each of the CCWS sub-loop consists of dedicated horizontal centrifugal pumps, pressurizers, Plate type Heat Exchanger (PHE), strainers, valves, flow elements and instruments including sensors and interconnecting piping. The chemical addition system is included for two of them (CCWS-1 and CCWS-2D). The other sub-loops CCWS-2A, CCWS-2B and CCWS-2C have water polishing units and in addition, CCWS-2A has the capability to remove dissolved oxygen to the required level. These provisions are in place for components with different wetted surface metallurgies and that need specific conductivity under precise limits [3].

The locations of all the CCWS equipment have been identified. The hydraulic analyses were carried out for each of the sub-loops to check the adequacy of the design. The design pressures and design temperatures of the sub-loops are presented in Table-III.

TABLE III. DESIGN PRESSURES AND DESIGN TEMPERATURES OF CCWS SUB-LOOPS

Sub-loops	**Maximum Operating Pressure (MPa)**	**Design Pressure (MPa)**	**Design temperature (°C)**
CCWS-1	1.36	1.5	90
CCWS-2A	1.3	1.4	90
CCWS-2B	1.2	1.4	90
CCWS-2C	1.2	1.4	90
CCWS-2D	1.4	1.6	90

System design pressures vary for different sub-loops of the CCWS. The design pressure has been selected based on the shut off head of the pump [3].

As it can be seen in Fig. 2, the CCWS-1 pumps deliver the cold water to PHTS and other systems/components and the hot water coming out of these systems/components loses heat while passing through CCWS-1 PHEs. The exchange of heat takes place in PHE between CCWS water and HRS water and the latter finally rejects the heat to the atmosphere with the help of CT. Similar pumping and heat exchange occur in other sub-loops CCWS-2A, CCWS-2B, CCWS-2C and CCWS-2D also, as in Fig.2.

Another major change made in CCWS design during preliminary design is an attempt towards reducing the flow rate on cold side of PHE and hence flow to the CT of HRS by increasing the approach temperature of PHEs from 2.4°C to 4°C.

Thus, the CCWS design and optimization resulted in ensuring that the components receive cooling water as per pre-defined demands in terms of temperature, pressure, flow rate and quality. In addition, it helped in achieving optimized HRS design.

B. HRS

The original HRS concept design envisaged an average heat rejection capacity and single common basin with the role to provide support for the CT structure apart from receiving the discharged water which carries the hot water from CCWS pumps [2].

However, during the preliminary design it became obvious that the envisaged scheme was not capable of rejecting the total heat load and hence not able to supply to the components cooling water with stable pre-set temperature [2]. Moreover the area reserved for CT was inadequate to accommodate required number of CT cells. Extensive studies have been carried out by exploring various alternatives and the results finally narrowed to two options those could make the HRS design executable.

One of the options was to design the CT for peak heat rejection capacity; another was introduction of an additional basin called hot basin and transfer pumps between hot and cold basins to limit the required CT thermal capacity.

The first option would require a much larger CT footprint because of full flow passing through the CT. Additional space would be required to locate the HRS circulation pumps. Since the temperature of water reaching CT is very low during the dwell period, the CT is under-utilized during this period. The electrical power requirement is significantly high for this configuration.

The second option (Fig.2) proposed an additional basin that could provide a buffer to store hot water during plasma burn time and hence presented the advantage of reduced thermal capacity requirement of CT.

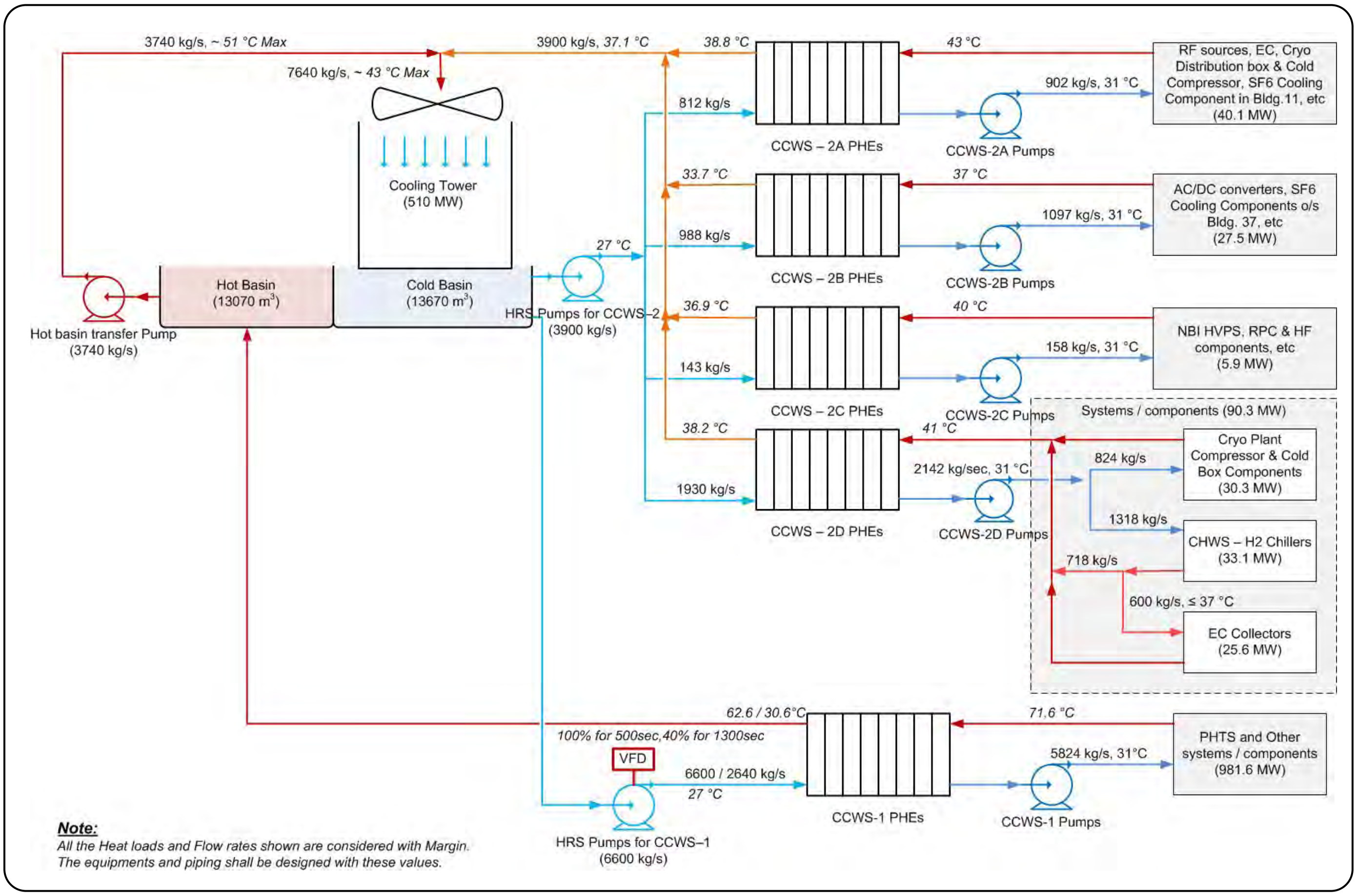

Fig. 2. Schematic of CCWS and HRS

The solution finally has been adopted for HRS is the second one mentioned above, i.e., introduction of an additional basin to reduce the CT thermal capacity by giving enough considerations to different project constraints like technical feasibility, environmentally friendly approach, available space, cost efficiency, simplicity and reliability.

The adopted HRS design consists of CT with ten cells, two basins (hot basin to store hot water coming from CCWS-1 PHEs and the cold basin to collect the cold water coming out of CT), three sets of vertical turbine pumps (first sets are to circulate water from cold basin through the PHEs of CCWS-2A, CCWS-2B, CCWS-2C and CCWS-2D and finally through CT; second sets equipped with Variable Frequency Drives (VFD) are to circulate the water from cold basin through the PHEs of CCWS-1 and to leave the hot water in the hot basin; and third set of pumps are to pass the hot basin water through CT), the chemical dosing system, ozonator, strainers, valves, associated instruments and interconnected piping. Moreover, the HRS has suitable provisions for make-up and blow down. The cold basin is compartmentalized for maintenance with each compartment collecting water from two of the CT cells.

In this configuration (Fig. 2), the entire hot water coming from CCWS-2A, CCWS-2B, CCWS-2C and CCWS-2D PHEs is allowed directly to the CT throughout the operation. The hot water loses the heat while passing through the CT and the cold water is collected at the cold basin. On the contrary, the hot water coming from CCWS-1 PHEs is directed to the hot basin with pre-defined initial water volume during entire cycle of operation, from where it is pumped at a constant rate to CT using hot basin transfer pumps. Having provided with VFDs, the HRS pumps for CCWS-1 shall reduce the flow up to 40% of rated flow during dwell period so as to keep the hot basin sufficiently hot. The temperature of water in the hot basin increases as the plasma pulse progresses, but drops gradually during the dwell period. The cycle is repeated continuously.

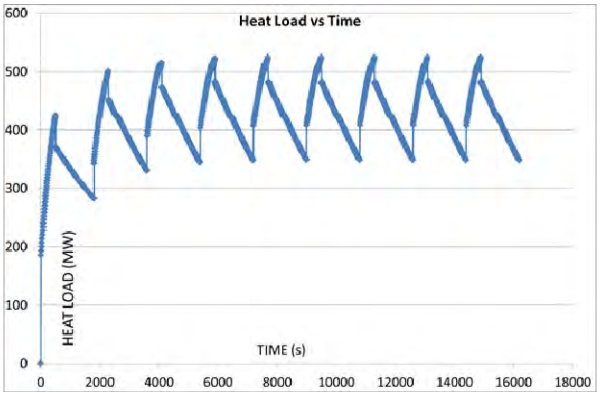

Fig. 3. Heat rejection requirement versus time (inductive scenario)

The two basins take care the fluctuations in heat load. The hot basin acts as a buffer tank to maintain sufficiently high average supply temperature to CT. As a result, CT efficiency remains steady irrespective of fluctuation in heat loads. In Fig.3, the simulation shows that the heat rejected through the CT does not vary significantly and is below the 510 MW and hence the water temperature in the cold basin remains within the intended temperature of 27 °C as shown in Fig. 4.

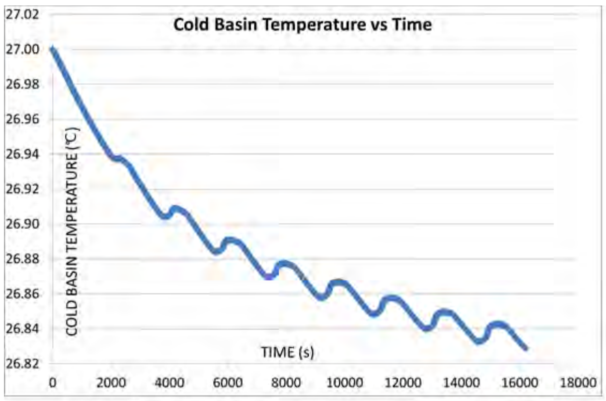

Fig. 4. Variation of temperature with time in the cold basin for the inductive scenario

The sizing of cold and hot basins, setting the initial fill-up water volume in the basins and the selection of hot basin transfer pumps capacity have been done in such a way to have mass balance. A three-dimensional CATIA model of HRS equipment along with partial CCWS equipment is presented in Fig. 5. The CT is installed over the cold basin and the extended portion of cold basin houses HRS pumps for CCWS-1 and CCWS-2. The hot basin transfer pumps are installed in hot basin.

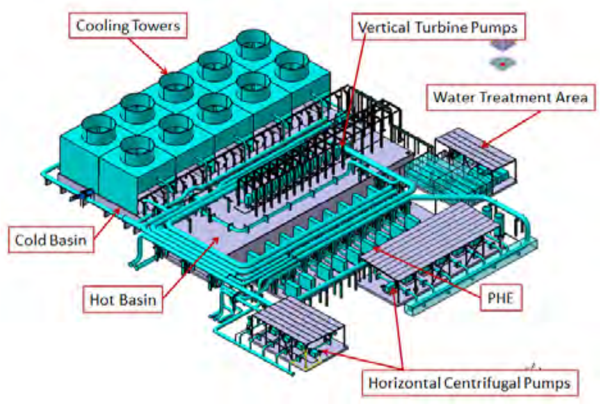

Fig. 5. Three Dimensional model of HRS and partial CCWS

Moreover the approach temperature of CT has been increased from 3.6 °C to 5 °C during preliminary design for further optimization so as to fit the CT cells within the available space.

The net result of this design is the effective utilization of CT and maintaining the temperature of cold basin water within the prescribed limit with the help of CT of average heat rejection capacity.

IV. CONCLUSIONS

The recent modification and the optimization of the ITER CCWS and HRS during preliminary design have changed the configurations significantly from the conceptual design. The new solutions adopted for the CCWS and HRS answered the challenges and succeeded in meeting the system requirements more effectively and efficiently as follows:

- Design of CCWS with several sub-loops has resulted in meeting the system and component requirements regarding wetted surface metallurgies type as well as specific water quality
- The sub-looping of CCWS has added advantages in terms of flexible and independent operations
- Inclusion of a hot basin in the HRS design configuration (acting as a thermal storage) has resulted in the optimal design of the CT at an average heat rejection capacity
- Control of the flow rate from CCWS-1 PHEs into the hot basin via VFDs during the plasma pulse/dwell phases has led to the effective utilization of CT
- Increase in approach temperatures of CT and PHE has led to the selection of equipment with optimal design parameters
- Improved efficiency of the electric power utilization, optimization of the plant space and the equipment sizing

Further optimization can be considered during the final design phase based on value engineering approach, related industrial experience and standardization.

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