Concept of calorimetry system for ITER

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Abstract—

The ITER tokamak is expected to produce up to 500 MW of fusion power. Other energy inputs will contribute up to 100 MW. All of this power ultimately converts to heat and the Tokamak Cooling Water System (TCWS) will remove most of it. To ensure safety, diagnostics methods, including calorimetry, will be used.
Thermal methods used in calorimetry are not suitable for online control but rather provide time-averaged or integrated values. The ITER calorimetric system aims to calculate the integrated fusion power after each pulse by determining the total tokamak power using data from the TCWS and other systems involved in the energy transfers. The total fusion power will be then determined by analyzing the thermal balance of the machine. As most of the energy transfers are realised by cooling loops, a general forward model has been developed for their analysis.
The system is designed to measure net fusion power production. At approximately 200MW, the accuracy is around 10%, and at about 500MW, the accuracy improves to 3%. The expected time constant of the measured instantaneous value is in order of 40s (the nominal ITER burn times are in the range 300 - 3000s). System will be most useful in cross-calibration with fast time resolution neutron systems. The developed system will also serve as a model for future tokamak-based fusion power plants, where its accuracy will be even higher. The paper gives a general description of the system concept, with main inputs required and the expected outputs.

Keywords **—ITER, fusion power, fusion energy, calorimetry, thermal analysis.**

I. INTRODUCTION

In the pursuit of controlled fusion energy ITER is a landmark project developing the tokamak. ITER will be equipped with a pressurized water cooling system to ensure efficient cooling of all surfaces exposed to the plasma. The effective removal of heat is essential during stationary long discharges to protect the machine. Fusion power generated in ITER is limited by regulatory requirements and capped at 700 MW although power in most scenarios does not exceed 500 MW [1].
Instantaneous control is provided by neutron flux monitors that have ms level response time, but accuracy limited to ≈10% suffering from incomplete knowledge of the local flux distribution as a function of the global power, calibration and geometrical errors [2]. Calorimetry can reduce the overall error, calibrate the fast neutron measurements and improve the confidence in the output power used in extrapolation to future reactors.
The total energy of the pulse can be accurately determined by calorimetric methods [3,4]. Various studies have demonstrated the accuracy of calorimetry as an informative source for quantifying energy or power deposition [5,6]. Additionally, this method is successfully applied in fission power plants [7]. Therefore, calorimetry can be used to calibrate neutronic diagnostics by comparing the obtained pulse energy with the integrated neutron flux. Calorimetric measurement in ITER can achieve high accuracy thanks to high fusion power, good coverage by the cooling system and excellent thermal insulation. The majority of heat from ITER is removed by the Tokamak Cooling Water System (TCWS) [8], which consists of several cooling loops and is accompanied by a number individual component cooling systems. Estimation of the heat extracted by a cooling loop can be performed using the sensors installed at the inlet and outlet of the loop. By combining data from all the cooling loops, one can analyse the global energy balance within the system.

The focus of this study is to develop an algorithm capable of determining an integrated value of fusion power - pulse energy. Understanding thermal fluxes in the cooling system offers insights into the dynamics of fusion reactions within the ITER reactor. This algorithmic approach provides a valuable tool for understanding the temporal behaviour of fusion power and contributes to the broader goal of optimising fusion reactor performance.

II. CALCULATION OF HEAT BALANCE

Various energy sources contribute to thermal balance of the tokamak. During power operation, the main contributors to the balance are the thermal energy resulting from fusion reactions (with its thermal flux denoted as P_{fusion}), and the energy supplied by the plasma heating system ($P_{heating}$). Minor contributing sources include the energy delivered by auxiliary devices such as lasers ($P_{auxiliary}$) and the enthalpy change in the pump (P_{pump}).
Heat from the tokamak is removed mostly by the cooling system which captures and transfers the combined energy from various sources. This is divided into two sections, tokamak (P_{TCWS}) and component (P_{CCWS}) cooling system. Some heat is captured by the cryogenic system, however, the values are quite small (in the order of watts), and will therefore be overlooked in this study.
There are additional thermal transfers that are not directly managed, including convection to and from the cryostat structure, heat conduction through the supports, and thermal

radiation from the machine (P_{losses}). Analysing these transfers is a complex task due to the non-uniform temperature distribution of the cryostat and the multi-directional heat flow.
The overall tokamak power balance can be expressed as:

$$P_{fusion} + P_{heating} + P_{auxiliary} + P_{pump} = P_{TCWS} + P_{CCWS} + P_{losses} \quad (1)$$

The power fluxes are visualised in Fig. 1. Table I describes the typical values of these flows.

TABLE I
TYPICAL THERMAL FLOWS VALUES

Symbol	Components	Value [MW]
P_{fusion}	Fusion power	500
$P_{heating}$	Induced current, ECH, ICH, NBI	100
$P_{auxiliary}$	Laser, control coils	O(1)
P_{pump}	Pumps	10
P_{TCWS}	Tokamak cooling water system	-560
P_{CCWS}	Component cooling water system	-50
P_{losses}	Convection, Conduction and radiation to and from the cryostat external surface	O(1)

P_{TCWS} and P_{CCWS} comprise the vast majority of heat being transferred away from the tokamak. The heat transfer in this system is realised by water cooling loops. In terms of measurements and analysis all the cooling loops can be treated similarly. The thermal energy carried by the cooling water is computed with formula (2). The experimental inputs to the formula are the temperatures and pressures measured at both the entrance and exit of a loop.

$$\mathrm{P} = \dot{\mathbf{m}} \cdot \left(\mathrm{h_{out}}(\mathbf{T_{out}}, \mathbf{p_{out}}) - \mathrm{h_{in}}(\mathbf{T_{in}}, \mathbf{p_{in}})\right) \quad (2)$$

Where h is the enthalpy and subscript "in" and "out" denote the inlet and outlet of the control volume, $\dot{\mathbf{m}}$ the mass flow, **T** the temperature and **p** the pressure. In this formula the bold characters ($\dot{\mathbf{m}}, \mathbf{T_{in|out}}, \mathbf{p_{in|out}}$) are directly measured in the cooling system. In the considered thermodynamic regime the variation of enthalpy is dominated by temperature, pressure has minor effect.

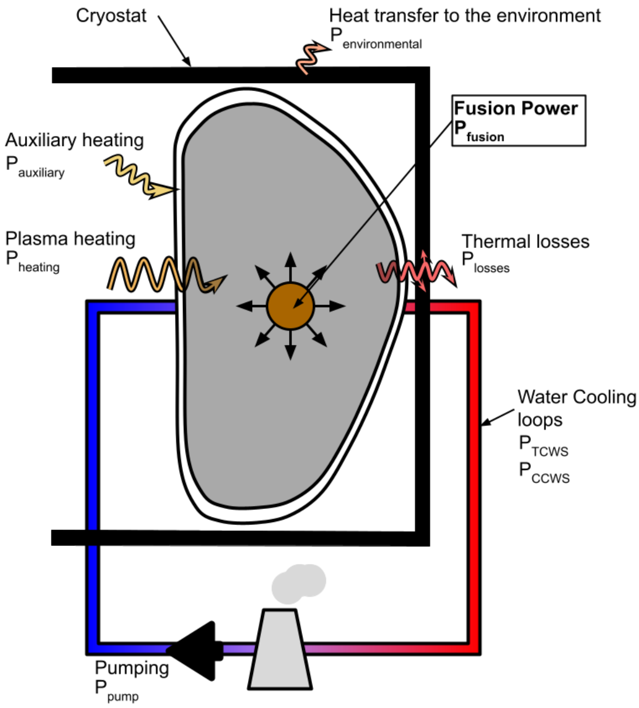

Fig. 1. Power balance schematic showing inputs ($P_{heating}$, $P_{auxiliary}$, P_{pump}), outputs (P_{TCWS}, P_{CCWS}, P_{losses}), and fusion-generated power (P_{fusion}). Tokamak Cooling Water System (TCWS) loop depicted with blue for cold water and red for hot water. Includes representation plasma heat interaction.

III. FORWARD MODEL

Since the cooling systems are still in their preliminary phase, there is a lack of experimental data to draw from. Consequently, the creation of the calorimetry system must rely on mathematical modeling and insights gained from past experiences. Developing this system necessitates the analysis of a substantial variety of pulse and operational scenarios. To generate the synthetic results allowing for the behaviour of the calorimetric system to be predicted, a forward model of the cooling loops has been created. A more complex model already exists such as RELAP5 [9]. However, the complexity of the existing model is not needed for the system development, as from the point of view of the calorimetry system the entire tokamak is treated as a single volume. The synthetic data from the forward model is compared with existing complex model results for validation (Fig. 2.).

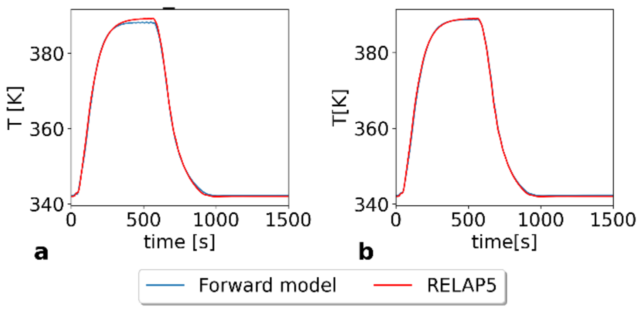

Fig. 2. Comparison between results from RELAP5 and forward model described in this paper obtained from different scenarios.

The principal outputs of the model used for testing the calorimetry diagnostic are inlet and outlet temperatures (**T$_{in|out}$**) of a fluid while the internal dynamics of heat exchange in the tokamak are simplified. The internal values of temperature of the tokamak obtained in the model do not directly represent the temperature of the actual tokamak structures.

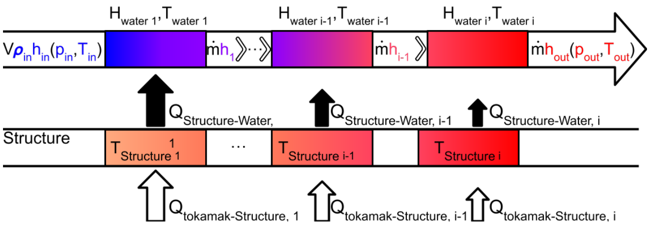

Fig. 3. Scheme of the model operation

The forward model has been implemented in Python. The modelled system is divided into two domains that represent cooling water flowing through the pipes, and a homogenised tokamak structure. The structure domain represents the first wall, the vacuum vessel, the cryostat and all other solid elements of the tokamak. This system could be modelled as a simple heat exchanger, but it was observed that it is not sufficient to align with RELAP5 model.

Thus, the domains are partitioned into multiple sections, as depicted in Fig. 3. The tokamak's structure captures the heat generated within it, which is subsequently removed by the water used as a working fluid in most loops.

The model is time dependent. At each time step heat balance Q_{bal} is calculated for each section, with (3) at the structural sections, and (4) at the water sections.

$$Q_{bal_i} = \tau \cdot \left(Q_{tokamak-structure_i} - Q_{structure-water_i}\right) \quad (3)$$

$$Q_{bal_i} = \tau \cdot \left(\dot{m} \cdot (h_{i-1} - h_i) + Q_{structure-water_i}\right) \quad (4)$$

In the TCWS model, the structure domain heat balance is a difference between the heat coming from the tokamak and the heat removed by a cooling fluid. For the water domain mass flow is conserved, and the heat balance is found as the sum of heat coming from the structure, and a difference between inlet and outlet enthalpies h. Thus, the heat transfer depends on the state of a section i and the preceding section i − 1 (judging by the mass flow direction). An inlet mass and energy flux with predefined temperature, pressure and mass flow is imposed on the first water domain section.

Heat transfer between the respective sections of water and structure domain $Q_{structure-water}$ is calculated with formula (5).

$$Q_{structure-water_i} = (T_{water} - T_{structure}) \cdot k \quad (5)$$

The parameter k is calculated using formula (6), which includes a coefficient γ to consider the geometry of the tokamak. As the determination of the actual heat exchange parameters is a complex task beyond the scope of the system, the coefficient γ is selected to match the pre-existing tokamak analyses performed with more complex models [10,11]. Parameter k is dependent on temperature through the parameters of dynamic viscosity (κ), thermal conductivity (μ), and Prandtl number (Pr) which are calculated using the PropSI library.

While (6) is often utilized for more intricate, temperature-dependent systems, it retains its effectiveness even for our less complex model. In fact we successfully managed to fit the power calculated from the complex model to ours, which validated its applicability (Fig. 2).

$$k = \gamma\, \kappa\, \mu^{-\frac{4}{5}} Pr^{-\frac{2}{5}} \quad (6)$$

All the structure domain sections are affected by a Neumann boundary condition of temperature-independent prescribed heat flux $Q_{tokamak-structure}$, representing the heat load from plasma and other sources. It is assumed that heat transfer by conduction between the sections of structure domains is negligible compared to the heat load from other sources.

The temperature change in a section of structure domain is found with formula (7).

$$T_{i_\tau} = T_{i_{\tau-1}} + \frac{Q_{bal_i}}{C_i\left(T_{i_{\tau-1}}\right)}, \quad (7)$$

C is a temperature-dependent parameter representing the thermal capacity of the structure. Temperature-dependance is assumed to be proportional to that of the stainless steel described with formula (8) [12].

$$C \propto 6.7 + 0.05 \times T + 80.7 \times \ln(T) \quad (8)$$

Similarly to k it is based on matching the results with the pre-existing calculations used to design the TCWS system.

Calculations in the water domain are done using CoolProp [13], with the thermodynamic state defined by enthalpy and pressure. Pressure in each section is pre-defined and assumed to drop linearly along the modeled system between the inlet and outlet values. It is also assumed to be independent from the flow conditions. In the actual system the inlet pressure is maintained by a pressurizer.

Initial conditions assume a constant temperature of 70°C across the modeled system, pre-defined mass flow and no heat input from the tokamak. During the model operation, scenarios with different heat input, mass flow and thermal inertia are analysed. The model in its current form calculates heat removal from the structure by a single loop. Works are on-going to include parallel operation of several loops and to mathematically close the loop by the inclusion of the heat rejection system, pump and a pressurizer.

IV. RESULTS AND DISCUSSION

Fig. 4. illustrates the temperatures of the water passing through the cooling system at the inlet and outlet of the tokamak. These temperatures are expected to be measured in operational mode. For the purpose of the paper, they are calculated by the forward model. In this simple approach it assumed that the entire internal power is removed by a single cooling loop.

In this example the inlet pressure is set at 4 MPa, while a pressure loss of 1.35 MPa is assumed to occur linearly along the sections. Throughout the calculation, the inlet mass flow is consistently maintained at 3300 kg.s^{-1}. The cooling tower system is considered perfect, giving a constant inlet temperature at 70°C. The simulated calorimetry system measures the power input into the cooling system based on the observed temperature and related enthalpy changes using (2).

The integrated pulse energy value is the primary focus of the results analysis. The imposed input power registers a total energy of 250.5 GJ, while the system reads it at 250.4 GJ. This near-perfect alignment between the input power and the system's measured integrated pulse energy is an expected outcome. It serves as a reassurance that the code is functioning as designed, with no identifiable bugs.

There is a shift between the instantaneous input power and the recalculated value, as shown by Fig. 5. This is due to the moderating effect of the tokamak structure thermal capacity. The shift does not has a significant effect on the integrated value of the pulse energy. The time constant of the power measurement can be estimated from this curve as 40s.

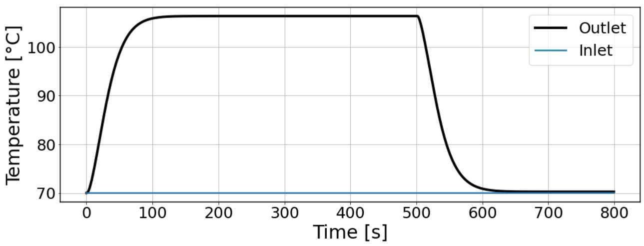

Fig. 4. The temperature of the cooling system over time. inlet (blue) and outlet (black) the tokamak.

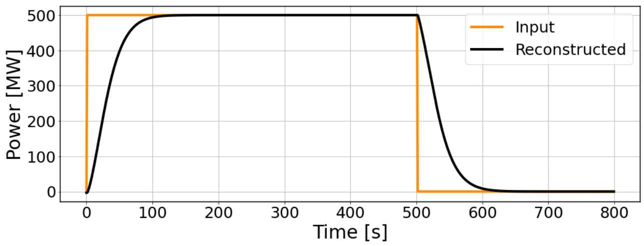

Fig. 5. Power comparison over time: original input (Orange) vs. recalculated (Black).

Because ITER is equipped with multiple cooling loop systems, a future step is to consider the individual inputs to the thermal balance of the tokamak. Additionally, the acquisition of results from various points across the device may enhance the temperature distribution reconstruction within the tokamak structure and lead to a better understanding of plasma power outputs.

A future aspect of this research involves reconstructing the initial and final stages of the calculated power, which will rely on the development of an algorithm. It will enable performing correlation analyses between the calorimetry and neutronics diagnostics, allowing for cross-calibration and actively contributing to anomaly detection. Correlation between integrated power and integrated neutron output will be analysed.

Based on the accuracy of sensors, the expected accuracy of the system has been estimated. The indicative results are given in the Table II, the exact assessment is ongoing.

TABLE II
ESTIMATED ACCURACY

Nominal Power [MW]	500s pulse energy [GJ]	Estimated error [GJ]	Accuracy [%]
100	50	+/- 6.7	13.4
250	125	+/- 6.8	5.4
500	250	+/- 7.1	2.8
700	350	+/- 7.4	2.1

If the temperature difference between input and output is higher, the accuracy can be even better. This will be the case in the future power generating fusion plants. In these facilities calorimetry system will play a crucial role in measuring the power output of the tokamak in the power cycle.

V. CONCLUSIONS

The calorimetry system is used to determine fusion power from temperature, mass flow and pressure measurements. It provides independent albeit slow measurement of the total pulse energy on its own but can be cross-utilised with the neutron systems to give a fast response**.**

This paper describes the operation of simulated calorimetric system using ideal sensors as inputs. An excellent agreement is reached between the simulated input pulse energy and the reading of the system. The accuracy of the actual system will be affected by the accuracy of the sensors. Nevertheless, since the result value is integrated, the accuracy will remain very high after identification and elimination of systematic errors. The development of analysis algorithms for this purpose is ongoing. Also, further investigation is needed using the forward model to quantify the actual accuracy. Calorimetry has a major role to play in the future fusion power plants not only as an offline system measuring pulse energy but also as an online system measuring actual thermal power output of the machine.

In the current state of the model, it is possible to estimate the change in temperature and enthalpy of the water in the cooling system based on the injected power. From this information, the model allows for the reconstruction of the power that was applied. Further accuracy studies are needed. The model will be improved to take into account the inlet temperature changes over time and to incorporate the parallel operation of the different cooling circuits. A reconstruction algorithm to enable "real-time" analysis of the calorimetry diagnostic will be developed.

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