Mathematical Modeling of the Cooling First Wall of the Tokamak Reactor

D Yu Sychugov\textsuperscript{1} and A S Zhilkin\textsuperscript{1,2}

\textsuperscript{1} Lomonosov Moscow State University, Faculty of Computational Mathematics and Cybernetics

\textsuperscript{2} Email: azhilkin2033@gmail.com

Abstract. In the course of designing the post-ITER fusion facilities, a number of new technical and scientific problems occurred that were unknown before and necessarily have to be solved. Among these problems, one of the most important is the design of the reactor first wall, which could withstand the continuous heat fluxes coming from the fusion plasma. In this article, the mathematical model of the cooling first wall of the reactor is constructed and the numerical analysis is performed of the currently accepted first wall design of the future DEMO-FNS reactor (Fusion Neutron Source).

1. Introduction
Over the past two decades, a number of countries have been developing projects of the post-ITER fusion facilities of the tokamak-type: the neutron sources \cite{1} and demonstration fusion reactors \cite{2}. As such facilities are being designed, a number of new technical and scientific problems occurred that did not arise at the facilities of the previous and current generations. These problems necessarily have to be solved. Among these problems, one of the most important is the design of the reactor first wall, which could withstand the continuous heat fluxes coming from the fusion plasma. Preliminary estimates have shown that the reactor first wall will require the additional inner cooling. In the short test shots, the first wall heating is negligible, but during the continuous operation of the commercial fusion facilities, the heat fluxes falling onto the first wall can cause its overheating.

In the near future, it is planned to launch reactors with DT fuel. Because of the short tritium half-life (\textasciitilde12.5 years), the reactor designers are faced with an acute problem of the tritium source for the fusion reaction. One possible solution of this problem is to utilize neutron radiation occurring as a result of the fusion reaction, in order to produce tritium directly inside the fusion facility. To do this, the designers of the DEMO-FNS reactor \cite{2} proposed to change the reactor blanket design and to include the tritium recovery zone into it. This creates the additional heat sources inside the blanket itself and impedes cooling of the first wall by means of the heat exchange with the blanket. So, to solve the problem of the first wall overheating, the new first wall design with the built-in cooling system was proposed.

2. Mathematical model of the cooling first wall
In the currently accepted design of the DEMO-FNS reactor \cite{2}, the cooling wall consists of two components: the layer of PFM tiles (Plasma-Facing Material) and the cooling tubes of two types. The tubes are installed vertically, and, in order to achieve more homogeneous vertical cooling, the directions of the coolant flows in two neighboring tubes are opposite (see Figure 1).
It is only logical to start constructing the model from considering the heat balance in a single annular cross section of the first wall. The balance equation takes into account the incoming and outgoing heat fluxes through the wall boundary, the heating of tiles, tube walls and coolant, as well as the heat fluxes carried out by the coolant. Due to the small sizes of the tiles and the tube walls, as well as the considerable large area of their contact, in calculations, we can assume that their temperatures are equal and depend only on the longitudinal coordinate $l$ and time ($T_{\text{tile}} = T_{\text{tube}} = T$). Due to the facts that the number of tubes installed on the outside of the torus is large (several hundred) and the first wall is very thin as compared to the plasma size and thickness of the blanket, we can perform averaging over the outside of the torus and construct the averaged one-dimensional model of the cooling wall. In this model, the coolant temperature will depend on time and the longitudinal curvilinear coordinate $l$ along the wall.

It is also necessary to take into account that, in the adjacent tubes, the coolant flows in opposite directions. Since the coolant temperature in the tubes in one cross section is different, it is impossible to construct a model considering the only one direction of the coolant flow. Since the coolant flows are separated by the tube walls, the heat exchange between the liquids flowing in opposite directions can be neglected. Taking into account that the tubes are thin and the tiles are not connected directly to each other, we include only the convection heat flux transported by the liquid in the model and neglect the thermal conductivity of the first wall, since its contribution to the heat balance is negligible. As a result, we obtain the following heat balance equation, on the basis of which a mathematical model of the cooling first wall is constructed:

$$W_{\text{in}} - W_{\text{out}} = \gamma_{\text{tile}} w \frac{dr}{dt} + \gamma_{\text{tube}} \frac{n}{2\pi r} (S - s) \frac{dr}{dt} + \gamma_{\text{cl}} \frac{n}{4\pi r} s \sum_{i=1}^{n} \left( \frac{dr_{i}}{dt} + (-1)^i \psi \frac{dr_{ci}}{dt} \right)$$

(1)

Here,

- $W_{\text{in}}$ is the heat flux from plasma to first wall,
- $W_{\text{out}}$ is the heat flux from the first wall to blanket,
- $t$ is time,
- $l$ is the longitudinal coordinate that corresponds to the tube length form the point of entry to the section the first wall under consideration,
- $\psi$ is the coolant flow rate along the tube,
- the subscripts “tile”, “tube” and “cl” refer to the characteristics of the PFM tile, coolant tube or coolant liquid, respectively,
- $S$ is the total cross-section area of the coolant tube,
- $s$ is the inner cross-section area of the coolant tube,
- $w$ is the width of PFM tile,
- $\gamma_{x} = c_{x} \rho_{x}$, where $c_{x}$ and $\rho_{x}$ are the specific heat and density of the parameter marked by the subscript $x$,
- $r$ is the radius of the annular cross section under consideration,
- $n$ is the number of tubes.

Heat balance equation (1) is supplemented by the equations describing the heat exchange processes between all elements of the first wall:
\begin{equation}
\begin{aligned}
    k \frac{dT}{dt} &= W_{in} - \alpha_1 (T - T_{cl}^1) - \alpha_2 (T - T_{cl}^2) - \alpha_3 (T - T_b) \\
    k_2 \left( \frac{\partial T_{cl}^1}{\partial t} - v \frac{\partial T_{cl}^1}{\partial x} \right) &= \alpha_1 (T - T_{cl}^1) \\
    k_2 \left( \frac{\partial T_{cl}^2}{\partial t} + v \frac{\partial T_{cl}^2}{\partial x} \right) &= \alpha_3 (T - T_{cl}^2) \\
    \frac{\partial T_b}{\partial n} &= \alpha_2 (T - T_b)
\end{aligned}
\end{equation}

Here,
- \(k = \gamma_{wall} w + \gamma_{tube} \frac{n}{2\pi r} (S - s)\),
- \(k_2 = \gamma_{cl} \frac{n}{4\pi r} s\),
- \(T_b\) is the blanket temperature at the point of contact with the first wall,
- \(\alpha_1\) and \(\alpha_2\) are the heat-transfer coefficients characterizing interactions of the first wall with the coolant and blanket, respectively.

Since this work is aimed to estimate the efficiency of the first wall cooling system, we introduce three more simplifying assumptions.

1. The heat flux to the first wall is constant in time;
2. The reactor blanket does not contain any heat sources and/or internal cooling systems. Therefore, in calculations of the temperature inside the blanket, the two-dimensional heat conduction equation with the boundary condition (5) on the inner wall of the blanket was used;
3. We assume that the coolant does not undergo phase transitions within the limits of the parameters used in calculations.

With allowance for the second assumption, the temperature variation can be described using the classical heat conduction equation:
\begin{equation}
\frac{\partial T_b}{\partial t} = \alpha^2 \Delta T_b = 0.
\end{equation}

3. Results of numerical simulations of the cooling first wall operation in the reactor

The set of equations (1)–(6) was solved numerically using the two-dimensional finite difference method. To estimate the efficiency of the described construction of the first wall, the boundary-value problem for the blanket was considered with the following boundary conditions:
\begin{align*}
    \left. \frac{\partial T_b}{\partial n} \right|_{\sigma_1} &= 0 \\
    \left. \frac{\partial T_b}{\partial n} \right|_{\sigma_2} &= W_{out}.
\end{align*}

Here, \(\sigma_1\) corresponds to the outer, lower and upper boundaries of the blanket, and \(\sigma_2\) is the inner boundary of the blanket, to which the first wall is attached. \(W_{out} = \alpha_2 (T - T_b)\) is the heat flux from the first wall to the blanket, obtained from solving the set of equations (2)–(6). Such boundary conditions make it possible to separate the effect of the cooling wall.

The initial temperature of the entire construction, including the coolant temperature, was assumed to be 24°C. Water was chosen to be the coolant liquid. The outer and inner diameters of the tubes were \(r_{out} = 1\) cm and is \(r_{in} = 0.8\) cm, respectively. The materials of the tiles, tubes and blanket were beryllium, chrome-zirconium bronze and stainless steel, respectively. The incoming heat flux was \(W_{in} = 1\) MW/m². The blanket height and width were 1.15 and 0.7 m, respectively.

In Figure 2, the red line corresponds to the time dependence of the temperature in the middle of the left blanket wall in the absence of cooling. It can be seen that, for the given heat fluxes, without cooling the first wall, the blanket temperature rapidly increases, which would result in its rapid thermal damage. The blue and green lines correspond to the temperature time dependences of the blanket first wall in the cases, when the cooling circuit is switched on and the coolant flow rates are equal to 5 and 1 m/s, respectively. It can be seen that, at the coolant flow rates of 5 and 1 m/s,
the quasi-stationary temperatures in the middle of the left blanket boundary are $\sim 42^\circ C$ and $\sim 88^\circ C$, and they are achieved in $\sim 1$ and $\sim 4$ seconds, respectively.

![Figure 2](image.png)

**Figure 2.** Time dependence of the blanket temperature

4. Conclusions
The averaged one-dimensional mathematical model of the cooling first wall of the reactor was constructed. The cooling first wall contains two types of coolant tubes. The numerical simulations, which were performed for the facility parameters similar to those of the DEMO-FNS reactor, have shown that, in the case, when water is used as a coolant agent, such a wall is able to withstand the heat fluxes from the fusion plasma and provide the constant blanket temperature. Moreover, such a design of the first wall has very high possibilities for cooling. This is very important, because the DEMO-FNS blanket will contain high-power heat sources that will heat the blanket, and, accordingly, the first wall.

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References
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