Prediction of the incident heat flux on the first wall of ITER using neural networks

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ITER will be the first operating research fusion reactor. One of the main parts of the reactor is the blanket on which the neutrons and photons fall. This makes it difficult to put sensors near or at the surface of the first wall which faces the plasma. A method is proposed to predict the steady state heat flux incident on the first wall, using an artificial neural network. The network uses the temperatures at three locations, which are located in the coolant channels of the first wall, as input. It has one input layer, three hidden layers and one output neuron. The designed neural network was able to predict the incident heat flux with 0.56% error.

سيكون مفاعل ايتر أول مفاعل اندماجي بحثي، احد الأجزاء الرئيسية في المفاعل هي الغلاف ويقع عليه كميات كبيرة من الفوتونات والنيوترونات، مما يجعل من الصعب وضع مجسات علي أو قرب الحائط الأول المواجه للبلازما. تم اقتراح طريقة للتنبؤ بالفيض الحراري الثابت والواقع على الحائط الأول، وذلك باستخدام الشبكات العصبية الاصطناعية، وهذه الشبكة تستخدم درجات الحرارة التي يتم قياسها من ثلاث مواقع موجودة في انابيب المبرد. الشبكة العصبية مكونة من طبقة مدخلات، ثلاث طبقات خفيفة ومخرج واحد، وقد تمكنت الشبكة من التنبؤ بكمية الفيض الحراري الواقع على الحائط الأول، وذلك بخطأ قدره ٥٦،%

Keywords: ITER, Neural networks, Heat flux, First wall

1. Introduction

ITER will be the first operating fusion reactor. Its programmatic objective is "to demonstrate the scientific and technological feasibility of fusion energy for peaceful purpose" [1, 2].

One of the main functions of the ITER blanket is that it removes the surface heat flux deposited by the plasma [3]. The blanket surrounds the plasma and protects the vessel material from high levels of nuclear radiation. In combination with the thick vessel, the blanket provides the shielding for the superconducting coils.

The first wall is the component of the blanket that faces the plasma. Thus it is subjected to the most severe conditions due to the photons and neutrons constantly bombarding it. This makes it very hard to insert measuring devices at and/or near its surface. Thus indirect methods must be used to determine the incident heat flux on the surface of the first wall without having to use sensors that are close to the plasma.

In 2003, Shahbunder [4] used neural networks to predict the steady state incident heat flux and heat generation inside the first wall, using the temperatures at 154 different locations as input data to the network. However, using the temperatures on the surface facing the plasma renders this method obsolete, since in reality there is no way to directly measure these temperatures. In addition, it is not feasible to put 154 sensors in ~ 4 x 10^{-5} m^3 volume.

In this paper, a method is proposed to predict the heat flux incident on the first wall, using artificial neural networks. The designed network uses the temperature at three different locations as input. These locations are at the far end of the first wall, which are easy to measure.

2. ITER first wall

The first wall is composed of flat panels and attachments to the shield block. Each first wall panel consists of a 10 mm beryllium armor in the form of tiles attached to a 22 mm Cu-alloy heat sink plate internally cooled by 3MPa water flowing in stainless steel cooling tubes. The Cu-alloy plate is attached to a ~ 50 mm thick steel backing plate that has a structural plus shielding function [5]. A simple straight poloidal cooling channel layout is

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used to cool the steel. The inlet coolant temperature is 100°C [6]. The total surface area of the first wall is 680m^2 [7]. Fig. 1 shows a schematic diagram of the first wall.

The average neutron wall loading is 0.7 MW/m^2. It induces in the first wall material bulk nuclear heating of 8 MW/m^3, which decays exponentially inside the module by about one order of magnitude for every 20cm [3]. The maximum average power of plasma radiation deposited on the wall is 0.2 MW/m^2, with local excursions up to 0.5 MW/m^2 [3].

A complete thermal analysis of the ITER first wall was performed by Shahbunder [4]. A unit cell of the first wall was divided into a large number of nodes, and the temperature at each node was calculated, using finite elements method, for different values of heat flux and generation. Fig. 2 shows the unit cell of the first wall for which the temperature distribution was calculated. The heat flux ranged between 0.12 – 0.5 MW/m^2. The maximum heat generation ranged between 0, which represents a case with no neutron heating, and double its expected value [7]. Table 1 shows the eight values of incident heat flux and maximum heat generation used in the calculations. Nine cases were chosen, each with a given heat generation and heat flux, and the temperature distribution was calculated for each case.

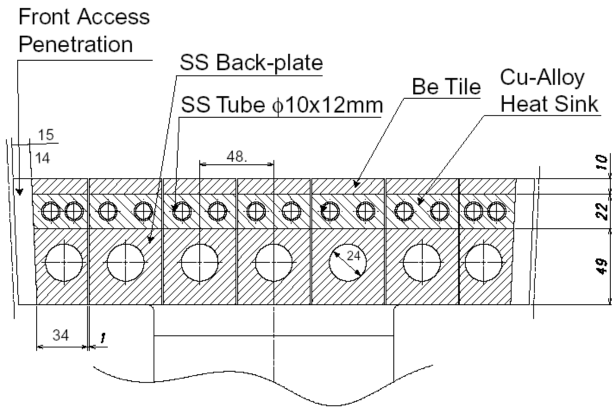

Fig. 1. A schematic showing the first wall of one of the blanket panels [6].

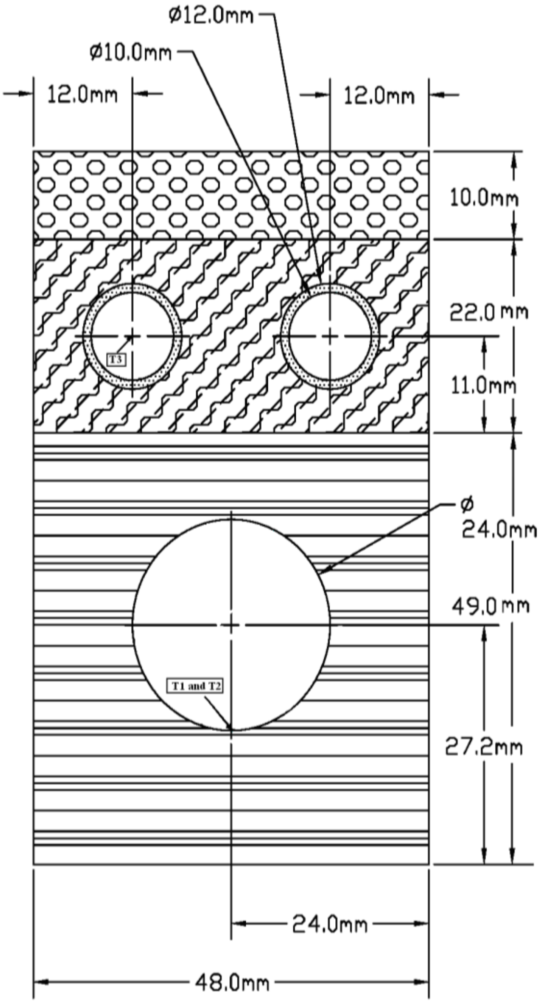

Fig. 2. A schematic diagram showing a unit cell of the ITER first wall. The diagram also shows the positions of the locations at which the temperature is measured and used as input to the neural network.

Table 1
Incident heat flux and maximum heat generation used in the thermal analysis calculations [8].

Case Number	Incident heat flux MW/m^2	Maximum heat generation MW/m^3
1	0.125	0
2	0.125	8
3	0.125	15
4	0.2	15
5	0.25	15
6	0.25	16
7	0.5	0
8	0.5	8
9	0.5	16

3. Design and training of the neural network

In this work, an artificial neural network was designed to predict the steady state incident heat flux. The network was trained using data from three points inside the first wall unit cell. The selected locations were:

1. The bottom of the coolant inside the stainless steel from the entrance side (T_1).
2. The bottom of the coolant inside the stainless steel from the exit side (T_2).
3. The temperature of the coolant exiting from the small pipes (T_3).

Those three locations were selected because it will be easy to measure their temperatures. Fig. 2 shows the three locations.

The designed neural network consists of one input layer with three nodes, three hidden layers each with three neurons, and one output neuron. Fig. 3 shows the topography of the neural network. The solid lines represent positive weights while the dashed lines represent negative weights.

The inputs and output of each neuron can be described with the aid of fig. 4. The figure shows that a neuron has a summation part and an output function. The neuron's input and output are related through [9]:

$$x_i = \sum_j w_{ji} a_j - \theta_i \,, \tag{1}$$

$$s_i = f(x_i)\,. \tag{2}$$

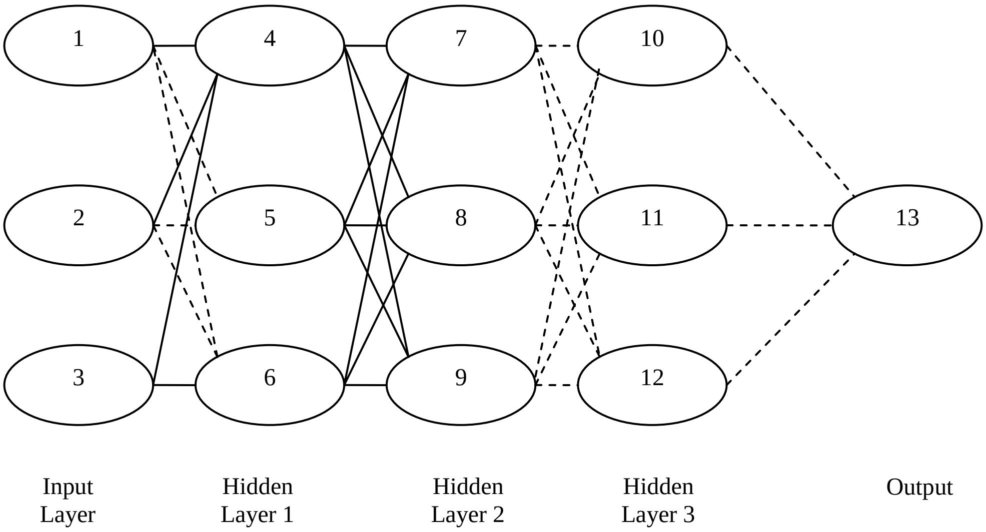

Fig. 3. Topography of the artificial neural network, with 3 input neurons, 3 hidden layers, and one output neuron.

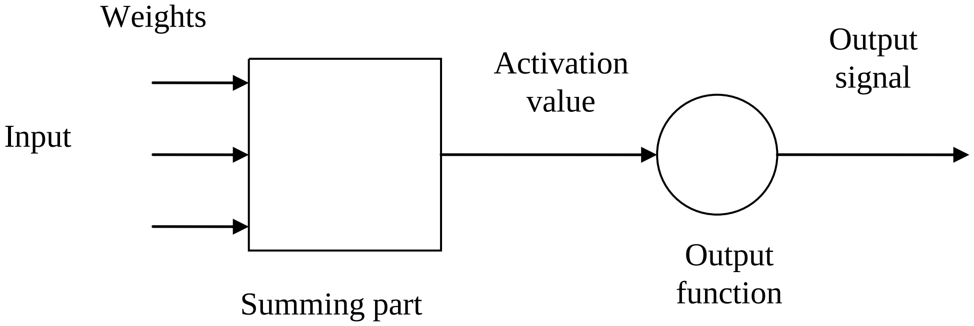

Fig. 4. A schematic showing different processes in the neuron. The input is multiplied by the weights then summed with the bias to give the activation value. The output is a function of the activation value.

Where a_j is the input coming from node (j), w_{ji} is the weight of input a_j going to neuron (i), θ_i is the bias to neuron (i), which is a constant, and s_i is the output of neuron (i). The function $f(x_i)$ depends on the scheme of the neural network used. The proposed network uses a hyperbolic function:

$$f(x_i) = \tanh(x_i) = \frac{e^{x_i} - e^{-x_i}}{e^{x_i} + e^{-x_i}} . \qquad (3)$$

The activation and bias to each neuron in the network are shown in table 2.

The designed neural network used a feedforward backpropagation pattern. In a feedforward network, each neuron takes its input from the neuron of the layer before it and gives its output to the layer after it. The network stopped learning when the average error was 10^{-6}. Table 3 gives the input and output used to train the neural network. Columns 2, 3, and 4 contain the temperatures used as training input. These temperatures were obtained from the results of the thermal analysis made by Shahbunder et al. [8]. The fifth column contains the values of incident heat flux used as training output. Each input neuron was given the value of the temperature at one of the three chosen locations. The output neuron gave the predicted value of the incident heat flux. This value was compared to the training output. If the error between the real and predicted values was more than 10^{-6}, the network continued learning and each of the weights was changed by the value:

Table 2
The activation and bias input to each neuron of the neural network

Neuron #	Activation	Bias
1	0.9128	0.1491
2	0.0707	-0.4355
3	0.0099	-0.1038
4	0.0809	-2.5903
5	0.0085	-1.3907
6	0.0767	-1.7418
7	0.0806	-2.8638
8	0.0177	-4.2895
9	0.0501	-3.1550
10	0.9706	-3.1550
11	0.8034	1.7459
12	0.7602	1.4833
13	0.0019	5.7732

Table 3
Input and output values used to train the neural network

Case #	Temp 1	Tamp 2	Temp 3	Heat flux
1	126.7	136.9	151.8	0.125
2	149.9	185.4	192.3	0.2
3	150.1	169.4	199.3	0.25
4	153.4	173.7	203.6	0.25
5	101.7	173.7	169.2	0.5
6	128.0	107.5	203.7	0.5
7	154.3	142.5	238.1	0.5
8	100.4	117.6	117.3	0.125

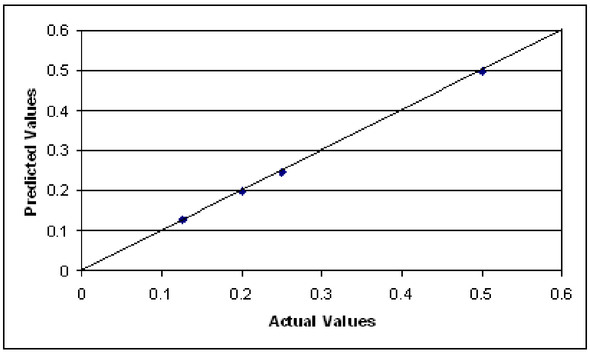

Fig. 5. The actual values vs. the predicted values of the network.

$$w_{ji}(m+1) = w_{ji}(m) + \alpha \Delta w_{ji}(m-1) + \eta \sum \delta_j(m) s_j(m) . \qquad (4)$$

$$\delta_j(m) = b - s_j(m) . \qquad (5)$$

$$\Delta w_{ji}(m-1) = w_{ji}(m) - w_{ji}(m-1) . \qquad (6)$$

Where b is the target output (i.e. training, or real output), α is the momentum constant, which has a value between 0 and 1, and η is the learning rate. When training the neural network, the learning rate was set to be 0.6 and the momentum rate was 0.8. Fig. 5 shows the predicted vs. the target output. In case of perfect prediction, they should be equal. The figure shows a good agreement between the predicted and real values.

After training, an additional set of data was used as a query, in order to determine whether the network produces accurate predictions. The query data were as follows: T_1 = 149.6°C, T_2 = 107.8°C, and T_3 = 118.5°C. This data produced a heat flux of 0.1257 MW/m^2. The error in this result is 0.56%, which shows the ability of the network to accurately predict the heat flux incident on the first wall.

4. Conclusions

An artificial neural network was used to predict the steady state incident heat flux, using the temperatures at three fixed places inside the first wall. These places were chosen far from the plasma, in order to avoid damaging the measuring devices.

The designed artificial neural network uses a feedforward, backpropagation scheme. It has one input layer, three hidden layers and one output neuron. The momentum rate was set to be 0.6, the learning rate 0.8, and the average error 10^{-6}. Eight sets of data were used to train the network and one set was used as query to show the network's efficiency in predicting the value of the incident heat flux. The network was able to successfully and accurately predict the steady state heat flux incident on the first wall, with a 0.56% error.

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