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A new method of rapid power measurement for MW-scale high-current particle beams

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ABSTRACT

MW-scale high current particle beams are widely applied for plasma heating in the magnetic confinement fusion devices, in which beam power is an important indicator for efficient heating. Generally, power measurement of MW-scale high current particle beam adopts water flow calorimetry (WFC). Limited by the principles of WFC, the beam power given by WFC is an averaged value. In this article a new method of beam power for MW-scale high-current particle beams is introduced: (1) the temperature data of thermocouples embedded in the beam stopping elements were obtained using high data acquire system, (2) the surface heat flux of the beam stopping elements are calculated using heat transfer, (3) the relationships between positions and heat flux were acquired using numerical simulation, (4) the real-time power deposited on the beam stopping elements can be calculated using surface integral. The principle of measurement was described in detail and applied to the EAST neutral beam injector for demonstration. The result is compared with that measured by WFC. Comparison of the results shows good accuracy and applicability of this measuring method.

1. Introduction

MW-scale high current particle beams are frequently employed for plasma heating on tokomak devices [1–7]. Beam power was considered as a vital parameter of plasma heating efficiency. Generally, water flow calorimetry (WFC) was employed as power measurement of MW-scale high current particle beam [8,9]. The principles of WFC are: (1) measure the temperature difference between the inlet and outlet of the cooling tubes and water flow rate through the heat load components; (2) calculate the heat removed from heat load components; (3) calculate the beam power deposited on heat load components using heat balance method for each shot. However, in this case, the real-time beam power of one shot cannot be calculated during the beam extraction process. A new measurement method based on thermocouples can solve this problem. In this study, the principle of measurement was described in detail and applied to the EAST neutral beam injector for demonstration. Compared with those obtained by WFC, the results are more efficient and of similar accuracy, even though there exist some limitations in the application of this method.

2. Principle and method

The thermocouples are embedded into beam stopping elements (see Fig. 1), such as calorimeters (see Fig. 2) and ion dumps, and coupled with high-speed data acquisition systems for recording the temperature data. Based on the temperature rise data, the beam power deposited on the heat load components can be obtained. This method can meet the requirement of the beam power measurement in real time mode.

Measurement principles of MW-scale high current particle beam power based on thermocouple include: (1) data processing of temperature acquired from the thermocouples; (2) calculation of heat flux on the surface of beam stopping elements; (3) derivations of beam power. Details are shown below.

When the beam particles hit the plate, their energy mainly transforms into thermal energy of the plate and transmits along the plate. Assuming a conversion efficiency of 100%, the power density impinging on the plate surface p is equal to the magnitude of heat flux vector q. As $D_x > D_y > > d$, the transfer of heat flux in

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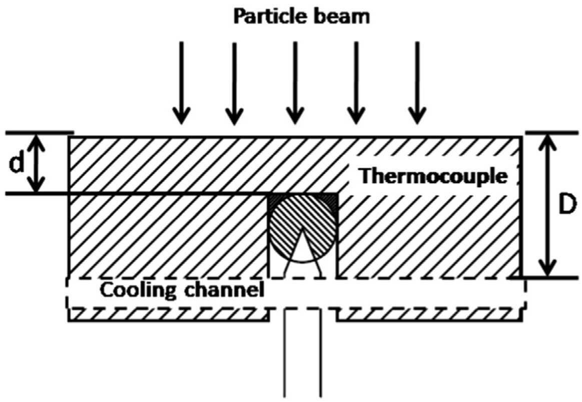

Fig. 1. Installation diagram of thermocouple on the beam stopping elements (D=38.10 mm, d=9.65 mm).

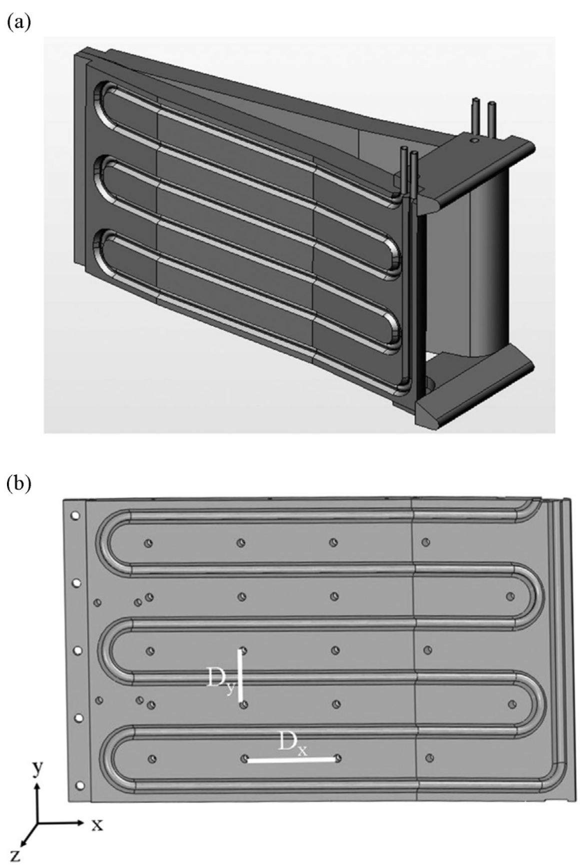

Fig. 2. The structure of the calorimeter (a) three dimensional structures (b) the layout of the thermocouple installed in the plate (D_x=15.24 cm, D_y=8.76 cm).

x and y direction can be ignored. The relationship between temperature difference, time, heat transfer depth and heat flux can be written as follows [10]

$$\theta = \frac{2q_w\sqrt{\frac{\alpha\tau}{\pi}}}{\lambda}\exp\left(\frac{-z^2}{4\alpha\tau}\right) - \frac{q_w z}{\lambda}\left(1-\mathrm{erf}\frac{z}{2\sqrt{\alpha\tau}}\right) \tag{1}$$

Here, θ is temperature difference, q_w is heat flux, τ is time, α is thermal diffusivity, λ is thermal conductivity of beam stopping elements, $\mathrm{erf}\frac{z}{2\sqrt{\alpha\tau}} = \frac{2}{\sqrt{\pi}}\int_0^{z/2\sqrt{\alpha\tau}} e^{-\eta^2} d\eta$ is the error function, and z is the distance from the surface of plate to the thermocouple. The power density can be obtained when the temperature rise is measured at some time τ

$$q_w = \frac{\lambda\theta}{2\sqrt{\frac{\alpha\tau}{\pi}}\exp\left(\frac{-z^2}{4\alpha\tau}\right) - z\left(1-\mathrm{erf}\frac{z}{2\sqrt{\alpha\tau}}\right)} \tag{2}$$

According to the temperature rise curve of thermocouple installed in the beam stopping elements, the temperature difference θ at τ can be obtained. The thermocouple positions have been determined before manufacturing of the beam stopping elements. So, the element's surface heat flux corresponding to thermocouple can be obtained. Similarly, the heat flux corresponding to other thermocouples installed in the beam stopping elements can be obtained and the relationship between the heat flux and coordinate value can be obtained based on synthesis analysis of heat flux at different positions. The heat flux can be written in Cartesian coordinates

$$q_w = f(x, y) \tag{3}$$

The power deposited on the beam stopping elements at some time τ can be written using surface integral

$$P = \iint q_w ds = \iint f(x, y) dx dy \tag{4}$$

Inserting appropriate boundary conditions into Eq. (4), the power can be obtained.

In practice, it is difficult to obtain the relationship $q_w = f(x, y)$ for a limited number of thermocouples installed in beam stopping elements. Generally, the solution is sought as follows: (1) interpolation and fitting numerically, or (2) obtaining detailed temperature data using high resolution infrared camera. For the first method, it is convenient to use but the precision is relatively low and affected by the selected fitting function and number of thermocouples. For the second method, it is difficult to operate for: (a) irregular shape of beam stopping element; (b) low emissivity of beam stopping element after beam polishing (for copper). In this article, numerical method is used in beam power measurement. The flow chart of data processing is given in Fig. 3. Here, T_τ, ΔT_τ and $q_{w\tau}$ are the temperature, temperature rise and heat flux at some time τ, respectively. Δx and Δy are the mesh spacing in the x and y direction during the interpolation process. The n and m are the number of grids in x and y direction, respectively.

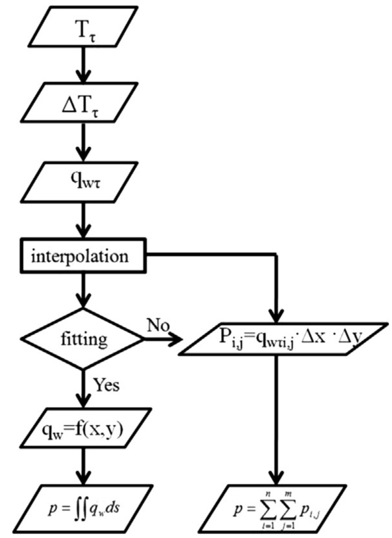

Fig. 3. The flow chat of data processing.