VAPOUR SHIELDING OF SOLID TARGETS EXPOSED TO HIGH HEAT FLUX

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The thickness of a Tungsten monoblocks composing future ITER divertor is supposed to be 8 mm only. Severe erosion caused by a high heat fluxes during transients, such as Type I ELMs and disruptions, therefore is a limiting factor to PFCs lifespan. Thermal loads over the range of $Q = 0.5 - 2\ \mathrm{MJ/m^2}$ on the timescale of $\tau = 0.3 - 0.6$ ms are expected during Type I ELMs. Even larger heat fluxes, of the order of $Q = 0.5 - 5\ \mathrm{MJ/m^2}$ are expected during thermal quench stage of disruption lasting approximately $\tau = 1 - 3$ ms [1]. Under the influence of the extreme heat fluxes serious surface modification and cracking of the Tungsten monoblocks is anticipated [2]. Moreover, melting of a thin surface layer is likely. Melt motion contributes seriously to the material erosion [3]. The other sources of erosion are melt splashing, in form of a droplet ejection, and stationary evaporation [4]. These mechanics lead to a cold dense secondary plasma region formation near the irradiated surface. Intense re-radiation of the incident plasma flow energy in the secondary plasma layer results in a significant reduction of the heat flux reaching the target surface [5]. Accounting for this vapour shielding effect is essential to estimate the surface erosion properly. Predicting the divertor plates lifespan therefore requires deep understanding of all the processes mentioned and their interplay.

A number of complicated numerical codes aimed at the erosion calculations has been developed over the years. These include MEMOS code [6] focused primarily on the melt motion modelling, FOREV-2 [7], TOKES [8] and HEIGHTS [9] that specialize in the vapour shielding studies. Straightforward calculations of the Tungsten target erosion, however, require simultaneous treatment of the melt motion, the droplet ejection and the vapour shielding problems. Moreover, the last one include overwhelming radiation transport calculations. Therefore, none of the presently developed codes is capable of the precise Tungsten target erosion modelling. On the other hand, complex nature of these codes overshadows underlying physics and does not allow for the qualitative estimations. Hence, simple models are needed, capable of indicating the crucial parameters the processes responsible for the target erosion depend upon.

In the present work a simple model is proposed capable of reproducing one of the key features of the vapour shielding, namely the saturation of the energy absorbed by the target. Approximate analytical solution is derived indicating the incident plasma flow and the material parameters the energy consumed by the target depends upon. The Model is validated against the experimental data obtained at MK-200 pulse plasma accelerator.

We consider a one-dimensional vapour shielding problem. The incident plasma is coming to the target surface resulting in the heat flux:

$$q(t) = q_0(t) - E_{rad}\int_0^t j_{ev}(T_s)\,\mathrm{dt'} \tag{1}$$

The first term on the right side of equation (1) $q_0(t)$ represents the heat flux associated with the incident plasma flow. The second term $q_{rad}(t) = E_{rad}\int_0^t j_{ev}(T_s)\,\mathrm{dt'}$ models the vapour shielding effect. . Exact value of $q_{rad}(t)$ can be found through the secondary plasma radiation transport calculations. In our model we simply assume that the re-radiated power is directly proportional to the amount of the evaporated material N_{ev}, $q_{rad} = E_{rad} N_{ev}$. Here E_{rad} is an effective coefficient that can be interpreted as the radiation power of the individual target material ion. $j_{ev}(\mathrm{T}_s)$ is a target material evaporation rate. We consider a stationary evaporation process only (i.e. neglect the droplet ejection contribution, if there is any). Therefore, the evaporation rate can be written as following:

$$j_{ev}(T_s) = \frac{C_1}{\sqrt{T_s}}\exp\left(-\frac{E_{ev}}{T_s}\right) \tag{2}$$

Here C_1 is the thermodynamic constant associated with the target material given, E_{ev} is the specific material evaporation energy, T_s is the surface temperature.

We now have to solve a thermal conduction equation for the heat transfer inside the target sample:

$$C_P(T)\rho(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\kappa(T)\frac{\partial T}{\partial x}\right) \tag{3}$$

Here $\rho(T)$, $\kappa(T)$ and $C_P(T)$ are the target material density, thermal conductivity and thermal capacity respectively. $T(x,t)$ is the temperature and x is the distance from the target surface. This equation is supplemented with boundary conditions.

$$\kappa(T)\frac{\partial T_s}{\partial t} = q_0(t) - E_{rad}\int_0^t j_{ev}(T_s)\,\mathrm{dt'} \tag{4}$$

$$T(l) = const \tag{5}$$

With some simplifications, the approximate analytical solution to the system can be derived. It yields the following expression for the energy absorbed by the target (see ref [10] for more detailes):

$$Q_{abs} \approx \sqrt{\pi \rho C_P \kappa \tau_{pulse}} \frac{E_{ev}}{2\ln(G_*)} \tag{6}$$

Here $G_* = \sqrt{\frac{\pi \kappa^2}{4\alpha t_0}} \frac{E_{ev}}{q_0}$. One can see that the saturation value of Q_{abs} depends on the pulse duration and thermodynamic properties of the target material only. It is virtually independent of the vapour shield dynamics and the radiation transport details.

The model was validated against the experimental data obtained at the MK-200 pulse plasma accelerator. For that purpose, the system of equations (3-5) was solved numerically. Dependence of the energy absorbed by the target on the impact heat loads is presented in Fig.2. Calculations indicate a linear growth of Q_{abs} with the impact heat load up to the value of approximately $0.5\ \mathrm{MJ/m^2}$. The vapour shield formation threshold is then crossed and Q_{abs} saturates quickly. One can see from Fig.2 that the model proposed is in a reasonable agreement with the experiment not only qualitatively but also quantitatively.

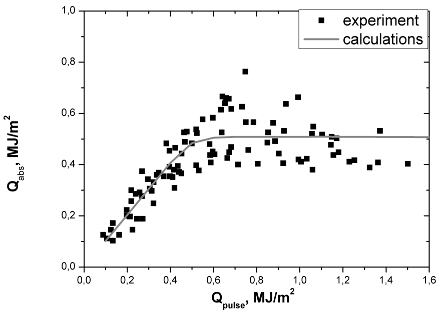

Fig. 2. The energy absorbed by the Tungsten target over the energy stored in the incident plasma. Dots represent the experimental data obtained on MK-200 pulse plasma accelerator; solid curve represents the result of numerical calculations performed using the described model.

The described model indicates that the saturation value of the energy absorbed by the target depends weakly (logarithmically) on the details the vapour shield dynamics, the details of the radiation transport and incident heat flux value. This is understandable as the sharp evaporation rate dependence on the surface temperature dominates those. The target erosion, on the other hand, depends on the shielding details. It can be illustrated with the simple model described. Indeed the complete shielding takes place if $q(t) = -q_0 + E_{rad} N_{ev} \quad 0$. Therefore, the amount of the evaporated material can be estimated as $N_{ev} = \frac{q_0}{E_{rad}}$. Thus, the amount of the evaporated material depend strongly on the E_{rad} that represents the radiation transport details and the vapour shield dynamics in the described model. Hence, one can conclude that matching the energy absorbed is rather pointless in terms of validating the vapour shielding models against the experiment. Since the energy absorbed is virtually independent of some model details, which are, however, crucial for the prediction of the amount of the evaporated material.

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