Estimation of the change in the gas flow rate from the surface of a tungsten plate under pulsed heat load

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Abstract. The work is devoted to the numerical implementation of the tungsten evaporation process model. The tungsten evaporation model is based on solving the two-phase Stefan problem for temperature in the sample area and gas dynamics equations over the sample. The calculation results for parameters corresponding to those used on the BETA facility at BINP SB RAS show that it is possible to use the boundary homogeneous conditions of the Neumann for the velocity when setting the gas density on the plate surface.

1. Introduction

On the experimental stand Beam of Electrons for materials Test Applications (BETA) created in the INP SB RAS [1], the results of heating the tungsten plate by the action of a high-speed electron beam on it were obtained. Currently, due to the development of thermonuclear fusion technologies, new practical problems of melting of refractory metals are emerging. To plan and analyze full-scale experiments it is necessary to have mathematical models that accurately take into account all the details and features of the process. Construction of a complete model of electron beam heating enables better assessment of the relevance of the simulation and determination of mechanisms that will occur in the case of plasma flow heating in modern plasma and future thermonuclear facilities. The work is devoted to the numerical implementation of the tungsten evaporation process model. The tungsten evaporation model is based on solving the two-phase Stefan problem for temperature in the sample area and gas dynamics equations over the sample. To calculate the velocity and mass flow of a substance evaporating from the sample surface, the system of equations of gas dynamics is solved numerically. The boundary conditions describing the heating and evaporation of the material have a great influence on the solution of the problem. They are discontinuous and nonlinear in time and space. The aim of the study is to simulate the erosion and droplets emission perpendicular to the...
surface of the sample surface as a result of evaporation and penetration of heat flux into the material taking into account microcracks [2].

Modeling the process of metal evaporation is a complex and not sufficiently studied problem. The problem of setting the boundary conditions for the process of evaporation of a solid substance has been posed for a long time [3]. However, they are still not precisely defined. Mathematical modeling of tungsten evaporation is usually associated with the study of industrial processing of materials [4-6]. The specifics of the problem under consideration does not allow the use of this data. Known models of heat transfer of the divertor wall for the ITER project do not take into account the characteristics of the material and are limited to determining the thermal field in the sample [7-8].

2. Problem definition

![Figure 1. Scheme of the computational domain. Tungsten plate with melt region (orange), evaporation region (red), gas flow (blue arrows) along the axis Z.](image)

In the mathematical model of melting in a tungsten plate exposed to a pulsed electron beam [9], the calculation of the surface gas flow is added. Consider the following gas dynamics equations in a cylindrical coordinate system to calculate the evaporation in vacuum (Fig. 1):

\[
\begin{align*}
\frac{\partial \rho}{\partial t} + \frac{1}{r} \frac{\partial (r \rho v_r)}{\partial r} + \frac{\partial (\rho v_z)}{\partial z} &= 0, \\
\frac{\partial (\rho v_r)}{\partial t} + \frac{1}{r} \frac{\partial (r \rho v_r)}{\partial r} + \frac{\partial (\rho v_z)}{\partial z} &= -\frac{\partial P}{\partial r}, \\
\frac{\partial (\rho v_z)}{\partial t} + \frac{1}{r} \frac{\partial (r \rho v_z)}{\partial r} + \frac{\partial (\rho v_z)}{\partial z} &= -\frac{\partial P}{\partial z}, \\
\frac{\partial T}{\partial t} + v_r \frac{\partial T}{\partial r} + v_z \frac{\partial T}{\partial z} - \frac{2T}{3} \left( \frac{1}{r} \frac{\partial (r \rho v_r)}{\partial r} + \frac{\partial v_r}{\partial z} \right) &= 0, \\
P &= \frac{R}{M} \rho T, \\
T |_{r=r,t} &= T^*(r,t), \quad \rho |_{r=r,t} = \frac{M}{2RT^*(r,t)} \exp \left( a1 - \frac{a2}{T^*(r,t)} \right), \quad \frac{\partial v_r}{\partial z} |_{r=r,t} = 0, \\
(n, \nabla f)|_{r=r,t} &= 0 \quad \text{at other boundaries}, \\
T |_{z=0} = T(r,z,0), \quad (v_r, v_z) |_{z=0} = 0, \quad \rho |_{z=0} = 0.
\end{align*}
\]
where $\rho$ is the gas density, $\vec{v} = (v_x, v_z)$ is the gas velocity, $P$ is the gas pressure, $T(r, z, t)$ is the temperature, $R = 8.31 \cdot 10^4 \, \text{W} \cdot \text{mol} \cdot \text{K}$ is the gas constant, $M$ is the molar mass, $T'(r, t)$ is the temperature on the surface $\gamma$ obtained from the calculation of Stefan problem [9]. The numerical values of the parameters are given in Table 1.

### Table 1. Dimensional parameters of nondimensionalization.

| Parameter | Typical value | Units  |
|-----------|---------------|--------|
| $r_0$     | $10^{-3}$     | m      |
| $t_0$     | $10^{-4}$     | s      |
| $T_0$     | $10^3$        | K      |
| $\rho_0$  | 10            | kg/m³  |
| $a_2$     | 83.9713       |        |
| $a_1$     | 26.191        |        |

### 3. Simulation results

The sample for shot 1228 has a $25 \, \text{mm} \times 25 \, \text{mm}$ cross section and a thickness of 4mm. Since the sample is heated to a depth of several hundred microns in such a short time, the simulation region was a transverse section of the sample, a region of $12 \, \text{mm} \times 4 \, \text{mm}$. As for the time, the numerical simulation continued until the moment of the last measurement. Comparison of the calculated and experimental temperature on the surface of the plate is given in papers [9, 11, 12]. Calculation results for the radial temperature distribution over the sample surface are consistent with experimental data and analytical estimates.

![Figure 2](image-url)

**Figure 2.** Graph of temperature dependence of gas density (a) and graph of time dependences of surface temperature (b) obtained from calculation for shot 1228.

The evaporation of a substance is set by the boundary condition for $\rho$ (Fig. 2a), which is an estimate of the surface gas density:

$$\rho|_\gamma = \frac{1}{2} \left( \frac{R}{M} \right)^{-1} \frac{1}{T'(r, t)} \exp \left( a_1 - \frac{a_2}{T'(r, t)} \right).$$

(2)

To calculate the boundary conditions, we used the temperature values in the most heated central part of the plate surface. First is linear growth and second is the surface temperature obtained from
numerical simulation \[9\] for shot 1228. Dependencies \( T(t) = T'(r,t) \mid_{r=0} \) (Fig. 2b) are used in numerical simulation. The calculation points show the temperature increase in the first 190 \( \mu \)s from the beginning of the experiment. The pulse has such a high power that the temperature immediately rises to 6000K. The temperature rises to 9000K. The temperature graph is not smooth due to the type of total beam power (Fig. 3b). As soon as the pulse stops, the temperature drops sharply to 7000K and continues to smoothly decrease to 5000K within 200 \( \mu \)s.

\[\]
\[\]

**Figure 3.** Radial distribution of heat flux power (a) and time dependence of total beam power for shot 1228 (b).

To calculate the temperature for shot 1228 used the melting point \( T_m = 3695K \), the heat of fusion \( L_m = 51.1 \cdot 10^5 \frac{W\mu s}{mm^3} \). The process of evaporation at the boundary is taken into account via a given resultant energy flux \( W_r(t,r) = W(t,r) - N(T) \gamma \), where \( W(t,r) \) is the power of the heat flux, \( N(T) \gamma = L_e \frac{1}{S} \frac{dm}{dt} \) is the power loss. The power of the heat flux is \( W(t,r) = W_{max}(t) \cdot \exp(-A \cdot r^2) \), \( A = 0.03088523 \) (Fig. 3a). At each time step in the numerical simulation, the variable \( W_{max}(t) \) is taken from the experimental data file (Fig. 3b). The distribution of the heating power density over the surface was measured using X-ray visualization [4].

The numerical implementation for equations (1) is based on the Rusanov finite difference scheme [13]. This method well approximates the flow of gas into a vacuum. The Dirichlet boundary condition for the temperature and the gas density on the heated surface and Neumann boundary conditions in all other cases are used. Of particular interest is the formulation of boundary conditions for gas velocity on the heated surface. There is an estimate for the gas velocity:

\[
v_r \bigg|_r = \sqrt{\frac{5}{3} \frac{R}{M}} \sqrt{T'(r,t)}.
\]

This estimate is exactly carried out with Neumann homogeneous boundary condition for gas density. In this case, the density of the gas on the heated surface increases as the root of the temperature, as does the velocity of the gas. This is contrary to the existing theoretical estimates.
Figure 4. Temperature dependence of the surface gas velocity for linear temperature growth (black dots) and for calculation temperature for shot 1228 (white dots). Estimate for the gas velocity (line).

At temperatures up to 4000 K, the gas density is zero. At high temperatures, the calculated gas velocity is 2-3 times higher than the analytical estimate. A linear temperature increase $T^*(r,t) = kt$ gives the same temperature dependence of the velocity of the outgoing gas at various values of the coefficient $k$ (Fig. 4, black dots). The value of the coefficient $k$ affects only the heating rate.

The calculation for the model linear temperature increase showed that at surface temperatures of 11000 K the speed can reach $v|_{1228} = 7.5 \text{ km/s}$. It is impossible to heat the surface more strongly, since the evaporation process will prevail at such high temperatures. To calculate the 1228 shot, the surface temperature dynamics (Fig. 2b) was approximated by two polynomials for heating and cooling. As a calculation result, two curves were obtained (Fig. 4, white dots). The first dependence is obtained by heating the sample to 9000K. This curve almost coincides with the result of the calculation of the model problem. The second curve was obtained in the process of cooling to 5000K. It is expected that during the cooling process, the gas velocity on the surface is lower than during heating. The temperature of the evaporating gas above the surface is lower than the surface temperature. It can be assumed that we must calculate the boundary condition (2) for the gas density from a lower temperature. Given this, it is possible to obtain results that satisfy both estimates (2) and (3).

4. Conclusion

The calculation results for parameters corresponding to those used on the BETA facility at BINP SB RAS show that it is possible to use the boundary homogeneous conditions of the Neumann for the velocity when setting the gas density on the plate surface. The calculation for the parameters taken from the experimental data shows close dependencies to the calculations of the model problem with a linear increase in temperature.

The constructed mathematical model is planned to be integrated with the calculation of the current distribution in the gas. The construction of a complete model of electron beam heating will enable better assessment of the relevance of the simulation and finding out which mechanisms will occur in the case of plasma flow heating in modern plasma and future thermonuclear installations.

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