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HEATING AND BREAKDOWN OF PROTECTIVE LAYER AT PLASMA RETAINING WALL

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Expressions are derived for estimating the parameters of the boundary layer of cold plasma forming through the action of radiation on the thermal protection in a pulse-type reactor with wall retention of thermonuclear plasma.

In designs of pulse-type thermonuclear reactors with wall retention of the plasma [1] it has been proposed that the first wall of the chamber in direct contact with the thermonuclear plasma be protected by means of a renewable thin layer of liquid metal (e.g., lithium). Meanwhile, processes in a hot plasma are usually analyzed without taking into account the effect of such a protective layer and assuming, for instance, a constant temperature of the wall surface [2, 3]. The magnitude of the effect of such a layer depends, obviously, on the number and the characteristics of products of breakdown of this thermal protection which will make contact with the hot plasma. Inclusion of the equations of the protective layer in the overall scheme of numerical analysis greatly complicates the model of the process and limits the capabilities of the calculation process. In the first approximation, however, the behavior of such a layer can be described quite simply on the basis of the following considerations.

When a hot plasma is retained by a wall, then during the fusion reaction ($t_r \sim$ 1-10 msec) the protective layer is exposed to radiation and the pressure in the chamber is usually supercritical for the layer metal ($p = 1$-10 kbar, $p_{cr} = 0.69$ kbar and $T_{cr} = 3223$°K [4]). Therefore, while absorbing the radiation energy, the metal passes continuously from liquid to plasmatic state without a discernable phase transition. During that time the thermal conductivity, which determines the rate of energy transfer through the layer, varies in an intricate manner (Fig. 1). Experimental data are available for the condensed state far from critical [4]. As the temperature rises and thus the density decreases, metals are found to lose their n-type conductivity [5] so that the thermal conductivity should decrease sharply down to levels characteristic of dielectrics. During transition to the plasmatic state, finally, the main role in energy transfer is played by radiative thermal conductivity.

The described trend of the temperature dependence of thermal conductivity of a metal suggests that the model of a thermal wave [6] propagating depthwise in the layer may be applicable here. The temperature is almost uniform behind the wave front, owing to the strong temperature dependence of radiative thermal conductivity. At the wave front the temperature drops sharply from the plasma level to $T_* \sim$ 2000-3000°K, at which the thermal conductivity of liquid metal becomes appreciable. Ahead of the wave front there propagates a heating "spike" produced as a result of this higher thermal conductivity.

The temperature dependence of energy, density, and thermal conductivity at constant pressure in the plasmatic state can be approximated with power laws:

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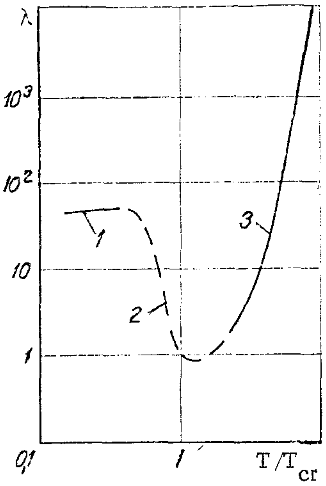

Fig. 1. Dependence of thermal conductivity λ (W/m•°K) of lithium on the referred temperature T/T_{cr} under pressure p = 1 kbar: 1) experimental data [4], 2) hypothetical transition range, 3) radiative thermal conductivity [7].

$$\varepsilon = aT^{\alpha},\ \rho = b/T,\ \lambda = cT^{n}. \tag{1}$$

In mass–time Lagrangian coordinates the transfer of energy is described by the equation of heat conduction

$$\frac{\partial \varepsilon}{\partial t} = \frac{\partial}{\partial m}\left[\lambda\rho\frac{\partial T}{\partial m}\right],\ m = \int_0^x \rho dx, \tag{2}$$

with the boundary conditions

$$-\lambda\rho\frac{\partial T}{\partial m} = q_s \text{ for } m = 0. \tag{3}$$

The density of the energy flux striking the wall is assumed to remain constant and equal to $q_s = E_s/t_r$, where E_s denotes total incident energy per unit wall surface area during the reaction time.

As has been done before [6], we will not solve the problem (1)-(3) exactly, but will use dimensional analysis for determining the location of the wave front and the temperature behind it, assuming a uniform temperature there. We obtain

$$m_f = \left[\frac{b^{\alpha}c^{\alpha}}{a^{n}}\right]^{\frac{1}{n+\alpha}} q_s^{\frac{n-\alpha}{n+\alpha}}\, t^{\frac{n}{n+\alpha}}, \tag{4}$$

$$T_f = (abc)^{-\frac{1}{n+\alpha}} q_s^{\frac{2}{n+\alpha}}\, t^{\frac{1}{n+\alpha}}. \tag{5}$$

As an example let us consider a typical reactor variant with the parameters p = 1 kbar, $E_s = 6 \cdot 10^{6}$ J/m², t_r = 3 msec. The coefficients in expressions (1) for lithium at the given pressure are a = 1800 J/kg•°K, α = 1.12, b = $4.2 \cdot 10^{4}$ kg•°K/m³, c = $2.7 \cdot 10^{-34}$ W/(m·°K), n = 8. Then expressions (4) and (5) yield $m_f = 2.5 \cdot 10^{-2}$ kg/m² and $T_f = 3.8 \cdot 10^{4}$ °K. With an initial density ρ_0 = 500 kg/m³, the thickness of a layer which has passed into the plasmatic state is

$$\delta = \frac{m_f}{\rho_0} = 5 \cdot 10^{-5}\ \text{m}.$$

At the temperature T_f, however, the plasma forms a layer which is 0.025 m thick. Considering that in the given types of reactors the radius of the chamber is of the order of 0.1 m, it is obvious that the buildup of such a thick boundary layer of cold plasma can appreciably influence the process in the hot plasma at the center of the channel.

It is well known that dimensional analysis yields solutions with an accuracy down to a numerical factor, usually of the order of unity. These factors in expressions (4) and (5) evidently differ very little from unity, since the energy stored in the plasma behind the wave front and calculated according to expressions (4), (5) is almost equal to the energy impinging on the wall

$$E_f = m_f \varepsilon_f = m_f a T_f^{\alpha} = 5.9 \cdot 10^6 \text{ J/m}^2.$$

Estimates indicate that the radiation energy is absorbed essentially by a thin slice of the protective layer, one which passes into the plasmatic state. The fraction of energy penetrating the depth of this protective layer to produce a heating "spike" is small. This can be verified with the aid of the boundary condition at the wave front

$$q_s = q_w + \rho v \Delta \varepsilon,$$

where q_w is the heat carried deeper into the wall, $\rho v = q_s/\varepsilon(T_f)$ is the mass rate of front propagation, and $\Delta\varepsilon = \varepsilon(T_f) - \varepsilon(T_*)$. Then

$$\frac{q_w}{q_s} = \frac{\varepsilon(T_*)}{\varepsilon(T_f)}$$

and, since $T_* \ll T_f$, usually $q_w/q_s \ll 1$. At a temperature $T_* = 2500°K$, therefore, 5% of the energy impinging on the wall penetrates deeper into the thermal protection layer.

In conclusion, we note that after completion of the fusion reaction, the cold plasma formed in the process fills the reactor chamber and, before it can be removed from there, spontaneous radiation from it can cause additional vaporization of the protective layer. This problem requires, obviously, a special study.

NOTATION

a, b, c, constants in expressions (1); E_s, radiation energy per pulse transmitted from a hot plasma to a unit of surface area of the first reactor wall; m, Lagrangian mass coordinate; n, a constant in expressions (1); p, pressure; q_s, energy flux density at the reactor wall; T, temperature; t, time; x, space coordinate measured from the layer surface depthwise; α, a constant in expressions (1); ε, internal energy of the metal; λ, thermal conductivity; ρ, density; subscripts: f refers to the front of the thermal wave; cr, to critical values of parameters; *, to the fictitious limit of the sharp drop of thermal conductivity in the metal.

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