

# Radiative heating of a fine-porous filled material

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(Received 10 July 1987)

**Abstract**—Consideration is given to the problem of heat conduction with a moving phase boundary in a fine-porous filled material with filler evaporation. In addition to the Stefan condition, another condition is formulated at the phase boundary, since the temperature at the phase interface is the unknown function of time. This condition for the rate of evaporation takes into account different modes of the efflux of vapours from capillaries. It is shown that a correct account for the evaporation condition is reflected in the surface temperature, evaporation front temperature, phase change rate and in the amount of energy absorbed for evaporation.

ONE OF the varieties of porous cooling is the so-called self-cooling. Porous materials operating on this principle find application in devices for which one of the conditions of service is their high resistance to erosion [1, 2]. For example, filling or impregnating porous tungsten with another material, which evaporates at fairly low temperatures [2], it is possible to attain a reduction in the temperature of a surface exposed to heating. We will consider the case of purely radiative heating of a porous body.

With extension of the evaporation front into the body the effect of resistance to the motion of vapours through the porous matrix on the evaporation rate increases. To mathematically formulate the problem of heat and mass transfer with a mobile evaporation boundary inside of a porous medium it is necessary, in addition to the Stefan condition, to prescribe another relation, because the temperature at the phase interface is not a constant which is known *a priori*. In the case of evaporation from an open surface this additional condition is generally obtained from the Hertz-Knudsen-type formula for the evaporation mass velocity

$$G = \frac{2\alpha(p_* - p)}{(2 - \alpha)\sqrt{(2\pi RT_*/M)}}$$

For evaporation into vacuum (and for  $\alpha = 1$ ) this expression takes the form

$$G = \frac{p_*}{\sqrt{(2\pi RT_*/M)}} \quad (1)$$

Note that a rigorous solution of a corresponding kinetic problem (e.g. ref. [3]) shows that the maximum flow rate, which corresponds to equation (1), is not achieved in a steady-state case, because a portion of escaping molecules (about 18–20%) returns to the surface by way of collisions even in the case of evap-

oration into vacuum. However, pursuing here the objective of a qualitative investigation into the effect of evaporation front depression on heat transfer in a porous body, we will adopt the closure condition in the form of equation (1) for the initial period of evaporation when the front of phase change virtually coincides with the body surface.

In order to take into account the resistance to vapour flow with a further recession of the evaporation front, it is necessary to specify the model of a porous body. We will consider the simplest model of a porous body consisting of a set of cylindrical capillaries of the same radius. The study of the kinetics of mass transfer in a separate capillary for small-rate processes was carried out earlier [4, 5]. In the case of a high-rate evaporation into vacuum there is no rigorous solution of this problem for all Knudsen numbers. Only for a free-molecular regime of vapour escape from an  $L$ -long capillary of radius  $r$  it is possible to write the expression [4, 5]

$$G = \frac{p_*}{\sqrt{(2\pi RT_*(1 + L/2r))}} \quad (2)$$

However, with an increase of  $p_*(T_*)$  and a deep enough recession of the evaporation surface there may take place change in the vapour escape regime along the length of the capillary: the regime of a continuous medium in the region adjacent to the evaporation surface and the free-molecular regime near the exit from the capillary. We will assume that the transition from the free-molecular flow to the continuous medium flow occurs at the point with  $Kn = 1$  (the section where  $0.1 < Kn < 10$  is not considered). Vapour pressure at this point can be found from the equality of vapour flow rates in both flow regions. For a viscous compressible gas flow in a cylindrical channel [6]

$$G = \frac{(p_*^2 - p_0^2)r^2}{16\mu RT(L - L_0)} \quad (3)$$

**NOMENCLATURE**

$H_s$	specific heat of filler evaporation	$T_0$	temperature at the point $x = L_0$
$j_0$	density of absorbed radiation flux	$T_*(t)$	temperature on evaporation surface.
$L$	coordinate of the point of change in flow regimes	<b>Greek symbols</b>	
$M$	molecular weight	$\alpha$	coefficient of evaporation
$p_0$	pressure at the point $x = L_0$	$\theta_0$	initial temperature
$p_*$	saturated vapour pressure at temperature $T_*$	$\rho_s$	filler density
		$\psi$	porosity.

and in the section with free-molecular escape into vacuum

$$G = \frac{p_0}{\sqrt{(2\pi RT_0(1 + L_0/2r))}} \quad (4)$$

where

$$\bar{T} = \frac{1}{L - L_0} \int_0^L T dx$$

and  $\mu$  is the coefficient of viscosity. Using equations (3) and (4) and the condition  $Kn(L_0) = 1$ , it is possible to determine  $L_0$  and  $p_0$ .

The said joining procedure and the description of flow in a capillary are approximate and are employed because of the absence of a rigorous solution for a respective kinetic problem. With such an approach, the presence of the initial period in the escape of vapours in a free-molecular regime is supposed (for the evaporation front in this regime to be extended into the body to a depth of a few diameters, i.e.  $0 < L_0 < L$ ). But if the radii of capillaries are great and the evaporation from an open surface passes over, with front recession into vapour escape in the continuous medium regime, another procedure for the approximate calculation of flow is needed.

Since in the present problem a fine-porous material is considered in which the diameter of capillaries is, in particular, smaller than the radiation wavelength, then the effects associated with radiation penetration into the pores can be ignored, i.e. a mobile radiation flux is virtually absorbed by the surface. The screening of radiation by escaping vapours and convective cooling of the porous layer are also disregarded, since the objective of the work is the evaluation of the effect of resistance to the escape of vapours on the evaporation rate and the body surface temperature, rather than calculation of a particular system of cooling.

With regard for the above assumptions, the mathematical model represents two heat conduction equations for a desiccated ( $0 \leq x \leq L$ ) and a filled ( $L \leq x \leq L_s$ ) layer of porous material with a mobile boundary between these regions (Fig. 1)

$$c_{pi}\rho_i \frac{\partial T_i}{\partial t} = \lambda_i \frac{\partial^2 T_i}{\partial x^2}, \quad i = 1, 2 \quad (5)$$

where subscripts 1,2 relate respectively to the desiccated and filled regions. The quantities  $c_{pi}$ ,  $\rho_i$ ,  $\lambda_i$  are the specific heat, density and thermal conductivity of the respective layers. Calculations were carried out for tungsten-zinc material with the use of the following relations :

$$\begin{aligned} \lambda_1 &= \lambda_w(1 - \psi), & c_{pi}\rho_i &= c_{pw}\rho_w(1 - \psi) \\ \lambda_2 &= \lambda_w(1 - \psi) + \lambda_{zn}\psi, \\ c_{p2}\rho_2 &= c_{pw}\rho_w(1 - \psi) + c_{pzn}\rho_{zn}\psi. \end{aligned} \quad (6)$$

The boundary and initial conditions are

$$-\lambda_1 \frac{\partial T_1}{\partial x} \Big|_{x=0} = j_0 - \epsilon\sigma T_1^4 \Big|_{x=0} \quad (7)$$

$$-\lambda_2 \frac{\partial T_2}{\partial x} \Big|_{x=L_s} = 0 \quad (8)$$

$$T_1|_{x=L(t)} = T_2|_{x=L(t)} = T_*(t) \quad (9)$$

$$-\lambda_1 \frac{\partial T_1}{\partial x} \Big|_{x=L(t)} + \lambda_2 \frac{\partial T_2}{\partial x} \Big|_{x=L(t)} = \psi\rho_s H_s \frac{dL}{dt} \quad (10)$$

$$\frac{dL}{dt} = \frac{1}{\rho_s} G(T_*, p_*, L, L_0) \quad (11)$$

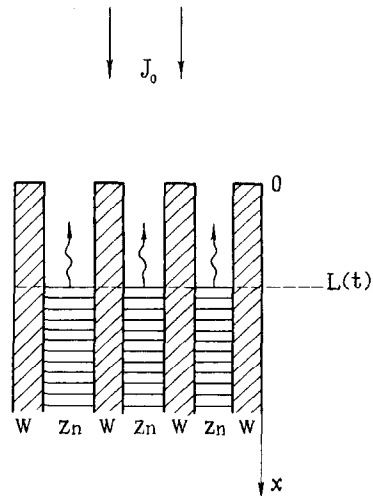


FIG. 1. Geometric scheme of the problem.

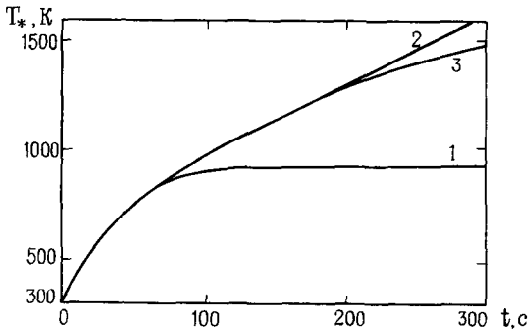


FIG. 2. The graph of the evaporation front temperature  $T_*$  vs time for three regimes of vapour escape at  $j_0 = 10^6 \text{ W m}^{-2}$  (1, free; 2, free-molecular; 3, combined).

$$T_1(0, x) = T_2(0, x) = \theta_0. \quad (12)$$

The Knudsen number was calculated from the formula

$$Kn = \frac{2\mu}{P \cdot r} \sqrt{\left(\frac{RT}{2\pi M}\right)}.$$

Problem (5)–(12) was solved numerically by the finite-difference technique for  $j_0 = 10^6, 10^8 \text{ W m}^{-2}$ ,  $r = 0.5 \times 10^{-6} \text{ m}$ ,  $\psi = 0.6$ ,  $L_s = 0.06 \text{ m}$  and for three expressions of  $G$ : equations (1), (2) and for a combined regime, equations (3) and (4). The regimes in which the region of free-molecular flow is absent ( $L_0 = 0$ ) were not attained for the values of the parameters used. The model considered postulates a one-phase version of region 2. The volume occupied by a liquid phase can be determined approximately from the isotherm of melting.

Figures 2 and 3 present the temperatures at evaporation fronts  $T_*$  vs time for three regimes of vapour escape from a body exposed to radiation fluxes  $j_0 = 10^6$  and  $10^8 \text{ W m}^{-2}$ , respectively. Only with the use of the condition of evaporation from an open surface (1), i.e. without regard for the resistance to the escape of vapours, the temperature  $T_*$  attains a

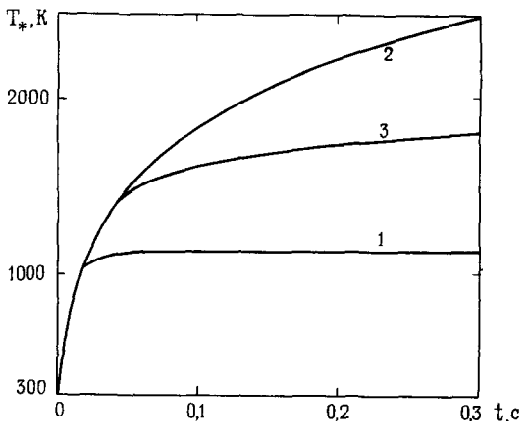


FIG. 3. Same as Fig. 2 but at  $j_0 = 10^8 \text{ W m}^{-2}$ .

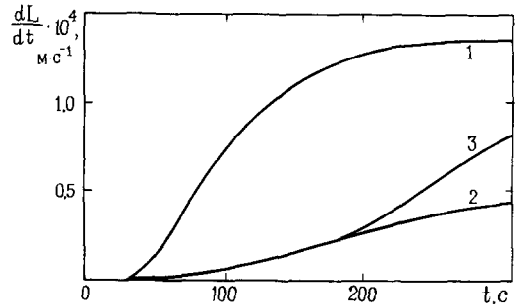


FIG. 4. The graph of evaporation front velocity vs time for three regimes of vapour escape at  $j_0 = 10^6 \text{ W m}^{-2}$  (1, free; 2, free-molecular; 3, combined).

certain, almost constant, value which depends on the density of absorbed radiation flux (for  $j_0 = 10^8 \text{ W m}^{-2}$  the temperature  $T_*$  slowly decreases starting from a certain time instant). In this case, the value of  $T_*$  does not coincide, of course, with the temperature of quasi-steady-state evaporation of zinc exposed to the same flux in vacuum because of the formation of a desiccated layer in the porous body. Taking into account the resistance to the escape of vapours by the free-molecular flow model, equation (2) substantially overestimates  $T_*$  and, although there is a tendency to approach the asymptotic value [7], it is not attained in real conditions. The curves that correspond to the case allowing for the resistance to vapour motion in the combined regime of vapour escape (the presence of transition from a free-molecular to a viscous regime in the capillary) lie, starting from a certain time instant, between the temperature curves obtained for the two other evaporation regimes. In this case there is a more distinct tendency to attain a certain asymptotic value.

Figures 4 and 5 present the curves of the evaporation front velocity vs time calculated from the same models of escape. The use of the condition of evaporation from a free surface for fine-porous bodies appreciably overestimates the evaporation rate. For

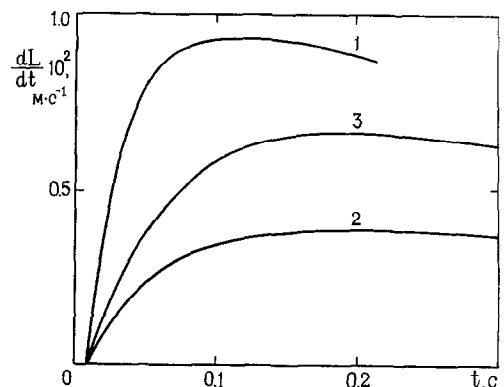


FIG. 5. Same as Fig. 4 but at  $j_0 = 10^8 \text{ W m}^{-2}$ .

free-molecular and combined regimes the results virtually coincide during a certain initial period (which depends on  $j_0$  and  $r$ ), and then the use of equation (2) overestimates the actual resistance and, correspondingly, underestimates the evaporation rate.

The data listed in Table 1 characterize the energy expended for phase transformations.  $E_1(t)$  is the energy absorbed by evaporation by the time instant  $t$  and related to the full energy  $j_0 t$  in the case of the use of condition (1);  $e_1(t)$  is the instantaneous value of this quantity (ratio of powers), i.e.

$$E_1(t) = \frac{1}{j_0 t} \int_0^t \psi \rho_s H_s \frac{dL}{dt} dt$$

$$e_1(t) = \psi \rho_s H_s \frac{dL}{dt} / j_0$$

Analogous quantities for free-molecular escape and for a combined regime are designated as  $E_2$ ,  $e_2$  and  $E_3$ ,  $e_3$ , respectively. These data for the energies confirm the importance of taking into account the resistance to motion of vapours in capillaries. For example, for  $j_0 = 10^8 \text{ W m}^{-2}$  and  $t = 0.2 \text{ s}$  the model without taking into account the resistance gives 51% of energy absorbed by evaporation ( $E_1$ ), and the models that take into account the resistance—only 19% ( $E_2$ ) and 32% ( $E_3$ ).

The surface temperature  $T_*$  of the material is first lower, because of the energy loss for phase change, than for an analogous specimen made of solid tungsten. But, in contrast to ref. [2], concerned with convective heating of an identical porous material, a reduction of  $T_w$  is of temporal character. Moreover, starting from some time instant the  $T_w$  of a desiccated layer becomes higher than for solid tungsten. The duration and degree of cooling depend on such characteristics of the material as porosity, specific heat of evaporation, radius of capillaries and also on the radiation flux density.

Figure 6 shows the dependencies of  $E_3$  and  $T_w$  on the porosity of a specimen for the model of a combined regime of vapour escape after 60 s of exposure to the flux  $j_0 = 5 \times 10^6 \text{ W m}^{-2}$ . Note that the function  $T_w(\Pi)$  has a minimum. And although taking into account the convective cooling of a porous layer by vapours would have somewhat changed the form of

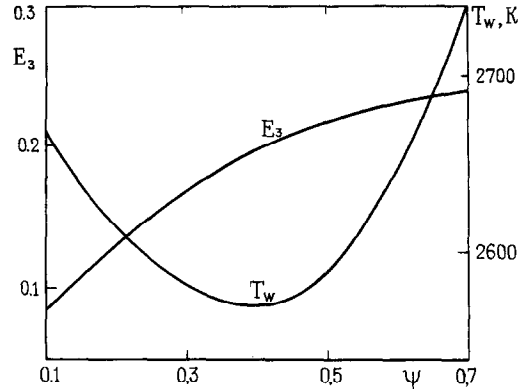


FIG. 6. Dependence of the body surface temperature  $T_w$  and energy  $E_3$  on the specimen porosity in the combined regime of vapour escape ( $j_0 = 5 \times 10^6 \text{ W m}^{-2}$ ;  $t = 60 \text{ s}$ ).

the curve  $T_w(\Pi)$ , the presence of two competing processes—cooling due to the phase change and increase of  $T_w$  due to a decrease of the thermal conductivity coefficient with an increase of porosity—retains the validity of the problem of finding the optimum porosity.

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Table 1. Dependence of the energy expended for filler evaporation on time for three regimes of vapour escape ( $j_0 = 10^8 \text{ W m}^{-2}$ )

$t(\text{s})$	$e_1$	$E_1$	$e_2$	$E_2$	$e_3$	$E_3$
$10^{-2}$	$2.3 \times 10^{-2}$	$4.1 \times 10^{-3}$	$1.6 \times 10^{-2}$	$3.1 \times 10^{-3}$	$1.6 \times 10^{-2}$	$3.1 \times 10^{-3}$
$2 \times 10^{-2}$	0.23	$6.3 \times 10^{-2}$	$6.2 \times 10^{-2}$	$2.2 \times 10^{-2}$	$6.8 \times 10^{-2}$	$2.4 \times 10^{-2}$
$4 \times 10^{-2}$	0.47	0.22	0.13	$6.2 \times 10^{-2}$	0.15	$7.2 \times 10^{-2}$
$6 \times 10^{-2}$	0.56	0.32	0.17	$9.3 \times 10^{-2}$	0.32	0.12
$8 \times 10^{-2}$	0.59	0.38	0.20	0.12	0.35	0.17
$10^{-1}$	0.60	0.43	0.22	0.14	0.39	0.21
$2 \times 10^{-1}$	0.58	0.51	0.25	0.19	0.44	0.32

## CHAUFFAGE RADIATIF D'UN MATERIAU FINEMENT POREUX

**Résumé**—On considère le problème de la conduction thermique avec frontière de phase mobile dans un matériau finement poreux et évaporation d'une charge. A la condition de Stefan est ajoutée une autre condition à l'interface car la température  $y$  est une fonction inconnue du temps. Cette condition pour l'évaporation tient compte de différents modes de progression des vapeurs dans les capillaires. On montre qu'une prise en compte correcte de la condition d'évaporation se répercute sur la température de surface, la température du front d'évaporation, la vitesse de changement de phase et la quantité d'énergie absorbée par l'évaporation.

## BEHEIZUNG EINES VERFÜLLTEN FEINPORIGEN MATERIALS DURCH STRAHLUNG

**Zusammenfassung**—Es wird das Problem der Wärmeleitung mit wandernder Phasengrenze in einem verfüllten feinporigen Material mit Verdampfung der Füllmasse betrachtet. Zusätzlich zur Stefan-Bedingung wird eine weitere Bedingung an der Phasengrenze formuliert, da die Temperatur an der Phasengrenze eine unbekannt Funktion der Zeit ist. Diese Bedingung für die Verdampfungsgeschwindigkeit berücksichtigt verschiedene Arten der Dampfabströmung aus den Kapillaren. Eine korrekte Berücksichtigung der Verdampfungsbedingung wirkt sich auf die Oberflächentemperatur, die Temperatur der Verdampfungsfront, die Phasenänderungsgeschwindigkeit und auf den Betrag der für die Verdampfung absorbierten Energie aus.

## РАДИАЦИОННЫЙ НАГРЕВ МЕЛКОПОРИСТОГО МАТЕРИАЛА С НАПОЛНИТЕЛЕМ

**Аннотация**—Рассматривается задача теплопроводности с движущейся границей фазового перехода в мелкопористом материале при испарении наполнителя. На границе фазового перехода помимо условия Стефана формулируется еще одно условие, так как температура на границе раздела фаз является неизвестной функцией времени. Это условие для скорости испарения отражает различные режимы истечения паров из капилляров. Показано, что правильный учет условий испарения сказывается на значениях температуры поверхности, температуры фронта испарения, скорости фазового перехода и величине энергии, поглощенной испарением.