Journal of Engineering Physics and Thermophysics, Vol. 66, No. 4, 1994

DESTRUCTION OF MOIST POROUS MATERIALS BY THERMAL SHOCK-INDUCED RAPID INTERNAL EVAPORATION

E. Yu. Shangareeva

UDC 536.24:536.42; 669-154

The process of destruction of a moist porous specimen exposed in a high-temperature medium is considered. The developed simplified mathematical model of the process is used to obtain a thermal decomposition curve for a spherical specimen with a microcapillary structure.

Introduction. When a moist porous body is placed in a medium whose temperature is much higher than that of the saturated vapor, pore liquid in the near-surface layer starts to boil intensely. As internal evaporation of the pore liquid proceeds, the boundary of the initial boiling advances into the bulk of the specimen.

On the surface of material subjected to laser radiation a similar effect where the material itself starts to boil and the boundary moves into the bulk of the specimen occurs [1–3]. In this case the internal temperature distribution depends substantially on evaporation inside pores. Since energy losses caused by evaporation prevent an increase in the internal temperature [4], the temperature tends to its equilibrium value, equal to the temperature of the saturated vapor at a pressure of 0.1 MPa. According to [4], internal evaporation not only brings about loss of material mass but also can induce destruction of the specimen when the pressure in the pores exceeds the ultimate strength of the material.

Resistance to mechanical destruction decreases in moist porous bodies as the moisture content rises due to a decrease in the adhesive forces between individual particles. Therefore a sharp drop in the temperature and moisture content between the surface and central layers of the porous body induced by intense heating initially causes cracking of the surface and then distortion of the structural integrity. Thus, in the case of a high initial moisture content of a material, destruction of a specimen is caused primarily by rapid expansion of vapor in the pores, while in heating of dry material internal evaporation of the pore material itself is decisive [4].

In the present work a simple mathematical model is used to investigate the destruction of a spherical specimen made of a moist (a moisture content of about 25%) microcapillary material, assuming that the internal temperature of the vapor is constant and equal to the saturation temperature at 0.1 MPa under high-temperature heating.

Strength of Moist Material. It is clear that the ultimate strength of a moist porous specimen is substantially lower than that of dry material due lower adhesive forces between the particles and it depends on the initial moisture content and porosity of the specimen.

For a microcapillary structure the relation between the length of a capillary and radius of the trunk has the form [4]

$$dr/dl = r/l \ll 1 ,$$

and therefore for $r < 0.1$ μm it can be assumed that $dr/dl \approx 0$ to simplify substantially the description of the internal structure of the test specimen. For convenience the simplest model for the structure of the capillary-porous material will be used. The moist porous material will be represented as a body with cylindrical pores. Capillaries emerging on the surface will be assumed to be uniformly distributed and to have the same diameter of the mouths.

In initial boiling of the pore liquid, an unsteady state of the thermodynamic steam-water system develops, which is accompanied by pressure fluctuations. As is known from statistical thermodynamics, in this system the

---

Siberian Power Institute, Irkutsk, Russia. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 66, No. 4, pp. 453-457, April, 1994. Original article submitted May 19, 1992.

1062-0125/94/6604-0398$12.50 ©1995 Plenum Publishing Corporation

pressure fluctuations are proportional to the heat capacity $c = \partial u/\partial T$ and in an isothermal state their magnitude is equal to or higher than the absolute pressure P. Then, in what follows, the quantity P in the strength condition for a cylindrical wall [5]

$$\sigma = Pr/\delta < [\sigma], \tag{1}$$

will mean a fluctuation of the order of P rather than an absolute pressure of value P. In relation (1) r is the channel radius. This suggests that the minimum thershold pressure required for destruction of the capillary walls has the form

$$P_{\min} = [\sigma]\,\delta/r. \tag{2}$$

When pores in a spherical porous specimen are distributed uniformly, the thickness of the capillary walls is determined by

$$\delta = 2R/N^{1/2} - r, \tag{3}$$

where N is the number of pores emerging onto the surface; R is the radius of the spherical porous specimen. The void fraction θ_V is defined by the ratio $\theta_V = V_p/V$, and the surface porosity θ_{s_x}, by the ratio $\theta_s = S_p/S$, where V is the total volume.

We will assume that $\theta_V = \theta_{s_x}$. Then, the relation between the capillary dimensions and the porosity has the form

$$\delta/r = \overline{\Theta}^{\,-1/2} - 1. \tag{4}$$

The threshold pressure of the moist capillary body will be expressed by

$$P = P_{\min} f(W),$$

where $f(W)$ is a decreasing function of the moisture content. The function $f(W)$ can be expanded in a Taylor series:

$$f(W) = f(W = 0) + f'(W = 0)\,W + \ldots$$

Taking only the first and second terms in the series, we obtain an expression for the threshold pressure of the moist body:

$$P^* = P_{\min}(1 - W) = [\sigma](\Theta^{-1/2} - 1)(1 - W), \tag{5}$$

where $W = m_{\text{liq}}/m$ is the moisture content of the porous material. It follows from Eq. (5) that an increase in the initial moisture content and porosity of the body leads to a decrease in its mechanical strength in reference to the destructive effect of intense vaporization. As soon as the pressure of the saturated vapor reaches the threshold value $P^* = P_s$, the body is fractured. Substitution of P_s for P^* in (5) gives the threshold moisture content sufficient to induce fracture of the material due to the destructive effect of internal evaporation of the pore liquid:

$$W^* = 1 - (P_s/[\sigma])/(\overline{\Theta}^{\,-1/2} - 1). \tag{6}$$

The plot $t(W^*)$ of the destruction time t^* versus the moisture content W^* will be called as the thermodestruction curve. To determine the mechanism of the destruction process, Eq. (5) should be supplemented by the law governing changes in the moisture content.

Change in the Moisture Content of a Porous Material in the Case of Thermal Shock. At a high ambient temperature, water in the mouths of emergent pores starts boiling almost instantaneously. As the liquid phase in the pores of a specimen is heated up, it transforms to the gas phase as a result of boiling and a boiling surface with the radius $R_b(t)$ arises in the bulk of the specimen. It moves with a velocity U_b. The heated volume will be divided arbitrarily into two regions: region 1 is the space filled with subcooled liquid, $r < R_b$; region 2 is the space filled with vapor, $r > R_b$.

The radius of the boiling surface depends on the moisture content as follows:

$$R^3(t) = 3m_p W/\rho_{liq}(1 - W) 4\pi , \tag{7}$$

where m_p is the mass of the dry porous material; ρ_{liq} is the density of the pore liquid.

Determination of the law governing the behavior of the moisture content requires knowledge of the displacement of the interface radius R_b into the bulk of the specimen. Below we present a calculation of R_b for capillary-porous materials with a microcapillary structure, i.e., with a pore radius smaller than 0.1 μm. In this case the transfer is molecular, and no gasdynamic flow, either laminar or turbulent, can arise in a microcapillary. Under a pressure differential, vapor molecules in these capillaries move independently of one another, colliding constantly with the pore walls [6].

Under the assumption of the thermal equilibrium between the vapor and the body, the number of molecules leaving a capillary per unit time is equal to the number of collisions with a wall surface that is equal to the area of the capillary mouth. An ordinary statistical calculation gives the relation [6]

$$dm_v/dt = (8/3)\frac{(P_e - P_s)\, r^3}{(4\pi R_v T_s)^{1/2}(R - R_b(t))} , \tag{8}$$

where T_s is the saturation temperature; P_s is the saturated vapor pressure; P_e is the ambient pressure. The vapor mass generated in a capillary channel is equal to

$$m_v = \pi \rho_v r^2 (R - R_b(t)) , \tag{9}$$

where ρ_v is the vapor density.

Using relation (9) and integrating Eq. (8) between R and $R_b(t)$, we obtain

$$R_b(t) = R - (D_b t)^{1/2} , \quad D_b = \frac{4(P_e - P_s)\, r}{3(4\pi R_v T_s)^{1/2} \rho_v} . \tag{10}$$

Equation (10) is the law governing changes in the boiling boundary with time. Equation (10) shows that the proportionality factor $(D_b)^{1/2}$ depends both on physical properties of the body and its structure and an ambient parameters, and an increase in the internal capillary pressure suppresses the evaporation process in the pores. A similar suppression effect due to an increase in the internal pressure was found in [4], the authors of which studied internal evaporation in dendritic porous structures [7, 8].

The time needed for complete boiling of the subcooled liquid filling the cold core of the specimen is $t_c = (R^2/D_b)$. Differentiation of (10) gives an expression for the velocity of the surface displacement:

$$U_b = dR_b/dt = -0.5(D_b/t)^{1/2} . \tag{11}$$

It should be noted that in real situations complete heating of the cold core to the saturation temperature is impossible without disruption of the structural integrity since the heating time is sufficient to destroy the surface layers of the specimen.

In the present work microcapillary materials with a pore radius smaller than 0.1 μm were investigated. In this case the displacement velocity of R_b should be determined by diffusion of vapor [4], which is Knudsen diffusion with a characteristic dimension equal to the pore radius. In Eq. (10) the proportionality factor is a diffusion coefficient similar to the Knudsen diffusion coefficient [9]

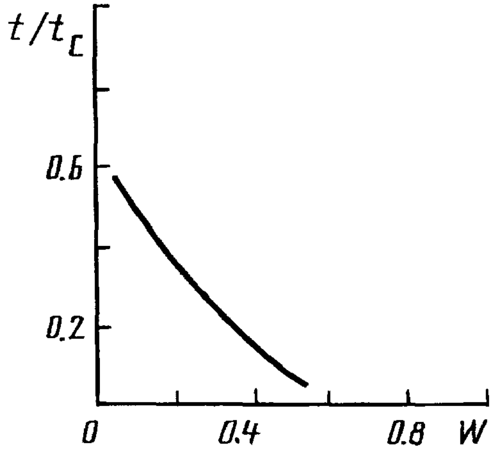

Fig. 1. Destruction curve for a spherical specimen subjected to thermal shock.

$$D_{b\,n} = (2/3)\, r\, (2T/M)^{1/2}.$$

Destruction of a Moist Porous Specimen Subjected to Thermal Shock. Now, knowing the strength condition of the moist material, the law describing changes in the moisture content, and the path of the phase interface, it is easy to find the destruction curve for a moist porous specimen subjected to thermal shock. Simultaneous solution of Eqs. (5), (6), and (10) gives the time of destruction in the form

$$t^* = t_c\,(1 - \varphi\,(W^*))\,, \tag{12}$$

$$\varphi\,(W^*) = (1/R)\,(0.239 m_p\, W^*/1 - W^*)\,\rho_{\text{liq}})^{1/3}\,,$$

$$W^* = 1 - P_s/[\sigma]\,(\Theta^{-1/2} - 1)\,.$$

This is the equation of destruction, which describes approximately the unsteady-state destruction process in a moist porous material heated to high temperatures. The plot of $t^*(W)$ is shown in Fig. 1.

Conclusions. The present model can be used to estimate the time and conditions of destruction of a moist specimen and the effect of the operating parameters on the thermal shock-induced fracture process and to investigate the behavior of the moisture content of a specimen under particular conditions.

This model can be used effectively in the case where intense internal vaporization is the main factor of destruction. This situation is possible only for a certain initial moisture content of the specimen.

Further studies should involve a more realistic approach to the description of structural properties of porous materials and, in addition, they should be concerned with the joint effect of pyrolitic decomposition and internal evaporation of the pore liquid on the destruction dynamics in porous materials subjected to thermal shock.

The present analyis can be useful in engineering calculations of particular technological processes using moist materials. This theoretical method can be used for rapid estimation of the destruction time for a moist porous specimen under high-temperature heating with different operating parameters. Moreover, the present method can be used to estimate the probability of destruction of moist porous materials subjected to high-power laser radiation, which is of practical interest in applications of lasers.

NOTATION

D_b, vapor diffusivity, m^2/sec; M, molecular mass of gas, kg; m, mass of moist material, kg; m_p, mass of dry material, kg; m_{liq}, mass of pore liquid, kg; P, vapor pressure, Pa; $P_{\min}$, minimum threshold pressure for capillary walls, Pa; R_b, radius of the vapor-liquid interface, m; R_v, gas constant for vapor, J/(kg·K); r, pore radius, m; S, surface area of a specimen, m^2; S_p, cross-sectional area of a pore, m^2; T, temperature of vapor in capillaries, K; t, time, sec; t_c, time of complete boiling of pore liquid, sec; V, volume of a specimen, m^3; V_p, volume of pores, m^3; W, moisture content of material per unit mass; U_b, velocity of displacement of the phase interface, m/sec; ρ, density, kg/m^3; σ, stress, Pa; $[\sigma]$, limiting tensile strength of dry material, Pa; δ, thickness of capillary walls, m; θ, material porosity. Subscripts and superscripts: *, destruction; b, boiling; e, environment; liq, liquid; p, porous; s, saturated; v, vapor.

REFERENCES

1. S. Anisimov, Soviet Physics JETP., 27, 182-183 (1968).
2. C. Knight, AIAA J., 17, 519-523 (1979).
3. C. Knight, J. Fluid Mech., 75, 469-486 (1976).
4. D. E. Hastings and A. A. Rigos, AIAA J., No. 5, 561-565 (1988).
5. G. I. Itskovich, Resistance of Materials [in Russian], Moscow (1982).
6. A. V. Luikov, Drying Theory [in Russian], Moscow (1968).
7. G. A. Simons, Prog. Energy Combustion Sci., 9, 269 (1983).
8. G. A. Simons, The 19th Symp. on Combustion (1982), pp. 1067-1076.
9. R. E. Cunningham and R. J. J. Williams, Diffusion in Gases and Porous Media, Plenum Press (1980), p. 77.