Journal of Applied Mechanics and Technical Physics, Vol. 41, No. 2, 2000

EXPERIMENTAL DETERMINATION OF THE BASIC CHARACTERISTICS OF HEAT AND MASS TRANSFER UPON THERMOEROSION FRACTURE OF MATERIALS

V. E. Abaltusov,* S. G. Gaga, I. K. Zharova, L. V. Zotova,
G. V. Kuznetsov, and E. V. Svetovets

UDC 536.24

Using an original technique, heat and mass transfer in the interaction between a high-temperature heterogeneous jet with a high concentration of particles and the surface of structural materials was studied for the first time. The characteristics of heat and mass transfer were obtained under conditions of intense destruction of the materials under the action of a heterogeneous jet whose axis is perpendicular to the heating surface. Based on the results of experimental studies, some signs of high-temperature fracture of steel and cement grout under the action of a heterogeneous jet were revealed.

The effect of intense local destruction of materials under the action of a high-temperature heterogeneous jet can be used in technological processes including cutting of metal and nonmetal constructions, underwater technical and repair emergency works, utilization of military equipment, etc. [1]. Particular technologies and devices based on this effect can be developed if theoretical models or experimental data are available for the main regularities of the examined process within the range of parameters corresponding to the range of practical implementation of the process of thermoerosion fracture.

Models and experimental data of this kind are currently unavailable.

Heat transfer on the surface of bodies in a high-temperature gas flow is usually studied with the help of thermally insulated calorimetric heat-flux probes whose main element is a calorimeter with a thermocouple attached to it [2, 3]. However, the interaction of a high-temperature gas with different materials can result in ablation from the surface as a result of intense physicochemical transformations. In this case, it is reasonable to use methods for heat-flux determination based on temperature measurement inside the sample, measurement of the ablation rate from the surface, and solution of inverse problems of heat and mass transfer [3–5].

Upon interaction between high-temperature supersonic jets with a high concentration of the condensed phase and the surface, high fracture velocities of the target material are reached (up to 40 mm/sec) [5]. In this case, the researches are mainly performed using numerical-experimental techniques based on the solution of inverse problems of heat and mass transfer. The application of these techniques requires obtaining rather accurate experimental information on the temperature distribution over the material depth $T(x,t)$ and the fracture velocity $V(t)$, which is not always possible.

Results of experimental investigations, which allow determination of the heat-flux temperature and density on the heating surface of the target upon local thermoerosion fracture of the material, are described in the present work.

---

*Deceased.

Tomsk State University, Tomsk 634050. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 41, No. 2, pp. 138–143, March–April, 2000. Original article submitted December 29, 1998; revision submitted May 11, 1999.

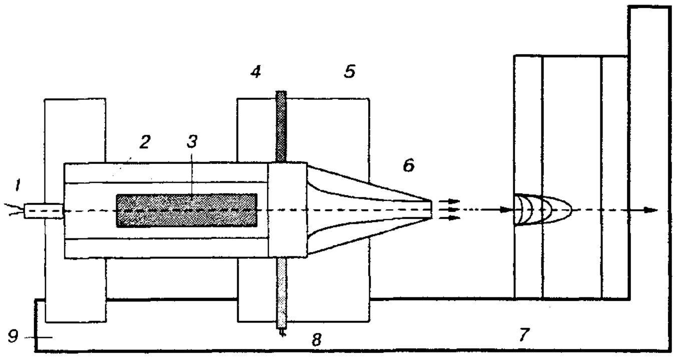

Fig. 1. Sketch of the setup: 1) pressure probe; 2) combustion chamber; 3) solid propellant charge; 4) output of the valve for depressurization; 5) nozzle block; 6) nozzle; 7) target; 8) output of the electric percussion cap; 9) bed plate.

Solid-propellant generators of heterogeneous jets were used in the experiments [6]. A distinctive feature of the solid-propellant generator is a possibility of varying the composition and concentration of particles introduced directly into the propellant and obtaining high values of the heat-flux density.

Figure 1 shows a sketch of the setup. A high-temperature supersonic heterogeneous jet is formed upon burning of a charge of a composite metallized propellant located in the combustion chamber of the generator [6]. The generator has a nozzle block, a pressure probe, and a valve for depressurization made in the form of a breakable membrane. The generator was started by an electric percussion cap. The working pressure in the chamber $P = (50\text{–}200) \cdot 10^5$ Pa was reached by varying the geometric characteristics of the charge and the nozzle throat diameter; it was calculated using the Bori formula [7].

Copper nozzles with throat diameter 3.0–3.2 mm were used. The charge was made in the form of a cylinder of length from 40 to 110 mm and diameter 36 mm, which was conically pointed on one side. The ensure uniform burning, the side surface of the cylindrical part of the charge and the flat butt end were coated by burning inhibitors. Varying the height of the conical part of the charge and, hence, the burning area, it was possible to change the pressure in the combustion chamber.

The targets exposed to the action of a high-temperature supersonic heterogeneous jet were made in the form of temperature and ablation probes [8]. Two types of samples were used: homogeneous and inhomogeneous materials.

The target of the first type was a steel probe made of three preliminary polished plates with Chromel–Alumel thermocouples located at the back wall of each plate. This construction of the probe allowed one to register the position of the measurement point in the material most accurately. The thermocouples were equipped by a thermoelectroprotective coating that ensured a high accuracy of high-temperature measurements and were located at a distance of 5.8, 8.2, and 16.0 mm from the outer surface of the plate.

The target of the other type was a probe in the form of a three-layered plate consisting of two steel plates of thickness 10 and 2 mm and a layer of cement grout between them (the cement/sand ratio was 1 : 3) of thickness 108 mm. The Chromel–Alumel thermocouples were located at a distance of 10, 60, and 118 mm from the outer surface.

The thermal state of the materials was determined from thermocouple data, and the fracture velocity was found from the time of thermocouple breaking.

It was found experimentally that the action of a high-temperature supersonic heterogeneous jet leads to formation of a crater in the plates. The profile of this crater is close to a strongly extended parabola. It is known [9] that the parabolic distribution of the heat flux obeys the relation

$$q/q_w = 1 - (x/x_*)^2,$$

where q is the heat-flux density in the direction perpendicular to the jet axis, q_w is the total heat-flux density at the stagnation point, and x and x_* are the current and stagnation-point coordinates, respectively.

Calculations performed with the use of experimental results show that q does not exceed 10% of q_w. Thus, the process of heat propagation over the depth of the target material can be described by a one-dimensional heat-conduction equation.

It was found [5, 10] that the temperature on the destroying surface is significantly lower than the melting point of the target material; hence, the thermophysical characteristics for a wide range of structural materials can be considered as constant quantities.

In considering the interaction of a supersonic heterogeneous jet with a target of thickness L, the calorimetric method cannot be directly used to estimate q_w because the following conditions are invalid [2]:

$$\mathrm{Fo} = \frac{\alpha t_{\mathrm{i}}}{L^2} \geqslant 0.35, \qquad \mathrm{Bi} = \frac{q_0 L}{\lambda T_{\max}} < 1. \tag{1}$$

Here Fo and Bi are the Fourier and Biot numbers, $\alpha = \lambda/(c\rho)$ is the thermal diffusivity, c is the specific heat capacity, ρ is the density, q_0 is the external heat-flux density, L is the initial thickness of the target, $T_{\max}$ is the maximum allowable temperature at the outer surface of the target determined by test conditions, and t_{i} is the time of interaction.

Nevertheless, the value of L decreases because of the high rate of thermoerosion fracture of the target and reaches a certain value δ at a time $t = t_*$ for which conditions (1) are satisfied. Thus, at the time t_* the target can be considered as a calorimetric probe of thickness δ. The origin is placed at the point $x = L - \delta$. Then, according to [2], the temperature field in the plate is determined as

$$T(x,t) = \frac{q_0 t}{C\rho\delta} + \frac{q_0\delta}{\lambda}\left\{\frac{3x^2 - \delta^2}{6\delta^2} - \frac{2}{\pi^2}\sum_{n=1}^{\infty}\left[\frac{(-1)^n}{n^2}\exp\left(\frac{a\pi^2 n^2 t}{\delta^2}\right)\cos\frac{\pi n x}{\delta}\right]\right\}, \quad \delta < L. \tag{2}$$

For $n \to \infty$, the second term in (2) is small as compared to the first one (0.01). Differentiating relation (2) with respect to time at the point $t = t_*$, we obtain the relation for the heat flux at the outer surface of the target

$$q_w = c\rho\delta\,\frac{dT_e(t_*)}{dt}, \tag{3}$$

where $T_e(t_*)$ is the temperature at the back wall of the calorimetric probe at the time $t = t_*$. In accordance with [2], the "maximally linear" section of the dependence $T_e(t)$ should be used to determine the heat flux from formula (3).

We introduce a quantity δ_{opt}, the optimal thickness of the target for which the dependence $T_e(t)$ is the "maximally linear" function ($\delta_{\mathrm{opt}} \leqslant \delta$) [2]:

$$\delta_{\mathrm{opt}} = \frac{\lambda T_{\max}}{1.366\, q_0}. \tag{4}$$

With account of (4), the function $T_e(t)$ is approximated by the linear dependence

$$T_e(t) = At + B, \qquad t \in [t_{\mathrm{opt}}, t_{\mathrm{i}}], \tag{5}$$

where t_{opt} is the time when the plate thickness is $\delta = \delta_{\mathrm{opt}}$ ($t_{\mathrm{opt}} \geqslant t_*$) and A and B are constants.

Thus, determining δ_{opt} from (4) and the corresponding time t_{opt}, we can use dependence (5) to determine the heat-flux density in accordance with (3). The values of t_* and δ satisfying conditions (1) were determined numerically by division of the section into an integral number of parts (or by dichotomy) with account of the mean of thermoerosion fracture velocity, which is determined from the moment of breaking of the thermocouple installed at the back wall:

$$\delta = L - Vt_*,$$

where $V = L/t_{\mathrm{i}}$ is the velocity.

Inspection of the probes after the tests showed that a blind hole whose profile had the shape of a strongly extended parabola was formed due to thermoerosion fracture. No signs of melting or cracking of the probes were observed. The absence of signs of melting on the outer surface of the steel plate of both

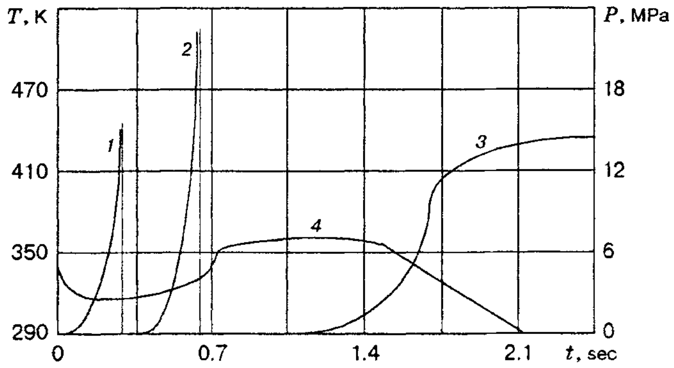

Fig. 2

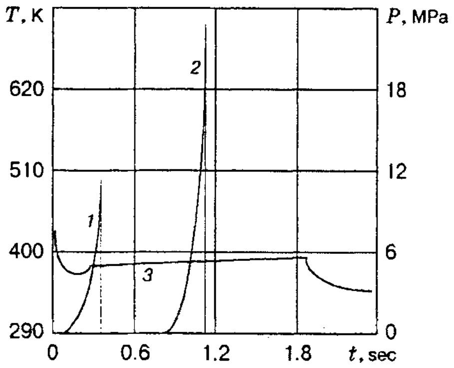

Fig. 3

Fig. 2. Results of experiments with a three-layered metal target: the temperature at the depth of 5.8, 14.0, and 30.0 mm (curves 1–3, respectively) and the pressure (curve 4).

Fig. 3. Results of experiments with a combined target: the temperature at the depth of 10 and 60 mm (curves 1 and 2, respectively) and the pressure (curve 3).

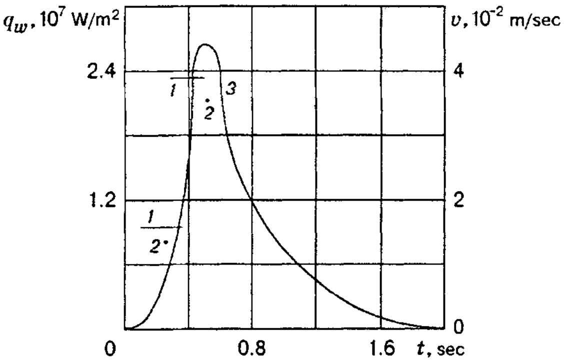

Fig. 4. Mean thermoerosion fracture velocity of the target (curve 1) and heat-flux density (curve 2) determined using the technique developed, and the heat-flux density obtained by solving the inverse problem of heat transfer (curve 3).

homogeneous and combined probes indicates that the melting point is not reached on the destroying surface of the metal target.

Figure 2 shows the test results on interaction of a supersonic high-temperature heterogeneous jet with a three-layered metal target. Figure 3 shows the experimental results for a combined target. The mean fracture velocity was 40 mm/sec for steel and 80 mm/sec for a mixture of sand and cement.

From the known mean fracture velocity, we determined the thickness δ and the time t_* corresponding to reaching this thickness for which the target can be considered as a calorimetric probe. The error of numerical calculation was about 0.001 %. For each probe, the optimal thickness δ_{opt} for which the temperature dependence on time is the "maximally linear" function was determined from formula (4), and the approximation coefficients were found from formula (5). Then the heat-flux density at the time t_* was calculated using relation (3). The calculation results for the case of interaction of a supersonic heterogeneous jet and a three-layered metal target are listed in Table 1.

Points 2 in Fig. 4 correspond to the values of the heat-flux density obtained by the method developed. A comparison of these results and results of solution of the inverse problem of heat and mass transfer [10] shows that the values of the heat-flux density differ by approximately 11% at the time $t_* = 0.192$ sec (first

TABLE 1

Probe	V, mm/sec	t_*, sec	δ, mm	δ_{opt}, mm	t_{opt}, sec	A, K/sec	$q \cdot 10^{-7}$, W/m^2
1	1.50	0.192	2.870	1.743	0.27	818.18	0.81
2	3.90	0.560	1.115	1.115	0.56	5333.30	2.10

probe), and the difference is about 22% at the time $t_* = 0.56$ sec (second probe). The difference in results obtained by the two methods is mainly caused by the fact that Abaltusov et al. [10] ignored the variation of the mean fracture velocity of the target by a heterogeneous jet.

The experiments conducted with three-layered targets consisting of different materials show that the rate of heat propagation over the depth of a steel plate does not exceed the fracture velocity as the pressure varies within the range $P = (50\text{–}150) \cdot 10^5$ Pa, which agrees with the data of [10]. This is evidenced by the data of thermocouples located at the back wall of the external plate. For $P > 150 \cdot 10^5$ Pa, the thermocouple is destroyed earlier than the heating of the steel plate is registered. Hence, for $P > 150 \cdot 10^5$ Pa, the velocity of the front of mechanical destruction is greater than the velocity of heat propagation over the depth.

Thus, the experimental technique proposed allows one to determine the basic characteristics of heat and mass transfer (temperature and fracture velocity, heat flux on the destroying surface) between high-temperature heterogeneous jets with a high concentration of particles and the surface of structural materials.

REFERENCES

1. Yu. V. Polezhaev and D. S. Mikhatulin, "Erosion of surfaces in heterogeneous flows," Preprint No. 2-277, Inst. High Temp., USSR Acad. of Sciences, Moscow (1989).
2. R. H. Kirchhoff, "Calorimetric heating-rate probe for maximum-response-time interval," *AIAA J.*, **2**, No. 5, 966–967 (1964).
3. O. M. Alifanov and I. V. Repin, "Investigation of heat transfer in heterogeneous flows by the method of inverse heat-conduction problems," *Teplofiz. Vys. Temp.*, **31**, No. 1, 78–82 (1993).
4. O. M. Alifanov, E. A. Artyukhin, A. V. Nenarokomov, and I. V. Repin, "Determination of the characteristics of thermal interaction of materials with two-phase flows by methods of inverse heat-conduction problems," *Teplofiz. Vys. Temp.*, **31**, No. 3, 450–458 (1993).
5. V. E. Abaltusov, S. G. Gaga, I. K. Zharova, and V. F. Pinkin, "Heat and mass transfer upon thermoerosion action of a high-temperature heterogeneous jet on a target," in: *Identification of Dynamic Systems and Inverse Problems*, Proc. II Int. Conf. (St. Petersburg, August 22–25, 1994), Part 2, Inst. of Precise Mech. and Optics, St. Petersburg (1994), pp. 11–18.
6. V. E. Abaltusov, N. N. Alekseenko, T. N. Nemova, and V. A. Shandakov, "Experimental investigation of thermoerosion fracture of materials upon their interaction with high-temperature heterogeneous flows," in: Proc. 1st Int. National Conf. on Heat Transfer (Moscow, November 10–14, 1994), Vol. 7, Moscow Energ. Inst. (1994), pp. 13–18.
7. R. E. Sorkin, *Theory of Intrachamber Processes in Solid-Propellant Rocket Systems* [in Russian], Nauka, Moscow (1983).
8. V. E. Abaltusov and I. K. Zharova, "Determination of thermal boundary conditions from temperature measurement data," *Izv. Sib. Otd. Akad. Nauk SSSR, Ser. Tekh. Nauk*, **2**, No. 7, 33–38 (1987).
9. V. Ya. Borovoi, *Gas Flow and Heat Transfer in Regions of Shock Wave/Boundary Layer Interaction* [in Russian], Mashinostroenie, Moscow (1983).
10. V. E. Abaltusov, S. G. Gaga, I. K. Zharova, et al., "Determination of the characteristics of heat and mass transfer on the surface of a target breaking down under the action of a supersonic heterogeneous jet," in: *Heat and Mass Transfer*: Abstracts of III Int. Forum (Minsk, May 20–24, 1996), Vol. 1, Part 2, Inst. Heat and Mass Transfer, Minsk (1996), pp. 227–231.