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A study of convective heat fluxes for materials interacting with dust-loaded flows by inverse problems method

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Abstract

An algorithm of a computational and an experimental study of heat transfer in the vicinity of the critical points of a specimen in a high-enthalpy dust-loaded flow are presented. The unknown parameters of the heat-balance equation at the external moving boundary of the specimen are determined by solving an inverse problem of heat transfer by the method of iterative regularization. The results of experimental data processing for the interaction of dust-loaded flows with the plane surfaces of cylindrical specimen are also presented.

Keywords: Dust-loaded flows; Inverse problems; Parameter estimating

1. Introduction

Identification of system parameters in the development of new materials and processes has been the prime goal in understanding and defining the relevant systems. Under development is an approach to a study of hightemperature thermal processes based on the principles of identification of nonlinear systems with distributed parameters. One of the main difficulties is how to determine the coefficients of a model, which would simulate real processes. Models based on the method of solution of boundary inverse heat conduction problems are also widely used in the experimental investigations of the thermal interaction between solids and the environment. By solving such inverse problems, the boundary conditions and nonstationary temperature field are reconstructed from the interior temperature distribution in solids.

Presently, heat and mass transfer in heterogeneous media are being studied intensively [1,2]. This interest is associated with the important practical applications of the results of such investigations in aerospace technology, nuclear power engineering, turbine manufacture, chemical technology, and other fields. In analyzing the thermal operating conditions of machines and units, the investigation of the mechanism of thermal and thermomechanical interaction of a high-rate dust loaded flow with the constructional material is an important problem. Heat flux measurements for the purpose of solving such problems are currently based on the use of a calorimetric or the thin-wall method. However, the basic deficiency of these methods is the requirement of conservation of either the calorimeter mass or the wall thickness during the course of the experiment. This significantly limits the measurement time, since with the prolonged action of a two-phase flow on a calorimeter or on a thin wall erosion breakdown begins. As a result, such methods cannot easily take into account the influence on the heat transfer of such factors as the particles ejected from the surface due to erosion, the change in the shape of the surface, the development of surface roughness, etc.

The present work describes a method of processing and analyzing experimental data based on the methods of solution of inverse heat transfer problems. It permits the investigation of two-phase heat transfer in surface erosion and the creation of an approximate mathematical model, which take into account the influence of various determining factors. The solution of the problem is constructed as follows: First, an approximate mathematical models are considered; this

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Nomenclature

b	length of a specimen	m
C	volumetric heat capacity	$J \cdot m^{-3} \cdot K^{-1}$
f	experimental measurements	K
G	mass rate	$kg \cdot m^{-2} \cdot sec^{-1}$
g	increment of unknown function	$W \cdot m^{-2}$
J	minimized (residual) functional	K^2
M	numbers of temperature measurements	
q	heat flux	$W \cdot m^{-2}$
s	iteration number	
T	temperature	K
u	unknown (desired) function	
$\bar{u}$	unknown (desired) parameters vector	
V	velocity	$m \cdot sec^{-1}$
x	spatial coordinate	m
X	thermocouples position	m

Greek symbols

γ	descent step	
δ	measurements error	K^2
λ	thermal conductivity	$W \cdot m^{-1} \cdot K^{-1}$
ϑ	temperature increment	K
σ	deviation of measurements	K
τ	time	sec
ψ	adjoint variable	$K^2 \cdot m^2 \cdot W^{-1}$

Subscripts

er	related to erosion
g	related to gas
m	thermosensors number
p	related to solid particles
w	related to external (exposed) surface

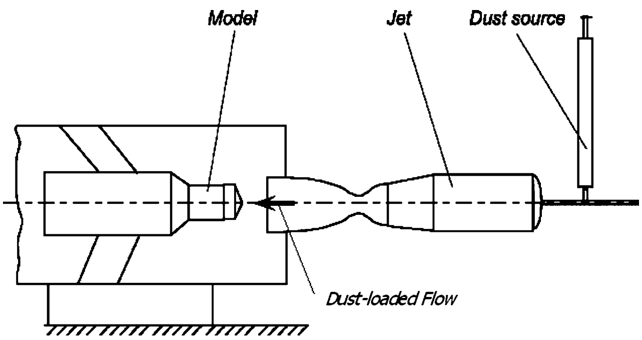

Fig. 1. Experimental facilities.

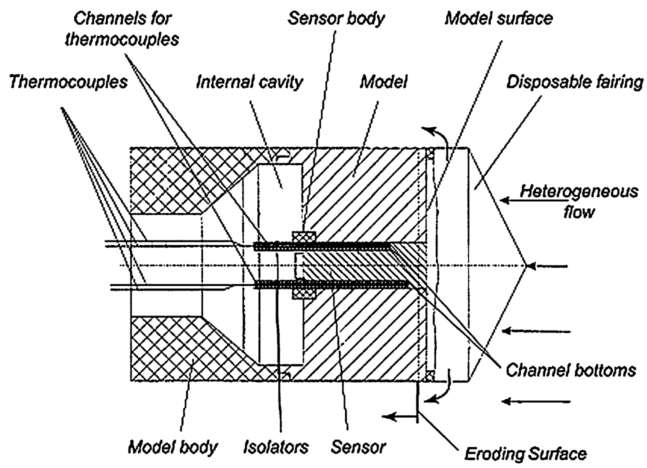

Fig. 2. Experimental module.

model takes into account the factors determining the two-phase heat transfer and includes the corresponding unknown characteristics. Then, using the results of measurements for the parameters of the incoming flow, the heating and the entrainment of material in the experiments, the inverse problem for the determination of the unknown characteristics is solved the two-phase heat transfer identification.

The experiments are conducted in a gas-dynamic tube specially designed for modeling dust-loaded flows in tubes. Solid 250 μm diameter particles are introduced into the gas flow through a special particle source (Fig. 1). The uniformity of the particle distribution over the flow cross-section and the steady flow rate of the particles during the experiment are ensured by a special supply system. A supersonic two-phase flow is formed in a nozzle, the profile of which ensures the most effective acceleration of the particles.

In the experiments, the mass concentration of particles in the flow is about 1%; this means that both the volume occupied by the particles and their mechanical and thermal effects on the gas may be neglected. Using well-known numerical methods, the gas-dynamic parameters are then determined over the whole flow region without taking the solid particles into account. The particle velocities are calculated as described in [3]. In the calculations, the following assumptions are made: the gas is perfect, non-viscous, and a nonconductor of heat; the gas viscosity and heat transfer are only taken into account in the action of the gas on the particle; the particles do not interact with one another and are spherical in form.

Experimental investigation of the thermal interaction of the dust-loaded flow with the material is conducted at a special calorimetric module (Fig. 2). The module is fitted with a disposable fairing to protect model surface from the action of high-temperature two-phase flow during the period when the gas-dynamic tube is reaching the steady operating conditions. After reaching the steady conditions and disposing of the deflector, the dust-loaded flow begins to act on the model surface. There is then intensive heating and erosional destruction of the material. Since the experimental model and the sensor are made of the same material (copper), a uniform front over the whole erosional surface is

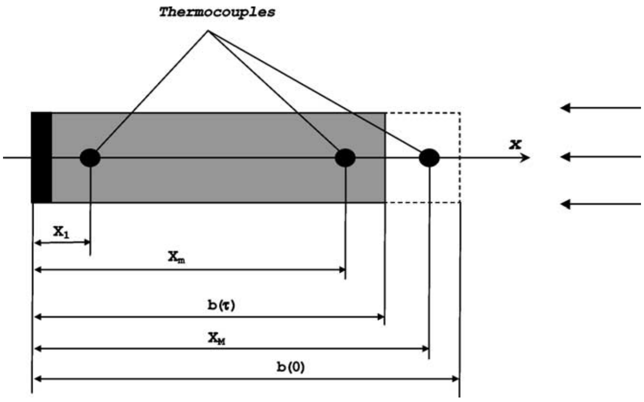

Fig. 3. Model for calculations.

ensured. The lateral surface of the sensor is both thermally and electrically insulated. Thermocouples are made with a dispersed "hot" junction and installed over the length of the sensor at different distances from the heated surface. This means that the change in the length of the sensor as a result of erosional destruction may be determined from the instant, when the thermocouple readings cease. (When the moving surface passes directly through the position of the thermocouple hot junction, the readings are significantly changed.)

The structure of the specimen permits the use of a one-dimensional mathematical model of thermal conduction (Fig. 3). The heat transfer in the specimen is governed by the heat-conduction equation:

$$C(T)\frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x}\left(\lambda(T)\frac{\partial T}{\partial x}\right)$$
$$T = (x,\tau), \quad x \in \big(0, b(\tau)\big),\ \tau \in (\tau_{\min}, \tau_{\max}] \tag{1}$$

where

$$b(\tau) = b(\tau_{\min}) - \int_{\tau_{\min}}^{\tau} V_{\mathrm{er}}\,\mathrm{d}\tau$$

is the coordinate of the specimen's external surface heated by a two-phase flow and undergoing erosion, and V_{er} is the linear rate of erosion. The values $\tau_{\min}$ and $\tau_{\max}$ are the times at which the experiment begins and ends. The initial temperature distribution and the boundary condition at the internal boundary are known, and take the form

$$T(x,\tau_{\min}) = T_0(x), \quad x \in \big[0, b(\tau_{\min})\big] \tag{2}$$

$$T(0,\tau) = T_1(\tau), \quad \tau \in (\tau_{\min}, \tau_{\max}] \tag{3}$$

At the external boundary (exposed to the dust-loaded flow) the following conditions are considered [4]:

$$-\lambda(T)\left(\frac{\partial T}{\partial x}\right)_{\omega} = q_2(\tau)$$
$$\left(\frac{\partial T}{\partial x}\right)_{\omega} = \frac{\partial T(b(\tau),\tau)}{\partial x} \tag{4}$$
$$q_2(\tau) = u \quad \text{(parameters of the dust} - \text{loaded flow)}$$
$$\tau \in (\tau_{\min}, \tau_{\max}]$$

where q_2 is the heat flux in the vicinity of the critical point. The theoretical estimates of q_2 provide only tentative values of this function [1]. Therefore, its value is usually estimated experimentally. If the identification technique is used, the required parameter is estimated from the available experimental information on the process under consideration. In formulating the inverse problem, we assume that certain information on the thermal statement of a specimen is available from the measurements, usually thermocouple nonstationary measurements at several internal points of the specimen. A mathematical formulation of such an inverse heat conduction problem for a slab takes the following form: $u(\tau)$ from mathematical model (1)–(4) is the desired boundary condition. Besides, the results of M temperature measurements in the internal points are available:

$$T_{\exp}(X_m,\tau) = f_m(\tau)$$
$$X_m \in \big[0, b(0)\big],\ m = 1,\dots,M \tag{5}$$

In addition, it is necessary to use experimental data on the time dependence of the specimen length $b(\tau)$, as well as on the parameters of the gas flow, and the diameter, velocity V_p and mass rate G_p of the solid particles to estimate the influence of these parameters on the desired function.

2. Inverse problem and its solution

One of the more promising directions in solving inverse heat conduction problems is to reduce them to extreme formulations and apply numerical methods of the optimization theory. In the exact extreme statement, the definition of the function $u(t)$ corresponds to the minimization of the residual functional $J(u(\tau), T(x,\tau), f_m(\tau),\ m = 1,\dots,M)$ characterizing a deviation of temperature $T(x,\tau)$ calculated for a certain density $u(\tau)$ from known temperatures $f_m(\tau)$, $m = 1,\dots,M$ in metric of space F of the input data.

The problem of determining the function $u(\tau)$ is solved by means of minimization of the residual functional, which is the mean-square deviation of temperatures calculated at the internal boundary using the mathematical model (1) to (4) from the experimental temperatures:

$$u = \arg\min_{u\in U} J(u) \tag{6}$$

where

$$J(u) = \sum_{m=1}^{M} \int_{\tau_{\min}}^{\tau_{\max}} \big(T(X_m,\tau) - f_m(\tau)\big)^2\,\mathrm{d}\tau \tag{6a}$$

is a functional in the space of functions $u(\tau)$ and its numerical value is the distance in the functional space L_2 between the given and calculated temperatures. Two approaches are possible to solve the extreme problem (6): (1) the solution is sought in a finite dimensional space R^N or (2) the problem is solved in any appropriate functional space U [5]. In the latter case, the choice of space U

depends on a priori information available about the unknown characteristics.

To realize the first approach the unknown function can be approximated in any form

$$u(\tau)=\sum_{k=1}^{N_p} u_k\varphi_k(\tau) \tag{7}$$

where u_k, $k=1,\dots,N_p$ are constant parameters, $\varphi_k(\tau)$, $k=1,\dots,N_p$ are a given system of basis functions for which different functions can be used; for example, polynomials, piecewise constant functions, B-splines and others.

The solution of problem (6) is obtained out with the help of conjugate gradient methods for an unconstrained minimization. The iterations are built in the following manner [3]:

$$u_k^s=u_k^{s-1}+\gamma^s g_k^s,\quad s=1,\dots,s^* \tag{8}$$

$$g_k^s=-\big(J_k'(u)\big)^s+\beta^s g_k^{s-1}$$
$$k=1,\dots,N_p,\qquad \vec{g}^0=0 \tag{8a}$$

$$\beta^s=\big\langle(\vec{J}')^s-(\vec{J}')^{s-1}\big\rangle_{R^{N_p}}/\big\|(\vec{J}')^s\big\|_{R^{N_p}}$$
$$s>1,\qquad \beta^1=0 \tag{8b}$$

The last iteration number s^* is chosen according to the iterative residual principle. It is possible to suppose that methods enabling the effective initiation of the iterative process from a distant approximation $u(\tau)$ and a sharp slowing down in approaching the functional minimum would appear useful when solving inverse heat conduction problems. Such a method of damping the instability when specifying an approximate solution for an ill-posed problem is based on "viscous" properties of numerical optimization algorithms. It is important to keep in mind that as the number of iterations increases an inverse problem solution can worsen, gradually losing its smooth character. Any waviness appearing in $u(\tau)$ will gain strength as fast as the increasing fluctuating errors amplify the initial temperature data and this effect will be greater for larger distances between the boundary with $u(\tau)$ condition sought and the point of temperature measurement. For this, a suggestion arises to halt the iterative process at a certain iteration $s=s^*$ without admitting a "shake up" of the solution.

The main question in such an approach is to select a halt criterion. A restriction to the residual level given as an error δ_f^2 including an error in temperature data and an approximation error in the boundary-value heat conduction problem can be used as such a condition. Thus, let us bind the iterative sequence (8) according to the condition

$$J\big(\bar{u}^{s^*}\big)\leqslant\delta_f^2 \tag{9}$$

where δ_f^2 is the integral temperature-measurement error

$$\delta_f^2=\sum_{m=1}^{M}\int_{\tau_{\min}}^{\tau_{\max}}\sigma_m^2\,\mathrm{d}\tau \tag{9a}$$

The gradient of the minimized functional is computed by using the solution of a boundary-value problem for an adjoint variable. The formula for the gradient is

$$J_k'=-\int_{\tau_{\min}}^{\tau_{\max}}\psi_{M+1}\big(b(\tau),\tau\big)\varphi_k(\tau)\,\mathrm{d}\tau,\quad k=1,\dots,N_p \tag{10}$$

where $\psi_{M+1}(b(\tau),\tau)$ is the solution at point $x=0$ of the following adjoint boundary-value problem, which has jumps in its derivative at points X_m, $m=1,\dots,M$. Therefore, it is convenient to consider a set of $M+1$ problems with M virtual internal boundaries:

$$C(T)\frac{\partial\psi_m}{\partial\tau}=-\frac{\partial}{\partial x}\left(\lambda(T)\frac{\partial\psi_m}{\partial x}\right)+\frac{\mathrm{d}\lambda}{\mathrm{d}T}\frac{\partial T}{\partial x}\frac{\mathrm{d}\psi_m}{\mathrm{d}x}$$
$$\psi_m=\psi_m(x,\tau),\quad x\in(X_{m-1},X_m),\ \tau\in[\tau_{\min},\tau_{\max})$$
$$m=1,\dots,M+1,\quad X_0=0,\quad X_{M+1}=b(\tau) \tag{11}$$

$$\psi_m(x,\tau_{\max})=0,\quad x\in\big[0,b(\tau_{\max})\big],$$
$$m=1,\dots,M+1 \tag{12}$$

$$\psi_1(0,\tau)=0,\quad \tau\in[\tau_{\min},\tau_{\max}) \tag{13}$$

$$\frac{\partial\psi_{M+1}}{\partial x}\big(b(\tau),\tau\big)=0,\quad \tau\in[\tau_{\min},\tau_{\max}) \tag{14}$$

$$\psi_m(X_m,\tau)=\psi_{m+1}(X_m,\tau)$$
$$\tau\in[\tau_{\min},\tau_{\max}),\ m=1,\dots,M \tag{15}$$

$$\lambda\frac{\partial\psi_m}{\partial x}(X_m,\tau)-\lambda\frac{\partial\psi_{m+1}}{\partial x}(X_m,\tau)$$
$$=2\big(T(X_m,\tau)-f_m(\tau)\big)$$
$$\tau\in[\tau_{\min},\tau_{\max}),\quad m=1,\dots,M \tag{16}$$

The descent parameter γ^s in (8) is determined from the condition

$$\gamma^s=\arg\min_{\gamma\in R^+}J\big(\vec{u}^s+\gamma\vec{g}^s\big) \tag{17}$$

where $\vec{u}=\{u_1,u_2,\dots,u_{N_p}\}$ and $\vec{g}=\{g_1,g_2,\dots,g_{N_p}\}$. A linear estimation is used for the determination of the descent step. It can be calculated as

$$\gamma^s=\left(\sum_{m=1}^{M}\int_{\tau_{\min}}^{\tau_{\max}}\big(T(X_m,\tau)-f_m(\tau)\big)\vartheta(X_m,\tau)\,\mathrm{d}\tau\right)\times\left(\sum_{m=1}^{M}\int_{\tau_{\min}}^{\tau_{\max}}\vartheta^2(X_m,\tau)\,\mathrm{d}\tau\right)^{-1} \tag{18}$$

where $\vartheta(x,\tau)$ is the Frechet differential of $T(x,\tau)$ at point $u(\tau)$ and is the solution of the corresponding linear boundary-value problem for temperature increment at point $u(\tau)$, when it is supposed that $\mathrm{d}u(\tau)=\sum_{k=1}^{N_p}g_k^s\varphi_k(\tau)$ (look at (8a) and (17))

$$C\frac{\partial\vartheta}{\partial\tau}=\frac{\partial}{\partial x}\left(\lambda\frac{\partial\vartheta}{\partial x}\right)+\frac{\mathrm{d}\lambda}{\mathrm{d}T}\frac{\partial T}{\partial x}\frac{\mathrm{d}\vartheta}{\mathrm{d}x}+\left(\frac{\mathrm{d}^2\lambda}{\mathrm{d}T^2}\left(\frac{\partial T}{\partial x}\right)^2+\frac{\mathrm{d}\lambda}{\mathrm{d}T}\frac{\partial^2T}{\partial x^2}-\frac{\mathrm{d}C}{\mathrm{d}T}\frac{\partial T}{\partial\tau}\right)\vartheta \tag{19}$$

$$\vartheta = \vartheta(x,\tau), \quad x \in \big(0, b(\tau)\big),\ \tau \in (\tau_{\min}, \tau_{\max}]$$

$$\vartheta(x,\tau_{\min}) = 0, \quad x \in [0, b(0)] \tag{20}$$

$$\vartheta(0,\tau) = 0, \quad \tau \in (\tau_{\min}, \tau_{\max}] \tag{21}$$

$$-\lambda \frac{\partial \vartheta}{\partial x}\big(b(\tau),\tau\big) - \frac{\mathrm{d}\lambda}{\mathrm{d}T}\frac{\partial T}{\partial x}\vartheta\big(b(\tau),\tau\big) = \sum_{k=1}^{N_p} g_k^s \varphi_k(\tau), \quad \tau \in (\tau_{\min}, \tau_{\max}] \tag{22}$$

When using B-splines according to [5], the time interval is divided into N parts and a uniform grid is introduced

$$\omega = \big\{\ \tau_k = \tau_{\min} + k\Delta\tau,\ k = -2, -1, 0, \ldots, N+3 \quad \Delta\tau = (\tau_{\max} - \tau_{\min})/N\big\} \tag{23}$$

The function

$$B^{(j-1)} = B^{(j-1)}(\tau_k, \tau_{k+1}, \ldots, \tau_{k+j}, \tau) = \sum_{s=k}^{k+j} \frac{(\tau_s - \tau)_+^{j-1}}{\omega_k'(\tau_s)} \tag{24}$$

where

$$\omega_k' = (\tau - \tau_k)(\tau - \tau_{k+1}) \cdots (\tau - \tau_{k+j}) \tag{25}$$

$$(\tau_s - \tau)_+^{j-1} = \max\big\{0, (\tau_s - \tau)^{j-1}\big\} \tag{26}$$

is called B-spline of the $(j-1)$ degree relative to the nodes $\tau_k, \tau_{k+1}, \ldots, \tau_{k+j}$. When solving practical problems, B-splines are used with the so-called "natural" boundary conditions:

$$u''(\tau_{\min}) = u''(\tau_{\max}) = 0 \tag{27}$$

Then, in the case of cubic B-splines $(j-1=3)$, the unknown function is presented as

$$u(\tau) = \sum_{k=1}^{N_p} u_k \varphi_k(\tau) \tag{28}$$

where

$$\varphi_1(\tau) = 2B_0(\bar\tau + \Delta\tau) + B_0(\bar\tau)$$
$$\varphi_2(\tau) = -B_0(\bar\tau + \Delta\tau) + B_0(\bar\tau - \Delta\tau)$$
$$\varphi_k(\tau) = B_{k-1}(\bar\tau), \quad k = 3, \ldots, N_p - 2$$
$$\varphi_{N_p-1}(\tau) = B_0\big(\bar\tau - (N_p - 2)\Delta\tau\big) - B_0(\bar\tau - N_p\Delta\tau)$$
$$\varphi_{N_p}(\tau) = B_0\big(\bar\tau - (N_p - 1)\Delta\tau\big) + 2B_0(\bar\tau - N_p\Delta\tau)$$

and

$$B_k(\tau) = B_0(\bar\tau - k\Delta\tau) \tag{29}$$
$$\bar\tau = \tau - \tau_{\min}$$
$$N_p = N + 1$$
$$B_0(\tau) = \big((\tau + 2\Delta\tau)_+^3 - 4(\tau + \Delta\tau)_+^3 + 6(\tau)_+^3 - 4(\tau - \Delta\tau)_+^3 + (\tau - 2\Delta\tau)_+^3\big)/\big(6\Delta\tau^3\big) \tag{30}$$

The function $B_0(\tau)$ has the property

$$B_0(\tau) = \begin{cases} > 0, & \text{if } -2\tau < \tau < 2\tau \\ = 0, & \text{if } |\tau| \geqslant 2\tau \end{cases} \tag{31}$$

This property makes the computational algorithm simpler.

In solving any particular inverse problem, the choice of the number of parameters of the unknown characteristics approximation N_p should be justified. As a rough approximation, the heat conduction mathematical model used may be inadequate with respect to the real process. As a result, it becomes impossible to obtain a satisfactory correspondence between the calculated and measured temperature values by means of changing the approximation parameters in the process of residual functional minimization. The greater the number of parameters, the better is the correspondence; however, the sensitivity of the considered temperature values to small variations of the unknown parameters becomes less.

Through numerical simulation, the following quite obvious approach has been proposed and substantiated:

(1) Begin with the minimum possible number of approximating functions N_p (e.g., 1—for polynomials, 3—for cubic B-splines with "natural" boundary conditions, etc.).
(2) Solve the problem of unknown parameters determination through a method of iterative regularization;
(3) if in the iterative process we achieve an error level (9), i.e., δ_f^2, a procedure of parametric identification is completed; should the functional converge to value $J(u) > \delta_f^2$, we must increase the number of approximation parameters and return to step 2.

3. Experimental validation

In implementing the algorithm described, the boundary-value problems are solved numerically by finite differences on an implicit four-point scheme. In the numerical solution, the direct nonlinear problem is treated by iteration in the coefficients. The approximation of the three boundary-value problems is carried out on the one and the same difference grid, making it possible to achieve error matching. Below, we provide results from the processing the experimental data obtained during the six tests at the experimental device. The tests differed from each other by the mass-discharge values of the solid phase. The particle diameter of the solid phase was 250 µm. The velocity of the solid particles was $V_p = 1083\ \mathrm{m\cdot sec^{-1}}$, the gas velocity was $V_g = 1797\ \mathrm{m\cdot sec^{-1}}$, and the mass flow rate of the gas was $G_g = 1490\ \mathrm{kg\cdot m^{-2}\cdot sec^{-1}}$. Variations of the lengths of the specimens, $b(\tau)$, as a result of erosional destruction in the course of the experiments are shown in Fig. 4(a). The measured temperature at the insolated internal (left) surface of specimen are presented in Fig. 4(b). The remaining parameters (solid particles mass rate and temperature of gas flow) are given in Table 1.

Cylindrical specimens of radius 40 mm, prepared from copper, had different initial lengths $b(0)$ (Fig. 4), as well as the numbers and coordinates of the thermocouples installed in the transducers (Table 1). While one of the thermocouples was located on the left surface ($x = 0$) and the remaining (one or two) at the internal points of the transducers, located in the vicinity of the critical point (center) of the model. The results of the thermocouple measurements in all specimens are shown in Fig. 5. In solving the inverse problem, the experimental data obtained in six tests were analyzed. The temperatures calculated in these cases at the points of the thermocouple installations are also given in Fig. 5. The estimations of the heat flux q_2 and the temperature of the external surface $T(b(\tau), \tau)$ as results of the experimental data processing are presented in Fig. 6. The results from the experimental data reveal a reasonably good agreement between the measured and calculated temperatures (Fig. 5).

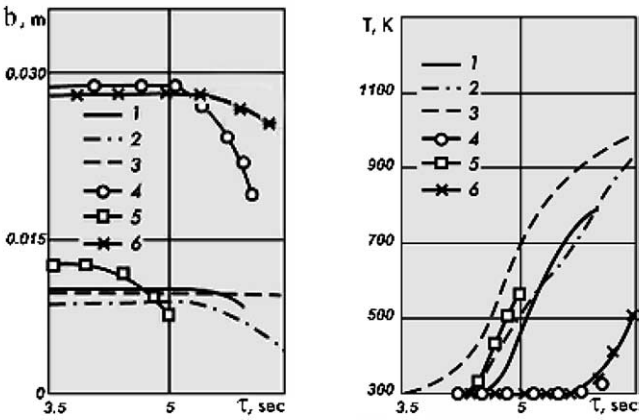

Fig. 4. Erosional destruction of specimens (a) and temperature at left (internal) boundaries (b) from six tests.

Table 1
Experimental data

No, of tests	G_p [kg·m^{-2}·sec^{-1}]	T_g [K]	V_{er} [kg·m^{-2}·sec^{-1}]	X_1 [m]	X_2 [m]
1	5.1	1451	2.51	0.0077	0.0083
2	6.9	1493	3.52	0.0049	–
3	0	1481	0.0	0.0093	–
4	7.2	1712	3.91	0.023	–
5	7.8	1779	4.14	0.0061	0.0075
6	2.1	1820	0.0	0.0041	0.005

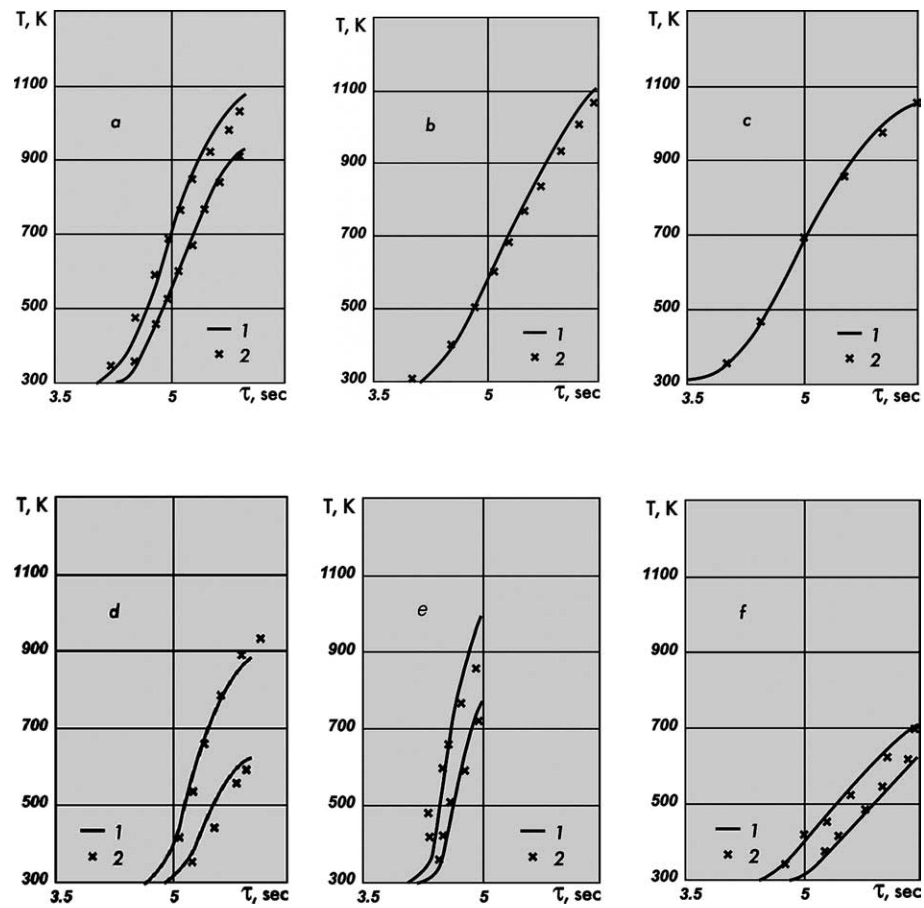

Fig. 5. Experimental (1) and calculated at the points of thermocouples installations (2) temperatures. (a) test 1, (b) test 2, (c) test 3, (d) test 4, (e) test 5, (f) test 6.

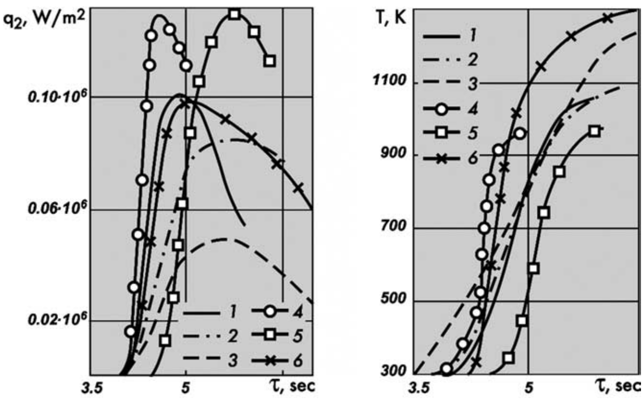

Fig. 6. Estimated heat fluxes and temperatures at the right (exposed) surfaces (6 tests).

4. Conclusions

In this paper, a method of formulation is presented for the solution of an inverse problem for the interaction between materials and dust-loaded high-enthalpy flows with the objective to investigate the influence of different factors on the intensity of heat transfer. The implementation of the optimization problem of the inverse formulation is carried out by the conjugate gradient method, while the direct adjoint and incremental problems in each iteration are solved by finite differences.

Determining the function q_2 in the boundary condition (4) from the temperature measurements at several internal points of the specimen X_m, $m = 1, \ldots, M$, is an well-known boundary inverse heat conduction problem [5]. This problem is solved for each experiment using the presented method. The results of the presented study indicate that, with increase in mass concentration of the incoming particles up to 1%, the heat flux reaching the material is about twice of that in the case of a flow with no particles. At the same time, the external-surface temperature does not reach the melting point of copper, which indicates mechanical erosion of the specimen material interacting with dust-loaded flow.

The results presented in this work should be considered to be another step toward the construction of adequate mathematical models that describe the interaction of materials with dust-loaded flows. Further parametric studies and tests on more complicated cases remain to be done in the future with preliminary experimental designs [6] to develop more complex mathematical models of heat transfer.

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