of the surrounding medium in a single-flow heat exchanger. For the latter, $Z(\tau) \equiv 1$, so that in this case τ_Z may be excluded from consideration.

NOTATION

τ, time, sec; x, normalized coordinate; T, temperature, K; C_p, isobaric specific heat, J/kg·K; G, heat-carrier flow rate, kg/sec; ρ, density, kg/m^3; Ω, pipeline volumes, m^3; α, heat-transfer coefficients, W/m^2·K; Π, heat-transfer surface, m^2; q, effective heat fluxes, W. Indices: S, forward flow; R, reverse flow; w, dividing wall.

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SOLUTION OF INVERSE PROBLEMS FOR A SYSTEM OF QUASILINEAR EQUATIONS OF HEAT CONDUCTION IN A SELF-SIMILAR REGIME

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Explicit solutions are obtained for inverse problems for a system of heat-conduction equations in a self-similar regime. The thermophysical characteristic being sought depend on the temperature distribution.

Mathematical modeling of a stationary heat-exchange process in two semiinfinite rods of different materials, joined by an "ideal" contact, is closely connected with the solution of an inverse problem concerned with the determination of the coefficients in the following system of nonlinear differential equations:

$$C_n(T_n)\,\frac{\partial T_n}{\partial t} = \frac{\partial}{\partial x}\left[\lambda_n(T_n)\,\frac{\partial T_n}{\partial x}\right] + \sum_{i=1}^{M_n} q_{in} t^{-3/2}\delta(x - x_i),$$
$$(x,\ t) \in \Omega_n, \tag{1}$$

with initial and boundary conditions

$$T_1(x,\ 0) = u_1, \quad x < 0, \quad T_2(x,\ 0) = u_2, \quad x > 0, \tag{2}$$

$$T_1(0,\ t) = T_2(0,\ t); \quad \lambda_1(T_1)\,\frac{\partial T_1}{\partial x}\bigg|_{x=0} = \lambda_2(T_2)\,\frac{\partial T_2}{\partial x}\bigg|_{x=0}, \quad t > 0, \tag{3}$$

where u_n are given constants, n = 1, 2.

The system (1)-(3) admits a self-similar solution of the form $T_n(x, t) = v_n(z)$, where $z = xt^{-1/2}$ and the function $v_n(z)$ satisfy the equations

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$$\frac{d}{dz}\left[\lambda_n(v_n)\frac{dv_n}{dz}\right]+\frac{1}{2}zC_n(v_n)\frac{dv_n}{dz}+\sum_{i=1}^{M_n}q_{in}\delta(z-z_i)=0,\quad z\in D_n, \tag{4}$$

and the conditions

$$v_1(-\infty)=u_1,\quad v_2(+\infty)=u_2, \tag{5}$$

$$v_1(0)=v_2(0),\quad \lambda_1(v_1)\frac{dv_1}{dz}\bigg|_{z=0}=\lambda_2(v_2)\frac{dv_2}{dz}\bigg|_{z=0}. \tag{6}$$

Our aim is to solve an inverse problem concerned with determination of the coefficients of Eq. (1). It is clear that Eqs. (1)-(3) are insufficient for determination of these coefficients. It is therefore necessary to adjoin additional conditions to system (1)-(3). We introduce several such typical conditions commonly employed in solving inverse problems:

$$T_n(\eta_n, t)=\varphi_n(t),\quad \eta_n\in D_n,\quad t>0, \tag{7}$$

$$T_n(x, t_{ob})=\psi_n(x),\quad x\in D_n,\quad n=1, 2. \tag{8}$$

Each of conditions (7), (8) has a real physical meaning. Functions $\psi_n(x)$ give the temperature distribution at the instant of observation $t = t_{ob}$; functions $\phi_n(t)$ yield the temperature values at points $\eta_n \in D_n$ for all times $t > 0$. By assigning the functions $\phi_n(t)$ or $\psi_n(x)$, the functions $v_n(z)$, and hence also the functions $T_n(x, t)$, are determined uniquely. Actually,

$$T_n(x, t)=v_n\left(\frac{x}{\sqrt{t}}\right)=\varphi_n\left(\eta_n^2\frac{t}{x^2}\right)=\psi_n\left(\frac{x}{\sqrt{t}}\sqrt{t_{ob}}\right),\quad x\in D_n,\ t>0. \tag{9}$$

Functions $T_n(x, t)$ are classical solutions of boundary-value problem (1)-(3). It is natural to assume that the functions $\phi_n(t)$, $\psi_n(x)$ satisfy compatibility conditions, i.e.,

$$\varphi_1(0)=u_1,\quad \varphi_2(0)=u_2,\quad \varphi_1(+\infty)=\varphi_2(+\infty),\quad \psi_1(0)=\psi_2(0),$$
$$\psi_1(-\infty)=u_1,\quad \psi_2(+\infty)=u_2.$$

Conditions, different, in fact, from conditions (7), (8) exist which make it possible to determine a self-similar solution of system (1). In order to avoid considering each of these cases separately, we assume that self-similar solutions $v_n(z)$ of system (1) are given and that it is required to determine one or several of the coefficients of system (1). Using relations (9), it is not difficult to rephrase the conditions imposed on functions $v_n(z)$ onto the functions $\phi_n(t)$, $\psi_n(x)$, $n = 1, 2$. We introduce the notation $r_n \min_z v_n(z)$, $R_n = \max_z v_n(z)$ and assume that functions $v_n(z)$ have continuously differentiable inverses $F_n(v_n)$, defined on $[r_n, R_n]$ with domain of values on D_n, $n = 1, 2$.

Let $C_n(T) > 0$ be given continuous functions, and let q_{in} be given numbers. From Conditions (1)-(3), for the given functions $v_n(z)$, twice continuously differentiable, we are required to determine functions $\lambda_n(T)$, $n = 1, 2$, positive and continuous on $[r_n, R_n]$. We assume, in addition, that the number $\lambda_1(v_1(0)) = \kappa_0 > 0$ is also given.

We integrate Eq. (4) for $n = 1$ from z to 0; for $n = 2$ we integrate it from 0 to z; we then obtain

$$\lambda_1(v_1)\frac{dv_1}{dz}=\lambda_1(v_1(0))\frac{dv_1(0)}{dz}-\int_z^0\left[\frac{1}{2}\zeta C_1(v_1)\frac{dv_1}{d\zeta}+\sum_{i=1}^{M_1}q_{i1}\delta(\zeta-z_i)\right]d\zeta,\quad z<0,$$

$$\lambda_2(v_2)\frac{dv_2}{dz}=\lambda_2(v_2(0))\frac{dv_2(0)}{dz}-\int_z^0\left[\frac{1}{2}\zeta C_2(v_2)\frac{dv_2}{d\zeta}+\sum_{i=1}^{M_2}q_{i2}\delta(\zeta-z_i)\right]d\zeta,\quad z>0.$$

If in these expressions we take account of conditions (6) and the fact that $\lambda_1(v_1(0)) = \kappa_0$, we obtain

$$\lambda_n(v_n)=\left(\frac{dv_n}{dz}\right)^{-1}\left\{\varkappa_0\frac{dv_1(0)}{dz}-\int_0^z\left[\frac{1}{2}\zeta C_n(v_n)\frac{dv_n}{d\zeta}+\sum_{i=1}^{M_n}q_{in}\delta(\zeta-z_i)\right]d\zeta\right\}. \tag{10}$$

In these expressions we go over to the inverse functions $z = F_n(v_n)$:

$$\lambda_n(v_n) = \frac{dF_n(v_n)}{dv_n}\left\{\varkappa_0\left[\frac{dF_n(v_n(0))}{dv_n}\right]^{-1} - \int\limits_{v_n(0)}^{v_n}\left[\frac{1}{2}F_n(s)C_n(s) + \sum_{i=1}^{M_n} q_{in}\delta(F_n(s)-z_i)\right]ds\right\}. \quad (11)$$

The right hand member in relations (10), (11) is assumed to be continuous, positive, and bounded.

We remark that if the coefficients $\lambda_n(T) > 0$, q_{in} are given, the coefficients $C_n(T) > 0$ can be found by the method presented above. The unknown coefficients $C_n(T)$ in the system (1)-(3), when $\lambda_n(T)$ and q_{in} are given, can be calculated from the expressions

$$C_n(v_n) = -2\left[z\frac{dv_n(z)}{dz}\right]^{-1}\left\{\frac{d}{dz}\left[\lambda_n(v_n)\frac{dv_n}{dz}\right] + \sum_{i=1}^{M_n} q_{in}\delta(z-z_i)\right\}, \quad (12)$$

or, in terms of the inverse functions,

$$C_n(v_n) = -2F_n^{-1}(v_n)\left\{\frac{d}{dv_n}\left[\lambda_n(v_n)\left(\frac{dF_n(v_n)}{dv_n}\right)^{-1}\right] + \frac{dF_n(v_n)}{dv_n}\sum_{i=1}^{M_n} q_{in}\delta(F_n(v_n)-z_i)\right\}. \quad (13)$$

The right hand side of these relationships is assumed to be continuous and positive. Using expressions (10)-(13), we can determine the pairs of functions $\{C_k(T), \lambda_{3-k}(T)\}$, $k = 1$ or $k = 2$.

We consider now a process described by the following system of equations:

$$C_n(T_n)\frac{\partial T_n}{\partial t} = \frac{\partial}{\partial x}\left[\lambda_n(T_n)\frac{\partial T_n}{\partial x}\right] + (-1)^n[d(T_1)-d(T_2)], \quad x>0, \quad t>0, \quad (14)$$

subject to the conditions

$$T_n(x,t)|_{t=0} = 0, \quad x>0, \quad T_n(x,t)|_{x\to\infty} = 0, \quad t>0, \quad (15)$$

$$T_1(0,t) = T_2(0,t), \quad \left(\lambda_1(T_1)\frac{\partial T_1}{\partial x} + \lambda_2(T_2)\frac{\partial T_2}{\partial x}\right)\bigg|_{x=0} = qt^k, \quad t>0, \quad (16)$$

where $k > 0$, $q \neq 0$ are given constants.

We assume that $C_n(T) = C_{0n}T^\gamma$, $\lambda_n(T) = \lambda_{0n}T^\sigma$, $d(T) = d_0T^\nu$, where $\lambda_{0n} > 0$, $c_{0n} > 0$, $d_0 \neq 0$, γ and σ are some numbers, and $\nu = \gamma + 1 - 1/k$, $1 - (\gamma - \sigma)k > 0$. System (14), under conditions (15), (16), admits a self-similar solution of the form $T_n(x, t) = t^k v_n(z)$, where $z = x/t^{1-(\gamma-\sigma)k}$. The functions $v_n(z)$ then satisfy the conditions of the system

$$c_{0n}v_n^\gamma(z)\left[kv_n(z) - (1-(\gamma-\sigma)k)z\frac{dv_n(z)}{dz}\right] = \lambda_{0n}\frac{d}{dz}\left[v_n^\sigma(z)\frac{dv_n(z)}{dz}\right] + (-1)^n[v_1^\nu(z) - v_2^\nu(z)], \quad z>0 \quad (17)$$

$$v_n(+\infty) = 0, \quad v_1(0) = v_2(0), \quad \left(\lambda_{01}v_1^\sigma\frac{dv_1}{dz} + \lambda_{02}v_2^\sigma\frac{dv_2}{dz}\right)\bigg|_{z=0} = q. \quad (18)$$

Assume now that we wish to determine the coefficients $C_n(T) > 0$, $\lambda_n(T) > 0$, $d(T)$ of system (14); this amounts to finding the unknown constants in their expressions. Let $c_{02} > 0$, $\lambda_{01} > 0$, σ, γ be given constants; we wish to determine $c_{01} > 0$, $\lambda_{02} > 0$, $d_0 \neq 0$. Let

$$A_n = v_n^\gamma(z_1)\left[kv_n(z_1) - (1-k(\gamma-\sigma))z_1\frac{dv_n(z_1)}{dz}\right], \quad D = v_1^\nu(z_1) - v_2^\nu(z_1);$$

$$B_n = \frac{d}{dz}\left[v_n(z_1)\frac{dv_n(z_1)}{dz}\right], \quad E_n = v_n^\sigma(0)\frac{dv_n(0)}{dz}.$$

Let $v_n(0)$, $dv_n(0)/dz$ be given; also, at an arbitrary point $z_1 > 0$ let the values of the functions $v_n(z)$, dv_n/dz, d^2v_n/dz^2, and $(q - \lambda_{01}E_1)/E_2 > 0$, $[B_1E_2\lambda_{01} + B_2(q - \lambda_{01}E_1) - A_2E_2c_{02}]/A_1E_2 > 0$, $A_1DE_2 \neq 0$ be given.

System (17) is valid for an arbitrary $z \in (0, \infty)$. If we write system (17) at point z_1, make use of relations (18) and the notation adopted above, we obtain

$$A_1c_{01} - Dd_0 = B_1\lambda_{01}, \quad B_2\lambda_{01} - Dd_0 = A_2c_{02}, \quad E_2\lambda_{02} = q - E_1\lambda_{01}.$$

Under the above assumptions this system has a unique solution:

$$c_{01}=[B_1E_2\lambda_{01}+B_2(q-\lambda_{01}E_1)-A_2E_2c_{02}]/A_1E_2;\quad \lambda_{02}=(q-\lambda_{01}E_1)/E_2,$$
$$d_0=[B_2(q-\lambda_{01}E_1)-A_2E_2c_{02}]/DE_2. \tag{19}$$

An analogous formulation is valid if, instead of c_{01}, λ_{02}, d_0, we seek other numerical parameters.

Assume now that $\nu = \sigma + 1$, $\gamma = (k\sigma + \sigma + 1)k^{-1}$. From conditions (14), (16), and

$$T_n(x,\ 0)=0,\quad T_n(l,\ t)=0,\quad 0\leqslant x\leqslant l,\quad t>0, \tag{20}$$

we are required to find the coefficients of system (14), where $l > 0$ is a given number. In this case problem (14), (16), (20) admits a self-similar solution in the form $T_n(x, t) = \left(\frac{\sigma+1}{k}t\right)^{k/(\sigma+1)} v_n(x)$. Proceeding as we did non the derivation of formula (19), we obtain analogous expressions for the unknown numerical parameters.

Finally, we consider a process described by the system

$$\bar{C}_n\left(\frac{\partial T_n}{\partial x}\right)C_n(T_n)\frac{\partial T_n}{\partial t}=\frac{\partial}{\partial x}\left[\bar{\lambda}_n\left(\frac{\partial T_n}{\partial x}\right)\lambda_n(T_n)\frac{\partial T_n}{\partial x}\right]+\bar{d}_n\left(\frac{\partial T_n}{\partial x}\right)d_n(T_n) \tag{21}$$

with initial and boundary conditions

$$T_1(x,\ 0)=u_1,\quad x<0,\quad T_2(x,\ 0)=u_2,\quad x>0,\quad T_1(0,\ t)=T_2(0,\ t), \tag{22}$$

$$\lambda_1(T_1)\bar{\lambda}_1\left(\frac{\partial T_1}{\partial x}\right)\frac{\partial T_1}{\partial x}\bigg|_{x=0}=\lambda_2(T_2)\bar{\lambda}_2\left(\frac{\partial T_2}{\partial x}\right)\frac{\partial T_2}{\partial x}\bigg|_{x=0}. \tag{23}$$

Here $\bar{C}_n(P) = \bar{c}_{0n}P^{\sigma}$, $\bar{\lambda}_n(P) = \bar{\lambda}_{0n}P^{\sigma}$, $\bar{d}_n(P) = \bar{d}_{0n}P^{\sigma+2}$, and $C_n(T) \geq 0$, $\lambda_n(T) \geq 0$, $d_n(T)$ are continuous functions defined in $(-\infty, +\infty)$, u_n are given numbers, $\bar{c}_{0n} > 0$, $\bar{\lambda}_{0n} > 0$, $\bar{d}_{0n}$ and σ are certain numbers, n = 1, 2.

System (21) under conditions (22) and (23) admits a self-similar solution of the form $T_n(x, t) = v_n(z)$, where $z = xt^{-1/2}$. Functions $v_n(z)$ then satisfy conditions of the system

$$\frac{d}{dz}\left[\lambda_n(v_n)\bar{\lambda}_n\left(\frac{dv_n}{dz}\right)\frac{dv_n}{dz}\right]+\frac{1}{2}zC_n(v_n)\bar{C}_n\left(\frac{dv_n}{dz}\right)\frac{dv_n}{dz}+d_n(v_n)\bar{d}_n\left(\frac{dv_n}{dz}\right)=0, \tag{24}$$

$$v_1(-\infty)=u_1,\quad v_2(+\infty)=u_2,\quad v_1(0)=v_2(0), \tag{25}$$

$$\lambda_1(v_1)\bar{\lambda}_1\left(\frac{dv_1}{dz}\right)\frac{dv_1}{dz}\bigg|_{z=0}=\lambda_2(v_2)\bar{\lambda}_2\left(\frac{dv_2}{dz}\right)\frac{dv_2}{dz}\bigg|_{z=0}. \tag{26}$$

Problems considered for this case are the inverse problems of determining the coefficients $\lambda_n(T)$, the coefficients $C_n(T)$, and the coefficients $\bar{\lambda}_n(P)$, $\bar{C}_n(P)$, $\bar{d}_n(P)$, n = 1, 2. All of these problems are similar to those considered above. In all cases involving determination of thermophysical characteristics, explicit expressions are obtained which differ insignificantly from corresponding expressions obtained above. We consider as an example the problem of determining $\lambda_n(T)$, n = 1, 2.

Let $C_n(T) > 0$, $d_n(T)$ be given continuous and bounded functions; let $\bar{c}_{0n} > 0$, $\bar{\lambda}_{0n} > 0$, $\bar{d}_{0n}$ and σ be given numbers; it is then required to determine from the given self-similar solutions $v_n(z)$ the unknown coefficients $\lambda_n(T)$. Then proceeding as was done in the derivation of formula (11), we obtain the following expression for the unknown coefficients $\lambda_n(v_n)$ in problem (24)-(26):

$$\lambda_n(v_n)=\bar{\lambda}_{0n}^{-1}\left[\frac{dF_n(v_n)}{dv_n}\right]^{\sigma+1}\left\{\varkappa_0\left[\frac{dF_n(v_n)}{dv_n}\right]^{-\sigma-1}-\right.$$
$$\left.-\int\limits_{v_n(0)}^{v_n}\left[\frac{1}{2}\bar{c}_{0n}F_n(s)C_n(s)+\bar{d}_{0n}d_n(s)\left(\frac{dF_n(s)}{ds}\right)^{-1}\right]\left(\frac{dF_n(s)}{ds}\right)^{-\sigma}ds\right\}. \tag{27}$$

TABLE 1. Comparison of Exact and Approximate Values of the Coefficient $\lambda_1(v_1)$

I	II	III	IV	V	VI	VI	VIII
2,1813	0,6	0,6045	$-2,841\cdot10^{12}$	0,6067	$1,042\cdot10^{-3}$	0,5858	0,5417
2,3297	0,7	0,7091	$1,216\cdot10^{11}$	0,7104	$1,963\cdot10^{-2}$	0,6863	0,6359
2,4512	0,8	0,8132	$5,458\cdot10^{12}$	0,8201	$2,878\cdot10^{-2}$	0,7862	0,7277
2,5507	0,9	0,9170	$4,614\cdot10^{12}$	0,9294	$3,784\cdot10^{-2}$	0,8854	0,8164
2,6321	1,0	1,0204	$-2,544\cdot10^{12}$	1,038	$4,680\cdot10^{-2}$	0,9936	0,9015
2,6988	1,1	1,1235	$-7,353\cdot10^{13}$	1,146	$5,564\cdot10^{-2}$	1,081	0,9821
2,7534	1,2	1,2262	$-2,840\cdot10^{13}$	1,251	$6,432\cdot10^{-2}$	1,176	1,057
2,7981	1,3	1,3286	$5,543\cdot10^{12}$	1,354	$7,282\cdot10^{-2}$	1,270	1,126
2,8347	1,4	1,4307	$3,720\cdot10^{13}$	1,453	$8,109\cdot10^{-2}$	1,363	1,186

It is assumed there that the right-hand side of Eq. (27) is continuous and positive.

Equation (1) describes nonstationary heat-exchange processes in two semiinfinite rods of different materials, joined by an ideal contact [1]. In [2, 3] and other papers, the inverse problems considered involved determination of coefficients of a single equation in a self-similar regime. In the present paper consideration is given for the first time to a self-similar regime process for a system of equations.

In studying inverse problems it is of great importance to separate out those special regimes for which explicit solutions are possible. These solutions can be used as the basis for experimental methods of determining physical characteristics of media. In this regard, however, one must take into account an instability of a solution of inverse problems [4-7]. Examples show that the problems considered above are also unstable. Explicit formulas are convenient in that they make it possible to find the simplest, and sufficiently precise, stable algorithms for the solution of the problems in question. For this purpose, in the explicit formulas (10)-(13) the derivatives of the unknown functions and the improper integrals are replaced by corresponding regularized operators [4]. In the calculations the derivatives $dv(z)/dz$ are replaced by the expression $[v(z + h) - v(z)]h^{-1}$, where $h = \delta^{1-\alpha}$, and δ is an error in the representation of the function $v(z)$; α is a parameter, $\alpha\in(0, 1)$. Integrals over an unbounded domain are replaced by integrals over a bounded domain so that the remainder terms would not exceed errors in the initial data. These approximations are comparatively crude, but their simplicity simplifies the computational process.

We carried out numerical calculations on model examples. We supply one of these here. Suppose we wish to determine the coefficients $\lambda_1(v_1)$, $\lambda_2(v_2)$ from conditions (1)-(3) when $C_1(T) = C_2(T) = 1$, $q_{in} = 0$, $i = \overline{1, M_n}$, $n = 1, 2$, $T_1(-1, t) = 3 - \exp(-t^{-1/2})$, $T_2(1, t) = 1 + \exp(-t^{-1/2})$. It follows from Eq. (11) that $\lambda_1(T) = 0.5[1 - \ln(3 - T)]$, $\lambda_2(T) = 0.5[1 - \ln(T - 1)]$. It can easily be seen through direct verification that in this case $T_1(x, t) = 3 - \exp(xt^{-1/2})$, $T_2(x, t) = 1 + \exp(-xt^{-1/2})$ satisfy the system (1)-(3).

Table 1 shows the results of numerical calculations of the solution of the inverse problem for determining $\lambda_1(v_1)$ from conditions (1)-(3) when $T_1(-1, t) = 3 - \exp(-t^{-1/2})$, $T_2(1, t) = 1 + \exp(-t^{-1/2})$. Use was made here of formula (10). Here in column I we give the nodes of a nonuniform grid introduced in the interval [2, 3]; column II gives the exact values of $\lambda_1(v_1)$; column III shows the results of computations of $\lambda_1(v_1)$ from formula (10) when the error δ of the initial data is equal to zero. Here there is no need to introduce regularization. Column IV shows results of calculations when $\delta = 0.001$ without regularization. The results testify to the instability of the solution. In column V we give results of the calculations when $\delta = 0.001$, $\alpha = 0.5$, i.e., in this case regularization is applied. These results agree with the exact solution. Column VI shows results of calculations when $\delta = 0.001$, $\alpha = 1.5$. Lack of agreement of the calculated results with the exact solution is a consequence of the fact that the criterion for choosing the parameter α is violated, since $\alpha = 1.5$ and $\alpha\notin(0; 1)$. The condition $\alpha\in(0; 1)$ of regularization is violated [4]. Columns VII and VIII give results of calculations for errors $\delta = 0.03$ and $\delta = 0.15$ for $\alpha = 0.1$. They are in good agreement with the exact solution. Similar results hold also for $\lambda_2(v_2)$.

NOTATION

T_n, temperature; $C_n(T)$, volumetric heat capacity; $\lambda_n(T)$, thermal conductivity coefficient; q_{in}, density of point sources; x, coordinate; t, time; t_{ob}, instant of observation; M_n, number of sources; x_i, coordinates of sources; $\delta(x)$, Dirac delta-function; $D_1\{x : x < 1\}$; $D_2 = \{x : x > 0\}$; $\Omega_n = D_n \times\{t : t > 0\}$, $n = 1, 2$.

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