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SIMULATION OF HEAT AND AERODYNAMIC PROCESSES IN REGENERATORS OF CONTINUOUS AND PERIODIC OPERATION. II. INVESTIGATION OF THE PARAMETERS OF A GAS-TURBINE PLANT REGENERATOR OPERATING IN DYNAMIC AND QUASI-STATIONARY REGIMES

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A mathematical model for investigating the processes in regenerative heat exchangers is described. A finite-difference scheme of numerical integration is proposed for solving the conjugate problem on unsteady heat exchange between one-dimensional flows and a two-dimensional matrix wall. Test calculations were compared with the known data of other authors. The quasi-stationary and dynamic processes in a gas-turbine plant regenerator with a matrix packed with gauzes have been investigated. The optimum design parameters of such a regenerator and rotational speeds of its rotor that which provide a maximum heat efficiency of the regenerator at a minimum aerodynamic drag in it have been determined.

Introduction. In [1], we proposed a generalized, distributed, nonlinear mathematical model for investigating the processes in regenerators of continuous and periodic operation as well as a scheme of numerical integration and an algorithm for solving the conjugate problem on unsteady heat exchange between one-dimensional flows and a two-dimensional matrix wall and presented data of identification of the mathematical model proposed.

In the present work, we briefly discuss the computational algorithm and program and propose methods for reducing the problem considered for matrices with various packings (which are widely used in practice) to the problem for matrices packed with spheres and straight channels. With the example of a gas-turbine plant regenerator with a matrix packed with gauzes, the quasi-stationary and dynamic heat processes and aerodynamic processes occurring in regenerative heat exchangers are considered in detail, and the design parameters of such a regenerator and the rotational speeds of its rotor that provide a maximum heat efficiency of the regenerator at a nonzero aerodynamic drag in it are calculated. Atmospheric pressure regenerators with other packings of their matrices were investigated in [2].

Brief Description of the Computational Algorithm and Program. The program for calculating regenerators of continuous and periodic operation is based on the mathematical model and algorithm described in [1] and is written in terms of the FORTRAN language. The first version of this program was presented in [3]. The initial data for calculation are as follows:

a) type of regenerator; design parameters of the matrix; duration of one cycle τ_c; total number of cycles (revolutions); relative areas occupied by gas ψ_g, air ψ_a, and packings ψ_p in the matrix; amount of leakages in the packing;

b) type, properties, and input parameters of the heat-transfer agents and directions of their flows;

c) coordinate system for the heat-conduction equation; parameters of the numerical scheme; integration steps;

d) service parameters used in the calculation.

The matrices of regenerators are usually not symmetric relative to the flows in them and have circular or conditionally rectangular cross sections. They can be made with straight channels different in cross section or be packed with various bodies or gauzes.

The program developed can be used for calculation of a regenerator with two types of heat-transfer agents. In the nonlinear variant of calculation of the thermophysical properties, these agents are air and products of combustion

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of any organic fuels of definite composition. In the case where the linear dependence of the thermophysical properties on the temperature is considered, the program can be used for any ideal gases and their mixtures.

Using the program proposed, one can calculate

a) the regimes of heating a regenerator in the process of putting it into operation, the transient regimes, and the regimes of cooling the shut-down regenerator;

b) the regimes of quasi-stationary operation with a given period of cycles (rotational speed);

c) all the characteristics at a varying design parameter of the matrix.

In parallel with the above-listed calculations, calculations of the heat and mass balances can be done:

a) at each time step $\Delta\tau$, in each band Δz, and for the channel as a whole:

b) in each characteristic cycle of heating τ_g and cooling τ_a (the integral balances are calculated by both the input–output and the heat and mass accumulation);

c) in each complete cycle τ_c (revolution of the rotor in a continuous-operation regenerator) by analogy with the calculations in each characteristic cycle of heating τ_g and cooling τ_a.

By the calculation data obtained, one may judge the accuracy of the mathematical model and the computational algorithm.

The algorithm has been tested for a wide range of spatial and time steps. The data of the calculations done by the program, except for the data of testing the solution of the heat-conduction equations in different coordinates and the estimates of the heat and mass balances, were compared to the data of analytical solutions [4–8], the data of simplified calculations done by other authors for various regenerators [5, 7–9], and the data of model and natural experiments [7, 10–13]. These comparisons have revealed a satisfactory qualitative and quantitative agreement between the indicated data (within the completeness of the calculations and experiments done). Examples of such comparisons done for quasi-static operating regimes of regenerators are presented in [1].

Method of Calculating a Matrix with a Packing. The mathematical model and algorithm for calculating a matrix with a packing is presented in [1]. However, the method of calculating matrices packed with spheres, cylinders, Raschig and Pall rings, gauzes, Berl saddles, moulded bricks, or other bodies of arbitrary shape was not described in sufficient detail in this work. The idea of this method can be outlined in the following way. An arbitrary element is reduced to an equivalent spherical element and then the problem is reduced to the problem of calculation of a matrix with straight channels [1].

The computational algorithm includes the following main operations:

1. Calculation of the volume V_1 and the total surface F_1 of one element of the packing.

2. Calculation of the diameter of the equivalent continuous sphere d_{eq} with a ratio between its volume and surface equal to that of the packing element considered:

$$V_{sp} = (4/3)\,\pi r^3\,; \quad F_{sp} = 4\pi r^2\,; \quad V_{sp}/F_{sp} = (1/3)\,r\,; \quad d_{eq} = 2r_{eq} = 6V_{sp}/F_{sp} = 6V_1/F_1\,. \qquad (1)$$

In this case, it is assumed that the processes of heat transfer in such a sphere are identical to the processes of heat transfer in the packing element. This is true, by definition, for spherical packings. For the other packings, this statement will be taken as an axiom (which was verified by the comparative calculations done by the author for matrices packed with gauzes and Raschig rings [2]).

3. Calculation of the total number N_{eq} of equivalent spheres of volume $V_{eq} = \pi d_{eq}^3/6$, which, on condition that the volume $V_{m.m}$ of the matrix material of porosity ε comprises $1 - \varepsilon$ of the matrix volume V_m, is equal to

$$N_{eq} = V_{m.m}/V_{eq} = (1 - \varepsilon)\,V_m/(\pi d_{eq}^3/6)\,.$$

It will also be assumed that only one elementary sphere is contained in the integration band Δz. Then, on condition that the length of a channel is divided into I bands, the calculated number of channels N_{ch} will be equal to $N_{ch} = N_{eq}/I$ and their cross section, at a total cross section of the matrix S_m, will be

$$S = \varepsilon S_m/N_{ch}\,. \qquad (2)$$

4. Calculation of the equivalent aerodynamic and heat diameters by the method of calculating the heat-transfer coefficient and the aerodynamic drag of matrices packed with particles, proposed by F. W. Schmidt and A. J. Willmott [5], which is based on the reduction of the packing elements to spherical elements of equivalent volume. The equivalent aerodynamic diameter is determined as the diameter of the sphere whose volume is equal to V_1, and the equivalent heat diameter is determined as the volume of the neighboring voids divided by the surface of one element F_1:

$$d_{\mathrm{aer}} = \sqrt[3]{(6V_1/\pi)}\ ,\quad d_{\mathrm{h}} = (\varepsilon/(1-\varepsilon))\ 4V_1/F_1\ . \tag{3}$$

If the data available on the heat-transfer coefficient and the aerodynamic drag were related not to the reduced dimensions but to the physical ones, as was done by W. M. Kays and A. L. London in [8], preference was given to the natural formulation. For example, the natural region of integration of the heat-conduction equation for the case of a gauze packing is a cylinder with heat-insulated ends.

Examples of Calculations. Below is an example of calculation of the characteristics of a gas-turbine plant regenerator with a drum-type matrix packed with gauzes. It is presented, as Example 4, in the popular monograph of Kays and London [8].

In accordance with [8], the following initial data were used: flow rate, temperature, and pressure, 9.64 kg/sec, 675^{o}C, and 105,000 Pa for gas and 9.50 kg/sec, 168^{o}C, and 329,000 Pa for air; total cross section of the matrix, 3.47 m^2; relative sections of the matrix for gas and air, ψ_{g} = 71.5 and ψ_{a} = 28.5; matrix of thickness L = 21.2 mm is packed with gauzes (950 cells, on average, per running meter, porosity ε = 0.725) made of a wire 0.34 mm in diameter (δ = 0.17 mm) of alloyed steel (5% chromium, heat conduction 20 W/(m·K), heat capacity 500 J/(kg·K), density 7817 $\mathrm{kg/m}^3$); the rotational speed of the drum rotor, 26.5 rpm, corresponds to the period of one revolution τ_{c} = 2.27 sec (durations of the heating and cooling cycles τ_{g} = 1.62 and τ_{a} = 0.65 sec).

The leakages of heat-transfer agents, as in [8], were not taken into account. Kerosene (C = 85.87%, H = 14.13%) was used as the fuel. The coefficient of excess of air in the gas was taken to be 4.5. The thermophysical properties of the combustion products, air, and matrix were calculated by the program. The main parameters of the numerical scheme for all the variants were as follows: Δy = 1.1δ, Δz = 0.05L, and $\Delta\tau$ = 0.01τ_{c}. A scheme implicit in time with time and space parameters σ_τ = 0.7 and σ_z = 0.5 was used. For quasi-stationary regimes, the calculated number of revolutions was equal to 30. An element of the gauze packing was calculated in a cylindrical coordinate system.

Quasistationary Distribution of Parameters. A quasistationary distribution of the parameters of the heat-transfer agents over the length of a channel (the thickness of the matrix), calculated at nonequidistant relative instants of time comprising 0.01, 0.05, 0.1, 0.15, 0.2, 0.3, 0.4, 0.5, 0.7, and 1.0 (curves 1–10) of the time of the heating τ_{g} and cooling τ_{a} cycles, is presented in Fig. 1.

The rotational speed of the rotor of 26.5 rpm selected by Kays and London [8] for the type of regenerators considered was sufficiently effective. The operation of a regenerator at effective rotational speeds is fairly stable if the flow rates of the heat-transfer agents are virtually equal. In this case, the temperature, heat-transfer coefficient, velocity, and pressure of the heat-transfer agents are constant in the cross sections (input for them) and begin to vary with an increasing amplitude downstream of them (see Fig. 1). The graphs of the heat-transfer coefficients and velocities of the heat-transfer agents are similar to the graphs of their temperatures. The pressure gradients are higher in the zones of high temperatures at the input of the channel for gas and at the output of the channel for air.

The temperatures of the matrix at different instants of time are shifted practically equidistantly. The gradient of matrix temperatures along the length of the channel is very large and is equal to 20^{o}C/mm. The temperature distribution over the radius of the gauzes' wire in all the not input cross sections of the channel (in Fig. 1, only the distribution in the middle cross section is presented) indicates that the thin wire manages to heat up and the matrix temperature follows, with a small delay, the temperature of the heat-transfer agents. The highest rate of heating is observed at the initial instants of time.

Figure 2 shows a quasi-stationary time distribution of the parameters of the heat-transfer agents within one complete revolution of the rotor. The upper four graphs show the dynamics of the process in five equidistant cross sections measured from the input for gas along the length of the channel. In the input cross section (z/L = 0 in the direction of the gas flow) the gas temperature is constant. In the other cross sections, it increases during the heating

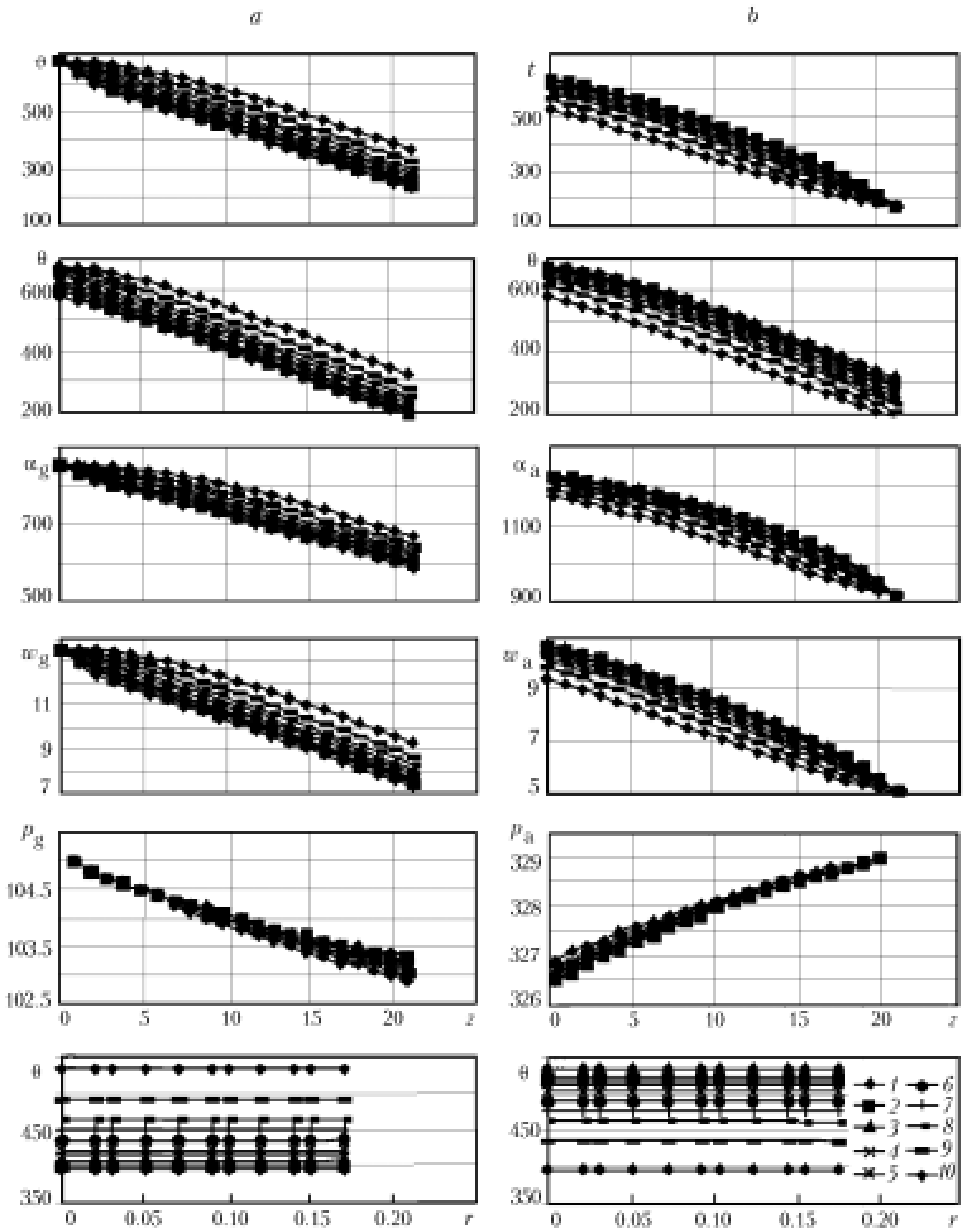

Fig. 1. Quasi-stationary distribution of the parameters of the heat-transfer agents and the temperature of the matrix in the cycles of heating by gas (a) and cooling by air (b) along the length of the channel z (mm) and the radius of the wire r (mm) of medium cross section of the gauze packing (at the bottom) within one complete cycle (revolution) at a rotational speed of the rotor of 26.5 rpm: a) τ = 0.02 (1), 0.07 (2), 0.16 (3), 0.23 (4), 0.32 (5), 0.49 (6), 0.65 (7), 0.81 (8), 1.13 (9), and 1.62 sec (10) (all the curves, except for p_g, are numbered from bottom to top); b) τ = 1.64 (1), 1.66 (2), 1.68 (3), 1.70 (4), 1.75 (5), 1.81 (6), 1.88 (7), 1.94 (8), 2.07 (9), and 2.26 sec (10) (all the curves, except for p_a, are numbered from top to bottom); p_g and p_a, kPa.

cycle. The reverse pattern is observed for the air in the cooling cycle. The magnitude of variations in the matrix temperature is about 89^{o}C in the cross section input for gas and about 126^{o}C in the output cross section. The local ve-

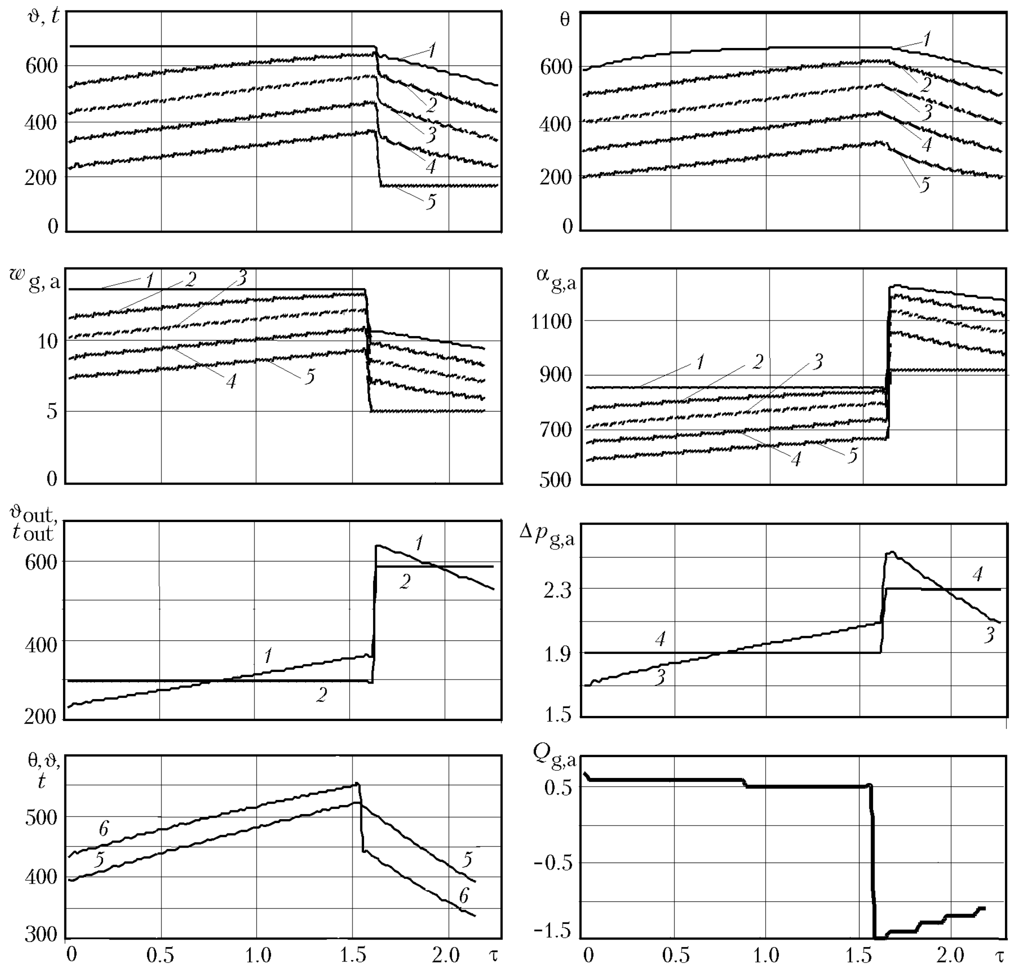

Fig. 2. Quasi-stationary time distribution of the parameters of the heat-transfer agents and the matrix in individual cross sections along the length of the channel [in the upper four graphs, *z/L* increases from top to bottom: 1) 0; 2) 0.25; 3) 0.50; 4) 0.75; 5) 1.00] and of the mean-integral parameters along the length of the channel and over the regenerator as a whole [the lower four graphs correspond to one complete revolution of the matrix at a rotational speed of 26.5 rpm: 1) and 2) for the channel and the regenerator, 3) and 4) for the channel and the matrix of the regenerator, 5) and 6) for the matrix and heat-transfer agents] in the cycle of heating by gas (initial portions of the curves corresponding to a time smaller than 1.62 sec) and in the cycle of cooling by air (finite portions of the curves). Δp_g and Δp_a, kPa.

locities and heat-transfer coefficients change very strongly along the length of the channel. Their mean values are 13.6 m/sec and 857 W/(m^2·K) in the cross section input for gas and 8.3 m/sec and 635 W/(m^2·K) in the output cross section. These quantities are equal to 5.1 m/sec and 920 W/(m^2·K) in the cross section input for air and 10 m/sec and 1200 W/(m^2·K) in the output cross section.

The lower graphs show the change in individual integral parameters with time. The behavior of the aerodynamic drags to the flows engaged our attention: they change with time along the channel and are constant in each sector of the matrix. The aerodynamic drag of the channel is lower (higher) than its mean value at the beginning of the heating (cooling) cycle and is higher (lower) than the mean value at the end of the cycle. This pattern corresponds to our formulation of the problem, according to which the input flow rates are constant. Clearly, in a real regenerator, the flow rates of the heat-transfer agents at the input of the channel change with time, while their total flow rate in the

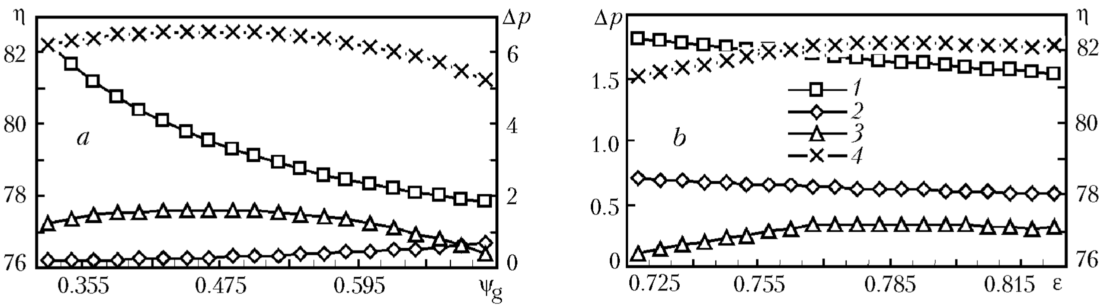

Fig. 3. Influence of the redistribution of the gas and air sections (a) and the change in the porosity of the matrix at a constant size of the gauze cell (b) on the efficiency and the relative aerodynamic drag of the regenerator at a rotational speed of the rotor of 26.5 rpm; 1) Δp_g; 2) Δp_a; 3) η_g; 4) η_a. η, Δp, %.

TABLE 1. Dependence of the Main Parameters of the Matrix on Its Porosity at a Constant Size of the Gauze Cell

Characteristics of the matrix	Porosity, %				
	72.5	75.0	77.5	80.0	82.0
Diameter of the wire, mm	0.340	0.311	0.282	0.253	0.229
Mass, kg	158.1	143.7	129.4	115.0	103.5
Heat-exchange surface, m^2	238.0	236.2	234.5	232.9	231.8
Compactness, m^2/m^3	3235	3211	3188	3166	3150
Equivalent diameter, mm	0.896	0.934	0.973	1.011	1.041
Efficiency of air cooling, %	81.26	81.88	82.18	82.16	82.15
Total aerodynamic drag, %	2.514	2.385	2.272	2.175	2.106

regenerator remains unchanged. An analogous pattern is observed for the temperature at the output of the channel and at the output of the regenerator. The mean-integral temperatures of the gas and the matrix increase practically uniformly in the heating cycle (at a constant head) and decrease in the cooling cycle.

The error in the calculation of the heat balance in the finite, 30th, cycle (where a quasi-stationary regime is not yet established), with account for the head accumulated by the matrix and the flows, is 0.0121%. Since the integration steps used in the numerical method proposed were fairly large, this result and, accordingly, the method proposed can be considered as fairly accurate.

Influence of Design Parameters of a Regenerator on Its Characteristics. We investigated the influence of deviations of individual design parameters of a regenerator (at constant other parameters) from their base values given in [8] on its characteristics at a rotational speed of the matrix of 26.5 rpm. The efficiency of cooling by air decreases by only 15% when the length of the channel (the thickness of the packing) decreases by almost two times; in this case, the aerodynamic drag decreases by approximately 30%. A decrease in the rotor diameter leads to the reverse effect: when the porosity of the matrix increases due to an increase in the size of the gauze cell at a constant diameter of the wire, both the efficiency and the aerodynamic drag decrease. This qualitative relation between the parameters is evident and the optimization reserves are limited here.

As is seen from Fig. 3, when the gas-flow section of the matrix decreases from 71.5 to 52% (at an analogous increase in the air-flow section), the efficiency initially significantly increases (by about 1%), then, in the range 52–45%, it remains constant, and, after 45%–28.5%, the efficiency decreases. Note that the highest heat efficiency, falling in the above-indicated efficiency-insensibility range, is characteristic of the air heaters of steam boilers. The total aerodynamic drag of the matrix to the gas and air has a stable tendency to increase. It is equal to 2.5, 2.8, and 3.4% for the initial (71.5%), intermediate (59.5%), and optimum (51.5%) flow sections of the matrix, respectively. Thus, the ratio between the flow sections should be selected in the process of thermodynamic and aerodynamic calculations of the gas-turbine plant cycle.

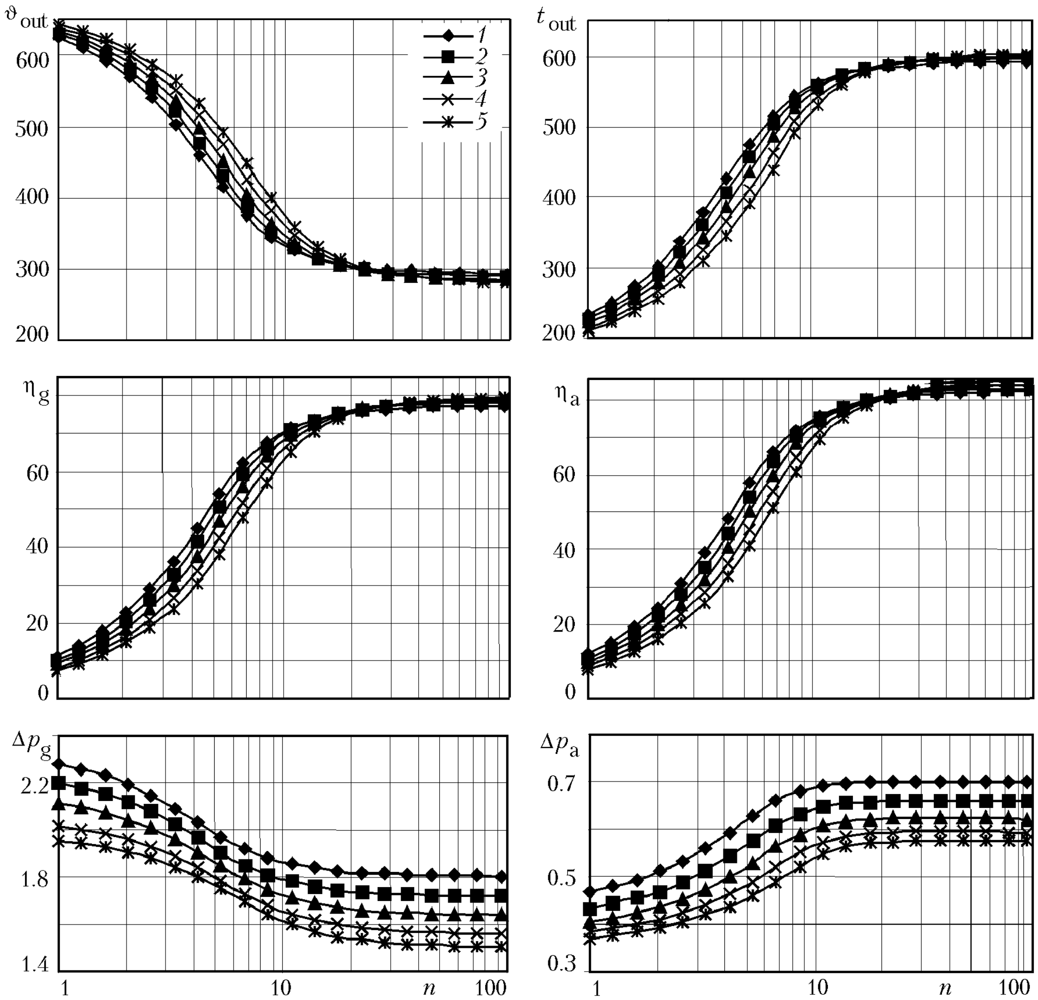

Fig. 4. Dependence of the regenerator parameters on the rotational speed of the rotor at different values of the matrix porosity and a constant size of the gauze cell: ε = 0.725 (1), 0.750 (2), 0.775 (3), 0.800 (4), and 0.820 (5). η, Δp, %.

When the porosity of the matrix increases from 72.5 to 78.5% due to a decrease in the wire diameter at a constant size of the gauze cell, the efficiency significantly increases and the aerodynamic drag decreases. A further increase in the porosity, at a definite number of rotor revolutions, leads to a small decrease in the efficiency and a decrease in the total aerodynamic drag. It is seen from the data presented in Table 1 that, as the porosity changes from 72.5 to 82%, the working mass of the matrix, the wire diameter, and the number of gauze layers decrease by approximately 1.5 times. The heat-exchange surface and the compactness of the matrix remain practically unchanged.

Let us briefly consider the influence of the thermophysical properties of the matrix on the regenerator characteristics. These characteristics remain practically unchanged when the heat conduction decreases by half because of the small diameter of the wire. A similar decrease in the heat capacity and density leads to a small decrease in the heat efficiency and an increase in the aerodynamic drag. This is entirely possible at the comparatively high rotational speed used in our calculations. As the rotational speed of the rotor decreases, the effects of the heat capacity and density significantly increase and determine the process of heat transfer.

Influence of the Rotational Speed of the Rotor on the Generator Characteristics. It is difficult to judge the influence of the porosity on the generator characteristics by the data presented in Fig. 3 and Table 1; therefore, it makes sense to investigate this effect in a wide range of rotational speeds of the rotor. For this purpose, it is well to use the mathematical model proposed rather than simplified classical models.

Figure 4 presents the dependences for the output temperature, efficiency, and aerodynamic drag of the regenerator on the rotational speed of the rotor changing in a wide range (from 1 to 100 rpm), calculated for the gas and air at different values of the matrix porosity (see Table 1), at which the efficiency of the regenerator is extremely low at low rotational speeds of the rotor (as low as 1 rpm). The efficiency sharply increases with increase in the rotational speed in the narrow range from 2 to 10 rpm; in this case, a higher efficiency corresponds to a lower porosity. At high rotational speeds (as high as 20 rpm), the efficiency increases much more slowly and approaches the limiting value. It is interesting that, as was mentioned when Fig. 3b was discussed, in this range of rotational speeds, a higher heat efficiency corresponds to a higher porosity. The aerodynamic drag to the gas (hot heat-transfer agent) monotonically decreases with increase in the rotational speed, and the aerodynamic drag to the air (cold heat-transfer agent) monotonically increases in this case. For the end regenerator considered and the intermediate regenerator [14] of a gas-turbine plant, in which the pressures of the heat-transfer agents are substantially different, the aerodynamic drag reaches the limiting value at lower rotational speeds as compared to the rotational speeds at which the limiting heat efficiency is attained.

It is interesting to compare the above-described data to the analogous data obtained in [2] for an atmospheric-pressure regenerator in which the rate of air flow is two times higher than the rate of gas flow and the ratio between the gas-flow and air-flow sections is the reverse of that of the regenerator considered in our example. It has been established that, for all four types of matrices — matrices with straight channels and matrices packed with spheres, Rachig rings, and gauzes — the aerodynamic drag to the air reaches a maximum at rotational speeds of the rotor at which the heat efficiency of the regenerator begins to approach its limit.

The data presented show that a comprehensive analysis of the heat characteristics of a regenerator, in the case of their thorough investigation, allows one to vary its design parameters in a fairly wide range, while the aerodynamic characteristics impose stringent requirements on them.

CONCLUSIONS

A nonlinear numerical mathematical model has been developed for investigating the heat and aerodynamic processes in regenerators of continuous and periodic operation with matrices packed with various bodies.

A convenient numerical algorithm eliminating global iterations in calculating the conjugate problem on unsteady heat exchange has been proposed. This algorithm is based on successive runs through a channel in the directions longitudinal and transverse with respect to the flow direction.

Comparison of the data of test calculations done using the algorithm and the program developed by us with the experimental data of other authors has shown that our data are in satisfactory agreement with the data obtained by other methods.

A comprehensive investigation of the quasi-stationary heat and aerodynamic processes in a gas-turbine plant regenerator with a rotating matrix packed with gauzes has made it possible to determine the optimum, with respect to the regenerator efficiency, rotational speeds of the rotor depending on the matrix porosity and the ratio between the flow sections of the matrix. It is shown that a gas-turbine plant regenerator should be designed with thorough consideration for its dynamic, heat, and aerodynamic characteristics.

NOTATION

d, equivalent hydraulic or heat diameter of the channel, m; F, heat-exchange surface, m^2; I, number of integration bands along the z coordinate; L, length of the channel, m; N, number of elements or channels of the matrix; n, rotational speed of the rotor; Q, heat given up/taken by a heat-transfer agent in the channel, J; r, radius of a sphere or a cylinder, m; S, cross section of the channel or the matrix, m^2; t, temperature of the air, ^oC; V, volume of an element, sphere, of the matrix, m^3; w, velocity of the flow in the channel (in the direction of the z coordinate), m/sec; y, coordinate perpendicular to the flow, m; z, coordinate parallel to the flow, m; α, heat-transfer coefficient, $W/(m^2 \cdot K)$; Δp, pressure drop, Pa; Δy, step of integration over the thickness, m; Δz, step of integration over the length, m; $\Delta\tau$, step of integration with respect to time, sec; δ, calculated thickness of the channel wall, m; ψ, relative cross section of the matrix; ε, porosity; σ, approximation parameter of the numerical scheme; τ, time, sec; η, heat-efficiency coefficient;

θ, temperature of the matrix wall, ^{o}C; ϑ, temperature of the gas, ^{o}C. Subscripts: aer, aerodynamic; a, air; g, gas; ch, channel; m, matrix; m.m, matrix material; sp, sphere; h, heat; p, packing; c, cycle; eq, equivalent; 1, individual element.

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