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OBTAINING SUPERADIABATIC TEMPERATURES IN COMBUSTION OF GASEOUS FUEL IN A SYSTEM OF TWO POROUS PLATES WITH A PERIODIC CHANGE OF THE DIRECTION OF PUMPING

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A mechanism of obtaining superadiabatic temperatures in a system of two porous plates is theoretically investigated. Data on the optimum pumping periods and on the value of the produced superadiabatic effect are presented.

It is possible to produce a superadiabatic effect on account of recuperation of thermal energy by porous plates. The recovery of heat by radiation in the combustion zone was dealt with in [1, 2]. The work [1] solves a one-dimensional nonstationary problem of burning of fuel gas in porous material, taking convective and radiation heat transfer into account. The combustion rate was found from the Arrhenius equation. The influence on the maximum gas temperature of the optical thickness, the absorption factor, and the position of the reaction zone relative to the porous layer boundaries was investigated. The work [2] proposes an unconventional scheme of a plant for performing the catalytic reaction, energy for which is transferred by radiation through a screen, transparent to the radiation from the particles of a porous layer heated by burning in it of the air mixture of low-grade fuel. To the matter the screen is impermeable.

Figure 1 shows the schematic diagram of the plant, which enables us to produce a superadiabatic effect. Low-calorie gaseous fuel (a mixture of air with natural gas or vapor of organic solvents) enters via one plate a narrow gap, where its combustion takes place. Hot combustion products whose temperature exceeds the fuel temperature by the value of adiabatic combustion are filtered through the other porous plate.

With such organization of the process the second (hot) plate warms up the first one by radiation. The fuel in turn is warmed up in the first plate on account of interphase heat transfer, and on combustion the maximum gas temperature goes above the adiabatic one. To simplify the model, we assume that the fuel in the plates does not oxidize and completely burns up in the gap between the plates. The combustion regime in such a model will be universally stable, which is not always observed in real physical processes. These assumptions do not enable us to model the processes of combustion dying down combustion in the system and break-down of the regime of self-sustaining combustion which may occur when real plants operate. Thus, the work considers only the issues of heat balance without specifying the chemistry of the combustion processes. The issues associated with the chemical behavior of the combustion processes are left for subsequent consideration. Realizing the model nature of our combustion scheme, we do believe that many conclusions will be acceptable for real systems as well. And for the case when the energy is introduced into the porous plate system by a heating element the model adequately reflects real physical processes.

Results of modeling of radiation convective heat transfer in the system shown in Fig. 1 with unidirectional pumping are given in [3]. Calculations have shown that the value of the superadiabatic effect depends on the physical parameters of the system: mass flow rate of the gas, energy contribution to the system, the interphase heat transfer coefficient, porous plate thickness, etc.

With the optimum values of the mass flow rate of the gas and the quantity DT it is possible to increase the

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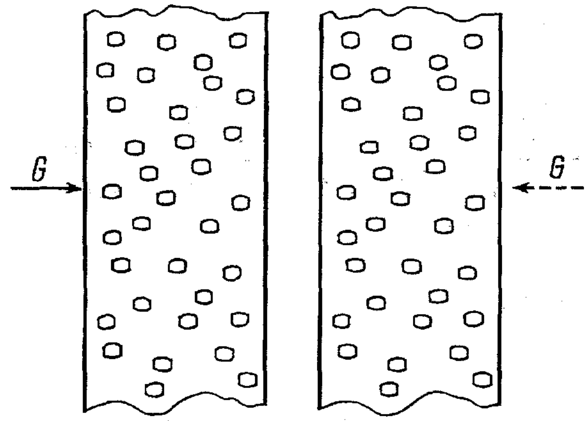

Fig. 1. Scheme for burning fuel in a system of two porous plates.

maximum gas temperature by 30% as compared to the adiabatic combustion temperature. The calculations were performed for the case where there were no lateral heat losses and the thermal-conductivity coefficient was fairly small [3].

The value of the superadiabatic effect can be considerably increased by periodically changing the direction of pumping of gaseous fuel and combustion products to the opposite one. Reverse of a gas flow is used by the authors of [4] to cut the flow rate of heat in thermal processing of a dispersed material layer. The work [5] deals with the experimental investigation of a reaction autowave in oxidation of xylol vapor in an air flow.

A superadiabatic temperature in the system with a reverse of the gas flow is attained on account of the recovery of thermal energy of combustion products in the reaction zone as the direction of pumping changes. Owing to this the energy in the system is blocked not only by radiation but also convectively. In this case the excess of the maximum gas temperature as compared to the adiabatic temperature will be much more considerable than with unidirectional pumping.

Of prime interest is modeling of processes with small energy contributions, which may be interpreted as burning of energy-poor air-natural gas mixtures.

We posed the problem to elucidate the scales of the obtained temperatures and the influence of physical and regime parameters on the produced superadiabatic effect.

The system of equations describing the considered process in a one-dimensional approximation was based on the following physical model. The gas flow rate is assumed constant, the porous plates are modeled by a system of balls with equal radius. The gas blown through the plates is considered an optically transparent medium. The interphase heat transfer between the gas and the porous plate particles is characterized by volumetric coefficients of interphase heat transfer.

Since the volumetric heat capacity of the carcass is much larger than the volumetric heat capacity of the gas, the energy equation for the gas can be written in a stationary approximation. Taking no account of heat conduction, the energy equation for the gas can be represented as

$$c_g G \frac{dT_i}{dx_i} = \alpha_i (\vartheta_i - T_i), \tag{1}$$

where G is the flow rate of the gas, with the following boundary conditions:

$$T_1(0) = T_0, \ T_2(0) = T_1(L_1) + DT. \tag{2}$$

The temperature of the porous plate carcass changes on account of radiation heat transfer, heat conduction over the carcass of the porous plates, and interphase heat transfer of the carcass with the gases flowing through the plates. Taking into consideration that a process of this kind is of technical interest in the case of optically thick plates, it is permissible to write the energy flux q_r transferred by radiation, assuming the medium nonscattering, in the form [6]

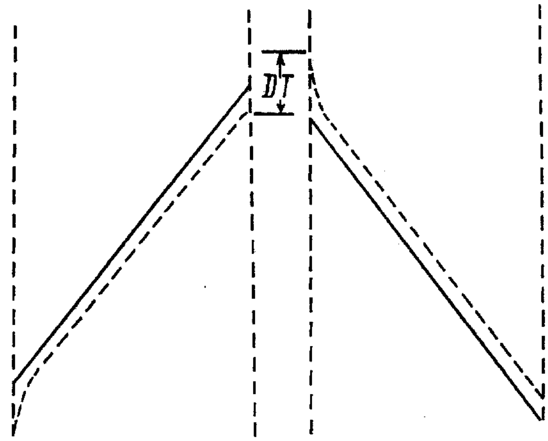

Fig. 2. Temperature profiles of the gas (dashed lines) and the carcass (solid lines) in the porous plates in the absence of radiation and heat conduction.

$$q_r = -\frac{4}{3\eta_i}\nabla(e_b), \tag{3}$$

where η_i is the absorption factor.

Since the free path of a photon is equal to the reciprocal of the absorption factor [6], η_i can be expressed in terms of the volume porosity of the plates and the radius of the particles which form the carcass of the porous plates. By using the expression for the photon free path [7] we rearrange (3):

$$q_r = -\frac{64\sigma R_i \Pi_i}{9(1-\Pi_i)}\vartheta_i^3 \frac{\partial \vartheta_i}{\partial x_i}. \tag{4}$$

In view of (4) the energy equation for the carcass will be written as

$$c_f\rho_f(1-\Pi_i)\frac{\partial \vartheta_i}{\partial t} = \frac{\partial}{\partial x_i}\left\{\left[k_i + \frac{64\sigma R_i \Pi_i}{9(1-\Pi_i)}\vartheta_i^3\right]\frac{\partial \vartheta_i}{\partial x_i}\right\} - \alpha_i(\vartheta_i - T_i) \tag{5}$$

(k_i is the effective thermal-conductivity coefficient over the carcass, dependent on porosity) with the initial conditions

$$\vartheta_i(x, 0) = T_0. \tag{6}$$

The boundary conditions for the first plate are

$$-k_{res_1}\frac{\partial \vartheta_1(0, t)}{\partial x_1} = \varepsilon_1\sigma T_0^4 - \varepsilon_1\sigma\vartheta_1^4(0, t),$$

$$-k_{res_1}\frac{\partial \vartheta_1(L_1, t)}{\partial x_1} = \frac{\sigma[\vartheta_2^4(0, t) - \vartheta_1^4(L_1, t)]}{1/\varepsilon_1 + 1/\varepsilon_2 - 1}, \tag{7}$$

where

$$k_{res_1} = k_1 + \frac{64\sigma R_1 \Pi_1}{9(1-\Pi_1)}\vartheta_1^3.$$

Similarly the boundary conditions for the second plate will be written.

If no account is taken of the influence of heat conduction and radiation on the heat transfer processes one can make some very useful analytical estimates.

The pumping half-period τ can be arbitrarily divided into two time intervals: $\tau = \tau_0 + \tau_e$. The quantity τ_0 is the time necessary to displace the combustion products from the system with changing direction of pumping, and τ_e is that part of the half-period when combustion of the fuel occurs. Then the second of the boundary conditions (2) will change:

$$T_2(0,\ t) = \begin{cases} T_1(L_1,\ t), & 0 \leqslant t \leqslant \tau_0; \\ T_1(L_1,\ t) + DT, & \tau_0 < t \leqslant \tau. \end{cases} \tag{8}$$

Without heat conduction and radiation the temperature profiles of the gas and the carcass will be practically linear across the thickness of each plate. In each plate the temperature drop δ between the phases will reach its constant value practically everywhere excluding the inlet sections. The temperature gradient β of the gas and the carcass will be equal. Figure 2 shows a basic pattern of the run of the temperature profiles in a time of pumping from left to right. The combustion products warm up the second, cooler plate. The entering fuel, having the ambient temperature T_0, will be warmed up in the first plate, whose carcass temperature decreases. The reverse of the gas flow results in a periodic displacement of the plate temperature profiles relative to each other. The above reasoning enables us to write the change in time of the gas temperature at the inlet to the second plate T_{in} in terms of the maximum carcass temperature ϑ_{max}:

$$T_{in} = \begin{cases} \vartheta_{max} - \delta - \nu t, & 0 \leqslant t \leqslant \tau_0; \\ \vartheta_{max} - \delta + DT - \nu t, & \tau_0 < t \leqslant \tau, \end{cases} \tag{9}$$

where

$$\delta = \vartheta - T; \quad \nu = \frac{c_g G \beta}{c_f \rho_f (1 - \Pi)}.$$

Correspondingly the equation for the evolution in time of the second plate surface temperature ϑ will take the form

$$\frac{d\vartheta}{dt} = \gamma (T_{in} - \vartheta), \tag{10}$$

where

$$\gamma = \frac{\alpha}{c_f \rho_f (1 - \Pi)}.$$

For the steady-state solution at the moment of reversal the temperature of the cooler plate will be $\nu\tau$ smaller than ϑ_{max}, i.e., the initial condition for Eq. (10) will be

$$\vartheta|_{t=0} = \vartheta_{max} - \nu\tau. \tag{11}$$

By integrating (10) it is easy to obtain the values of the temperature ϑ for the instants τ_0 and τ:

$$\vartheta|_{t=\tau_0} = \vartheta_{max} - \nu [\tau_0 + \tau \exp(-\gamma\tau_0)], \tag{12}$$

$$\vartheta|_{t=\tau} = \vartheta_{max} - \nu\tau [\exp(-\gamma\tau) + 1] + DT [1 - \exp\{-\gamma(\tau - \tau_0)\}]. \tag{13}$$

In the steady-state regime at the moment the direction of pumping is reversed the temperature ϑ becomes maximum, i.e., ϑ_{max}. This makes it possible to obtain the expression for the temperature gradient β:

$$\beta = \frac{c_f \rho_f (1 - \Pi) DT [1 - \exp\{-\gamma(\tau - \tau_0)\}]}{c_g G \tau [1 + \exp(-\gamma\tau)]}. \tag{14}$$

From (14) the extremal value of β depending on the pumping half-period τ can be found. Taking the derivative with respect to τ and setting it equal to zero, we obtain the transcendental equation for determining τ_{opt}:

$$\tau_{opt} = \frac{[1 + \exp\{-\gamma\tau_{opt}\}][1 - \exp\{-\gamma(\tau_{opt} - \tau_0)\}]}{\gamma [\exp(-\gamma\tau_{opt}) + \exp\{-\gamma(\tau_{opt} - \tau_0)\}]}. \tag{15}$$

Its solution gives us the value of the optimum half-period, dependent on the physical characteristics of the system and the time τ_0. Correspondingly the maximum temperature gradient will be

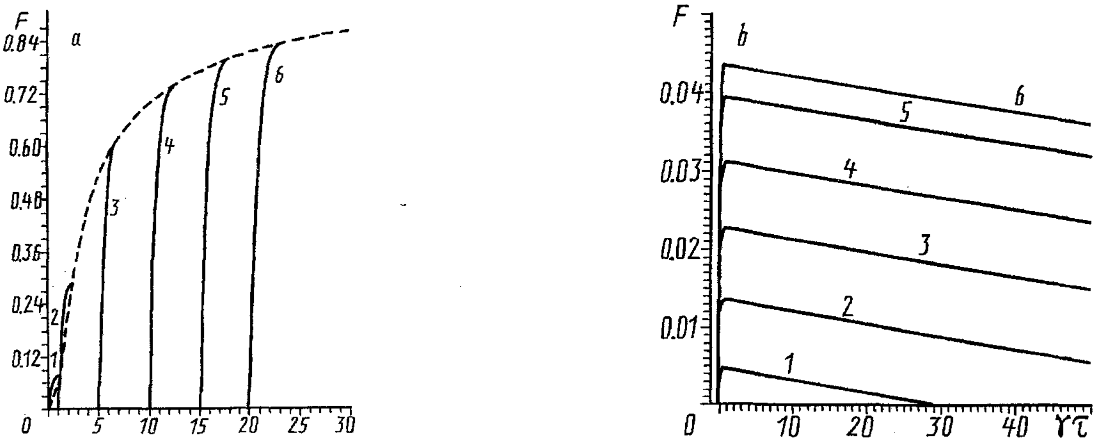

Fig. 3. Dependences of the dimensionless function $f(\gamma\tau_0, \gamma\tau)$ on the parameter $\gamma\tau$: a: 1) $\gamma\tau_0=0.2$; 2) 1; 3) 5; 4) 10; 5) 15; 6) 20; b: 1) $\gamma\tau_0=0.01$; 2) 0.03; 3) 0.05; 4) 0.07; 5) 0.09; 6) 0.1

$$\beta_{\text{opt}} = \frac{c_f\rho_f(1-\Pi)DT\,[1-\exp\{-\gamma(\tau_{\text{opt}}-\tau_0)\}]}{c_g G\tau_{\text{opt}}\,[1+\exp(-\gamma\tau_{\text{opt}})]}. \tag{16}$$

If the time τ_0 is approximately represented as $\tau_0 = L/u$, then (14) can be written as

$$\beta = \frac{c_f\rho_f(1-\Pi)DT}{Lc_g\rho_g}F(\gamma\tau_0,\ \gamma\tau], \tag{17}$$

where

$$F(\gamma\tau_0,\ \gamma\tau) = \frac{\gamma\tau_0\,[1-\exp\{-\gamma(\tau-\tau_0)\}]}{\gamma\tau\,[1+\exp(-\gamma\tau)]},\quad \tau_0<\tau\leqslant\tau_{\text{opt}},$$

is a dimensionless function, dependent on the parameters $\gamma\tau_0$ and $\gamma\tau$, which has the maximum at τ_{opt}.

A similar expression can be written for β_{opt}. Since the optimum half-period τ_{opt} is a function solely of τ_0 (with fixed γ), then $F(\gamma\tau_0, \gamma\tau_{opt}) \equiv f(\gamma\tau_0)$. The curve $f(\gamma\tau_0)$ is presented in Fig. 3a by a dashed line. From the figure it can be seen that with $\gamma\tau > 30$ the curve $f(\gamma\tau_0)$ reaches saturation.

Knowing β, it is easy to find ΔT - the increment of the gas temperature in one plate:

$$\Delta T = \beta L. \tag{18}$$

The temperature profiles will remain linear as long as the value of the pumping half-period $\tau \leq \tau_{opt}$, and for $\tau > \tau_{opt}$ the carcass temperature profile maximum will be displaced into the plate. Assuming that ϑ_{max} travels over the plate with the velocity of a thermal wave, we can obtain an analytical formula to calculate the temperature increment ΔT:

$$\Delta T = \begin{cases} \dfrac{c_f\rho_f(1-\Pi)DT}{c_g\rho_g}F(\gamma\tau_0,\ \gamma\tau), & \tau_0<\tau\leqslant\tau_{\text{opt}}; \\ \beta_{\text{opt}}\left(L-\dfrac{W\tau}{2}\right), & \tau>\tau_{\text{opt}}, \end{cases} \tag{19}$$

where L is the plate thickness; W is the velocity of the thermal wave.

For periods $\tau > \tau_{opt}$ the functional dependence $F(\gamma\tau_0, \gamma\tau_{opt})$ transforms:

$$F(\gamma\tau_0,\ \gamma\tau) = f(\gamma\tau_0)\left[1-\frac{\tau}{2\tau_0}\,\frac{c_g\rho_g}{(1-\Pi)c_f\rho_f}\right],\quad \tau>\tau_{\text{opt}}. \tag{20}$$

Figure 3b gives the dependences of the function $F(\gamma\tau_0, \gamma\tau)$ on $\gamma\tau$ for different $\gamma\tau_0$. Consequently, formula (19) will take the form

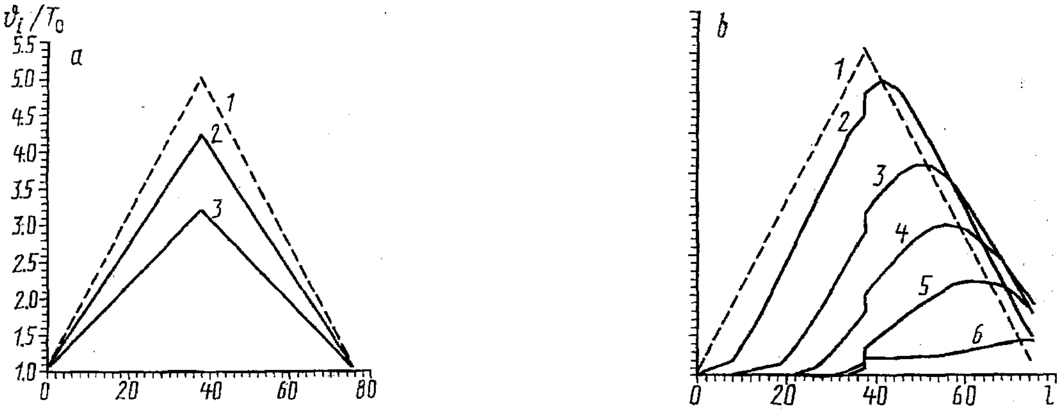

Fig. 4. Dependences of the dimensionless temperature of the carcass ϑ_i/T_0 on the total optical thickness of the plates l: a: 1) $\tau=\tau_{opt}$; 2) $\tau=0.2\tau_{opt}$; 3) $0.1\tau_{opt}$; b: 1) $\tau=\tau_{opt}$; 2) $\tau=20\tau_{opt}$; 3) $50\tau_{opt}$; 4) $70\tau_{opt}$; 5) $90\tau_{opt}$; 6) $130\tau_{opt}$.

$$\Delta T = \frac{c_f\rho_f(1-\Pi)DT}{c_g\rho_g}F(\gamma\tau_0,\ \gamma\tau). \tag{21}$$

Thus, knowing τ_0 and the physical parameters of the system, we can compute the temperature increment and calculate the value of the superadiabatic effect, which can be taken as the upper bound for the given parameters.

Figure 4 presents dimensionless temperature profiles of the carcass, calculated without heat conduction or radiation for different τ related to τ_{opt}. The values of the temperature increments obtained in this case are in complete agreement with those yielded by formula (19).

From simple considerations it is easy to show that the carcass temperature on cool edges of the plate with the values of the pumping half-periods $\tau \le \tau_{opt}$ is expressed by the following relation:

$$\vartheta_{in}^{min} = \frac{DT(\tau-\tau_0)}{\tau} - \frac{\beta W\tau}{2}. \tag{22}$$

Recall that all the above estimations are correct only in the absence of heat conduction, radiation, and lateral heat losses. The results of computational modeling completely confirm the performed analysis.

When radiation and heat conduction are involved in the process of heat transfer the shape of the temperature curves changes and the values of the maximum temperatures decrease (see Fig. 5).

CONCLUSIONS

Reversal of a gas flow makes it possible to considerably, tens of times, increase the value of the superadiabatic effect in comparison with the regime of unidirectional pumping. We obtained analytical estimations, yielding the value of the temperature increment for absence of heat conduction and radiation. For thin plates radiation and heat conduction considerably decrease the superadiabatic effect. As the plate thickness increases, losses associated with these processes decrease and the real situation is close to the idealized one.

Numerical solutions for the limiting cases show complete agreement with the results of the analytical estimations. Analysis shows that the temperature gradient growth reaches saturation. But one is not to be oriented to these limiting values of the gradient, because real limitations on the thickness associated with pressure losses due to filtration begin much earlier. The choice of the regime is governed by permissible hydraulic losses and the desired value of the superadiabatic effect.

The given mechanism is supposed to be used for obtaining superadiabatic temperatures in recovery of industrial discharges containing dangerous organic impurities. Initially the system is heated to temperatures ensuring ignition of the mixture, by burning natural gas or other fuel. Then by using the given method the system can be switched to the regime of self-sustaining combustion, in which organic impurities will decompose. If the energy

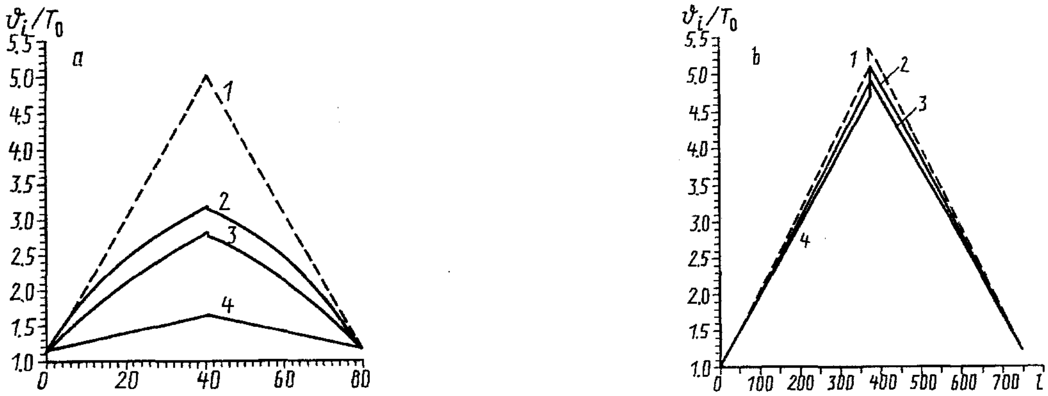

Fig. 5. Dependences of the dimensionless temperature of the carcass ϑ_i/T_0 on the total optical thickness of the plates l: a) $L_i = 0.05$ m; b) $L_i = 0.5$ m; $\tau = \tau_{opt}$; 1)

released in burning the impurities is not sufficient to maintain the required temperature regime, and it is necessary to add, for example, natural gas in order to increase the calorific power of the mixture.

In the case of purification, τ should considerably exceed the value of τ_0, since with a reversal of the direction of pumping the portion of unreacted organic impurities in the cool zone will be discharged into the environment. Therefore the system will be effective when the condition $\tau/\tau_0 \simeq 100$ is fulfilled. Analysis of the results shows that in these regimes the value of the superadiabatic effect decreases as compared to the optimum regime only slightly.

Another application of this method of burning is the use of low-calorie fuel to produce high temperatures which cannot be attained by using this fuel under standard conditions. In this case use can be made of the optimum half-period of pumping when the value of the superadiabatic effect is the maximum possible.

NOTATION

L_i, thicknesses of porous plates ($i = 1, 2$); Π_i, porosities of porous plates; α_i, (volumetric) coefficients of heat transfer between porous plate carcass and gas; k_i, thermal-conductivity coefficients of porous plate carcass; T_0, initial gas temperature; ε_i, emissivity factor of porous plate particles; ρ_g, density of gas; c_g, specific heat capacity of gas; G, mass flow rate of gas; ρ_f, density of porous plate carcass; c_f, specific heat capacity of porous plate carcass; T_i, gas temperature in porous plates; ϑ_i, temperature of porous plate particles; DT, gas temperature jump owing to chemical reaction; u, gas velocity; ΔT, gas temperature increment on the thickness of one plate; δ, temperature difference between gas and porous plate particles; β, temperature gradient; ν, rate of variation in gas temperature; W, thermal wave velocity; τ, half-period of pumping; τ_0, time of displacement of combustion products from the system; τ_e, time of fuel combustion; σ, Stefan-Bolzmann constant; e_b, total emissivity of black body.

REFERENCES

1. Y. Yoshizava, H. Sasaki, and R. Echigo, National Heat Transfer Conference, Pittsburgh (1987).
2. R. Echigo, Y. Yoshizava, and H. Yoshida, Department of Mechanical Engineering, Tokyo (1987).
3. S. A. Zhdanok, V. V. Martynenko, and S. I. Shabunya, Inzh.-Fiz. Zh., **62**, No. 1, 95-101 (1992).
4. A. M. Zavatko and L. P. Petrova, Processes of Heat and Mass Transfer of Matter in Capillary Porous Bodies, Collection of Scientific Papers [in Russian], Minsk (1982), pp. 36-38.
5. G. A. Fateev, V. M. Kisarov, G. N. Toropkina, et al., Physicochemical Processes in Nonequilibrium Systems, Collection of Scientific Papers [in Russian] (1986), pp. 106-112.
6. E. M. Sparrow and R. D. Sess, Heat Transfer by Radiation [Russian translation], Moscow (1971).
7. G. E. Gorelik, V. V. Levdanskii, V. G. Leitsina, and N. V. Pavlyukevich, Inzh.-Fiz. Zh., **50**, No. 6, 999 (1986).