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Modeling of gas dynamics in a pulse combustion chamber to predict initial drying process parameters

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Abstract

A mathematical model of gas-dynamical processes in a pulse combustion chamber for drying of materials is formulated with regard for the second viscosity. Results of numerical solution of the gas-dynamical problem are reported. In particular, it is shown that the time dependences of the gas pressure and velocity represent sinusoidal plots with a phase shift. Introduction of the dissipation term with a second viscosity factor is found to stabilize a computational process.

Keywords: Gas dynamics; Pulse combustion; Drying

1. Introduction

In the last few years, the use of pulse combustion in various technological processes has aroused considerable interest in many countries. Though the technology of pulse combustion has long been known, the devices based on it are not widely used despite their many attractive characteristics. Recent trends in development of pulse combustion apparatuses are toward creation not only of units with a low thermal capacity but also of industrial-scale apparatuses. There is a consensus of opinion that the main promising candidates for practical use of technological pulse combustion are air heaters, water heaters, steam generators, drying, etc. Experience which has been gained over a number of years confirms that pulse combustion is a promising form of technological combustion. It allows one to considerably increase a heat and mass transfer rate and a combustion rate to decrease carbon oxide emission [1–5].

Pulse combustion chambers (PCCs) are highly efficient sources of high-temperature pulsating gas streams. A gas medium, which leaves a pulse combustion chamber, is characterized by velocity fluctuations making, approximately, 100 m/s with a frequency ranging from 50 to 200 Hz. A high-speed high-temperature pulsating jet can be employed to atomize solutions and to dry the latter efficiently without any rotating sprayers and atomizers [6].

A design basis of the pulse combustion technology is a special fire apparatus in which a pulsating regime of gas flow is realized. Two types of PCC are known and used in industry, namely, PCCs with mechanical and aerodynamic valves. In chambers of the first type, the valves execute either by reciprocating or through rotary motion. PCCs with a mechanical rotary valve allow gas flow oscillations with high acoustic parameters to be obtained. However, they possess certain drawbacks which include the presence of moving elements subjected to wear in a high-temperature zone.

PCCs with aerodynamic valves do not possess the above drawbacks. In literature [3,7], the scheme of a conic tangential-type PCC with an aerodynamic valve is known. Pressure feed of air and mixture ignition are required only at the moment of start. An aerodynamic valve in this design ensures a smaller resistance to a gas flowing into the combustion chamber than in the reverse direction.

Proceeding from an analysis of PCCs and dryers on their basis, it follows that a PCC is the efficient source of high-temperature gas flows allowing intensification of heat and mass transfer processes under drying conditions. It is evident that dynamics of gas flows has a decisive role in the efficiency of a drying process.

2. Theory

In the present work, gas-dynamical processes in a PCC are investigated by the method of mathematical modeling. Up-to-date hydrodynamic models of gas dynamics and turbulence are built in the assumption of small pressure gradients

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Nomenclature

c_p, c_v	heat capacity of the gas at constant pressure and volume (J/(kg K))
d	diameter of the combustion chamber (m)
h	enthalpy (J/kg)
P	gas pressure (Pa)
q_0	flow rate of the combustible mixture (m^3/s)
R	universal gas constant (J/(kmol K))
t	time (s)
T	gas temperature (K)
v	gas velocity (m/s)
V_0	amount of air theoretically required for complete combustion (m^3/m^3)
x	coordinate (m)

Greek symbols

α	coefficient of the excess of air
η	coefficient of shear viscosity (Pa s)
λ	distance between the layers (m)
μ	molecular mass (kg/mol)
ξ	second coefficient viscosity (Pa s)
ρ	density (kg/m^3)

Subscripts

i, k, e	components of the stress tensor
z	cycle
x	coordinate
1	fuel
2	combustion products
3	air
0	initial value
(1), (2)	cross-sections of the chamber

Superscript

–	mean value

in a flow. However, in the presence of considerable pressure fluctuations in a combustion chamber, the assumption about smallness of pressure gradients is already incorrect.

2.1. Structure of the viscous stress tensor

It is known that the equations for viscous fluid motion can be obtained by adding the complementary term δ_{ik}, determining irreversible viscous momentum transfer in fluid (gas), to the ideal momentum.

The tensor of second rank satisfying these conditions is known [8] in the general form as

$$\sigma'_{ik} = \eta\left(\frac{\partial v_i}{\partial x_k} + \frac{\partial v_k}{\partial x_i} - \frac{2}{3}\delta_{ik}\frac{\partial v_e}{\partial x_e}\right) + \xi\delta_{ik}\frac{\partial v_{\mathrm{e}}}{\partial x_{\mathrm{e}}} \tag{1}$$

Now we will show that (1) is valid in the case when the temperature and pressure gradients are sufficiently small. For this, from simple molecular-kinetic considerations we will determine the resultant momentum $L = L' - L''$ between fluid layers moving with velocity v'_x and v''_x, respectively.

A magnitude of the momentum L transferred across unit area of the small area S^0 per unit time is determined by the difference of the momentum L' and L'' transferred by molecules crossing the area on the left and on the right; the momentum L' transferred by molecules from the left to the right is equal to the product of the momentum of a single molecule by the number of molecules per unit area per time. The latter, as shown in [9], is equal to $\frac{1}{6}n\bar{v}$, where n is the number of molecules per unit volume, $\bar{v}$ the mean velocity of gas molecules. If the gas velocity at the distance λ to the left from S^0 is v'_x, the mean molecular velocity is $\bar{v}'$ and the gas pressure is ρ', then the momentum L' acquires the form

$$L' = \tfrac{1}{6}\rho'\bar{v}'v'_x \tag{2}$$

By analogy,

$$L'' = \tfrac{1}{6}\rho''\bar{v}''v''_x \tag{3}$$

Consequently,

$$L = L' - L'' = \tfrac{1}{6}(\rho'\bar{v}'\bar{v}'_x - \rho''\bar{v}''\bar{v}''_x) \tag{4}$$

whence at the distance 2λ, it follows that

$$L = \frac{1}{3}\lambda\frac{\partial(\rho\bar{v}v_x)}{\partial y} \tag{5}$$

For $\rho\bar{v} = \text{const.}$, we have an ordinary expression for L:

$$L = \frac{1}{3}\rho\bar{v}\lambda\frac{\partial v_x}{\partial y} = \eta\frac{\partial v_x}{\partial y} \tag{6}$$

Using a small difference between the mean and root-mean-square velocities (9%) of the gas molecules (3), we express a molecular flux of mass in terms of the pressure and density [9]:

$$\rho\bar{v} \cong \rho\sqrt{\bar{v}^2} \cong \sqrt{3P\rho} \tag{7}$$

The mean molecular velocity is determined not only by thermal motion but also by pulsating and turbulent motion, therefore it is preferable, in our opinion, to write the molecular flux of mass in terms of the pressure. At constant $P\rho$, formula (5) must turn into formula (6), therefore an approximate expression for L can be represented in the form

$$L = \frac{\eta}{\sqrt{P\rho}}\frac{\partial\left(\sqrt{P\rho}\cdot v_x\right)}{\partial y} \tag{8}$$

An expression for the viscous stress tensor for gases at large pressure gradients or frequencies with allowance for (8) has the form

$$\sigma_{ik} = \frac{\eta}{\sqrt{P\rho}}\left[\left(\frac{\partial\sqrt{P\rho}\cdot v_i}{\partial x_k} + \frac{\partial\sqrt{P\rho}\cdot v_k}{\partial x_i}\right) - \frac{2}{3}\delta_{ik}\frac{\partial\sqrt{P\rho}\cdot v_e}{\partial x_e}\right] + \xi\frac{\delta_{ik}}{\sqrt{P\rho}}\frac{\partial\sqrt{P\rho}\cdot v_e}{\partial x_e} \tag{9}$$

It is easily to verify that the tensor σ_{ik} is symmetrical and goes to zero when all fluid, as a whole, executes a uniform motion [8].

2.2. Equations of fluid dynamics

As it is known, the equations of viscous fluid motion can be obtained directly by adding the expressions $\partial\sigma'_{ik}/\partial x_k$ to the right-hand side of the Euler equation. Thus, we arrive at

$$\rho\left(\frac{\partial v_i}{\partial t}+v_k\frac{\partial v_i}{\partial x_k}\right) = -\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_k}\left\{\frac{\eta}{\sqrt{P\rho}}\left(\frac{\partial\sqrt{P\rho}\cdot v_i}{\partial x_k}+\frac{\partial\sqrt{P\rho}\cdot v_k}{\partial x_i} -\frac{2}{3}\delta_{ik}\frac{\partial\sqrt{P\rho}\cdot v_e}{\partial x_e}\right)\right\}+\frac{\partial}{\partial x_e}\left(\frac{\xi}{\sqrt{P\rho}}\frac{\partial\sqrt{P\rho}\cdot v_e}{\partial x_{\mathrm{e}}}\right) \quad (10)$$

If there are periodic changes or large gradients $\sqrt{P\rho}$ in the flow, then instead of the known Navier–Stokes equations it is preferable to use the modified equations (10) and, in doing so, in the case of "acoustic" flows it is desirable to preserve the term

$$\left(\xi+\frac{\eta}{3}\right)\mathrm{grad}\left(\frac{1}{\sqrt{P\rho}}\mathrm{div}\left(\sqrt{P\rho}\cdot\vec{v}\right)\right)$$

if $\xi = \text{const.}$ and $\eta = \text{const.}$ (11)

related to compressions or rarefactions. In the equations of gas dynamics, the viscosity terms are, as a rule, not taken into account. Next, we will show that in a compressible pulsating gas flow in a combustion chamber, a peculiar "dissipative" term leads to smoother solutions.

2.3. System of the equations of gas dynamics

Finally, we will write the equations of gas dynamics with an account for second "acoustic" viscosity [10].

The equation of continuity

$$\frac{\partial\rho}{\partial t}+\mathrm{div}(\rho\vec{v})=M \quad (12)$$

The equation of momentum conservation:

$$\frac{\partial\rho\vec{v}}{\partial t}=-\mathrm{grad}\left(P+\frac{\rho\vec{v}^2}{2}\right)+\bar{v}M +\left(\xi+\frac{\eta}{3}\right)\mathrm{grad}\left(\frac{1}{\sqrt{P\rho}}\,\mathrm{div}\left(\sqrt{P\rho}.\vec{v}\right)\right) \quad (13)$$

The equation of energy conservation:

$$\frac{\partial}{\partial t}\left[\rho\left(h-\frac{P}{\rho}+\frac{\vec{v}^2}{2}\right)\right] = \frac{M\vec{v}^2}{2}-\mathrm{div}\left\{\rho\bar{v}\left(\frac{\vec{v}^2}{2}+h\right)\right\} +\vec{v}\left(\xi+\frac{\eta}{3}\right)\mathrm{grad}\left\{\frac{1}{\sqrt{P\rho}}\,\mathrm{div}\left(\sqrt{P\rho}\cdot\vec{v}\right)\right\} \quad (14)$$

The second coefficient of viscosity ξ has the same order of magnitude as the viscosity coefficient η. The viscosity of the present gas, unlike the fluid, is independent of the density or pressure and does not increase but, on the contrary, decreases with the temperature. For air, the viscosity is $\eta = 1.8\times10^{-5}$ Pa s. Note that the system of equations obtained allows the "acoustic" dissipation of energy to be taken into account.

3. Mathematical model

Consideration is given to a compressible fluid flow in a pulse combustion chamber of a variable section (Fig. 1). The chamber consists of the following main units: combustor 1, nozzle (tail pipe) 2, arrangements for feed of air (valves) and fuel (shown by arrows), and spark plug 3. Its operational principle is as follows. When the valves are opened, air enters into the combustor. A combustible gas under excess pressure is fed via the burner to the chamber. The mixture formed is ignited by the spark plug. At the moment of mixture ignition, the valves are shut. After ignition, the pressure in the combustor increases, fuel feed is ceased and combustion products are rejected through the nozzle. At this moment rarefaction develops in the combustion chamber which proceeds in step with opening of the valves. At this time the next portion of air and fuel is fed to the chamber where they are rapidly mixed. The valves are shut, the mixture is ignited and the cycle is repeated.

For modelling of gas-dynamical processes in the PCC, unsteady 1D equations of gas dynamics have the form of a "channel" approximation. The x-axis is directed along the PCC. The origin of the co-ordinates is made to agree with the left-hand wall of the chamber. The gas flow moves along the x-axis.

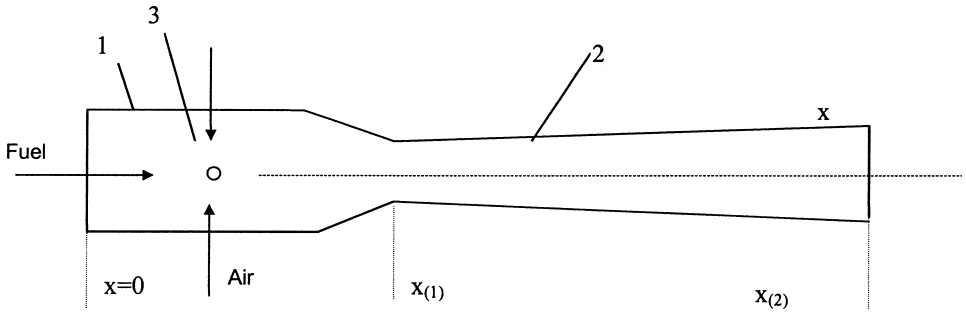

Fig. 1. Schematic of the pulse combustion chamber.

The equations of one-dimensional, time dependent, compressible gas flow in a variable-section channel, which represent the conservation laws for mass, momentum and energy, are written in the form

$$\frac{\partial(S\rho)}{\partial t} + \frac{\partial}{\partial x}(S\rho v) = M \tag{15}$$

$$\frac{\partial(S\rho v)}{\partial t} + \frac{\partial}{\partial x}\left[S(P+\rho v^2)\right] = P\frac{\partial S}{\partial x} + S\left(\xi+\frac{\eta}{3}\right)\frac{\partial}{\partial x}\left(\frac{1}{\sqrt{P\rho}}\frac{\partial}{\partial x}(v\sqrt{P\rho})\right) + F \tag{16}$$

$$\frac{\partial}{\partial t}\left[S\rho\left(h-\frac{P}{\rho}+\frac{v^2}{2}\right)\right] + \frac{\partial}{\partial x}\left[S\rho v\left(h+\frac{v^2}{2}\right)\right] = vS\left(\xi+\frac{\eta}{3}\right)\frac{\partial}{\partial x}\left(\frac{1}{\sqrt{P\rho}}\frac{\partial}{\partial x}\left(v\sqrt{P\rho}\right)\right) + Q \tag{17}$$

where $S = S(x)$ is the cross-sectional area of the chamber which is a function of the x-coordinate.

It is assumed that in the combustion zone each particle of the gaseous mixture is at the state of chemical equilibrium. For this, the characteristic time of the chemical reaction must be considerably less than the time of turbulent mixing and the residence time of a mixture particle in the reaction zone [11,12].

The enthalpy is $h = c_1h_1 + c_2h_2$, here c_1 and c_2 are the cross-section-averaged concentrations of fuel and combustion products; h_1 and h_2 the enthalpy of fuel and combustion products, respectively, $h_{1,2} = h_{1,2}(T) = c_{p1,2}T$.

Assume that the combustion (heat release) zone lies within $0 \le x \le x^*$ and a concentration of the components of combustion products does not change behind it (in the nozzle $x^* < x \le x_{(2)}$. In this case, $c_2 = c_3$, $c_2 = 1 - c_1$ at $0 \le x \le x^*$ and $c_1 = 0$, $c_2 = 1$ at $x^* < x \le x_{(2)}$). To close the system of equations (15)–(17), use is made of the equation of state

$$P = \rho\frac{R}{\mu}T \tag{18}$$

The assumptions made slightly simplify a structure of the flow in the PCC. However, they satisfy the integral conservation laws, rather adequately fit large-scale motions of the medium and can provide some information on variation of gas-dynamical quantities.

The source terms are determined by the following relations:

$$M = c(t)q_0 f\delta(x-x^*) \tag{19}$$

$$F = Mv_0 \tag{20}$$

$$Q = c^*(t)q_0\rho_0 f\left(\frac{v_0^2}{2}+q_c\right)\delta(x-x^*) \tag{21}$$

where $f = S_q/V_q = 1/x^*$, S_q, V_q are the cross-sectional area and the volume of the combustion chamber, respectively; v_0 the velocity of the supplied gaseous mixture (m/s); $\delta(x-x^*)$ is the step function, $\delta = 1$ at $0 \le x \le x^*$ and $\delta = 0$ at $x^* < x \le x_{(2)}$ and

$$c(t) = \begin{cases} \beta c_1'\rho_1, & nt^* \le t < (n+1)t^*,\ n = 0, 2, 4, \ldots \\ (1-c_1')\rho_3 + (1-\beta)c_1'\rho_1, & n = 1, 3, 5, \ldots \end{cases} \tag{22}$$

$$c_1' = \frac{1}{\alpha V_0 + 1} \tag{23}$$

$$c^*(t) = \begin{cases} 1, & nt^* \le t < (n+1)t^*,\ n = 0, 2, 4, \ldots \\ 0, & n = 1, 3, 5, \ldots \end{cases} \tag{24}$$

where $t^* = t_z/2$, t_z the cycle time (s). A value of the parameter β lies within $0 < \beta < 1$.

As the boundary condition at the left-hand boundary, the conditions for a fixed wall impenetrable for the gas are adopted. Consequently, $v = 0$ at $x = 0$.

The pressure P at $x = 0$ is determined according to [13]. At the right-hand boundary, the conditions for free gas efflux at a subsonic speed are adopted. The initial conditions are as follows:

$$t = 0, \qquad v = 0, \qquad P = P_0, \qquad T = T_0, \qquad \rho = \rho_0.$$

3.1. Numerical methodology

For numerically solving the system of gas-dynamical equations (15)–(18) with an account for the "acoustic" viscosity, we have employed the Lax–Wendroff finite difference scheme and the correction method for flows.

An analysis of the results obtained has revealed that introduction of the correction term (11), related to dissipation of the acoustic energy, has a beneficial effect on the computational process. Introduction of the dissipative term with an account for the second viscosity has markedly stabilized the computational process, considerably decreased the amplitude of quasi-steady solutions. In some cases, the velocity amplitude decreased by ~30%. Moreover, an amount of the high- frequency harmonics decreased, i.e. the term (11) is a peculiar filter of high frequencies. We succeeded in, approximately, a 1.5–2 fold increase of the time step which ensured the stability of calculations. However, the correction term exerts an influence not only on PCC design but also on solutions of the peculiar classical problem on gas pipeline rupture or damage. Numerical simulation of the gas pipeline damage has showed that introduction of (11) also exerts a favorable influence on the computational process. Already 37 s later after the damage of a 10 km long gas pipeline at a pressure of 52 atm, the gas outflow velocity shows a marked (up to 10–20%) wavy swinging and a solution becomes unstable. An account of (11) stabilizes the computational process and velocity variation becomes a monotonic process.

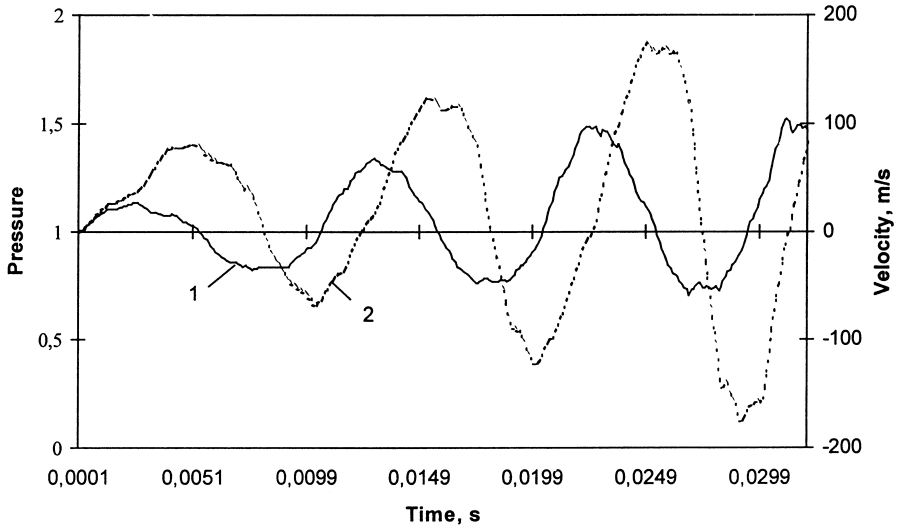

Fig. 2. Time dependence of the pressure $(1 - P/P_0)$ and the gas velocity (2) in the section $x_{(1)}$: $d_{(1)} = 0.07$ m, $d_{(2)} = 0.08$ m, $x_{(2)} = 0.7$ m, $t_z = 0.01$ s.

4. Results and discussion

Calculations have been made for different operation regimes of the PCC and ratios of its design components. The calculations are carried out at the following values of the main parameters: fuel is the propane–butane gas: $R = 8314$ J/(kmol K); $q_0 = 0.0219\,\mathrm{m}^3/\mathrm{s}$; $\rho_0 = 1.23\,\mathrm{kg/m}^3$; $\alpha = 1.05$; $q_c = 2.9 \times 10^6$ J/kg; $c_\mathrm{p} = 1060$ J/(kg K); $c_\mathrm{v} = 776$ J/(kg K); $\mu = 29.58$ kg/kmol; $\mu_2 = 28.36$ kg/kmol; $c_{p2} = 1200$ J/(kg K); $P_0 = 10^5$ Pa; $T_0 = 293$ K; $d = 0.12$ m; $x^* = 0.2$ m; $x_{(1)} = 0.3$ m.

As is seen in Fig. 2, during fuel combustion $nt^* < t < (n+1)t^*$, $n = 0, 2, 4, \ldots$, of the "positive" part of the cycle, in the region $0 \le x \le x^*$ of the chamber heat is released and the gas pressure increases.

This causes outflow of combustion products through the nozzle. The gas velocity increases in the nozzle up to some maximum value. Then rarefaction develops in the combustion chamber which makes the gas to flow back from the tail pipe to the combustion chamber, which leads to negative gas velocity. At the moment of rarefaction, a new portion of fresh air and some amount of fuel are fed to the chamber. Thus, the cycle is repeated. Data in Fig. 2 show a time dependence of the pressure and velocity of the gas flow in the critical cross-section $x = x_{(1)}$. As is seen, the pressure and the gas velocity are sinusoidal and phase-shifted by $\pi/2$. This is attributable to the standing waves which are formed in the pulse combustion chamber. The existence of this effect in the PCC is confirmed by Keller et al. [2] and Popov et al. [3].

The amplitude of pressure fluctuations in the combustion chamber is larger than in the nozzle. Note that at $t = 0$, the parameter values are determined by the initial conditions.

Fig. 3 illustrates profiles of the pressure, density, temperature, and gas velocity over the PCC chamber at $t = 0.025$ s,

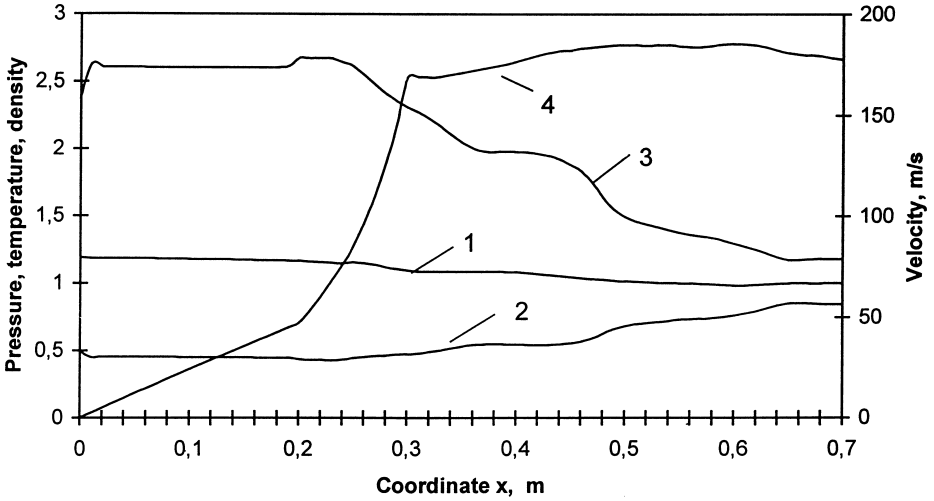

Fig. 3. Profiles of the gas-dynamical parameters at $t = 0.025$ s: (1) gas pressure (P/P_0); (2) density (ρ/ρ_0); (3) temperature (T/T_0); (4) velocity.

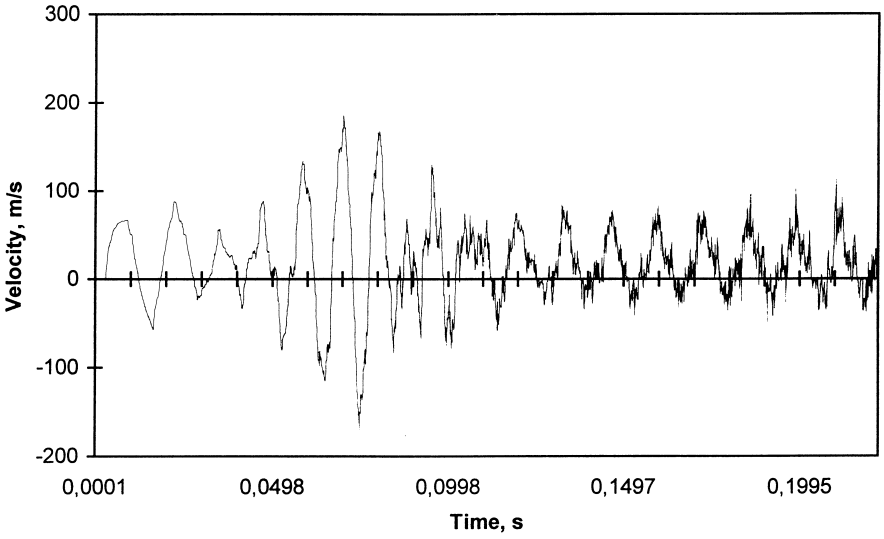

Fig. 4. Time dependence of the gas velocity at the nozzle outlet $x_{(2)} = 1.3\,\text{m}$.

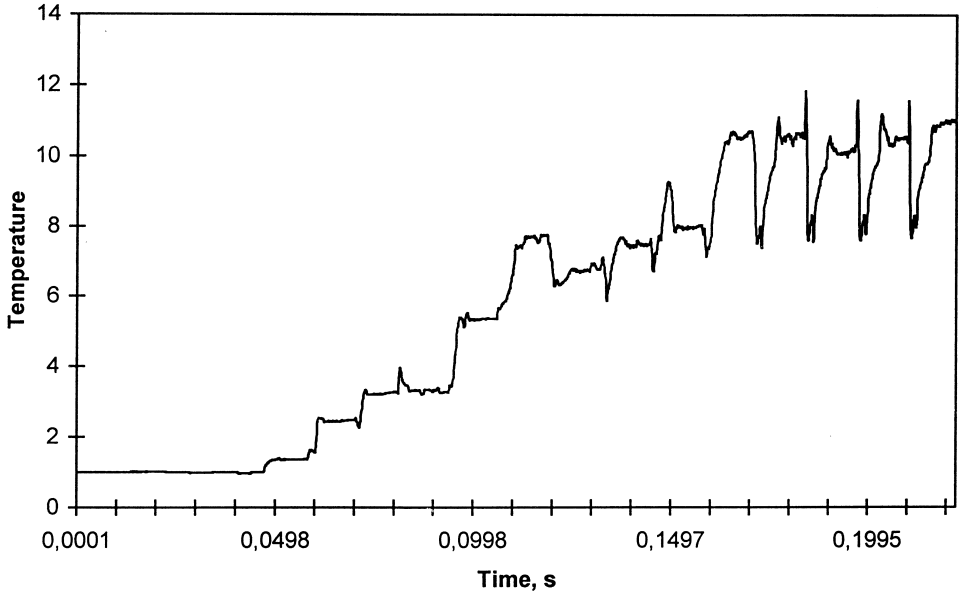

Fig. 5. Time dependence of the gas temperature (T/T_0) at the nozzle outlet ($T_0 = 293\,\text{K}$).

corresponding to the moment of completion of the "positive" part of the cycle. It is seen that the pressure and the temperature are higher in the combustion chamber than in the PCC nozzle. The gas velocity increases in the chamber from 0 to some value and then changes insignificantly in the nozzle.

Figs. 4 and 5 represent calculation results for the velocity and the gas temperature at the nozzle outlet $x = x_{(2)}$ for a chamber with the length $x_{(2)} = 1.3\,\text{m}$ at $t_z = 0.013\,\text{s}$ (see the remaining parameters above). The data are given without account for the term with the second viscosity coefficient. As is seen in Fig. 4, at the instant the chamber is energized, the velocity amplitude increases considerably, and then decreases and reaches the steady oscillating regime at a small mean gas velocity. After some delay from the moment of energizing the chamber, the gas temperature at the PCC outlet increases in the course of time, in accordance with the present model, up to the calorimetric temperature. Here, temperature fluctuations occur.

5. Conclusions

Thus, the gas flow field in the chamber and in the outlet section of the nozzle can be characterized as a high-temperature flow with sufficiently strong velocity oscillations imposed on the comparatively small mean gas velocity. A change in the fuel rate in the PCC and the geometry will result in changing the gas-dynamical parameters and flow

conditions. Nevertheless, the reported data qualitatively fit the operation conditions of the pulse combustion chamber intended for drying of materials. In conclusion, a strongly pulsating high-temperature gas flow generated by the pulse combustion chamber can be efficiently used for drying of solutions and dispersed materials.

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