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GASDYNAMIC PROCESSES IN A PULSATING-COMBUSTION CHAMBER FOR DRYING OF MATERIALS

P. V. Akulich, P. S. Kutz,
E. F. Nogotov, and Cz. Strumillo

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Consideration is given to aspects of application of pulsating-combustion chambers to the drying of solutions and disperse materials. A mathematical description of the gasdynamic processes in these chambers is given and results of a computational experiment are analyzed.

In recent years, the problem of the use of pulsating combustion in various technological processes has aroused much interest in many countries. The technology of pulsating combustion has been know for a long time; however, devices that use it have not found widespread application in spite of their numerous attractive characteristics.

Pulsating-combustion devices are being developed in the direction of producing not only units of small thermal capacity but also industrial-purpose units. Researchers are agreed that the main immediate promising variants of practical use of technological pulsating combustion are air heaters, water heaters, steam generators, drying units, etc. Accumulated experience confirms that pulsating combustion should be considered a promising form of technological combustion. It enables us to increase considerably the heat- and mass-transfer rate and the combustion intensity and to decrease carbon monoxide emissions [1, 2].

Pulsating-combustion chambers (PCCs) are a very efficient source of high-temperature pulsating gas flows. In a gas medium that leaves a pulsating-combustion chamber, velocity fluctuations are approximately 100 m/sec, while the frequency is from 50 to 200 Hz. This pulsating jet with a high temperature can be used to atomize solutions and dry them efficiently without using rotating sprayers or atomizers.

Designs of pulsating-combustion chambers are described in [1] in sufficient detail. Here we consider briefly the principle of operation for the PCCs proposed for use in drying units.

The constructional basis of pulsating-combustion technology is a special fire apparatus in which a pulsating regime of gas flow is realized. Two types of PCCs – with mechanical and aerodynamic valves – are known and are used in industry. In the first type of chamber the valves execute a reciprocating or rotary motion.

In [3], a PCC with diaphragm-type mechanical valves that are sensitive to gas pressure is proposed. The diaphragm travel is no more than 0.0015 m. In a high-pressure cycle the valve elements with diaphragms close the inlets to the chamber, while for a low pressure they open them, and air enters the combustion chamber. This chamber is intended primarily for drying of materials. The dried material is introduced in the nozzle (the rear tube) of the chamber, where it is exposed to a pulsating high-temperature gas flow. The nozzle is a smooth cylindrical tube with an expanded end portion.

A PCC with a rotating mechanical valve [4, 5] consists of two cylindrical sleeves with identical slots of reactangular shape. One sleeve is fixed, whereas the other rotates using a motor. The principle of operation for a PCC with this valve is similar to the operation of a diaphragm-valve chamber. Via the rotating valve, when the slots in the sleeves coincide, and then via an air diode, air under an excess pressure of $0.42 \cdot 10^5$ Pa is supplied to the chamber. Simultaneously, a fuel gas under an excess pressure of 10^5 Pa is supplied to the chamber by a separate channel. The mixture formed is ignited by a spark plug. At the instant the mixture is ignited the valve is closed.

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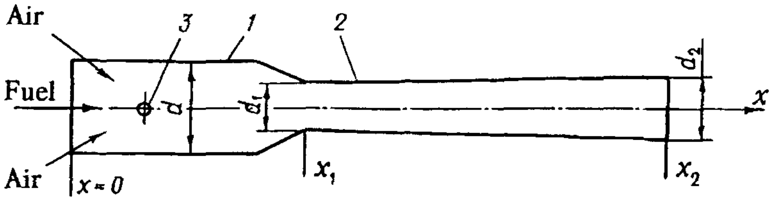


Fig. 1. Scheme of a pulsating-combustion chamber.

Upon ignition excess pressure is produced in the combustion chamber, which stops the gas flow and forces the pulsating flow of combustion products to the rear tube. The combustion products that move via the nozzle produce a partial vacuum in the combustion chamber that is synchronized with opening of the rotating valve. At this time, from the corresponding systems the next charge of air and fuel, which mix rapidly, is supplied. The valve closes, and the mixture is ignited from the remaining combustion products and the hot chamber walls. Each pulse sends a pressure wave toward the exhaust pipe, which is followed by a partial vacuum. Here provision is made for protection of the valve from the combustion products using an air diode, which keeps them from penetrating the valve. The chamber permits oscillations with a frequency of up to 200 Hz and a sound-pressure level of up to 180 dB.

In [4], horizontal and vertical schemes of drying units with the above-considered PCC for drying of disperse materials are proposed. In [5], a vertical cocurrent spray dryer with the same PCC is presented that was developed by the Verekh Company (USA). Presented results of tests of a laboratory setup showed that such designs can process solutions and suspensions that contain up to 90% dry substances. The pilot setup evaporated up to 270 kg/h, using 2800–3270 kJ/kg of removed moisture. The mixture of air and combustion products is supplied to the drier at a temperature of 540–1100°C. Antibiotics, egg melange, etc. were dried. The particles had the shape of microballoons without swelling.

In [6], data on the drying of food solutions in a similar drying unit are given. The author is of the view that the unit dehydrates food solutions in a hot zone in approximately 0.01 sec. The very short time of contact of the material particles with the high-temperature drying agent makes it possible to dry heat-sensitive solutions with a content of dry substances of 50–60%.

PCCs with a rotating mechanical valve permit oscillations of the gas flow with high acoustic parameters. However the presence of moving elements, which are prone to wear in the high-temperature zone, and the necessity of synchronizing the steps of the process should be classified among their drawbacks.

The indicated drawbacks are absent in PCCs with aerodynamic valves. A scheme of these PCCs with forced air supply is proposed in [7]. It contains a combustion chamber with an open inlet end and an exhaust pipe at the outlet of the chamber in line with it. Opposite the inlet to the combustion chamber, in line with it, too, there is a device for supplying compressed air so that the open inlet end of the chamber is completely covered by the compressed-air flow. A horizontal unit intended for drying of solutions is equipped with this PCC. The drying chamber has a cylindrical shape, and the PCC is arranged along its axis.

In [8], it is pointed out that introduction of material into the PCC's exhaust pipe can have a harmful effect on the acoustic characteristics. Here, a scheme of a dryer with a so-called controlled PCC is given. A distinguishing feature of this chamber is the presence, along its axis, of a disk-shaped flame stabilizer that is fixed on a bar. When the gas flows over the flame stabilizer, vortices form that excite acoustic oscillations in the rear tube.

A scheme of a conical tangential PCC with an aerodynamic valve is known [1]. Forced air supply and ignition of the mixture are needed only at the instant of start. The aerodynamic valve in this design provides a lower resistance to the motion of gas into the combustion chamber than in the opposite direction. The need for blowing devices is eliminated.

From the above analysis of PCCs and drying units based on them it follows that PCCs are an efficient source of high-temperature gas flows that permit intensification of heat- and mass-transfer processes in the drying of materials. Clearly, the dynamics of the gas flows has a decisive effect on the efficiency of drying.

In the present work, to study gasdynamic processes in PCCs, we use the method of mathematical modeling. We consider the flow of a compressible medium in a pulsating-combustion chamber of variable cross section (Fig.

1). The latter consists of the following main parts: combustion chamber 1, nozzle (rear tube) 2, devices for supplying air (valves) and fuel (shown as arrows in the diagram), and spark plug 3. The PCC operates in the following manner. When the valves are open, air enters the combustion chamber. Under excess pressure the fuel gas is supplied to the chamber via a burner. The mixture formed is ignited by the spark plug. At the instant of ignition the valves are closed. Upon ignition the pressure increases in the chamber, the fuel supply stops, and combustion products are forced out via the nozzle. In the chamber, a vacuum is produced that is in synchronization with opening of the valve. At this time, the next portion of air and fuel, which mix rapidly, is supplied to the chamber from the corresponding devices. The valves close, and the mixture is ignited. Thus the cycle is repeated.

To model the gasdynamic processes in PCCs, we employ unsteady one-dimensional gasdynamic equations in the form of the "channel" approximation. The x axis is directed along the PCC. The origin of coordinates is aligned with the left wall of the chamber, and the gas flow moves along the x axis.

The equations of one-dimensional unsteady flow of a compressible gas in a channel of variable cross section that express the laws of conservation of mass, momentum, and energy are written as

$$\frac{\partial (S\rho)}{\partial \tau} + \frac{\partial}{\partial x}(S\rho v) = M\,, \tag{1}$$

$$\frac{\partial (S\rho v)}{\partial \tau} + \frac{\partial}{\partial x}[S(P + \rho v^2)] = P\frac{\partial S}{\partial x} + F\,, \tag{2}$$

$$\frac{\partial}{\partial \tau}\left[S\rho\left(h - \frac{P}{\rho} + \frac{v^2}{2}\right)\right] + \frac{\partial}{\partial x}\left[S\rho v\left(h + \frac{v^2}{2}\right)\right] = Q\,, \tag{3}$$

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

Each particle of the gas mixture in the combustion zone is assumed to be in chemical equilibrium. This can be assumed if the characteristic time of the chemical reaction is substantially smaller than the turbulent-mixing time and time of stay of a particle in the reaction zone [9, 10].

The enthalpy of the mixture is $h = c_f h_f + c_{pr} h_{pr}$, here c_f and c_{pr} are, respectively, the average concentration of the fuel and the combustion product over the cross section; h_f and h_{pr} are the enthalpy of the fuel and the combustion products, $h_{f,pr} = h_{f,pr}(T) = c_p T$.

Let us assume that the combustion (heat-release) zone lies in the range $0 \le x \le x^*$ and the concentration of the components of the combustion products behind it (in the nozzle $x^* < x \le x_2$) does not change. In this case, $c_{pr} = c_{air}$, $c_{pr} = 1 - c_f$ for $0 \le x \le x^*$ and $c_f = 0$, $c_{pr} = 1$ for $x^* < x \le x_2$. To close the system of equations (1)-(3), we employ the equation of state

$$P = \rho \frac{R}{\mu} T\,. \tag{4}$$

The enumerated assumptions simplify the structure of flow in PCCs somewhat. However, they satisfy the integral laws of conservation, reflect large-scale motions of the medium to a sufficient degree of correctness, and can give the concepts of a change in gasdynamic quantities.

The source terms are determined by the following relations:

$$M = c(\tau)\, q_0\, l\, \delta(x - x^*)\,, \tag{5}$$

$$F = M v_0\,, \tag{6}$$

$$Q = c^*(\tau)\, q_0 \rho_0\, l \left(\frac{v_0^2}{2} + q\right) \delta(x - x^*)\,, \tag{7}$$

where $l = S'/V' = 1/x^*$; S' and V' are the cross-sectional area and volume of the combustion chamber; v_0 is the velocity of the supplied gas mixture, m/sec; $\delta(x-x^*)$ is the step function, $\delta = 1$ for $0 \le x \le x^*$ and $\delta = 0$ for $x^* < x \le x_2$;

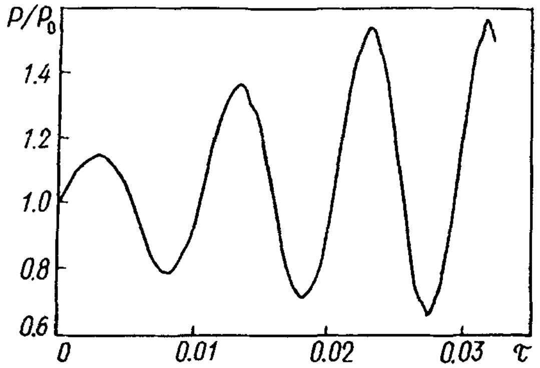


Fig. 2. Chamber pressure vs. time for $x = 0.1$ m: $\tau_c = 0.01$ sec; $d_1 = 0.07$ m, $d_2 = 0.08$ m, $x_2 = 0.7$ m. τ, sec.

$$c(\tau) = \begin{cases} \beta c'_f \rho_f, & n\tau_1 \le \tau < (n+1)\tau_1, \quad n = 0, 2, 4, \dots, \\ (1 - c'_f)\rho_{air} + (1 - \beta)\, c'_f \rho_f, & n = 1, 3, 5, \dots, \end{cases} \tag{8}$$

$$c'_f = \frac{1}{\alpha V_0 + 1}, \tag{9}$$

$$c^*(\tau) = \begin{cases} 1, & n\tau_1 \le \tau < (n+1)\tau_1, \quad n = 0, 2, 4, \dots, \\ 0, & n = 1, 3, 5, \dots, \end{cases} \tag{10}$$

where α is the excess-air coefficient; V_0 is the theoretical amount of air required for complete combustion, m^3/m^3; $\tau_1 = \tau_c/2$, τ_c is the cycle time, sec. The parameter β lies in the $0 < \beta < 1$ range.

The condition for a fixed wall impermeable to gas is taken as the boundary condition at the left boundary; consequently, $v = 0$ for $x = 0$.

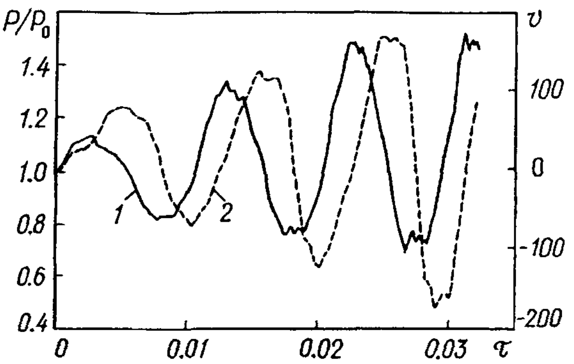
The pressure P for $x = 0$ was determined according to [11]. At the right boundary, the conditions for free outflow of gas at a subsonic velocity are taken. The initial conditions are: $\tau = 0$, $v = 0$, $P = P_0$, $T = T_0$, and $\rho = \rho_0$.

For a numerical solution of this problem, a modified Laks–Wendrof finite-difference scheme is used. Calculations for different regimes of PCC operation and relations of the structural elements are performed. The following basic parameters are taken: the fuel is butane-propane gas; $R = 8314$ J/(kmol·K); $p_0 = 0.0219$ m^3/sec; $q_0 = 0.0219$ m^3/sec; $\rho_0 = 1.23$ kg/m^3; $\alpha = 1.05$; $f = 2.9 \cdot 10^6$ J/kg; $c_p = 1060$ J/(kg·K); $c_V = 776$ J/(kg·K); $\mu = 29.58$ kg/kmol; $\mu_{pr} = 28.36$ kg/kmol; $c_{ppr} = 1200$ 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.

From Fig. 2 it is evident that during the time of fuel combustion $n\tau_1 < \tau < (n+1)\tau_1$, $n = 0, 2, 4, \dots$, (the "positive" part of the cycle) in the chamber region $0 \le x \le x^*$ heat is released and the pressure increases. This leads to discharge of the combustion products via the nozzle. The gas velocity in the nozzle increases to a maximum. Then in the combustion chamber a vacuum is produced that induces reverse flow of the gas from the rear tube to the combustion chamber, i.e., negative velocity of the gas. At the instant of vacuum, a new portion of fresh air and, partially, the fuel is supplied to the chamber. Thus, the cycle is repeated. The data in Fig. 3 show the pressure and velocity of the gas flow as functions of time in the critical cross section $x = x_1$. From an analysis of them follows that the gas pressure and velocity are sinusoidal and phase-shifted by approximately 90°. This is due to the property of standing waves that form in the pulsating-combustion chamber. The existence of this effect in PCCs is confirmed by the results of [1, 2].

The amplitude of the pressure oscillations in the combustion chamber is higher than in the nozzle. We note that, for $\tau = 0$, the parameters are determined by the initial conditions.

Figure 4 illustrates the pressure, density, temperature, and velocity profiles for the gas along the PCC axis at the instant $\tau = 0.025$ sec, which corresponds to the instant the "positive" part of the cycle is completed. It is



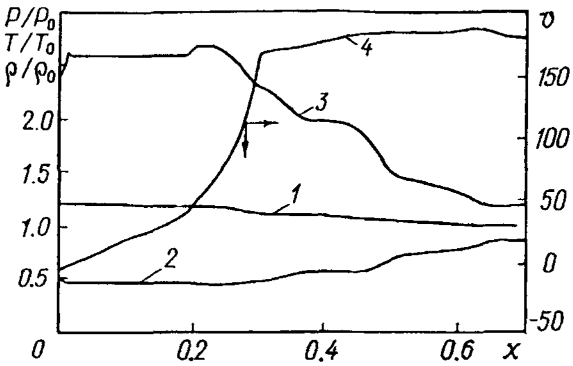


Fig. 3. Pressure (curve 1) and velocity of a gas flow (2) vs. time in the cross section $x = x_1$. v, m/sec.

Fig. 4. Profiles of gasdynamic parameters for $\tau = 0.025$ sec: 1) gas pressure (P/P_0), 2) density (ρ/ρ_0), 3) temperature (T/T_0); 4) velocity.

evident that the pressure and temperature in the combustion chamber are higher than in the PCC nozzle. The gas velocity in the chamber increases from zero to some value and then changes insignificantly in the nozzle.

Thus, the field of gas flow in the chamber and in the outlet cross section of the nozzle can be characterized as a high-temperature flow with rather strong velocity oscillations that are superimposed on a comparatively low average velocity. Different flow rates of the fuel in the PCC and geometry of it will, of course, lead to different gasdynamic parameters and conditions of flow. However, the data presented qualitatively correspond to the conditions of pulsating-combustion chamber operation and the results of [1, 2].

In summary we note that a strongly oscillating high-temperature gas flow formed by a pulsating-combustion chamber can be used efficiently for drying of solutions and disperse materials.

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NOTATION

c_p, c_V, heat capacity of the mixture at constant pressure and volume, J/(kg·K); d, combustion-chamber diameter, m; h, enthalpy, J/kg; P, pressure of the mixture, Pa; q_0, volumetric flow rate of the fuel mixture, m^3/sec; q, specific heat of combustion for the fuel mixture, J/kg; R, universal gas constant, J/(kmol·K); v, velocity of the mixture, m/sec; T, mixture temperature, K; μ, molecular weight, kg/kmol; ρ, density, kg/m^3; τ, time, sec. Subscripts: pr, combustion products; f, fuel; air, air; 0, initial parameters.

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