ции и дисперсности металлообразующего вещества, а также однородности распределения его по объему, движение агломерата вглубь топлива может происходить квазистационарно.

Окись магния *MgO* очень устойчивый окисел, с температурами плавления и кипения выше температур горения пороха. Восстановление его, например углеродом, в атмосфере воздуха возможно при температуре 2 013 °С, но поскольку чистый магний очень активный металл, возможно, что в процессе горения он восстанавливается с последующим окислением при охлаждении.

Таким образом, экспериментальные исследования доказывают справедливость предложенной физической модели образования сквозных отверстий в топливе С-2 при сгорании его в поле массовых сил.

Выводы

1. Обнаружено, что при горении пороха С-2 в условиях перегрузок более 400 g формируются неразгорающиеся каналы ∅ 0.5–1 мм, вытянутые по направлению действия вектора ускорения.
2. Использование метода качественного рентгенофазового анализа конденсированных продуктов сгорания показало, что при сжигании порохов происходит восстановление окислов, входящих в состав топлива элементов.
3. Показано, что по теплофизическим и химическим свойствам ответственными за образование отверстий могут быть восстановленные до металлического состояния частицы β-*Co*. Наличие β-*Co* в продуктах сгорания подтверждено другими методами.
4. Фотосъемка разрезанных вдоль образовавшихся каналов образцов, погашенных в разные промежутки времени, наглядно показала процесс формирования и развития неразгорающихся отверстий.
5. Предложена физическая картина явления, объясняющая эффект беспламенного проникновения под действием перегрузок агломератов β-*Co* вглубь образца исходя из физических свойств частиц и разницы давлений в пространстве под и над частицей.

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GASDYNAMIC ANALYSIS OF THE AIRBAG GAS GENERATOR WITH A POROUS CHARGE

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В статье представлена математическая модель работы airbag-газогенератора с пористым моноблочным зарядом. Выполнен сравнительный анализ результатов вычислений и экспериментальных данных. На основе анализа развития основных физических процессов предложена и обсуждена новая конструктивная схема airbag-газогенератора.

Mathematical model

In the present time car airbags, in which a source of pressure are low temperature solid propellant gas generators, have received wide spread occurrence and successfully develop. An autonomy, compactness, the large potential reserves of gases in small volumes of energetic material make by their indispensable at problem solving of car safety and in a number of extreme situations. In the most widespread design with a granular (peleet) charge the high temperature of gaseous combustion products and high-temperature particles of a condensed phase in combustion products are main disadvantages causing difficulty of gas generator application. The given defects of the design are overcome by use of special units of cooling and mechanical filters.

Different perspective design largely deprived indicated disadvantages, are the airbaggas generators with porous solid propellant charge, which combustion will be organized in a wake filtration mode [1].

The design concepts of similar gas generators provide such organization of surface combustion of a porous charge, when the combustion products are essentially cooled, diffusing through a porous structure of a charge.

The filtration of the heat-carrier through a charge in a direction of reaction front results, in turn, in local heating of a combustion zone. The redistribution of energy between gaseous and condensed combustion products allows to get a low temperature gases. Besides the output of condensed combustion products is reduced due to their partial settling in a porous structure of a charge.

In the present paper the results of gas dynamic research of processes accompanying airbag gas generators with porous solid propellant charge (fig.1) operation are submitted. The following scenario of physical processes development was considered. From the moment of igniter start-up high-temperature pyrotechnic combustion products go in the gas generator combustion chamber, causing a gradual warm-up and ignition of a solid charge, which porous structure is represented by a system connected among themselves propellant's granules of the cylindrical shape.

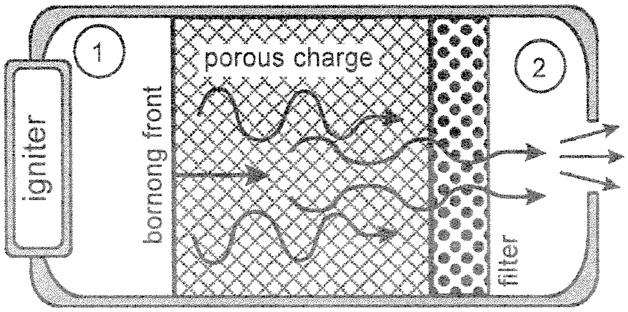

Fig. 1. Gas generator with porous charge

The front «working» charge surface, connected to combustion, results in increase of pressure in the gas generator combustion chamber head volume; after nozzle gag breaking up the quasistationary process of end face burning begins. The combustion products, diffusing through a porous structure of a charge, cause preliminary (before the shave of combustion front) a warm-up of propellant, providing, in consequent, increased burning rate.

The mathematical model describing indicated processes, is founded on equations expressing laws of mass, momentum and energy conservation, which are formulated for igniter in averaged parameters, flow of combustion products through a porous charge – in one-dimensional description of internal ballistic characteristics changes.

The mathematical model describing a change of gas dynamics parameters in a igniter case cavity, is represented by a system of ordinary differential equations for averaged on internal free volume W internal ballistic characteristics. It is supposed, that spherical granules of a pyrotechnic composition forming a igniter charge, flames simultaneously on all surface, and the design of the perforated case prevents take out of igniters grains. The system of equations for the conservation of mass and energy and for the variation in the free interior volume in the igniter then becomes [2]:

$$\frac{d}{dt}(\rho W)=(1-z)M_i-M_*,$$

$$\frac{d}{dt}(\rho RW)=(1-z)R_iM_i-RM_*,$$

$$\frac{d}{dt}(\rho CpW)=(1-z)Cp_iM_i-CpM_*,$$

$$\frac{d}{dt}\left(\frac{pW}{\gamma-1}\right)=(1-z)Cp_iTp_iM_i-\frac{1}{\gamma-1}\frac{p}{\rho}M_*,$$

$$\frac{dW}{dt}=-\frac{d\omega}{dt},\ M_i=-\rho_i\frac{d\omega}{dt},$$

where t – time; p, ρ – pressure and density; R, γ – gas constant and adiabatic coefficient (ratio of specific heats); C_p, T_p – specific heat of gas components or mixture and isobaric combustion temperature; z – portion of the condensed phase in the combustion products; sub i relate to individual properties of pyrotechnic mix.

The gas flow, M_*, through the perforation holes is calculated by the familiar quasi – stationary equations into the external (in the gas generator chamber) pressure [2]. The transient volume of the pyrotechnic grains depends on the flame depth ($m_o/\rho_o \geq \omega \geq 0$, m_o, ρ_o – mass and powder density) and is a function of the grain shape. For a wide spectrum of shapes, the relationship between the transient volume of these grains, ω, and their sizes is very simple

$$\omega=\frac{m_i}{\rho_i}\cdot\frac{\prod_{j=1}^{3}(e_j-e)}{\prod_{j=1}^{3}e_j},$$

where e_j (j = 1, 2, 3) is the initial geometric grain characteristics.

The variation of the typical size of a grain as a result of the burning is described through the burning rate, u_i, and the depth, e, by the equations $de/dt = u_i$.

The mathematical model of the processes in the combustion chamber of a gas generator is based on the integral equations of gas dynamics derived from the laws of mass, momentum, and energy conservation. Additional special equations define the thermal and physical properties of the multicomponent combustion products from the igniter charge and the air that initially fills the chamber. This system of equations is applied to a reference volume, V, bounded by a closed surface comprised of both gas-permeable (A) and gas-impermeable (S) materials. Heat and mass are exchanged between gas flow and gas generator elements. The changes of mass, momentum and energy in the control volume are coupled by the volume interactions, the influence of the external surroundings on each of the mentioned quantities, and their transfer through A. This system of conservation equations is written below in the integral form with a generalized coordinate system [2]:

$$\frac{\partial}{\partial t}\int_V \rho dV + \int_V \rho N dA = \int_S M_p dS,$$

$$\frac{\partial}{\partial t}\int_V \rho \mathbf{u} dV + \int_V \mathbf{\Pi} dA + \int_S \mathbf{\Pi} dS + \int_S \rho \mathbf{f} dS = 0,$$

$$\frac{\partial}{\partial t}\int_V E dV + \int_V (E+p) N dA + \int_S q dS = \int_S Cp_p Tp_p M_p dS,$$

$$\frac{\partial}{\partial t}\int_V \rho R dV + \int_V \rho R N dA = \int_S R_p M_p dS,$$

$$\frac{\partial}{\partial t}\int_V \rho Cp\, dV + \int_V \rho Cp N dA = \int_S Cp_p M_p dS,$$

$$E = \frac{p}{\gamma - 1} + \frac{\rho|\mathbf{u}|^2}{2},$$

with u – vector of velocity; N – modulus of the velocity normal to the surface determined by the scalar product of the vector of the velocity u and the unit vector normal to the outer surface n, $N = (u, n)$; Π – flow of impulse, $P\mathbf{n} + \rho\mathbf{u}N$; M – mass supply density; H – enthalpy of flow products; f – friction stress; q – heat flux density; sub p relate to porous propellant charge.

Density of mass income from combustion surface M_p, is determined by a ratio $M_p = u_p\left[1 + \beta \bar{T}(x,t)\right]$, where β – temperature coefficient of burning rate dependence from «initial» temperature of propellant. Local temperature of a charge $\bar{T}(x,t)$ is determined by average of a local temperature profile obtained from the solution of a heat conduction equation, describing change of a charge temperature owing to a filtration through it of combustion products. The particular values of surfaces sizes A and S are determined by a factor of a porosity of a charge.

The ignition time calculation is made in frameworks of the solid theory received broad development in activities of V. Vilyunov [3]. The mathematical model of an ignition problem of solids includes a heat conduction equation with allowance for of exothermal responses and equation of a chemical kinetics [3, 4].

The mathematical statement of a problem is closed by appropriate initial and boundary conditions. The systems of ordinary differential equations are decided by the predication – correction schemes; the spatial motion of gas is calculated by a modified Godunov method of any gap decay [5] with the increased order of approximating. For implementation of an ignition equation the adapted computational grid varying depending on conditions of a warm-up is used [4].

Calculation Results

The calculations were realized for the gas generator with a charge with the following main characteristics: Diameter of a charge – 90 mm; Length of a charge L = = (120–140) mm; Length of a charge together with the filter – 150 mm;

Characteristic of a material of a charge:

Density – 1920 kg/m^3; Coefficients of propellant thermal conductivity – 6.3 × 10^{-7} m^2/s; Coefficients of propellant heat conduction – 0.86 W/(m×K); Porosity – (0.3–0.6); Temperature coefficient of the burning rate law (0.001–0.004).

On fig. 2 the results of comparison of computational and experimental data [1] for relation of pressure to time for area 1 of head volume and 2 – parameters of gas behind the filter (fig. 1) are submitted.

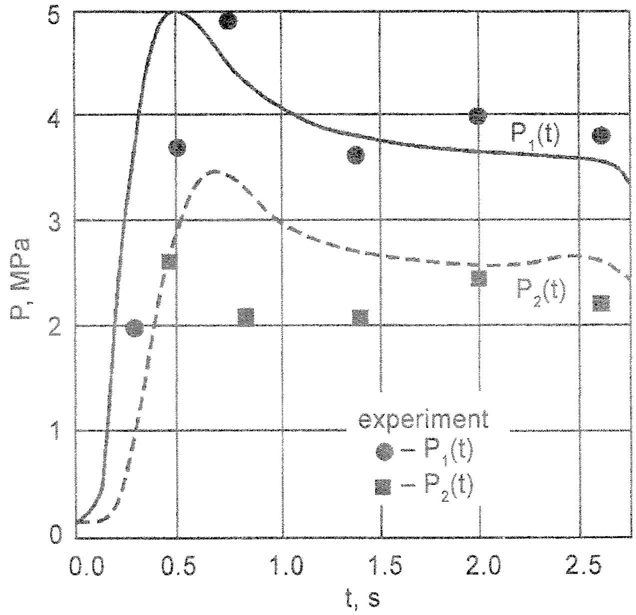

Fig. 2. Comparisons of computational and experimental data for relation «pressure – time»

The analysis of calculations results shows their good qualitative conformity to experimental data. Relation of pressure $p_1(t)$ (head volume of the gas generator) has rather good quantitative conformity with experiment. The curve $p_2(t)$ in all time range is situated above than experimentally determined level. Some rise of pressure on the given curve during completion of a charge combustion is connected as to smaller losses of heat into propellant, so by heating of a filter to the given point of time. It is possible to explain more significant rise of the experimentally measured pressure by the factor of lowering of the filter area, free for pass of gas, owing to a settling in it of condensed particles.

On fig. 3 the pressure profiles on the combustion chamber in various points of time are shown. Qualitatively character of submitted relations is stipulated, mainly, motion of combustion front.

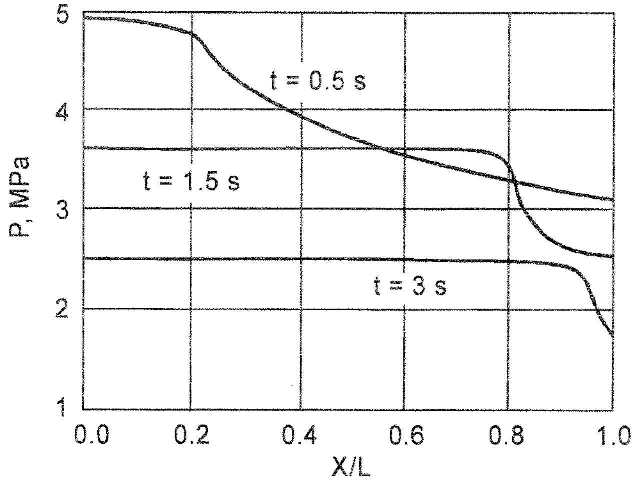

Fig. 3. Pressure profile on length of a charge in various points of time

Character of gas distribution (combustion products) temperature is poor change of its profile with regard to coordinate of a current position x_f of combustion front during gas generator operating time. The particular kind of relation is adduced on fig. 4.

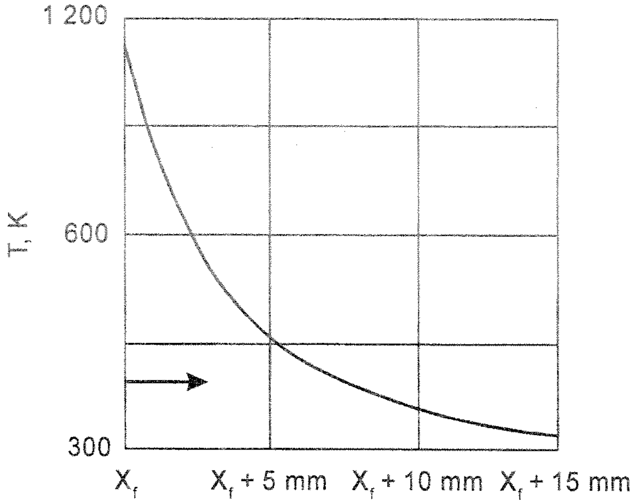

Fig. 4. A profile of gas temperature in a neighbourhood of combustion front

On fig.5 the outcomes of a pressure differential size (between head volume and area behind the filter) comparison for charges of a various porosity η are submitted. The painted area represents a field of a series of experimental results; a solid line – averaged (on operating time of the gas generator) computational values. It is visible, that the computational pressure differential practically is always less significant, that it is possible to explain by difference of actual «internal» geometrical parameters of a porous charge and used model and also absence of the registration of motion and settling of a combustion products condensed phase in a charge.

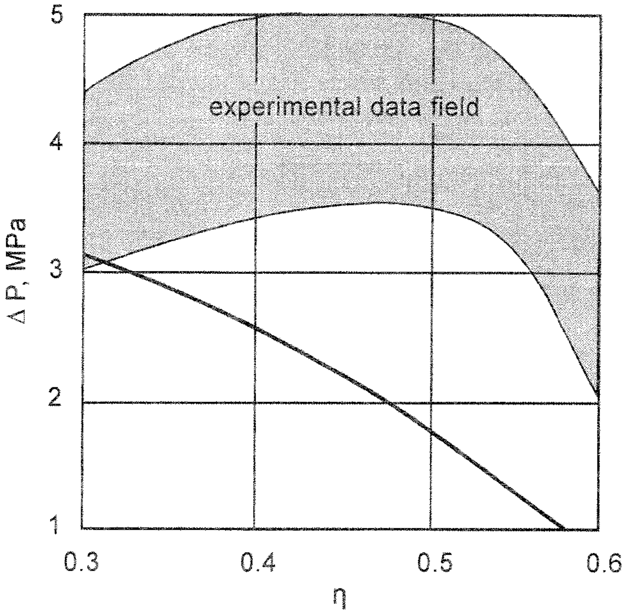

Fig. 5. Comparison of experimental and computational values of pressure differential along a charge

As a whole concurrence of the experimental and computational data is satisfactory, that allows to use the offered approach for designing of gas generators with a porous charge.

Based on discovered features of a gas dynamics of processes in the gas generator with end face burning charge it is possible to offer the following design of porous charges for airbag gas generators application. In perforated on an external surface (see fig. 6) a case the charge of the tubular form is placed, igniter is located in channel. The igniter provides ignition of a channel surface of a charge and further mode of cocurrent combustion.

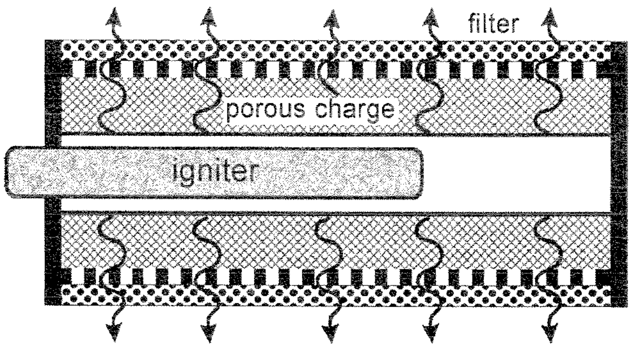

Fig. 6. Scheme of gas generator

For this design the solution was constructed similarly to foregone scheme – the averaged parameters in a channel of a charge and one-dimensional flow and heat conduction along a radius of a porous charge and filter (but for the axisymmetrical description of flows) were calculated. The geometry of a charge was selected so that the initial combustion surface corresponded to similar value for a previous calculations. On fig. 7 the time history of averaged on a channel of a charge pressure is shown.

It is necessary to note qualitative and quantitative difference of processes in comparison with the gas generator, where the porous charge burns on an end face surface. In particular, the relation of pressure to time (fig. 7) has increasing character during all active operating time, that is caused both development of geometry of a combustion surface, and higher degree of a warm-up of a much more thin porous charge mass. Mean temperature of combustion products on an output of the device is higher on 74 K (in comparison with calculation for the gas generator with a end face charge) as combustions products which are flowing past through a rather thin porous charge, have no time to be cooled up to its temperature.

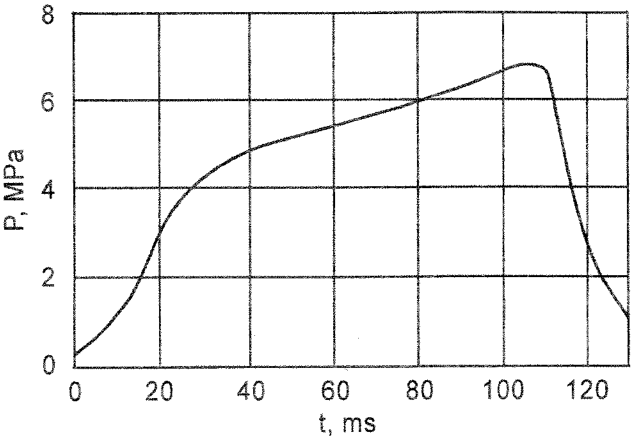

Fig. 7. A time history of averaged on a charge channel pressure

Thus, in the given paper the technique of the gas dynamic analysis of airbag-gas generators with a porous charge ensuring calculation of their main parameters is submitted. The legitimacy of the offered approach application is confirmed by the satisfactory matching with experimental data. The new design of airbag-gas generators with porous charges of surface combustion high-energy materials in a mode of a cocurrent filtration is offered; the key features of a gas dynamics of processes devices are ascertained.

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