Dynamics of pressure and temperature during flame propagation in a closed vessel with a porous medium

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It was experimentally studied flame propagation (gas explosion) in closed vessel containing stoichiometric propane-air mixture and partially filled with a porous medium. As the porous media there were used packing of steel balls of 3.2 and 6 mm in diameters, and also ceramic balls of 6 mm. Experimental dependence of maximum pressures during flame propagation on the filling factor of the vessel with the porous medium was obtained. There were found theoretical estimates of the pressures that satisfactory agree with the experimental data. Estimates that are the most close to the experiment data based on the assumptions that gas burns adiabatically in the free space and is compressed isothermally in the porous medium. The effect of heat losses from the gas into the porous medium and vessel walls on the value of the maximum pressure is analyzed.

Kee words: explosion pressure, closed vessel, porous medium.

1.1 Introduction

The possibility of flame propagation in a combustible gas mixture (gas explosion) in a porous medium depends on the size of the pores. The porous medium is characterized by an average pore size and porosity (a fraction of the free volume in relation to the whole volume), ε. There is a critical (quenching) pore size. The flame cannot propagate in a porous medium (PM) with a lower pore size. The critical size depends on fuel, oxidizer, temperature and pressure [9]. With increase in pressure, the critical size decreases [9]. Filling the volume of the vessel with a porous medium provides passive explosion protection. If pore sizes is below the critical one the flame will not spread, the pressure in the vessel will not exceed the initial pressure. However, this method has disadvantages due to the fact that filling the porous medium reduces the free volume, and the extended surface of the fine pores increases the hydraulic resistance when transporting the gas through the vessel.

If the pore size is above the critical one, the flame propagation in the PM can occur in different regimes having their own ranges of velocities and pressures evolved in the combustion wave. These regimes are implemented in dependence on pore size, initial pressure, temperature and laminar burning velocity of the gas mixture. Reviews on these combustion regimes are available in [3,4]. From these reviews it follows that explosion safety of the closed volumes can be ensured without excluding combustion of the gas. In this case the most suitable combustion regime is the regime of flame propagation with the velocities lower 10 m/s. Since flame propagation velocity in this regime is substantially lower than sonic one the pressure all over the vessel is equal and is changed in time in according with the mass fraction of the burnt gas. In the high porosity medium ($\varepsilon \approx 0.98$), the pressure increases during the flame propagation. The maximum pressure depends on the heat release of the gas and the volumetric heat capacity of the PM. In the low porosity medium, for example, in irregular packing with balls ($\varepsilon \approx 0.4$), the pressure does not increase, but decreases during the flame propagation [10]. It seems promising, in some cases, the use of porous media with a pore size greater than critical, but with partial filling of the vessel with a porous medium. This allows one to increase part of free volume.

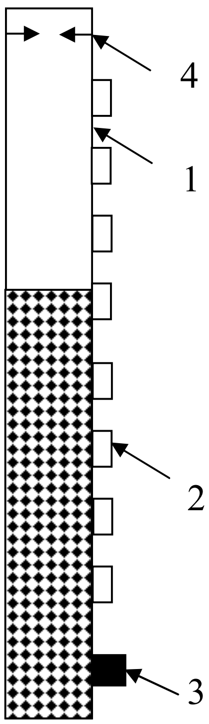
The aim of this work is to obtain an experimental and theoretical dependence of the maximum pressure in the vessel on the filling factor of the vessel with a porous medium. Knowing the limits of the strength of the vessel, one can always find such filling factor that the maximum pressure does not exceed a given value.

1.2 Experimental

Experimental vessel is the same as in [7, 8, 10, 11]. It is vertical tube. In upper part of the tube was free space and lower part contained PM. The tube was quadratic cross section 48x48 mm^2 and 1.68 m in length with regular windows.

Distance between the windows is 12 cm. At each of the windows there were photodiodes. Such length of the tube allows being steady-state of flame propagation in porous medium in the case when filling factor $k=l/L$ was sufficiently high. Here L is length of the tube and l is length of that part that filled with porous medium (Fig. 1). Maximum pressure reached at flame propagation depends on this filling factor. Filling factor is varied from 0 to 1. In the most experiments the porous medium represents filling with steel balls of diameter of d=6 mm. The tube was filled with balls up to the required window. This window is just over the PM at the distance of 5-10 mm in free space. The porosity ε of a porous medium of identical balls of irregular packing is about 0.4 and it does not depend on the diameter of the ball. This porosity was in our experiments.

Fig. 1. Set up. 1 - tube , 2 – windows with photodiodes, 3 – pressure sensor, 4 – ignition electrodes, volume with a porous medium is shaded.



As the combustible gas mixture (unburnt gas) we used the mixture of 4% in volume of propane with air (purity of propane 99.99%). Accuracy of mixture preparation is 0.1%.

Experiments carried out in the following manner. The tube was filled up to definite height with balls of the same diameter. Then it was vacuumized and filled with unburnt gas prepared in advance in the high pressure mixer. The range of initial pressures in the tube was 0.08 – 0.43 MPa. After electric spark ignition near upper end of the tube there were registered pressure and photodiodes signals. Photodiodes signals allow determining propagation velocity of the flame and the pressure at the moment when flame has approached to the PM. Average velocity was defined as distance between the windows with photodiodes divided into time between maximum of signals from these photodiodes.

1.3 Results

For estimate of heat loss from free space into the tube walls and characteristic time of flame propagation that are dependent on initial pressure there were carried out experiments in the tube without PM for initial pressures in the range of 0.1 – 0.2 MPa.

After ignition, the flame propagates with acceleration. Then it slows down, the flame speed tends to a constant value. The flame propagation was accompanied by a continuous increase in pressure in the vessel. The average flame propagation velocity is 6-7 m/s, the maximum velocities at the beginning of propagation immediately after ignition are 12-18 m/s, the velocity at the end of propagation is 4-5 m/s. It should be noted that as the initial pressure increases, a small increase in the average flame velocity occurs. The value of the relative end pressure $\pi_e = p_e/p_0$, where p_e pressure at the end of combustion (which is the maximum at propagation in the vessel without PM) varied from 3 at initial pressure p_0=0.1 MPa to 4.6 at p_0= 0.2 MPa. This pressures are lower than calculated adiabatic relative end pressure π_a=9.5 and 9.6 for p_0=0.1 and 0.2 MPa correspondingly. It means that conditions are non-adiabatic. Increase in π_e with increase in initial pressure points to decreasing heat loss during flame propagation at increase in initial pressure.

Typical dependences of relative current pressure $\pi = p/p_0$ on time in the tube partially filled with PM for different *k* and p_0 are presented in Fig. 2.

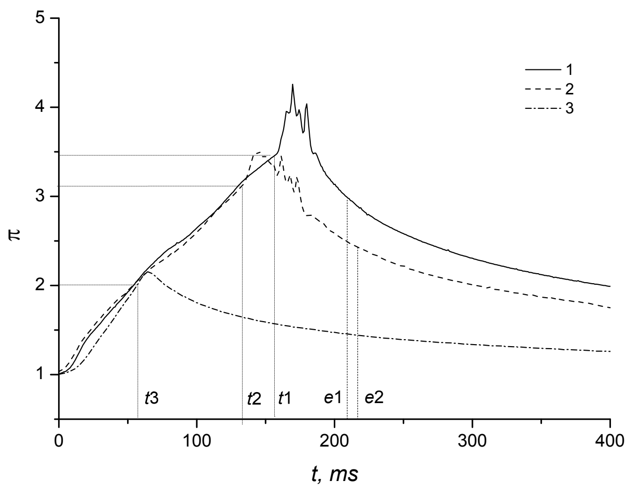


Fig. 2. Dependences of relative current pressures on time. 1 – k=0.25, p_0=0.195 MPa; 2 – k=0.32, p_0=0.175 MPa; 3 – k=0.61, p_0= 0.175 MPa; marks $t1$ - $t3$ point to the moment of flame approach to PM and the value of relative pressure π; $e1$, $e2$– the moments of flame propagation end (for curve 3, $e3$ is out of the presented time interval).

Flame propagation begins in free space and flame propagates approximately the same manner as in the tube without PM. At the moment of flame approach to PM that is marked $t1$ ($t2$, $t3$) in Fig. 2 the combustion wave in porous medium begins to form. At that there is small pressure rise occurs and pressure reaches its maximum. After combustion wave formation in the porous medium it propagates with smooth decreasing of pressure.

Shortly, for comparison, describe flame propagation in the tube completely filled with PM (k=1) as in [7, 8, 10, 11]. In this case after combustion wave formation the flame also propagates with decreasing of pressure but with small characteristic fluctuations of pressure. Cooling of burnt gas to temperatures below the dew point and condensation of water from the burnt gas result in pressure decrease. At the moment of approach to the end of the tube there begins short-term sharp pressure drop and then pressure decrease ceases [11]. This sharp pressure drop is due to disappearing of the combustion wave and fast cooling of burnt gas [10]. Since earlier burnt gas has already the temperature close to temperature of the porous medium further pressure drop ceases due to absence of heat loss.

In the tube partially filled with PM unlike the case k=1 there is no characteristic pressure fluctuations after formation of combustion wave and there is no noticeable pressure drop at the moment of combustion wave approach to the end of the tube. Pressure decreases smoothly. The pressure decrease is due not only to the cooling of gas by tube walls and surface of the porous medium and also the condensation of water from burnt gas, but mainly by tube walls. The pressure drop from the maximum by the end of combustion is greater than would be due to the condensation of water. With increase in initial pressure the rate of pressure drop decreases. The end of combustion is almost unnoticeable on pressure record and it can be fixed only by the signals of photo diodes.

It should be noted that the process of flame penetration into a porous medium or the formation of a combustion wave can occur with a sudden increase in the rate of pressure increase and pressure fluctuations (curves 1, 2 in fig. 2), and with smooth increase in pressure and without fluctuations (curve 3, fig. 2). It is seen that growth of pressure due to formation of the combustion wave is small comparatively to pressure gain at flame approach to PM.

Fig. 3 demonstrates influence of the filling factor k on the value of maximum pressure. Maximum pressure π_m is presented in relative values p_m/p_0. This allows us to generalize data obtained under different initial pressures. Ranges of pressures were 0.08 – 0.2 MPa for balls of 6 mm and 0.1 – 0.43 MPa for balls of 3.2 mm diameter.

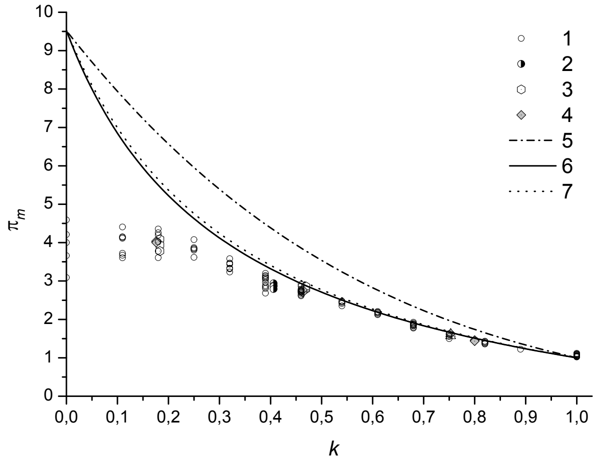


Fig. 3. Dependence of maximum pressure on k. 1, 2 – steel balls of 6 mm (L=1.68 m – 1; L=1.89 m - 2); 3 – ceramic ball of 6 mm; 4 – steel balls of 3.2 mm; 5-7 – theoretical estimates.

The main number of the experiments were carried out in the tube of L=1.68 m of length. It is seen that material and diameter of the balls does not influence on the value of maximum relative pressure. Increase in the tube length decreases a little the maximum pressure.

In the case when velocity of acoustic compression wave is much more than flame propagation velocity the pressure will be approximately identical all over the vessel. To be convinced that this condition is implemented there are compared maximum pressures obtained under equal initial pressures and filling factors for balls of 3.2 mm and 6 mm of diameters. Experiments showed that maximum pressures at the same filling factor for these balls are approximately equal. It is worth noting that for balls with a diameter of 3.2 mm, the pressure at the moment of flame approach to PM is also the maximum, since the flame does not propagate further (is quenched)

1.4 Discussion

After ignition at the top end of the tube flame begins to propagate from top to down towards PM. Pressure increases and the unburnt gas which is in front of the flame moves from free space into PM. Let's estimate pressure which is reached at the moment when the flame has approached to PM. For this purpose we will make the following assumptions. Flame propagation in the free part of the tube occurs adiabatically, i.e. we do not consider heat exchange of burnt gas and unburnt gas with walls. But further we consider two variants of assumptions. The first assumption is that gas in PM compresses also adiabatically, without heat exchange with the porous medium. The second assumption is the following. Unburnt gas penetrating PM takes initial temperature T_0 and further during pressure rise it is compressed isothermally. Other assumptions are the same as in classical formulations, it is accepted that gas is ideal, thermal capacities do not depend on temperature [1, 12], pressure of gas is identical overall the vessel.

Note that even if the process of compression of unburnt gas is quasi-equilibrium, the temperature of the unburnt mixture and PM can increases if the heat capacity of the solid phase per unit of the gas phase is small. But in our case this relative heat capacity is not small but very large and is about 10^3. Therefore whether temperature in our case will increase depends only on rate of the compression process.

Temperature measurements outside the PM in the fresh mixture showed that despite the heat loss into the vessel walls the compression of the fresh mixture occurs in the process close to adiabatic one. Gas compression in the PM occurs in the process close to isothermal. Figure 4 shows the dependences of the gas temperature in the PM, the current relative pressure $\pi = p/p_0$ and $d\pi/dt$ as a function of time during flame propagation. The initial gas pressure p_0=0.11 MPa. The PM occupied a height of 0.21 m in the lower part of the tube and the thermocouple was placed in the pore at a depth of 0.12 m from the boundary with free space.

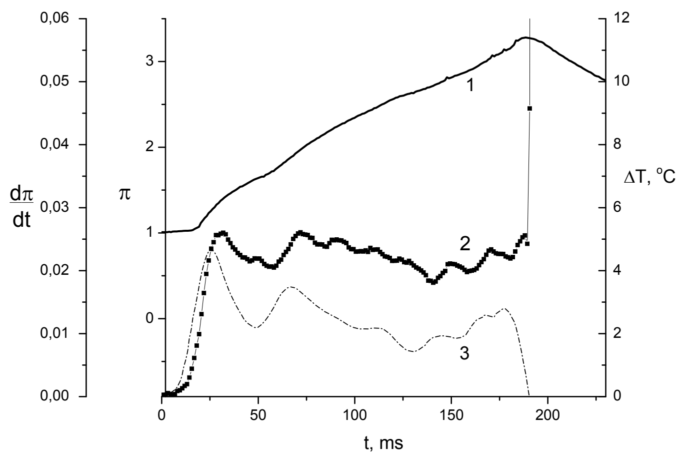


Fig. 4. Dependences of pressure (1), gas temperature increase in PM (2), and pressure derivative $d\pi/dt$ (3) on time.

It is seen that at the first moment the gas is heated to

$\Delta T \approx 4^{\circ}$C and then the temperature remains almost constant. When the flame enters into the PM at 0.12 m, the pressure drop begins when the flame propagates further in the PM (Fig. 4, t>190 ms). It can be seen that both the temperature rise level and the temperature correlation with $d\pi/dt$ dt indicate the dependence of the gas temperature in the PM on the rate of change of pressure.

Theoretical estimates, assuming a constant rate of pressure growth, show that gas compression in the free space occurs almost adiabatically. In the porous medium, the gas temperature first becomes slightly above the temperature of the porous medium, and then the temperature tends to an asymptotic value, which depends on the PM specific surface, the pressure growth rate and its initial value. Thus, the temperature of the unburned gas in the PM can be considered equal to T_0.

1.4.1 Pressure estimates at the moment of flame approach to PM. Adiabatic case. The first estimate is based on the assumption that the gas burns only in free space and it is compressed in PM adiabatically. The internal energy of gas initially is

$$U_0 = \frac{p_0 V}{\gamma_u - 1}(1 - k + k\varepsilon),$$

where V – vessel volume. After flame approach to PM it is

$$U_x = \frac{p_x V}{\gamma_b - 1}(1 - k) + \frac{p_x V k \varepsilon}{\gamma_u - 1},$$

where p_x – unknown pressure at the moment of flame approach to PM, ε – porosity, γ - the ratio of specific heats at constant pressure and constant volume, subscripts u and b attribute to unburnt and burnt gas correspondingly.

Change of an internal energy is:

$$\Delta U = \frac{p_x V}{\gamma_b - 1}(1 - k) + \frac{p_x V k \varepsilon}{\gamma_u - 1} - \frac{p_0 V}{\gamma_u - 1}(1 - k + k\varepsilon). \quad (1)$$

In the first estimate this change is caused by heat release (hr) $m_b Q_{hr}$ where Q_{hr} is heat release of chemical reaction per mass unit of unburnt gas, and m_b –is mass of burnt gas. The mass of the burnt gas is equal to a difference between the mass of entire gas m_0 and mass of the unburnt gas m_u. Where m_u is the mass of unburnt gas that penetrated into the porous medium by the time of flame approach to PM:

$$m_b = m_0 - m_u = \frac{\mu_u p_0 V}{RT_0}(1 - k + k\varepsilon) - \frac{\mu_u p_x V k\varepsilon}{RT}. \tag{2}$$

Hereinafter μ_u and μ_b are molecular masses of unburnt and burnt gas correspondingly. As according to the assumption of the first estimate unburnt gas was compressed adiabatically therefore its temperature in a porous medium will be $T = T_0\left(\frac{p_{xa}}{p_0}\right)^{\frac{\gamma_u - 1}{\gamma_u}}$, where p_{xa} is the unknown pressure in the case of adiabatic compression in PM. Substituting this expression for temperature in (2) we find m_{ba}. Where m_{ba} is mass of the burnt gas before the flame approaches to the PM in the case of adiabatic combustion.

Q_{hr} can be expressed through heat capacities of the gas and pressure of adiabatic combustion in the closed vessel [13]: $Q_{hr} = \frac{RT_0}{\mu_u(\gamma_b - 1)}\left(\pi_a - \frac{\gamma_b - 1}{\gamma_u - 1}\right)$.

Since work on the entire gas was not carried out, the change in internal energy is equal to the heat supplied

$$\Delta U_1 = m_{ba} Q_{hr} \tag{3}$$

$$\frac{p_{xa}V}{\gamma_b - 1}(1 - k) + \frac{p_{xa}Vk\varepsilon}{\gamma_u - 1} - \frac{p_0 V}{\gamma_u - 1}(1 - k + k\varepsilon) = \frac{RT_0}{\mu_u}\frac{\pi_a - \frac{\gamma_b - 1}{\gamma_u - 1}}{\gamma_b - 1}\left[\frac{\mu_u p_0 V}{RT_0}(1 - k + k\varepsilon) - \frac{\mu_u p_{xa} V k\varepsilon}{RT_0\left(\frac{p_{xa}}{p_0}\right)^{\frac{\gamma_u - 1}{\gamma_u}}}\right]$$

Substituting the expressions for Q_{hr} and m_{ba} in (3) after transformations, we have:

$$\pi_{xa}\left(1 - k + k\varepsilon\frac{\gamma_b - 1}{\gamma_u - 1}\right) = (1 - k + k\varepsilon)\pi_a - \left(\pi_a - \frac{\gamma_b - 1}{\gamma_u - 1}\right)k\varepsilon\pi_{xa}^{\frac{1}{\gamma_u}} \tag{4}$$

Solving the equation (4) relatively π_{xa} for various values of k we obtain dependence $\pi_{xa}(k)$ for the case of adiabatic combustion. This dependence is presented in fig. 3 with curve 5.

1.4.2 Pressure estimates. Isothermal case.

The second estimate will be made in the assumptions that the unburnt and burnt gases in free space compress adiabatically. But when unburnt gas penetrates into the porous medium it is instantly cooled to initial temperature and then it compressed isothermally.

For the second estimate in the right hand of the equation (6) to calculate heat supplied it is necessary to consider heat loss due to work of isothermal compression of unburnt gas and also heat loss in the porous medium from the unburnt gas heated owing to adiabatic compression in the free space. Heat loss of Q_w due to work (w) of an isothermal compression (ic):

$$Q_w = \frac{m_{uic}}{\mu_u} R T_0 \ln \frac{p_{xic}}{p_0} = p_0 V k \varepsilon \pi_{xic} \ln \pi_{xic}, \tag{5}$$

where p_{xic} is unknown pressure, and m_{uic} is the mass of unburnt gas penetrated in the PM by the time the flame approaches to the PM in the case of isothermal compression of unburnt gas in the PM.

Now let's estimate heat loss δQ_{hl} at penetration of mass dm with temperature T into the porous medium. It will be:

$$\delta Q_{hl} = \frac{c_{pu}}{\mu_u}(T - T_0)dm, \tag{6}$$

at that pressure in the vessel will increase by $dp = \dfrac{RT_0}{\mu_u V k \varepsilon} dm$, expressing in the equation (6) temperature and mass through the current pressure and its increase dp, (6) takes the form:

$$\delta Q_{hl} = \frac{c_{pu} T_0}{\mu_u}\left(\frac{T}{T_0} - 1\right)\frac{\mu_u V k \varepsilon}{R T_0} dp = \frac{\gamma_u}{\gamma_u - 1} p_0 V k \varepsilon \left(\pi^{\frac{\gamma_u - 1}{\gamma_u}} - 1\right) d\pi \ . \tag{7}$$

Integrating (7) in the range from $\pi=1$ to $\pi=\pi_{xic}$ we obtain heat loss from unburnt heated gas that penetrates into PM:

$$Q_{hl} = \frac{\gamma_u}{\gamma_u - 1} p_0 V k \varepsilon \left(\frac{\pi_{xic}^{2 - \frac{1}{\gamma_u}} - 1}{2 - \frac{1}{\gamma_u}} - \pi_{xic} + 1 \right). \tag{8}$$

Taking into account these heat losses change of an internal energy of gas takes a form:

$$\Delta U_2 = m_{bic} Q_{hr} - Q_w - Q_{hl}, \tag{9}$$

where m_{bic} has already less value than at the adiabatic process as unburnt gas compressed isothermally and it penetrates more into PM, than at adiabatic compression. To find m_{bic} we substitute $T=T_0$ in the equation (2).

$$m_{bic}=m_0-m_{uic}=\frac{\mu_u p_0 V}{RT_0}(1-k+k\varepsilon)-\frac{\mu_u p_{xic} V k\varepsilon}{RT_0}=\frac{\mu_u p_0 V}{RT_0}(1-k+k\varepsilon-\pi_{xic}k\varepsilon).$$

Substituting in (9) expressions for m_{bic}, Q_{hr}, Q_w, Q_{hl} after transformation we obtain:

$$\pi_{xic}\left[1-k+k\varepsilon\left(\pi_a+(\gamma_b-1)\ln\pi_{xic}\right)\right]=(1-k+k\varepsilon)\pi_a-k\varepsilon\gamma_u\frac{\gamma_b-1}{\gamma_u-1}\left(\frac{\pi_{xic}^{2-\frac{1}{\gamma_u}}-1}{2-\frac{1}{\gamma_u}}-\pi_{xic}+1\right). \quad (10)$$

Solving this equation relatively π_{xic} for various values of k we obtain unknown dependence of $\pi_{xic}(k)$ for the case of an isothermal compression of the unburnt gas. This dependence is presented in fig. 3 with curve 6.

In fig. 3 along with experimental data presented as symbols there are three theoretical curves. From fig. 3 it is seen that influence of the porous medium on maximum pressure is not reduced only to the fact that some part of unburnt gas has not burnt (curve 5). Experimental symbols lie lower this curve. The curve (6), which takes into account the cooling of the unburnt gas in PM, is much better corresponds the experiments.

Let's consider what reasons are and how they affect the pressure decrease in comparison with the adiabatic compression of unburnt gas in the PM. Above we have named two reasons. These are the work of the isothermal compression Q_w and the heat loss from unburnt gas heated due to adiabatic compression in the PM immediately upon penetration into the PM, Q_{hl}. The third reason is implicitly taken into account in (9) in the form of a smaller mass of the gas burnt in free space. That is, the heat supplied to the system and, accordingly, ΔU in this case will be lower by the value of Q_{ug}, due to less mass of the burnt gas. In other words there is larger mass of unburnt gas will be in PM at the moment when flame approaches to the PM in the case of an isothermal compression comparatively with the case of an adiabatic compression in PM. Let's calculate this ΔU

$$\Delta U = Q_{ug} = (m_{uic} - m_{ua})Q_{hr} = \left[\frac{\mu_u p_{xic} V k \varepsilon}{RT_0} - \frac{\mu_u p_{xa} V k \varepsilon}{RT_0 \left(\frac{p_{xa}}{p_0} \right)^{\frac{\gamma_u - 1}{\gamma_u}}} \right] \frac{RT_0}{\mu_u} \frac{\pi_a - \frac{\gamma_b - 1}{\gamma_u - 1}}{\gamma_b - 1}.$$

After transformations we obtain:

$$Q_{ug} = \frac{p_0 V k \varepsilon}{\gamma_b - 1} \left(\pi_{xic} - \pi_{xa}^{\frac{1}{\gamma_u}} \right) \left(\pi_a - \frac{\gamma_b - 1}{\gamma_u - 1} \right). \qquad (11).$$

Thus, decrease in the maximum pressure in the closed vessel partially filled with a porous medium is caused by three reasons. Work of an isothermal compression of unburnt gas (Q_w), heat loss from heated unburnt gas into porous medium (Q_{hl}) and less amount of the reacted gas at the moment of flame approach to the porous medium. The last leads to decrease in an internal energy of entire gas on the value of Q_{ug}.

Let's estimate on which value of $\Delta\pi$ the maximum pressure decreases due to the action of each reason. Let's write down the difference between the internal energies of the gas in adiabatic combustion U_a and in combustion, taking into account the cooling of unburnt gas in PM, U_{ic}:

$$U_a - U_{ic} = \frac{p_{xa} V}{\gamma_b - 1}(1-k) + \frac{p_{xa} V k \varepsilon}{\gamma_u - 1} - \frac{p_{xic} V}{\gamma_b - 1}(1-k) - \frac{p_{xic} V k \varepsilon}{\gamma_u - 1} = p_0 V (\pi_{xa} - \pi_{xic}) \left(\frac{1-k}{\gamma_b - 1} + \frac{k\varepsilon}{\gamma_u - 1} \right). \quad (12)$$

This difference is due to the influence of the above three factors

$$U_a - U_{ic} = Q_w + Q_{hl} + Q_{ug}. \qquad (13)$$

Substituting the corresponding expressions from (12), (5), (8), (11) into (13), after transformations we obtain:

$$\Delta\pi = \pi_{xa} - \pi_{xic} =$$

$$\frac{k\varepsilon \pi_{xic} \ln \pi_{xic}}{\frac{1-k}{\gamma_b - 1} + \frac{k\varepsilon}{\gamma_u - 1}} + \frac{\frac{\gamma_u}{\gamma_u - 1} k\varepsilon \left(\frac{\pi_{xic}^{2 - \frac{1}{\gamma_u}} - 1}{2 - \frac{1}{\gamma_u}} - \pi_{xic} + 1 \right)}{\frac{1-k}{\gamma_b - 1} + \frac{k\varepsilon}{\gamma_u - 1}} + \frac{\frac{k\varepsilon}{\gamma_b - 1} \left(\pi_{xic} - \pi_{xa}^{\frac{1}{\gamma_u}} \right) \left(\pi_a - \frac{\gamma_b - 1}{\gamma_u - 1} \right)}{\frac{1-k}{\gamma_b - 1} + \frac{k\varepsilon}{\gamma_u - 1}}. \quad (14)$$

Here, the first term on the right-hand side $\Delta\pi_w$ is responsible for the pressure decrease due to isothermal compression, the second term $\Delta\pi_{hl}$ for the decrease due to cooling of unburnt gas, the third term $\Delta\pi_{ug}$ for the pressure decrease due to the lesser mass of the burnt gas.

From the analysis of equation (14), it is found that the heat losses from fresh gas due to its cooling by a porous medium and the work of isothermal compression have little effect on the pressure decrease. The main factor that influences pressure reduction is a smaller amount of unburnt gas that burns in free space.

1.4.3 Pressure estimates. Simple expression.

Consider equation (10) without taking heat losses Q_w, Q_{hl} into account, since they are small. Equation (10) takes the simple form:

$$\pi_x = \frac{1-k+k\varepsilon}{1-k+k\varepsilon\pi_a}\pi_a \qquad (15).$$

The calculated dependence of $\pi_x(k)$ by the equation (15) is shown in Fig. 3 curve (7). It is seen that the curves (6) and (7) are close. This again indicates that the contributions to the pressure decrease due to heat losses from unburnt gas and the work of adiabatic compression have little effect on the pressure estimate. For fast practical estimates it is convenient to use equation (15).

The increase in heat loss from unburnt gas leads to a decrease in pressure due to the possibility of containing more unburnt gas in the PM. And how will the heat loss from the burnt gas in the free space affect the maximum pressure? On the one hand, it is obvious that this should lead to a decrease in the gas pressure, and on the other hand, this will lead to the fact that a smaller amount of unburnt gas will be in the porous medium by the moment of flame approach to PM. That is unburnt gas will burn more, this should lead to an increase in pressure. The calculation shows that for $k > 0.23$, not penetration of some unburnt gas in the PM, and its combustion in free space, lead to the fact that the pressure decrease due to heat loss from the burnt gas in free space will be lower than in the absence of the porous medium. It is seen from fig. 3 that with the filling factors $k > 0.5$, the heat losses from the combustion products do not greatly reduce the maximum pressure of the relative to the theoretical one (curve 6).

Analysis of equations (10), (15) shows that the use of high porosity media even more effectively reduces the maximum pressure for a given *k*.

1.5 Conclusions

The dependence of the maximum pressure in the vessel on the filling factor of the porous medium is experimentally obtained. It is shown that the pressure does not depend on the material and characteristic size of the porous medium element.

An analytical estimate of this dependence is given, which agrees satisfactorily with experiment at filling factors above 0.4.

The influence of heat losses from unburnt and burnt gas in the porous medium and vessel walls on the value of the maximum pressure is analyzed.

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