

REFERENCES

1. Khlevnoy S.S., Kalmykov A.P. Firing nitroglycerin powder with light in cold gas flow // Physics of combustion and explosion. – 1968. – V. 4. – № 1. – P. 122–124.
2. Price Bredly, Deority Ibritsu. The solid fuel ignition theory// Rocket engineering and astronautics. – 1966. – № 1. – V. 3–41.
3. Mikheev V.F., Kovalskiy A.A., Khlevnoy S.S. Ballistit powder light ignition // Physics of combustion and explosion. – 1968. – V. 4. – № 1. – P. 3–9.
4. Isakov G.N., Sandrykina T.S., Subbotin A.N. Heat exchange and critical conditions of VEV ignition by heated bodies of finite sizes // Fundamental and applied problems of modern mechanics: All-Russian scientific conference. Materials of the reports. – Tomsk: Tomsk State University Press, 2002. – P. 297–298.
5. Isakov G.N., Subbotin A.N., Sandrykina T.S. On VEV ignition at shielding penetration by high-speed compact body // The third Okunvskie readings: International research practice conference. Materials of the reports. – Saint-Petersburg: BGTU Press, 2004. – V. 2. – P. 77–80.
6. Grishin A.M., Zinchenko V.I., Subbotin A.N. et al. Iterated-interpolation method and its supplements. – Tomsk: Tomsk State University Press, 2004. – 319 p.
7. Polubarinova-Kochina P.Ya. The theory of groundwater motion. – Moscow: Nauka, 1977. – 664 p.
8. Belyaev A.F., Bobolev V.K., Korotkov A.I., Sulimov A.A., Chuiiko S.V. Transition of the condensed system combustion into explosion. – Moscow: Nauka, 1973. – 292 p.
9. Kovalskiy A.A., Khlevnoy S.S., Mikheev V.F. On the issue of ballistit powder ignition // Physics of combustion and explosion. – 1967. – V. 3. – № 4. – P. 527–541.
10. Mikheev V.F., Khlevnoy S.S. Pyroxylin ignition by light radiation // The second All-Union symposium on combustion and explosion (abstracts of the reports). – Chernogolovka, 1969. – P. 9–10.
11. Averson A.E., Barzykin V.V., Merzhanov A.G. Regularities of condensed explosive system ignition at the ideal heat exchange on the surface subject to burning out // Engineering-physical review. – 1965. – V. 9. – № 2. – P. 245–249.
12. Merzhanov A.G., Averson A.E. The Present State of the Thermal Ignition Theory // Combustion and Flame. – 1971. – V. 16. – № 1. – P. 89–124.
13. Merzhanov A.G. Theory of Stable Homogeneous Combustion of Condensed Substances // Combustion and Flame. – 1968. – V. 13. – № 4. – P. 421–434.

Received on 08.12.2006

UDC 536.46

ON THE THEORY OF EROSION BURNING OF SOLID ROCKET FUELS

K.O. Sabdenov, O.Yu. Dolmatov

Tomsk Polytechnic University
E-mail: sabdenovko@mail.ru

The explanation of the erosive burning threshold presence has been offered. It is shown that such kind of burning begins at decrease in thickness of the laminar sublayer (in a turbulent boundary layer) below width of the laminar burning zone. The expressions connecting critical (threshold) rate of the blowing stream and critical number of V.N. Vilyunov with properties of fuel and gas formed at its decomposition are obtained. Simple power dependences on blowing stream rate are found for burning rate.

Introduction

Further improvement of Russian nuclear-missile board requires, besides development of up-to-date nuclear military loads, the efficient carriers – the rocket system, as well; in particular, rocket engine on solid fuel. One of significant elements in this issue is the detailed appreciation of fuel charge burning laws and production of improved methods for their accounting at engine construction and calculation of rocket target flight dynamics.

Among the majority of factors (fuel burning nonstationarity, stability etc.) there is an effect of erosive burning. It is known [1, 2] that such kind of burning refers to the group of threshold phenomena and appears as increase of burning rate u under the action of burning blowing the surface with hot gas flow. It occurs, as a rule, at excess of average (or maximal) gas rate w_∞ along burning surface of critical value w^* . If the burning rate is denoted by u_w at erosive effect then one of widely used expression (for bounded variation interval w_∞) for u_w has the form:

$$u_w = u[1 + k_e(w_\infty - w^*)], \quad w \geq w^*;$$

$$u_w = u, \quad w_\infty < w^*; \quad k_e = \text{const.}$$

Numerical constant k_e is called the erosion factor. At the early stages of studying, specialists did not pay attention to threshold character of erosive burning. Therewith, the physics of the phenomenon itself was not clear.

In the theory of V.N. Vilyunov [3] inner mechanism of erosion effect consists in intensification of heat, pulse and mass transfer processes in burning zone of gas phase under the influence of turbulence. Overall it results in growth of heat flow from chemical reaction zone in gas phase to fuel decomposition surface increasing its temperature T_s . As a result, burning rate grows as well. The (criterion) number of Vilyunov acts here as the principle parameter determining the process

$$J = \sqrt{C_f} \frac{\rho w_\infty}{\rho_c u},$$

where C_f is the coefficient of hydrodynamic resistance; ρ_c is the fuel density. Appropriately, the formula recommended for practical use has the form [4]

$$\frac{u_w}{u} = \begin{cases} 1, & J < J_* \\ 1 + k_e (J - J_*), & J \geq J_* \end{cases}$$

containing new erosion coefficient k_e . It is available, as a rule, for rather narrow variation interval J , as the formula given above.

Physical meaning of Vilyunov's parameter J is easy to be opened if $\rho_c u$ is changed into ρv in it, bearing on mass conservation law for stationary burning in the form $\rho_c u = \rho v$. Then a new (obviously, simpler and more elegant) type of criterial number

$$J = \sqrt{C_f} \frac{w_\infty}{v}$$

states the presence of competing factors: gas flowing off the surface of fuel decomposition with the rate v tends to displace a turbulence boundary layer from burning zone. Occurrence of this layer is induced by gas flow longitudinal motion to fuel surface with the rate w with typical value w_∞ ; presence of factor with coefficient of hydrodynamic resistance C_f indicates this.

Critical number J_* (or critical speed w^*) in the theory of V.N. Vilyunov is not determined by it is found experimentally. Therefore, the reason of threshold character of erosive burning is not clear. And, as a result, one can not say a priori, without dangerous and expensive experiment, when and on what section of engine fuel charge the erosive effect starts shows itself.

The first [2, 4] and so far the only attempt to determine the nature of erosive burning criticality led to the result varying considerably with the experimental data:

$$J_* = \frac{2T_s}{T_b \sqrt{C_f}},$$

where T_s , T_b are the temperatures of the surface of fuel and flame decomposition.

The nature of threshold character of erosive burning is connected [2, 4] with disappearance of shearing friction stress τ , on the surface of gas contact with fuel surface due to the presence of the rate v .

Nevertheless, explanation of erosive burning threshold character and search for the method of calculating the value of critical number J_* , ascertainment of its connection with fuel properties are still urgent and the aim of the given work.

The practical value of such knowledge is clear – the possibility of controlling better the behavior of burning rate of rocket fuels and other high-energy materials occurs.

Calculation of parameters of erosive burning near the threshold

Let us consider an arbitrary small area of fuel charge in rocket engine chamber. As consideration concerns the space scales much smaller than typical sizes of fuel

charge geometric heterogeneity then the selected area near fuel surface may be considered a flat one. Axis x is vertically directed to this surface (Fig. 1).

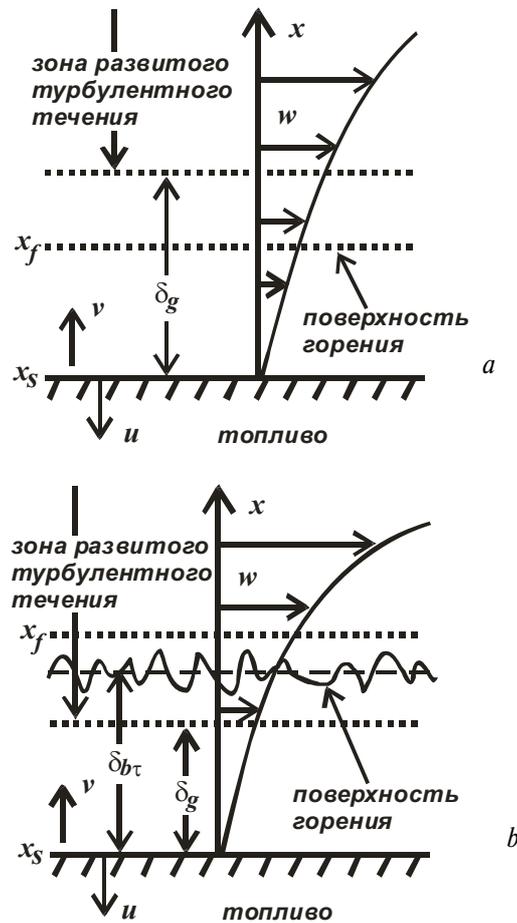


Fig. 1. Relative arrangement of burning front and laminar sublayer: a) $\delta_g > x_f$; ; b) $\delta_g < x_f$

Зона развитого турбулентного течения – Zone of developed turbulent burning; Поверхность горения – Burning surface; Топливо – Fuel

Then let us understand the values changed by turbulent pulses in the sense of their average values, as in the expressions given above.

Fuel surface where the primary decomposition of solid phase into gas occurs has a coordinate x_s . Burning zone in gas phase which is considered to be infinitely thin is at a point x_f . A kernel of developed turbulent fuel and transition region is understood here under the area of the developed turbulent fuel.

Examining physical picture of erosive burning, the ratio between the width $x_f - x_s$ of burning zone when there is no turbulence and thickness of laminar (viscous) sublayer of turbulent boundary layer is the most important [2, 4]. In papers [2, 5] the universal and key part of the ratio of these typical length scales when describing the erosive burning laws is shown.

In comparison with the given papers the following reasoning is accepted here. The shearing friction stress τ , at rate v is not gone to zero. If thickness δ_g of laminar

sublayer of hydrodynamic boundary layer is greater than the width $x_f - x_s$ of burning zone (Fig. 1, *a*) then turbulence does not practically influence the burning process. Turbulence intensity is very low in laminar sublayer [6], the flame zone is at distances $x > x_f - x_s$ where chemical equilibrium has already established.

Let us write down for this case the energy conservation law on interface $x = x_s$ of solid and gas phases:

$$\lambda_c \frac{\partial T_c}{\partial x} = \lambda_g \frac{\partial T}{\partial x} - L \rho_c u, \quad (1)$$

where λ_c, λ_g are the coefficients of fuel and gas heat conductivity; T_c, T are the temperatures in solid and gas phases; L is the thermal effect of chemical reaction of fuel decomposition into gas, and if $L > 0$ the reaction is endothermic. Negative L sign responds to exothermal reaction.

The derivative in the left part of this equality may be written down as [7]

$$\frac{\partial T_c}{\partial x} = \frac{u}{\kappa_c} (T_s - T_0),$$

where κ_c is the solid phase thermal conductivity; T_0 is the original temperature of fuel.

Let us give temperature derivative in the right part (1) accurate within numerical literal A_1 in the form of division of difference of flame temperature T_b and fuel surface temperature T_s by burning zone width:

$$\frac{\partial T}{\partial x} = A_1 \frac{T_b - T_s}{x_f - x_s}.$$

Then, taking into account definition $\kappa_c = \lambda_c / c_p \rho_c$ (c_p is the fuel substance heat capacity) and said from the equation (1) we obtain the equation

$$c_c m (T_s - T_0) = A_1 \lambda_g \frac{T_b - T_s}{x_f - x_s} - L m, \quad m = \rho_c u. \quad (2)$$

Hereof, let us express mass burning velocity:

$$m = A_1 \frac{\lambda_g}{c_c (T_s - T_0) + L} \frac{T_b - T_s}{x_f - x_s}. \quad (3)$$

If laminar sublayer thickness is smaller than the width of (laminar) burning zone then a zone of turbulent burning zone with width δ_{br} is formed (Fig. 1, *b*). According to similarity and dimensions theory [6], the dependence

$$\delta_{br} = (x_f - x_s) \cdot F_\delta \left(\frac{\delta_g}{x_f - x_s} \right),$$

containing universal function F_δ of its argument is acceptable. One of its simplest forms is a power function

$$F_\delta = A_2 \left(\frac{\delta_g}{x_f - x_s} \right)^n, \quad A_2, n = \text{const}, \quad 0 \leq n < 1.$$

Accepting it (as it is seen below, it is justified) we have the expression

$$\delta_{br} = A_2 \delta_g^n (x_f - x_s)^{1-n}.$$

for turbulent burning zone width.

The equality

$$\delta_g = x_f - x_s \quad (4)$$

may be taken for the condition of beginning of erosive effect appearance. This assumption is rather oversimplified; moreover, it should be determined accurate within numerical constant. But it is not significant and the constant is omitted for notation simplification.

At erosive burning the equation (2) takes the form

$$c_c m_w (T_{sw} - T_0) = A_3 \lambda_g \frac{T_{bw} - T_{sw}}{\delta_{br}} - L m_w, \quad m_w = \rho_c u_w,$$

where index w indicates the dependence of parameters on blowing flow rate. Appropriately, for mass velocity of erosive burning m_w we obtain the expression

$$m_w = A_3 \frac{\lambda_g}{c_c (T_{sw} - T_0) + L} \frac{T_{bw} - T_{sw}}{\delta_{br}}. \quad (5)$$

Taking into account representation for δ_{br} from (3) and (5) we find:

$$\frac{m_w}{m} = \frac{A_3}{A_1 A_2} \frac{c_c (T_s - T_0) + L}{c_c (T_{sw} - T_0) + L} \frac{T_{bw} - T_{sw}}{T_b - T_s} \left(\frac{x_f - x_s}{\delta_g} \right)^n.$$

Performing the equality (4) all fractions in the last expressions containing physical values should be transformed into a unit. Therefore $A_3/A_1 A_2 = 1$. Besides, let us note that, differences $T_b - T_s$ and $T_{bw} - T_{sw}$ equals in pairs the total thermal effect Q of chemical reactions in gas phase divided by heat capacity c_p at constant pressure. It is explained by the fact that presence of longitudinal component w of gas velocity does not influence the chemical composition of burning products.

Thus, we have the formula

$$\frac{m_w}{m} = \frac{c_c (T_s - T_0) + L}{c_c (T_{sw} - T_0) + L} \left(\frac{x_f - x_s}{\delta_g} \right)^n. \quad (6)$$

Laminar sublayer thickness is connected with average rate w_∞ (in flow core) according to the ratio [6]

$$\delta_g = 32,5 \frac{v_g}{\sqrt{C_f w_\infty}},$$

where v_g is the gas kinematic viscosity. Then the equality (4) determines critical (threshold) speed w^* :

$$w^* = \frac{32,5}{\sqrt{C_f}} \frac{v_g}{x_f - x_s}. \quad (7)$$

Taking into account this expression the formula (6) is rewritten relative to blowing-off velocity of fuel surface:

$$\frac{m_w}{m} = \frac{c_c (T_s - T_0) + L}{c_c (T_{sw} - T_0) + L} \left(\frac{w_\infty}{w^*} \right)^n, \quad (8)$$

and $m_w/m = 1$, if $w_\infty < w^*$.

On the other hand, the burning rate is determined by decomposition surface temperature by Arrhenius equation with activation energy of chemical reaction in solid phase E_c . Therefore the equality [3]

$$\frac{m_w}{m} = \exp \left[\frac{E_c}{2RT_s} \left(1 - \frac{T_s}{T_{sw}} \right) \right], \quad (9)$$

where R is the universal gas constant is valid.

Formulas (7–9) give the solution of erosive burning problem. In this case, it should be noted that so-called positive erosion appearing vividly at high velocity of blowing flow is meant. At relatively low velocities w_∞ weak effect of negative erosion, at which burning rate decreases occurs (at rather low initial temperatures T_0 [8]).

Comparison of theoretical and experimental results

Let us give the estimation of threshold speed magnitude w^* . Viscosity of typical gases forming decay products of ballistic solid rocket fuels. (O_2 , CO , Cl_2 , NO , H_2O etc.), at temperatures of the order $T_s \approx 600 \dots 800$ K is within the range of $(3,2 \dots 4,6) \cdot 10^{-5}$ m²/s [9]. The width $x_f - x_s$ of burning zone is usually (at atmospheric pressure) amounts to $(0,6 \dots 1,1) \cdot 10^{-4}$ m [1, 7]. Taking their average values from the given intervals and accepting $C_p \approx 0,03$ [3, 6], we find $w^* \approx 100$ m/s. This magnitude of critical velocity is conformed by order of magnitudes with known experimental data [1, 3].

Distance $x_f - x_s$ between the flame zone and fuel surface depends rather strongly on pressure and decreases at its growth.

If activation energy is rather high ($E_c/RT_s \sim 16$ and more) then the first fraction in (8) changes slightly and it may be put equal a unit. Then for increase coefficient of burning rate we obtain the power dependence:

$$\frac{m_w}{m} = \begin{cases} 1, & w_\infty < w^*, \\ (w_\infty / w^*)^n, & w_\infty \geq w^* \end{cases} \quad (10)$$

where negative erosion is neglected as a weak effect.

The comparison of theoretical results obtained by the formula (10) taken from the work [3] and experimental data for the fuel JPN [3] (pressure 19,6 atm.) consisting mainly of nitrocellulose (51,5 %) and nitroglycerine (43,0 %) is given in Fig. 2.

The fact that only the index of degree n was selected at construction of continuous curve and critical velocity value is taken from the experimental data attracts attention.

In the book [10] the experimental curves for two types of nitroglycerine powder which are well presented by power functions of the type are given (10). And deviation between theoretical and experimental curves is so small (about 4 % and smaller) that there is no sense to give all of them. Therefore, in Fig. 3 the curves are constructed only by the formula (10) and experimental magnitudes are marked.

So close arrangement of theoretical and experimental data found out here, is probably a result of a chance. Therefore, further check of formulas (8–10) validity becomes an urgent future task due to the presence of intriguing shade in them. Against this background one should also pay attention to (rather weak) decrease of burning rate for some types of fuels at $w_\infty < w^*$ [1] and for

certain intervals of initial temperature mentioned before.

Besides, the above accepted power form for burning zone width δ_{bc} at turbulence is an intermediate asymptotic dependence. It follows from the fact that the rate w_f should influence the index n besides fuel properties. Although, as it was seen, at rather wide interval of changing, this value n may be considered as a constant parameter.

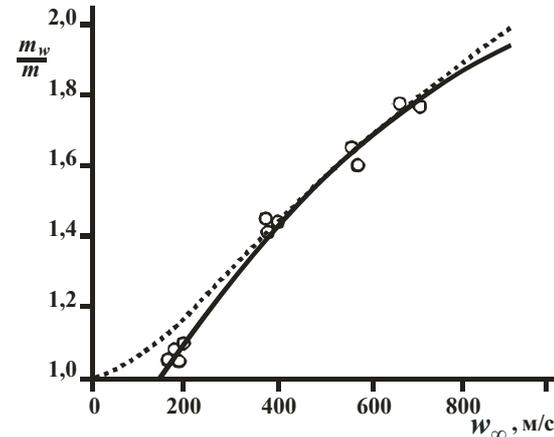


Fig. 2. Theoretical curves (dashed line – from [3], solid line – by the formula (10), $w^* = 165$ m/s, $n = 0,39$) and experimental data (circles)

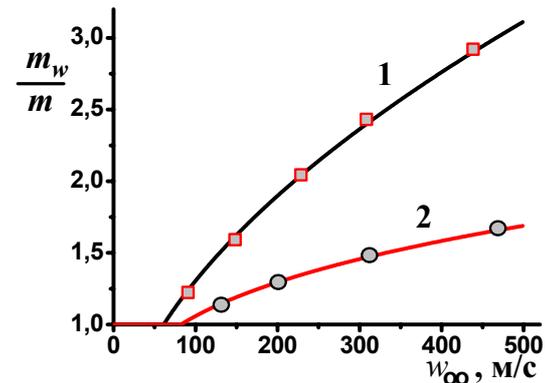


Fig. 3. Calculated and experimental ($(, ($) dependences of increase coefficient of burning rate on blowing flow velocity: 1) $w^* = 61$ m/s, $n = 0,54$; 2) $w^* = 82$ m/s, $n = 0,29$

The ratio of velocities w_∞/w^* may be written down in terms of V.N. Vilyunov's number if the formula (7) is used, attract the equality $c_p \rho_0 v_g \approx \lambda_g$ [3] and ratio

$$x_f - x_s = \frac{\kappa_c}{u} Z, \quad (11)$$

with constant Z , depending on fuel properties:

$$Z = \frac{\sigma \rho_c}{\rho_0} \left[\frac{T_b - T_s}{T_s} + \frac{T_0 - L/c_c}{T_s} \ln \frac{Q}{c_c (T_s - T_0) + L} \right], \sigma = \frac{D \rho^2}{\kappa_c \rho_c},$$

where ρ_0 is the gas density on fuel surface; D is the diffusion coefficient of chemically reacting component in gas phase.

Formula (11) is obtained in burning models of high-energy materials [7] where chemical reaction zone in solid and gas phase is supposed to be infinitely thin. The

method of obtaining and concrete expression for Z is given in Appendix.

Parameter σ has sense of the ratio of two relaxation times: transfer processes in gas and heat-conduction process in solid phase. It is proportional to pressure as density ρ_0 . Therefore, their ratio does not depend on pressure.

After simple transformations we obtain

$$\frac{w_\infty}{w^*} = A \cdot J, \quad A = \frac{Z}{32,5} \frac{c_p \lambda_c}{c_c \lambda}.$$

Then reciprocal quantity of parameter A is no other than critical value of Vilyunov's number: $J_* = 1/A$.

Physical values included in it depend weakly on pressure. But according to equalities (7) and (11) pressure growth (at constant velocity w_∞) results in threshold rate increase

$$w^* = \frac{32,5}{\sqrt{C_f}} \frac{v_g u}{\kappa_c} Z^{-1},$$

that means pushing the developed turbulence area aside fuel the surface due to burning rate increase.

Let us approximately calculate the burning zone width in gas phase knowing experimental values of threshold velocity. Let us express

$$x_f - x_s = \frac{32,5}{\sqrt{C_f}} \frac{v_g}{w^*}$$

from the formula (7).

Let us take $v_g \approx 3,8 \cdot 10^{-5} \text{ m}^2/\text{s}$, $C_f \approx 0,03$ for all fuels listed above (Fig. 2, 3). It gives the following number sequence:

w , m/s	$x_f - x_s$, 10^{-4} m
165	0,43
82	0,89
61	1,19

These data are in the range of the observed values.

Let us note that within the diagram of solving the erosion burning problem suggested above all the results [2, 5] of calculation stating the relevance of presenting erosive burning rate as a function of friction shearing stress τ_s or the ratio $\delta_g/(x_f - x_s)$ as this ratio is directly connected with τ_s may be obtained.

Conclusions

The carried out analysis of erosive burning gave the following explanation of the reasons of its threshold character. Such kind of burning occurs in the case if (conditional) thickness of laminar sublayer over burning fuel surface becomes smaller the width of burning zone forming without gas blowing flow. In other words, at high blowing-off rates, turbulence penetrates the burning zone being till the moment in laminar-flow condi-

tions. Then, owing to intensification of the transfer processes the turbulent burning zone with smaller width is formed that results in increase of heat flow to fuel decomposition surface, its temperature and burning rate. The increased gas outflow from solid phase surface tends to move the turbulent flow area aside and reduce the laminar burning mode. But (in over-threshold area) it is not possible without increasing pressure at constant blowing-off rate.

The following conclusions may be drawn by the results of this work:

- 1) physical picture of erosive burning threshold is proposed and its validity is shown;
- 2) increase of heat flux from gas flame to fuel surface is conditioned by decrease of burning zone width due to the turbulence;
- 3) the threshold occurs at decrease of laminar sublayer thickness below burning zone width without turbulence (or blowing-off);
- 4) threshold (critical) rate of blowing-off is proportional to gas viscosity and inversely to square root from coefficient of hydrodynamic resistance and the width of laminar burning layer;
- 5) critical number of V.N. Vilyunov depends weakly on pressure;
- 6) power function is preferable for erosive burning rate instead of linear function.

Appendix

As all values in gas phase are determined in Lagrange mass coordinate ξ [7] then let us start the procedure of calculation of coefficient Z from transfer to general Euler coordinate x . these two coordinates are connected by the ratio

$$\xi = \frac{u}{\sigma \kappa_c \rho_c} \int_{x_s}^x \rho dx', \quad \frac{\partial \xi}{\partial x} = \frac{u \rho}{\sigma \kappa_c \rho_c}. \quad (12)$$

Density is determined in Lagrange coordinate and connected with gas temperature T as (that follows from state equation of ideal gas) $\rho = \rho_0 T_0 / T = \rho_0 / \theta$, $\theta = T / T_0$. Let us substitute it into the second equality from (12) and, taking into account $\theta = \theta_0 - l + (1 - \theta_0 + l) \exp(\xi)$ perform integration

$$\int_0^{\xi_f} [\theta_0 - l + (1 - \theta_0 + l) \exp(\xi)] d\xi = \frac{u \rho_0}{\sigma \kappa_c \rho_c} (x_f - x_s),$$

where $\theta_0 = T_0 / T_s$; $l = L / T_s c_c$; ξ_f is the position of flame rising edge in Lagrange coordinate [5],

$$\xi_f = \ln \frac{Q}{c_c (T_s - T_0) + L}.$$

Performing simple calculation we obtain the formula (11).

REFERENCES

1. Orlov B.V., Mazing G.Yu. Thermodynamics and ballistic basis of designing rocket engines on solid fuel. – Moscow: Mashinostroenie, 1968. – 536 p.
2. Bulgakov V.K., Lipanov A.M. Theory of erosive burning of solid rocket fuels. – Moscow: Nauka, 2001.
3. Vilyunov V.N. On the theory of erosive burning // Reports of USSR AS. – 1961. – V. 136. – Issue 2. – P. 381–383.
4. Vilyunov V.N., Dvoryashin A.A. On laws of powder H burning in gas flow // Fizika Goreniya i Vzryva. – 1971. – V. 7. – № 1. – P. 45–51.
5. Bulgakov V.K., Lipanov A.M., Kamelatinov A.Sh. Numerical investigations of erosive burning of condensed substances // Fizika Goreniya i Vzryva. – 1986. – V. 22. – № 6. – P. 83–88.
6. Loitsznskiy L.G. Mechanics of liquid and gas. – Moscow: Nauka, 1987. – 840 p.
7. Sabdenov K.O. Theory of nonstationary burning of solid rocket fuels. – Tomsk: TPU Press, 2006. – 236 p.
8. Vilyunov V.N., Dvoryashin A.A. On influence of initial temperature of condensed substance on negative erosion value // Fizika Goreniya i Vzryva. – 1973. – V. 9. – № 4. – P. 602–608.
9. Babichev A.P., Babushkina N.A., Bratkovskiy A.M. et al. Physical magnitudes: Reference book. – Moscow: Energoatomizdat, 1991. – 1232 p.
10. Alemasov V.E., Dregalin A.F., Tishin A.P. Theory of rocket engines. – Moscow: Mashinostroenie, 1969. – 548 p.

Received on 7.12.2006

UDC 536.46

ON ASCERTAINING NATURE OF THE CONCENTRATION BURNING LIMIT

K.O. Sabdenov, O.Yu. Dolmatov

Tomsk Polytechnic University
E-mail: sabdenovko@mail.ru

The elemental theory of concentration limits of slow burning and detonation existence has been offered on the basis of development of Lewis' and Elbe's ideas, theoretical works of A.M. Klimov on convective flame extinguishing and works of Ya.B. Zeldovich on flame disappearance at decrease in burning temperature below the critical value.

Introduction

In atomic power engineering, as in any industry, assurance of fire- and explosion safety at enterprises is not the least of the factors. In this case, the incidents of unauthorized formation of gas mixtures on the basis of air as oxidizer are the most dangerous. Acetylene, hydrogen, methane, propane, oil vapors etc. are more often used as fuel [1]. One of the principle characteristics of combustible mixture, according to which its hazard is estimated, is relative percentage of combustible and oxidizer. It is also known that at excess of their concentration over a certain value (too depleted or concentrated mixture), burning is not possible at the given external conditions, i.e. concentration limit of flame spread occurs. To be more precise, concentration limit of flame existence appears as abrupt burning termination at combustible structure deviation from stoichiometric value [1–3]. In spite of the important applied value, the satisfactory theory of this phenomenon has not been developed yet.

Yu.U. Linnet and Yu.S. Simpson (1956) suggested that experimentally determined limits are not mixture fundamental property [2]. Concentrating or depleting excessively the mixture, the convective streams which depend on experiment conditions start influencing greatly the combustion. Facts of dependence of concentration limits on combustion front moving direction relative to gravity vector indicate as well the important part of convective streams. Later B. Lewis and G. Elbe reached

the conclusion about flame suppression near concentration limits by convective streams [2]. But they did not developed the detailed theory allowing calculating the dependence of combustion rate on mixture structure by deviating from stoichiometric composition and explaining a number of laws of concentration limits. The aim of this work is to suggest a simple explanation of concentration limit existence on the basis of development of ideas of Linnet, Simpson, Lewis and Elbe.

The main positions of the theory and its content

Two facts

- 1) upper and lower concentration limits of deflagration and detonation propagation are placed just symmetrically relative to stoichiometric composition with respect to rearrangement «fuel ↔ oxidizer»;
- 2) at combustion limit with considerable decrease of flame velocity its temperature differs insignificantly from the value corresponding to stoichiometric composition. serve as the experimental base of the theory given below [2].

Let us disclose more detailed the content of the given facts. The effect of termination of combustion wave propagation is observed in very rich or in very weak mixtures which are supposed to consist only of fuel A and oxidizer B and having close molecular masses. But weak mixture may be considered as a rich one relative to oxidizer. In both cases the excess part of oxidizer or fu-