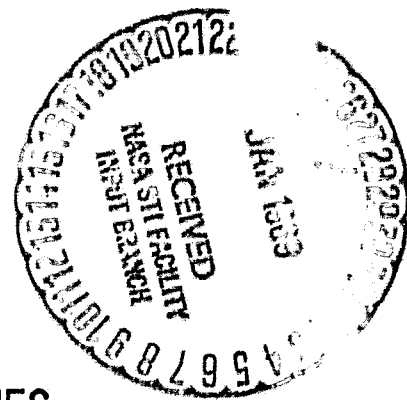


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COMBUSTION IN SOLID-PROPELLANT ROCKET ENGINES
[Spalanie w Silnikach Rakietowych na Paliwo Stałe]

by

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Abstract: Survey of the problems involved in the process of combustion of solid-propellant rocket engines with a description of the important factors influencing the combustion rate. The effects of the following parameters are examined: pressure, fuel temperature, flow velocity over the burning surface, fuel composition, grain dimensions of the oxidizer, heat transfer through radiation, fuel- and combustion-chamber dimensions, manufacturing criteria, and catalysts. The combustion process is described in terms of a mathematical model for combustion of homogeneous and complex fuels and by a model for unstable combustion under certain given conditions. The sources of instability and causes of combustion-rate variations are described for unstable-combustion conditions.

T.M.

FACTORS AFFECTING THE COMBUSTION PROCESS

The theory of combustion of solid propellants is a very slightly developed field and some of its problems constitute only a collection of empirical data. A large number of parameters affecting the combustion process, as well as the lack of systematic studies, make the theoretical development difficult, and the simplifying assumptions used do not allow for clarification of all the phenomena appearing in combustion processes.

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Frequently, these theories pertain to very narrow groups of parameters, or even deal with very idealized models. For these reasons it seems appropriate to consider the factors which affect the combustion processes:

- the pressure of the gases which are in contact with the combustion surface,
- the initial temperature of the charge,
- the flow rate over the combustion surface in contact with the gas flow,
- the composition of the propellant,
- the size of the oxidizer grains (for complex propellants),
- radiation
- the geometry of the charge,
- manufacturing criteria of the charges,
- the deformation of the charges,
- catalysts.

Pressure is the most important parameter. Generally, its increase causes an increase in the combustion rate. It is possible to isolate several regions in which the dependence of the combustion rate on the pressure is different. In the range 30-40 kg/cm² the effect of pressure is well described by the exponential combustion law:

$$r = \beta p^n \quad (1)$$

In the ranges of pressure from 30-40 kg/cm² to 200-300 kg/cm², the following relationship holds:

$$r = a + bp \quad (2)$$

For higher pressures it is admissible to replace eq. (2) by eq. (3):

$$r = bp \quad (3)$$

An even better description of the effects of pressure is described by:

$$r = a + \beta p^n \quad (4)$$

For some complex propellants and, particularly, for propellants containing ammonium perchlorate, the effect of pressure is best described by the following equation:

$$r = \frac{1}{\frac{c}{p} + \frac{d}{p^n}} \quad (5)$$

The parameter characterizing the effects of pressure is the so-called pressure coefficient defined by

$$P = \frac{\partial \ln r}{\partial \ln p} \quad (6)$$

For most propellants the pressure coefficients are in the range from 0.05 to 1. However, for some propellants and pressure ranges, these coefficients may be equal to 0 (the combustion rate is not a function of the pressure) or even negative.

Another essential factor is the temperature of the fuel the increase of which raises the combustion rate. Its greatest effect is observed in high-temperature regions. The effect of temperature can be expressed by the equations:

$$r = r_0 \frac{B}{B - [T - T_0]} \quad (7)$$

$$r = r_0 e^{s(T-T_0)} \quad (8)$$

where

T, T_0 - the fuel temperature and the reference temperature,

B, s - the coefficients,

r_0 - the linear combustion rate at normal temperature.

The effect of the temperature is characterized by the temperature coefficient defined by

$$r = \frac{\partial \ln r}{\partial \ln T} \quad (9)$$

The gas flow parallel to the combustion surface generally increases the combustion rate. This property is well manifested in long-burning

charges [fuels]. There are many empirical relationships which describe the effect of the flow velocity. The simplest is represented by the equations:

$$r = r_0 (1 + k_u v) \quad (10)$$

$$r = r_0 \left(1 + k_G \frac{G}{G_x} \right) \quad (11)$$

where

r_0 - the combustion rate with zero parallel gas flow,

k_u, k_G - coefficients of erosion,

v - the linear flow velocity,

G - the flow output,

G_x - the critical flow output.

If the difference in pressures along the duct is not too great, then eq. (11) can be represented in the form of eq. (12):

$$r = r_0 \left(1 + K_G J \frac{X}{L} \right) \quad (12)$$

where

J - the ratio of the critical cross section of the nozzle to the free cross section,

X - the distance from the front end of the charge,

L - the length of the charge.

Research has shown [ref. #2] that there exists a flow velocity, the so-called threshold, above which the flow begins to affect the combustion rate. There exists a viewpoint [ref. #8] that the gas flow increases the combustion rate by a constant factor depending only on the properties of the flow. The investigations of Lake and Marklund [ref. #7] have shown that in the case of a relatively slow gas flow along the surface, the combustion rate does not increase; on the contrary, it decreases proportionally to the combustion rate. This phenomenon is called negative erosion.

Rocket propellants have an insufficient amount of oxidizer in relation to the stoichiometric proportions and for this reason combustion is incomplete. An improvement of the energy characteristics of propellants can be achieved by increasing the amount of the compound containing oxygen. Addition of oxidizer is limited by technological conditions; thus, experimentation continues to search for a means of increasing the quantity of oxygen by using oxidizers of high oxygen content, or increasing the quantity of oxygen in binders and by adding mineral oxidizers to colloidal propellants.

The effect of propellant composition is of two kinds: it is related to the change of the temperature of the flame and to the physico-chemical changes of the properties of the combustion zone. The changes of the physico-chemical properties of the combustion zone are always present at low pressures and have to do mainly with complex propellants.

The form of the oxidizer in a complex propellant, particularly the size of the grain, has a very definite effect on the combustion process. The grain size has various effects depending on the kind and properties of the oxidizer; moreover, the effect of the grain size is not the same over the entire range of pressures. For propellants containing ammonium perchlorate it is possible to use the following equation which takes into account the effects of the grain size:

$$r = \frac{1}{\alpha + \psi d} \quad (13)$$

where

α & ψ - parameters which are independent of grain size,

d - the grain size.

Between the hot combustion gases and the combustion surface an exchange of heat occurs by radiation. The radiation is generally thermal in nature and is greatest for transparent propellants. The radiation source is a

very narrow flame zone lying close to the combustion surface. Its intensity can be expressed by

$$I = \sigma T_f^4 \left(1 - e^{-k \rho_g l} \right) \quad (14)$$

where

σ - the Stefan-Boltzmann constant,

T_f - the temperature of the flame,

k - the coefficient characterizing the radiative ability of gases,

ρ_g - the gas density,

l - the mean distance from the zone of radiation.

As a result of the energy absorption by the propellant, the temperature of the combustion surface increases and this explains the increase in the combustion rate. The increase in the combustion rate due to radiation can reach 7 percent.

Research has shown that there are great differences between the combustion of charges of various sizes and shapes used in different combustion chambers. This phenomenon as yet does not have sufficient clarification. Considering the radiation, there may appear differences in the combustion rate, e.g., for charges of cylindrical and conical shape, this difference may reach 7 percent. Another source of difference is the heat losses which are a function of the shape of the combustion chamber and are always greater for small chambers. Heat losses cause the enthalpy of combustion gases to be lower than the enthalpy of the solid propellant and lead to a reduction in the combustion rate. Heat losses may also cause the appearance of a minimum pressure below which combustion is not possible. In general, the temperature of the combustion surface is close to boiling temperature. As the pressure increases, the boiling temperature increases if the critical pressure is not exceeded. It is possible that finally the boiling temperature exceeds the combustion

temperature as pressure increases. This indicates the existence of a certain upper limit of pressure above which combustion does not occur. Such upper limits of pressures exist and can be most easily observed in engines using linear combustion fuels [charges].

Another factor having an effect on the combustion process is the manufacturing criteria of the charges. The means of producing the charges and also some parameters of the manufacturing process, such as pressure and temperature, affect the combustion rate. The combustion of pressed charges is different from the combustion of cast charges. Differences are known in the combustion rate of a charge in the axial direction or in a radial direction. Samples prepared in a matrix burn about 7 percent faster than samples cut out of a block. Retardation also has an effect on the combustion rate.

The charge in the chamber is subjected to the action of forces coming from two sources, i.e., gas pressure and inertial forces. During test-stand operation only forces of the first kind appear along with the force of gravity. The forces mentioned cause deformations not only of the charge, but also of the engine chamber and also speed up the gas flow; they may also erode the boundary layer. This all has an effect on the combustion process.

A separate discussion is required for catalysts whose effects on the combustion process are quite noticeable and of many kinds. Catalysts act by means of radiation, dissociation of oxidizer, and physical changes. The radiation intensity increase with the addition of catalysts. Besides the thermal activity of catalytic addition, photolysis has a considerable effect on the combustion rate. Research has shown [ref. #1, 5] that some chemical compositions, particularly metal oxides, accelerate the dissociation of the oxidizer in complex propellants, thereby increasing

the combustion rate. Some chemical compositions alter the structure of the gas zone and thus change the combustion mechanism. The addition of a catalyst can eliminate the initial gas zone or it can widen it. Zero or even negative coefficients of pressure, as well as low coefficients of temperature, are the primary effects of catalytic activity. In addition to changes in the combustion rate and in the temperature and pressure coefficients, catalysts also affect the ignition and the composition of combustion products.

THE COMBUSTION MECHANISM

During combustion the surface of the propellant is heated by the addition of heat from the hot gaseous reaction products. The heat transfer from the flame zone to the lower temperature zones assures the necessary temperature and the dissociation of the solid propellant along with its transformation into volatile ingredients which, after having been produced in the chemical reaction, produce the final combustion products. The rate of dissociation of the solid propellants is described by the Arrhenius equation:

$$r = B_s \exp \left[- \frac{E_s}{RT_s} \right] \quad (15)$$

where

B_s - the chemical constant,

E_s - the activation energy,

T_s - the temperature of the combustion surface,

R - the universal gas constant.

The diagram of the propellant's combustion is shown in fig. 1; it shows that combustion processes take place in four zones: foaming, gasification, preparatory, and flame.

The foaming zone is characterized by the fact that here reactions occur in the solid phase. During these reactions, the temperature rises from T_0 to T'_s where the final temperature can be described by the following equation:

$$T'_s = T_0 + \frac{Q_0}{c} \quad (16)$$

where

T_0 - the temperature of the solid propellant,

Q_0 - the heat of reaction of foaming,

c - the mean heat capacity of the foaming zone.

Due to the exchange of heat with the surrounding layers, the actual temperature of the combustion surface T_0 is higher than temperature T'_s .

In the gasification zone which is immediately adjacent to the propellant surface, the solid propellant is transformed by melting and vaporizing, even by sublimating. In complete reactions also have a place here as they result in the production of heat. The temperature of the gases increases to temperature T'_1 described by equation (17):

$$T'_1 = T'_s + \frac{Q_1}{c_1} = T_0 + \frac{Q_0}{c} + \frac{Q_1}{c_1} \quad (17)$$

where

Q_1 - the heat of reaction in the gasification zone,

c_1 - the mean heat capacity of the gasification zone.

The actual temperature at the end of the gasification zone T_1 is higher than temperature T'_1 , because heat is conducted to this region from adjoining layers.

The preparatory zone appears after the gasification zone. Here there is no production of heat but active centers arise necessary for the final reactions. Due to the supply of heat from the final zone, the temperature at the end of the preparatory zone increases from T_1 to T_2 .

In the flame zone the final combustion reactions occur and heat Q_3

is produced. As a result of these reactions, the temperature of the gases rise to the temperature of combustion T_f described by the following equation:

$$T_f = T'_{-1} + \frac{Q_3}{c_{23}} = T_0 + \frac{Q_0}{c} + \frac{Q_1}{c_1} + \frac{Q_3}{c_{23}} \quad (18)$$

where

Q_3 - the heat of reaction in the flame zone,

c_{23} - the mean heat capacity of the preparatory zone and the flame zone.

The model presented is general. It is also possible to represent it under simpler circumstances, e.g., the model in which the preparatory phase does not appear; this happens at very high pressures.

For complex propellants, which are a mixture of two different chemical compounds, i.e., the propellant and the oxidizer, the linear dissociation rate of the individual components must be equal. The dissociation rates are described by the Arrhenius equation having the following relationship:

$$B_{sp} \exp\left(-\frac{E_{sp}}{RT_{sp}}\right) = B_{su} \exp\left(-\frac{E_{su}}{RT_{su}}\right) \quad (19)$$

[sp = combustion; su = total]

Because the chemical coefficients, i.e., the frequency coefficients, for the propellant and oxidizer are different as are the activation energies, the surface temperature must also be different. This conclusion is known as the postulate of two temperatures. The processes of dissociation (pyrolysis) of the propellant are endothermic; of the oxidizer exothermic. Because the amount of oxidizer is greater than the amount of propellant, the final process of dissociation is actually exothermic. Most oxidizers have a dissociation temperature which is higher than the pyrolysis temperature of the propellant (binder). Thus, the crystals of the oxidizer protrude above the propellant surface and are in contact with the higher temperature zones. The diagram of the combustion surface of this type

of propellant is shown in fig. 2. . The diagram of the combustion surface of propellants containing ammonium nitrate whose dissociation occurs at a lower oxidizer temperature is shown in fig. 3.

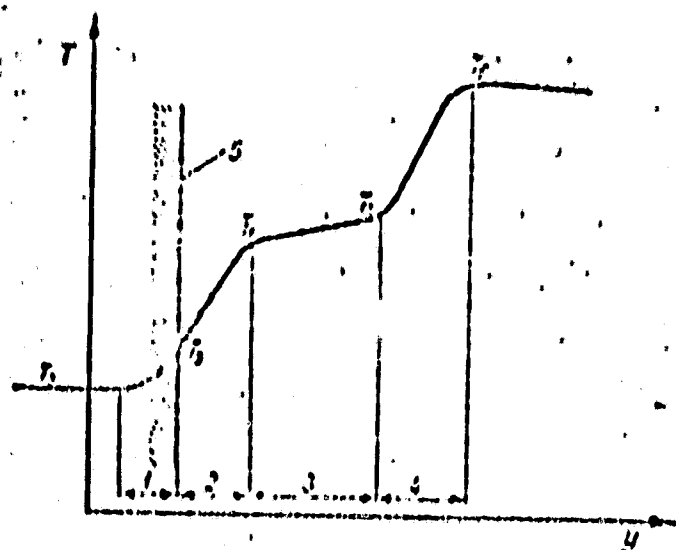


Fig. 1. Diagram of combustion
1 - foaming zone, 2 - gasification zone, 3 - preparatory zone, 4 - flame zone, 5 - combustion surface.

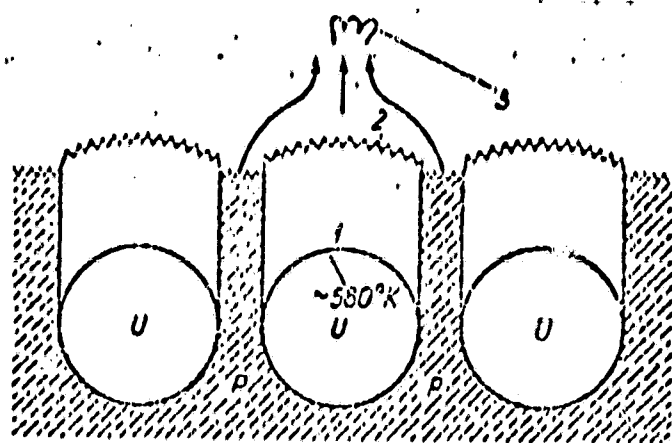


Fig. 3. Diagram of the combustion surface of a propellant on a fabric of ammonium perchlorate [11].

1 - Thermal layer, 2 - initial reactions of oxidation, 3 - reactions in the gaseous phase.

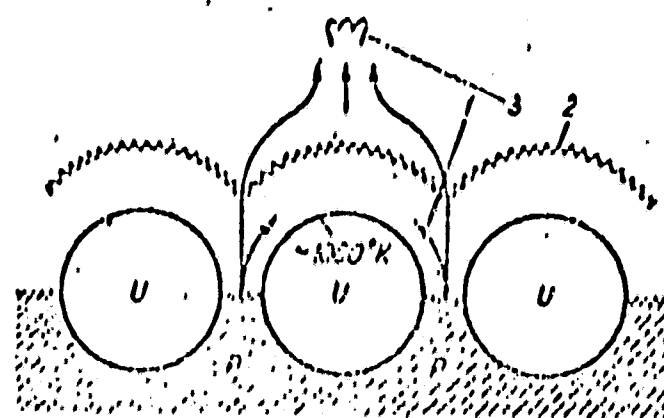


Fig. 2. Diagram of the combustion surface of a propellant on a fabric of ammonium perchlorate [11]

1 - Diffusion of gaseous propellant to the thermal layer, 2 - partial oxidation reaction, i.e., dissociation flame, 3 - combustion reaction, 4 - diffusion flame.

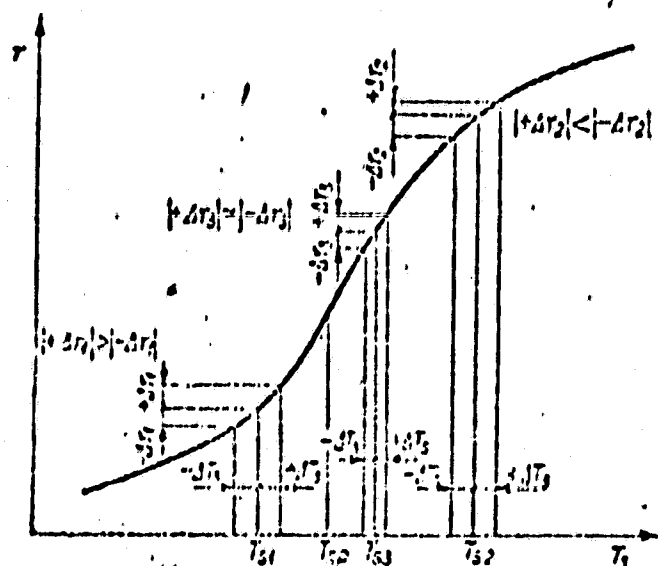


Fig. 4. Dependence of variations in the combustion rate on temperature variations of the surface.

T_{s1} - stable temperature of the surface which is lower than the inflection temperature T_{sp} .

T_{s2} - stable temperature of the surface which is greater than the inflection temperature T_{sp} .

T_{s3} - stable temperature of the surface on the almost linear slope.

[In the above figures, U = oxidizer and P = propellant.]

The inconsistency of complex propellants causes inhomogeneity of the gaseous zone. Therefore, chemical reactions precede mixing. If gasification of the solid propellant occurs after prior melting, then the combustion zone will contain mixed ingredients. If gasification occurs as sublimation, mixing does not appear.

In the case where differences of the surface temperature of the dissociated propellant and oxidizer are not too great, it is possible to take advantage of the model that is used for homogeneous propellants. The differences are smaller, the smaller the oxidizer grains.

As has been mentioned above, the inhomogeneity of the complex propellants in the solid phase makes mixing necessary. At low pressures, the mixing rate of the gaseous dissociation products of the propellant and the oxidizer surpasses the rate of the chemical reactions. The processes controlling combustion are the reactions in the gas phase. In this case the combustion has a kinetic nature. At high pressures where the rate of chemical reaction is great, the combustion rate is controlled by diffusion of the gaseous components. Combustion then has the nature of diffusion.

Unstable combustion. Sometimes during combustion, jumps [discontinuities] of pressure are observed which cannot be explained on the basis of the theory of stable combustion. Detailed studies of this phenomenon have shown that these jumps are the result of an increase in the combustion rate in the form of high-frequency tangential pressure pulsations [surges] which cannot be recorded by typical sensors. It has also been established that these pressure pulsations lead to variations in the mean combustion rate.

Variations in the quantity of heat received by the combustion surface also appear during the pressure pulsations and produce variations

in the temperature of the combustion surface. The temperature dependence of the combustion rate is described by the Arrhenius law. The dependence curve has a point of inflection at the temperature described by the following equation:

$$T_{sp} = \frac{E_s}{4R} \quad (20)$$

The curve is concave below the point of inflection and convex above.

If the equilibrium temperature T_s is lower than the inflection temperature, then an equal change in temperature T_s will have a correspondingly lower drop and greater increase in the combustion rate so that the mean combustion rate over the entire period of the vibration will be greater than the stable rate.

If the equilibrium temperature T_s is greater than the inflection temperature, then when the temperature of the combustion surface decreases, a greater decrease will occur in the combustion rate than increase in the rate when the temperature increases an equivalent amount. The mean combustion rate during the period of vibration will thus be lower than the stable rate. When temperature variations of the combustion surface are not too great, the mean combustion rate will not change. It is possible in a case when the stable temperature of the combustion surface is located on the section of the slope having slight curvature that even with large pressure pulsations the variation in the mean combustion rate will be quite small. Variations in the combustion rate for a given change in temperature of the combustion surface are shown in fig. 4.

The combustion rate as a function of the pressure pulsations is a necessary condition, but insufficient for the appearance of instability. Instability appears only when appropriate delays appear among the several processes connecting pressure pulsation and combustion rate so that initially small perturbations are reinforced by the energy received from

combustion. The delays are a function not only of the kind of propellant but also of the structural properties of the engine.

Theoretical analysis verified experimentally, shows that for each set of thermodynamic and ballistic properties of the engine and propellant, there is a definite pulsation frequency of the gas-flow parameters with a corresponding high-amplitude pulsation of the temperature of the combustion surface and it varies (in most cases increases) the mean combustion rate. At the same time, as indicated by the analysis conducted by L. Green [ref. #3], the low-frequency pulsations do not lead to greater variations in temperature of the combustion surface—its maximum deflections do not exceed two percent of the stable value. It is only at high frequencies greater than 10^4 rad/sec that the temperature variations of the combustion surface can produce real changes in the combustion rate.

Due to the large number of parameters affecting combustion processes, the development of a universal theory of a theoretical model explaining the effect of all these factors or even the different effects of some of them is an extremely complex problem.

The lack of results from systematic investigations makes it almost impossible to explain many of these phenomena and repeatedly makes impossible the verification of whether or not they might not arise from measurement errors or from the effects of unrecognized [unperceived] phenomena (e.g., negative erosion).

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