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# ANALYSIS OF PHYSICAL PARAMETERS DURING THE COMBUSTION PROCESS IN A SOLID-PROPELLANT ROCKET MOTOR

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**Annotatsiya** Ushbu maqolada qattiq yoqilg‘ili raketa dvigatelining yonish jarayonida yuzaga keladigan asosiy fizik kattaliklar, jumladan, bosim, harorat, yonish tezligi, gazlarning zichligi, massa sarfi va issiqlik almashinuvi nazariy jihatdan tahlil qilinadi. Qattiq yoqilg‘ining yonishi natijasida hosil bo‘ladigan gazlarning yonish kamerasidagi oqimga ta’siri hamda yonish tezligi bilan bosim o‘rtasidagi bog‘liqlik ko‘rib chiqiladi. Tadqiqotda yonish jarayonini ifodalovchi asosiy matematik munosabatlar umumlashtirilib, ularning fizik mazmuni tahlil qilinadi. Shuningdek, alyuminiy zarrachalari mavjud bo‘lgan kompozit yoqilg‘ilarda zarrachalarning yonish mahsulotlari oqim xususiyatlariga ta’siri yoritiladi. Tahlil natijalari yonish jarayonining o‘zaro bog‘langan termik, kimyoviy va gazodinamik hodisalardan tashkil topishini ko‘rsatadi.
**Kalit so‘zlar:** qattiq yoqilg‘ili raketa dvigateli, yonish jarayoni, yonish tezligi, yonish kamerasi bosimi, harorat, massa sarfi, issiqlik almashinuvi, gazodinamik jarayonlar.

**Abstract** This article presents a theoretical analysis of the principal physical parameters involved in the combustion process of a solid-propellant rocket motor, including pressure, temperature, burning rate, gas density, mass flow rate, and heat transfer. The relationship between propellant regression, gas generation, and chamber pressure is discussed using established physical models. Governing equations are introduced to explain the mass balance within the combustion chamber, pressure-dependent burning behavior, and the role of nozzle flow in the motor’s internal ballistics. Particular attention is given to thermal feedback at the burning surface and the possible influence of condensed-phase particles in composite propellants. The analysis indicates that solid-propellant combustion is a coupled process involving chemical reactions, heat transfer, and gas dynamics. The article provides a theoretical framework for interpreting the physical parameters without presenting unverified experimental measurements.
**Keywords:** solid-propellant rocket motor, combustion process, burning rate, chamber pressure, temperature, mass flow rate, heat transfer, gas dynamics.

**Аннотация** В статье представлен теоретический анализ основных физических параметров, возникающих при горении твёрдого ракетного топлива: давления, температуры, скорости горения, плотности газа, массового расхода и теплообмена. Рассматривается взаимосвязь между скоростью регрессии поверхности топлива, образованием газообразных продуктов и давлением в камере сгорания. Приводятся

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основные математические зависимости, позволяющие объяснить баланс массы в камере и влияние истечения газа через сопло на внутреннюю баллистику двигателя. Отдельное внимание уделяется тепловой обратной связи на поверхности горения и возможному влиянию конденсированных частиц в составе смесевого топлива. Теоретический анализ показывает, что горение твёрдого ракетного топлива представляет собой взаимосвязанную систему химических, тепловых и газодинамических процессов.

**Ключевые слова:** твердотопливный ракетный двигатель, процесс горения, скорость горения, давление в камере сгорания, температура, массовый расход, теплообмен, газодинамика.

## I. Introduction

Solid-propellant rocket motors are widely studied in aerospace engineering because their internal behavior depends on the interaction of chemical energy release, heat transfer, gas generation, and compressible flow. During combustion, the solid propellant decomposes and reacts at or near its exposed surface, producing hot gaseous products that accumulate in the combustion chamber and subsequently flow through the nozzle. The resulting pressure and temperature fields influence the rate at which the propellant surface regresses and determine the thermodynamic state of the gas flow.

The combustion of solid propellants cannot be adequately described by a single physical variable. Pressure affects the burning rate; the burning rate determines the rate of gas generation; gas generation influences chamber pressure; and heat transfer from the reaction zone to the unburned propellant contributes to sustaining combustion. These relationships make the process inherently coupled and, under transient conditions, time-dependent [1; pp. 497–551].

Previous research has examined the chemical mechanisms of propellant ignition and combustion, transient burning-rate behavior, and the combustion of metallic particles in rocket exhaust plumes. Beckstead et al. reviewed approaches to modelling propellant combustion and ignition, while Greatrix developed a numerical model for analyzing transient burning-rate behavior in solid rocket motors [1; 2]. Chen et al. experimentally investigated aluminum-particle combustion in solid-propellant plumes using optical measurement techniques [3].

Despite differences in research methods, these studies demonstrate that combustion characteristics should be interpreted through the relationships among chemical reactions, heat transfer, and gas dynamics.

The aim of this article is to analyze the main physical parameters involved in solid-propellant rocket-motor combustion and explain their interdependence using established theoretical relationships.

The objectives are:

1. To identify the principal physical parameters characterizing combustion.
2. To explain the relationship between burning rate, gas generation, and chamber pressure.
3. To describe the role of heat transfer and gas flow in the combustion process.
4. To discuss the limitations of simplified mathematical models.

## II. MATERIALS AND METHODS

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### 2.1. Research approach

This study employs a theoretical and analytical approach based on published scientific literature and established conservation principles. The analysis focuses on the physical interpretation of the governing variables rather than on experimental testing or the design of a specific rocket motor.

The principal methods are literature analysis, mathematical modelling, dimensional interpretation, and qualitative assessment of the relationships between combustion parameters.

### 2.2. Principal physical parameters

The main variables associated with solid-propellant combustion are summarized in Table 1.

**Table 1. Principal physical parameters of solid-propellant combustio**

| Parameter | Symbol | SI unit | Physical significance |
|---|---|---|---|
| Chamber pressure | $P_c$ | Pa | Pressure of combustion products inside the chamber |
| Gas temperature | $T_g$ | K | Thermal state of the combustion products |
| Burning rate | $r_b$ | m/s | Rate of regression of the propellant surface |
| Propellant density | $\rho_p$ | kg/m³ | Mass per unit volume of solid propellant |
| Gas density | $P_g$ | kg/m³ | Mass per unit volume of gaseous products |
| Burning surface area | $A_b$ | m² | Exposed propellant area undergoing combustion |
| Gas mass flow rate | m | kg/s | Mass transported per unit time |
| Specific heat capacity | $c_\rho$ | J/(kg·K) | Heat required to change gas temperature |
| Thermal conductivity | k | W/(m·K) | Ability of a material to conduct heat |
| Heat-transfer rate | Q | W | Thermal energy transferred per unit time |

The parameters are interdependent. For example, changes in the exposed burning area may alter gas generation, while variations in chamber pressure can influence the burning rate. Temperature affects gas properties and reaction kinetics, whereas heat transfer influences the thermal state of the unburned propellant [1; 2].

### 2.3. Burning-rate relationship

A commonly used empirical representation of steady-state solid-propellant burning is the pressure-dependent power law, often called Saint Robert's law or Vieille's law:

$$r_b = a p_c^n$$

where:

- **$r_b$** is the linear burning rate;
- **a** is an empirical coefficient for the selected propellant and consistent units;
- **$p_c$** is the chamber pressure;
- **n** is the pressure exponent.

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The coefficients must be determined for the particular propellant and applicable operating conditions. The relationship does not imply that all propellants respond identically to pressure.

For two pressure states, assuming **a** and **n** remain constant, the relationship becomes:

$$\frac{r_{b,2}}{r_{b,1}}=\left(\frac{p_{c,2}}{p_{c,1}}\right)^n$$

This expression illustrates the mathematical relationship between relative changes in pressure and burning rate. It is not, by itself, sufficient to predict the behavior of a real motor, particularly during transient combustion. More comprehensive models account for the time-dependent thermal state of the propellant [2].

**2.4. Gas-generation rate**

Under a simplified model in which the burning surface regresses normally and the propellant density is treated as constant, the rate of gas-producing propellant consumption can be represented as:

$$m_g=p_p A_b r_b$$

where $m_g$ denotes the mass-generation rate expressed in kg/s.

The equation follows from the mass of solid material consumed per unit time. It assumes a known burning area and a representative linear burning rate. In a more detailed treatment, the effective mass transferred to the gas phase may require corrections for condensed products, incomplete gasification, and nonuniform surface conditions.

The expression nevertheless establishes a fundamental relationship: for a fixed propellant density and burning area, an increase in burning rate increases the mass of propellant consumed per unit time.

**2.5. Chamber mass balance**

The chamber pressure is connected to the difference between mass entering the chamber from combustion and mass leaving through the nozzle. The corresponding general mass balance is:

$$\frac{dm_c}{dt}=m_g-m_n$$

where $m_c$ is the mass of gas retained in the chamber and $m_n$ is the mass flow rate through the nozzle.

This equation indicates that chamber gas mass increases when gas generation exceeds nozzle discharge and decreases when discharge exceeds gas generation. At a steady operating state, the idealized balance is:

$$m_g \approx m_n$$

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This condition represents approximate mass equilibrium, not necessarily the absence of local fluctuations or combustion instability. The transient response of a motor requires consideration of the time-dependent behavior of both combustion and internal flow [2].

**2.6. Nozzle flow and gas properties**

For a simplified ideal-gas model, the relationship between pressure, density, and temperature is expressed by:

$$p=p_g R_s T_g$$

where $\mathbf{R_s}$ is the specific gas constant of the combustion products.

This relationship demonstrates that pressure depends on gas density and temperature. In an actual combustion chamber, these quantities may vary spatially, and the gas composition can change with temperature and chemical reaction progress.

For a converging-diverging nozzle operating under appropriate conditions, the flow may become choked at the throat. In an ideal, steady, one-dimensional model, the mass flow rate can be represented as:

$$m_n=A_t p_c \sqrt{\frac{\gamma}{R_s T_c}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}}$$

where $\mathbf{A_t}$ is the nozzle-throat area, $\mathbf{T_c}$ is the chamber stagnation temperature, and $\gamma$ is the ratio of specific heats.

This equation assumes ideal-gas behavior, approximately uniform chamber stagnation conditions, and choked flow at the throat. It is a theoretical relation rather than a complete description of a real motor, in which heat transfer, gas composition, particle loading, and nonuniform flow may influence performance.

**2.7. Heat transfer at the burning surface**

The combustion process is sustained partly by the transfer of energy from the reaction zone to the unburned propellant. A simplified conductive heat-transfer relation is Fourier's law:

$$q''=-k\frac{dT}{dx}$$

where q" is the heat flux, k is thermal conductivity, and dT/dx is the temperature gradient normal to the surface.

The negative sign indicates that conductive heat transfer occurs in the direction of decreasing temperature. This relationship helps explain why the temperature distribution within the solid propellant is important to the burning process.

In reality, the energy balance at the surface can include gas-to-surface heat transfer, radiation, energy consumed by decomposition and chemical reactions, and energy conducted into

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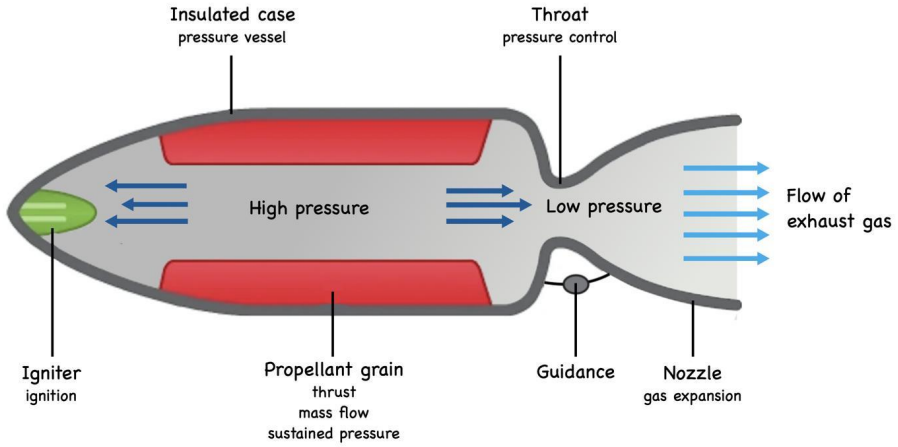
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the solid. The relative importance of these contributions depends on the propellant composition and operating conditions [1; 2].

### 2.8. Conceptual two-dimensional representation

The combustion process can be illustrated by a two-dimensional conceptual cross-section of a rocket motor. The figure should identify the solid propellant, burning surface, combustion-gas region, chamber walls, nozzle throat, exhaust direction, and heat feedback toward the unburned propellant.

**Figure 1. Conceptual 2D schematic of combustion in a solid-propellant rocket motor**




The illustration is conceptual. It should not be interpreted as a validated computational fluid dynamics (CFD) simulation or as experimental data.

In the schematic, combustion products are generated at the exposed propellant surface and flow toward the nozzle. Heat transfer toward the unburned solid is represented as a feedback process, while the nozzle provides the principal exit path for the gas. The actual spatial distributions of temperature, pressure, velocity, and species concentration require a specified geometry, material model, boundary conditions, and validated numerical or experimental data.

## III. RESULTS AND DISCUSSION

### 3.1. Relationship between chamber pressure and burning rate

The theoretical analysis shows that chamber pressure and burning rate are closely related. According to the pressure-dependent power law, the burning rate varies with pressure according to the empirical exponent **n**. The magnitude of the response therefore depends on the specific propellant rather than on a universal constant applicable to every formulation.

An increase in pressure can be associated with a higher burning rate for propellants exhibiting a positive pressure exponent within the relevant operating range. A higher burning rate, in turn, increases the rate of solid-propellant consumption and gas generation when the exposed burning area remains unchanged.

These relationships contribute to the internal feedback of the combustion process. However, the pressure exponent should not be interpreted as a complete description of transient combustion. During ignition, pressure disturbances, and the final stages of burning, the thermal state of the solid may lag behind changes in the gas phase. Greatrix's research highlights the importance of

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accounting for transient burning behavior when modelling the internal ballistics of solid rocket motors [2].

### 3.2. Temperature and thermal feedback

Temperature is a central variable because it influences reaction kinetics, gas properties, and heat transfer. The reaction zone releases chemical energy, part of which is transferred toward the unburned propellant. This energy contributes to heating and decomposition of the solid near the surface.

The combustion wave is therefore not restricted to a single geometric interface. It includes thermal and chemical processes occurring in the condensed phase and in the gaseous region above the surface. Detailed combustion models can describe temperature distributions and species concentrations across these regions [1].

A simplified model that assumes uniform temperature throughout the chamber can be useful for preliminary analysis, but it cannot represent local flame structures or steep thermal gradients near the burning surface. More advanced models may be necessary when these local characteristics significantly affect the research question.

### 3.3. Gas density and mass flow

Gas density is connected to pressure and temperature through the equation of state. Under ideal-gas assumptions, increasing temperature at constant pressure decreases density, whereas increasing pressure at constant temperature increases density.

The mass balance demonstrates that the amount of gas retained in the chamber depends on the difference between the gas-generation rate and the nozzle discharge rate. This distinction is important because high gas-generation rates do not automatically imply a proportional increase in chamber pressure at every instant. The pressure response also depends on the chamber volume, gas temperature, nozzle flow, and transient conditions.

Consequently, mass flow, density, pressure, and temperature should be considered as mutually related variables rather than as independent measures of combustion intensity.

### 3.4. Influence of condensed-phase particles

Some composite solid propellants contain metallic ingredients that can form condensed particles during combustion. Such particles may continue reacting after leaving the immediate vicinity of the propellant surface, influencing the structure and thermal characteristics of the exhaust plume.

Chen et al. investigated aluminum-particle combustion in plumes produced by ammonium-perchlorate-based solid propellants. Their study used digital in-line holography and imaging pyrometry to examine particle positions, sizes, velocities, and thermal behavior [3].

This research illustrates that a gas-only description may be insufficient for some propellant systems. Where condensed particles are present, a more comprehensive model may need to account for particle motion, heat exchange between phases, and chemical reactions associated with the particles.

The significance of these effects depends on the propellant formulation and the purpose of the analysis. The cited study provides experimental evidence for the importance of particle

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characterization, but its findings should not be generalized quantitatively to every solid-propellant motor.

### 3.5. Interpretation of the mathematical model

The relationships presented in the Materials and Methods section provide a consistent conceptual framework for interpreting the principal combustion variables.

**Table 2. Qualitative interpretation of the principal relationship**

| Relationship | Physical interpretation | Main limitation |
|---|---|---|
| $r_b=ap_c^n$ | Describes empirical pressure dependence of burning rate | Valid only within the applicable calibration range |
| $m_g=p_pA_br_b$ | Relates propellant consumption to gas generation | Simplifies condensed products and nonuniform burning |
| $\frac{dm_c}{dt}=m_g-m_n$ | Expresses chamber mass conservation | Does not alone determine pressure or temperature |
| $p=p_gR_sT_g$ | Relates pressure, density, and temperature for an ideal gas | May not capture spatial nonuniformity or changing composition |
| $q''=-k\frac{dT}{dx}$ | Describes conductive heat transfer | Does not represent all surface energy-transfer mechanisms |

Taken together, the equations show that no single parameter completely characterizes combustion. The burning rate is linked to pressure and surface conditions; gas generation is linked to propellant consumption; chamber mass depends on the difference between gas generation and discharge; and the thermal field influences the combustion process itself.

These equations are useful for conceptual analysis and for constructing simplified models. Quantitative predictions, however, require experimentally supported material properties, an appropriate combustion model, and well-defined boundary conditions. Theoretical consistency should not be mistaken for experimental validation.

### 3.6. Limitations of the study

This article is based on a theoretical synthesis of published research. No new laboratory experiments, motor firing tests, or validated CFD calculations were performed for the present analysis. Therefore, no numerical measurements of pressure, temperature, burning rate, or thrust are claimed as original results.

The simplified equations also rely on assumptions such as representative average properties, ideal-gas behavior, and known burning surface area. A real motor may exhibit spatially nonuniform combustion, transient pressure fluctuations, changing burning geometry, condensed-phase particles, and interactions between the combustion chamber and nozzle.

Future studies could investigate these limitations through validated numerical models and experimental data, with appropriate attention to measurement uncertainty and the range of validity of the chosen model.

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## IV. CONCLUSION

The theoretical analysis indicates that combustion in a solid-propellant rocket motor is a coupled physical process involving chemical energy release, heat transfer, gas generation, and compressible flow. Chamber pressure, temperature, burning rate, gas density, and mass flow rate are interdependent and should be interpreted within a common physical framework.

The pressure-dependent burning-rate relationship explains how pressure can influence propellant regression under specified conditions. The gas-generation equation connects the burning surface and propellant consumption to the mass supplied to the chamber. The chamber mass balance clarifies the relationship between gas generation and nozzle discharge, while the ideal-gas equation and heat-conduction relation help explain the roles of temperature, density, and thermal feedback.

The analysis also indicates that condensed-phase particles may be relevant to the combustion and exhaust behavior of certain composite propellants. Published experimental work on aluminum-particle combustion demonstrates the value of investigating the particulate phase when it is present [3].

Overall, understanding solid-propellant combustion requires an integrated consideration of thermochemical, thermal, and gas-dynamic phenomena. The equations and qualitative relationships presented in this article provide a theoretical basis for further investigation. Their quantitative application should be supported by propellant-specific data, appropriate model validation, and experimental evidence.

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