# STUDY ON THE DESIGN OF SOLID PROPELLANT FOR RANGE EXTENSION OF THE 122 MM UNGUIDED ROCKET LAUNCHED FROM BM-21

# NGHIÊN CỨU THIẾT KẾ THUỐC PHÓNG NHẰM TĂNG TẦM BẮN CHO ĐẠN PHẢN LỰC KHÔNG ĐIỀU KHIỂN 122 MM TRÊN XE BM-21

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**Abstract -** This paper presents a design solution to enhance the rocket motor of the 122 mm unguided rocket launched from the BM-21 multiple rocket launcher, aiming to extend its firing range from 20 km to approximately 40 km. The research methodology integrates theoretical modeling with internal ballistics calculations to determine chamber pressure, combustion temperature, thrust profile, and total impulse, combined with external ballistics analysis to predict the rocket's trajectory. Numerical results indicate that increasing the propellant mass from 20.45 kg to 28 kg and extending the grain length from 0.9 m to 1.61 m raises the average thrust to about 26,200 N, yielding a total impulse of ~52,400 N·s and extending the maximum range to 41 km. These findings demonstrate the technical feasibility of upgrading BM-21 rockets using existing domestic technologies, while further static and field firing tests are required to validate and calibrate the proposed models.

**Key words -** BM-21; unguided Rocket Projectile; solid propellant; range extension; ballistic modeling.

**Tóm tắt -** Bài báo này trình bày giải pháp thiết kế cải tiến động cơ đạn phản lực cỡ 122 mm của hệ thống pháo phản lực BM-21 nhằm tăng tầm bắn từ 20 km lên đến khoảng 40 km. Phương pháp nghiên cứu kết hợp giữa mô hình hóa lý thuyết, tính toán thuật phóng trong để xác định các thông số nhiệt – động như áp suất buồng đốt, nhiệt độ cháy, lực đẩy tức thời và tổng xung lực, cùng với tính toán thuật phóng ngoài để dự đoán quỹ đạo bay của đạn. Kết quả tính toán cho thấy, việc tăng khối lượng thuốc phóng từ 20,45 kg lên 28 kg, đồng thời kéo dài chiều dài thuốc phóng từ 0,9 m lên 1,61 m đã giúp lực đẩy trung bình động cơ đạt khoảng 26.200 N, tổng xung lực ~52.400 N·s, qua đó nâng tầm bắn tối đa của đạn lên 41 km. Kết quả nghiên cứu chứng minh tính khả thi của giải pháp cải tiến trên cơ sở công nghệ sẵn có trong nước, đồng thời mở ra hướng nghiên cứu tiếp theo về thử nghiệm đo tĩnh và thử nghiệm thực địa nhằm hiệu chỉnh mô hình và xác nhận độ tin cậy.

**Từ khóa -** BM-21; đạn phản lực không điều khiển; thuốc phóng rắn; tăng tầm bắn; mô hình thuật phóng.

## 1. Introduction

The BM-21 "Grad" multiple launch rocket system, developed by the Soviet Union in the 1960s, has demonstrated high combat effectiveness thanks to its ability to launch salvos of unguided rocket projectiles (URP) with high firepower density and excellent mobility. Its main missions include neutralizing and suppressing enemy forces and combat vehicles in concentrated areas, destroying defensive fortifications, and eliminating enemy firepower clusters. However, the standard firing range of the rocket is only about 20–21 km, which currently does not meet the requirements of modern battlefields, where the general trend is to increase firing range, enhance firepower mobility, and ensure the safety of launch platforms against enemy counter-battery fire. Therefore, research into solutions to extend the range of URP is not only of tactical significance but also a crucial step towards mastering rocket technology in Vietnam.

Advanced scientific and technological achievements are being actively applied to the development of multiple launch URP systems, focusing on increasing range, firing accuracy, and projectile lethality. Thanks to new materials and advanced propellants, the range of URPs has increased by 50% to 100% without significantly increasing overall weight or reducing warhead mass. The Russian Grad system, after upgrades, has extended its range from 20 km to 41 km. URPs are effective not only against infantry but also in destroying modern tanks, armored vehicles, and fortified structures. Russia has further upgraded the BM-30 Smerch system to a range of up to 90 km; China has developed the Weishi-2 multiple rocket system with a range of up to 200 km based on modernization of imported rocket artillery; and the United States has developed new mobile multiple launch rocket systems, Block-I and Block-II, based on the M270 system, extending the range up to 120 km. The development and modernization of multiple launch URP systems demonstrate that major military powers continue to value the effectiveness and importance of artillery firepower on future battlefields.

International and domestic research on solid-propellant rocket motors has achieved significant milestones. Abroad, George P. Sutton and Oscar Biblarz [1] have systematized the theoretical and technological foundations of solid-propellant rocket motors; Naumann et al. [2, 3] have researched two-stage motor solutions to improve performance; Orlov [4] and Vinitsky [5] have detailed the thermodynamic foundations and design of solid-propellant rocket motors; Sokolovsky [6], Sorkin [7], and Lipanov [8] have deeply analyzed internal combustion dynamics and thrust curve optimization, synthesizing various rocket motor design methods.

In Vietnam, research on rocket motors and projectiles began in the 1960s, mainly based on technology transfer from the Soviet Union and China. Notable works include those by Pham The Phiet [9, 10] on the theory and calculation methods for URP; Dang Hong Trien [11] and Nguyen Ngoc Du et al. [12] on the combustion laws of solid propellants; Doan Quy Hieu et al. [13, 14] on gas flow simulation and flight stability; and Nguyen The Dung et al. [15] on the design of the second-stage motor for the TV-02 rocket. However, specialized studies on range extension for rocket projectiles launched from the BM-21 vehicle remain limited, and no comprehensive calculation-design model has been published.

Research into upgrading URP to increase firing range not only enhances tactical capabilities but also demonstrates the ability to master solid-propellant rocket technology under the constraints of Vietnam's industrial base. Particularly, focusing on improving the solid-propellant motor rather than changing the entire projectile structure helps minimize costs, shorten deployment time, and maintain compatibility with existing BM-21 launch platforms.

This paper focuses on developing a theoretical model for motor calculation and simulating the flight process of the 122 mm URP launched from the BM-21, aiming to increase firing range by optimizing solid-propellant motor parameters and propellant mass, while considering the effects of environmental factors such as wind and air density. The research results are expected to provide scientific and technical foundations for the domestic improvement and modernization of the BM-21 system under the conditions of Vietnam's defense industry.

## 2. Research methodology

The research methodology in this paper is based on a combination of theoretical modeling, numerical computation, kinematic–aerodynamic simulation, and experimental analysis referenced from previously published results.

Initially, the study begins with a survey of the original characteristics of the BM-21 Grad multiple rocket launcher and existing 122 mm URP types. Basic parameters such as firing range, number of launch tubes, tube length, projectile length, caliber, warhead mass, and overall projectile mass are synthesized from original technical documents as well as academic publications both domestic and international (see Table 1). These data serve as the foundation for constructing the kinematic and aerodynamic models of the projectile.

***Table 1.*** *Basic technical specifications of the 122-mm URP*

| Basic technical specifications | Value |
|---|---|
| Firing range, km | 20 |
| Number of launch tubes | 40 |
| Launch tube length, m | 3 |
| Projectile length, m | 2.87 |
| Caliber, mm | 122 |
| Warhead mass, kg | 18.4 |
| **Projectile mass, kg** | **68.2** |

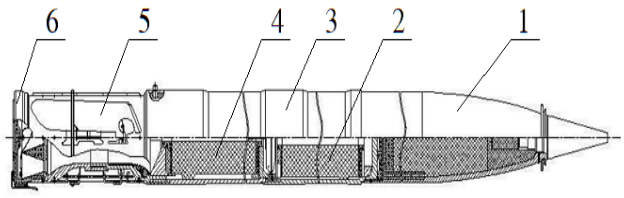


***Figure 1.*** *Structural diagram of the 122 mm URP on BM-21 vehicle*

*1- Warhead section, 2- Propellant grain 1, 3- Combustion chamber casing, 4- Propellant grain 2 (the upgraded projectile will have this grain lengthened by 710 mm), 5- Fins, 6- Nozzle assembly*

To modernize and improve combat mobility, it is necessary to increase the maximum firing range of the projectile to 35–40 km. The process of upgrading the rocket motor consists of the following main steps: calculating the required motor impulse, analyzing and selecting the motor structure. The initial basic weapon parameters for preliminary motor calculations are as follows: warhead mass 18.4 kg, launch tube length 3 m, firing range approximately 35–40 km.

The research procedure is based on two groups of models: internal ballistics to calculate combustion characteristics and motor thrust, and external ballistics to determine the flight trajectory.

### *2.1. Internal ballistics*

During the combustion phase, the regression of the propellant surface is described by the burning rate equation:

$$\frac{de}{d\tau} = u = u_1 p^v$$

where, e - burn thickness (m), u – burning rate (m/s), p – chamber pressure (MPa), $u_1$, $v$ – empirical constants depending on the propellant type [5], [7], [9].

The burning surface area S, free volume of the combustion chamber $W_{td}$ and mass flow rate $\dot{m}$ are calculated as follows:

$$\frac{dW_{td}}{d\tau} = Su; \dot{m} = \frac{\varphi_2 A_k F_{th} p}{\sqrt{RT}};$$

The pressure and temperature variation laws in the combustion chamber over time $p = p(\tau); T = T(\tau)$ are the results of the internal ballistics problem:

$$\begin{cases} \frac{W_{td} p}{T} \frac{dT}{d\tau} = S\rho_T uR(\chi T_v - T) - (k-1)\dot{m}RT; \\ W_{td} \frac{dp}{d\tau} = S\rho_T uR\chi T_v - k\dot{m}RT - Spu. \end{cases}$$

where, $T$ is the combustion temperature, $R$ is the specific gas constant, $F_{th}$ is the nozzle throat area; $\rho_T$ is the propellant density; χ is the heat loss coefficient; $k$ is the adiabatic index, isentropic index; $T_v$ is the isochoric temperature.

The instantaneous thrust of the motor:

$$P = \dot{m}V_e + (p - p_a)F_{th}$$

where, $V_e$ – exhaust gas velocity, $p_a$ – atmospheric pressure. The total impulse of the motor:

$$I_t = \int_0^{\tau} P(\tau)d\tau$$

### 2.2. External ballistics

After leaving the launcher, the URP enters the external flight phase, described by the system of dynamic equations:

$$\begin{cases} m(t) = M_d - \dot{m}t; \\ m(t)\frac{d}{dt}V(t) = P_d - F_{kh} - F_g sin\theta(t); \\ \frac{d}{dt}X(t) = V(t)\cos\theta(t);\ \frac{d}{dt}Y(t) = V(t)sin\theta(t) \end{cases}$$

where, $m(t)$ is the projectile mass $M_d$ accounting for the propellant mass burned over time ($\dot{m}t$), V(t) – instantaneous projectile velocity, θ – angle between the projectile axis and the horizontal, $F_{kh}$ – aerodynamic drag, $P_d$ – motor thrust during the propellant burning phase (then zero), (x,y) – trajectory coordinates in the 2D system.

These differential equations are solved using the fourth-order Runge–Kutta method with a small time step Δt. The significance of the model: accounting for the projectile mass reduction due to propellant burning enables continuous simulation from the combustion phase inside the chamber to the free flight phase outside the atmosphere. This forms the basis for determining average thrust, total impulse, muzzle velocity, trajectory, maximum range, impact point error, and the influence of design parameters (propellant mass, nozzle throat area, launch angle).

Compared to previous studies [8], [10], [14], this calculation model is compact, easily applicable to upgraded projectile configurations, while still accurately reflecting the main factors governing the flight dynamics of the URP launched from the BM-21.

### 2.3. Range extension upgrade solution

The task is to design a URP motor to extend the projectile range to 35–40 km. First, preliminary calculations are needed for the parameters of the upgraded projectile. From the external ballistics solution, to achieve the required range, the total motor impulse must reach about 52,000 N·s. Keeping the internal diameter of the projectile motor unchanged, the propellant mass is increased to raise the total motor impulse and thus achieve the desired range. Increasing the propellant mass means that the burning surface area S(t) and volume increase throughout the combustion phase, resulting in a higher propellant mass flow rate ṁ over time. According to the thrust equation P = $\dot{m}V_e + (p - p_a)F_{th}$, an increase in ṁ leads to higher instantaneous thrust. The nozzle throat area $F_{th}$ can be adjusted to keep the chamber pressure p within safe limits (ensuring projectile structural integrity), so the value $(p - p_a)F_{th}$ in the thrust formula does not change significantly. The overall result is that average thrust and total impulse increase as propellant mass increases.

Two propellant grains are manufactured from RSI-12M adhesive propellant, with the first grain having a blank size of Φ100 /24.7; and the second grain Φ94 /16.8. The technical parameters of the propellant: density: ρ = 1,570 kg/m$^3$; specific pressure impulse β for RSI-12M propellant: β = 1,377 m/s; adiabatic index of combustion products k = 1.25.

**Calculation of additional propellant mass required**

The total required propellant mass is calculated by:

$$\omega = \varphi \frac{I_{tp}}{C_p\beta}, \text{kg}$$

where: *Cp* - motor thrust coefficient, chosen as *Cp* = 1.4; $I_{tp}$ - total impulse (N.s); $\varphi$ - coefficient accounting for propellant loss due to incomplete combustion in the motor chamber, chosen as φ =1.05÷1.2. Total propellant mass: ω = 28 kg. Thus, an additional Δω = 7.55 of propellant is needed.

To reduce erosive burning, the length of grain 2 (see Figure 1) is increased. The required additional length is:

$$\Delta L = \frac{4\Delta\omega}{\pi\rho(D^2 - d^2)}$$

The increase in the length of grain 2 is ΔL ≅ 0.71 m = 710 mm. The initial burning surface area of the propellant charge is determined by:

$$S = \pi((D_1 + d_1)L_1 + (D_2 + d_2)L_2)$$

Initial burning surface area: S = 0.885 m$^2$.

**Determining the nozzle throat area**

The critical throat area of the nozzles is calculated by:

$$F_{th} = \frac{S.u.\rho.\beta}{\varphi_c p}$$

where, u – propellant burning rate; $\varphi_c$ – nozzle loss coefficient, $\varphi_c$ = 0.95 ÷ 0.99; p - average operating chamber pressure, with p = 8 Mpa, giving: Critical nozzle throat area: $F_{th}$=0.00265 m$^2$. Critical nozzle throat diameter:

$$d_{th} = \sqrt{\frac{4F_{th}}{n.\pi}}$$

with number of nozzles n = 7, $d_{th}$ ≅ 0.022 m.

**Determining the average thrust**

The average motor thrust is calculated by:

$$P = C_p.p.F_{th}.cos\alpha$$

where, α - nozzle axis inclination angle relative to the motor axis. nozzle axis inclination angle relative to the motor axis α = 0°, average thrust: $P_{TB}$ =26,000 N. The range of working parameters for the original and upgraded URP are shown in Table 2.

The simulation and calculation procedure is implemented using Mathcad software, consisting of two main stages: internal ballistics and external ballistics. In the first stage, the model solves the internal ballistics problem to determine chamber pressure and temperature, and instantaneous thrust over time. These thrust results are then used as input for the external ballistics problem, to calculate the projectile's trajectory, muzzle velocity, and firing range. The simulation flowchart illustrates the data flow and relationships between calculation steps from input to output results as shown in Figure 2.

***Table 2.*** *Summary of calculated working parameters*

| No. | Parameter | Origi-nal | Impr-oved | Unit |
|---|---|---|---|---|
| 1 | Propellant mass | 20.45 | 28 | kg |
| 2 | Propellant charge length | 900 | 1,610 | mm |
| 3 | Combustion chamber diameter | 112 | 112 | mm |
| 4 | Critical nozzle throat diameter | 18 | 22 | mm |
| 5 | Number of nozzles | 7 | 7 | pcs |
| 6 | Average chamber pressure | 8,65 | 8,42 | MPa |
| 7 | Average thrust | 20,000 | 26,000 | N |
| 8 | Motor operating time | 1,9 | 2 | s |
| 9 | Total impulse | 38,000 | 52,000 | N.s |
| 10 | Projectile length | 2.87 | 3.58 | m |
| 11 | Firing range (approx.) | 20 | 35-40 | km |

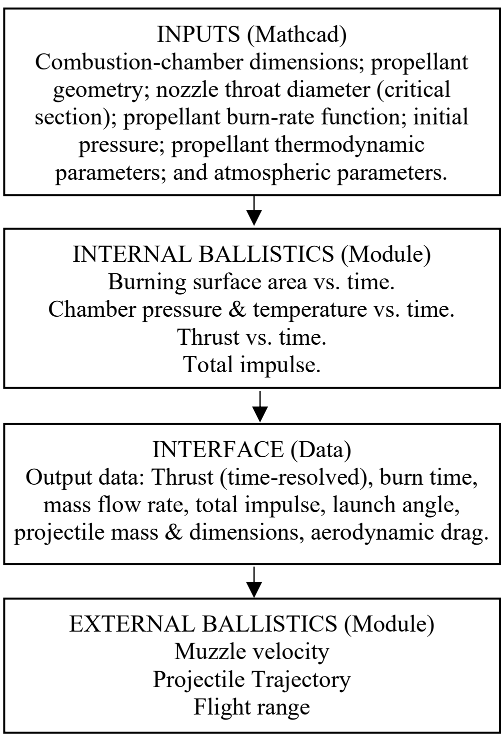


***Figure 2.*** *Simulation and calculation process flowchart*

## 3. Research results and discussion

### *3.1. Internal ballistics calculation results*

Based on the preliminary calculated parameters of the URP as described above, internal and external ballistics analyses are required to verify whether the combustion chamber pressure, motor thrust, and flight range meet the requirements. The results of the internal ballistics calculations are shown in Figures 3–5.

The average chamber pressure is 8.42 MPa, and the average temperature is 2,165 K. The average thrust is 26,200 N, and the total motor impulse is 52,400 N·s. The internal ballistics calculation results indicate that the combustion process of the solid-propellant motor in the upgraded configuration exhibits significant changes compared to the standard projectile motor. When the propellant mass is increased from 20.45 kg to 28 kg and the grain length is extended from 0.9 m to 1.61 m, the combustion chamber pressure reaches a peak of 8.6–10 MPa in the initial phase, then stabilizes at an average value of 8.42 MPa. The chamber temperature fluctuates around 2,165 K, consistent with theoretical calculations for the decomposition–combustion process of RSI-12M propellant [12]. The instantaneous thrust reaches a maximum of approximately 30,000 N, while the average thrust remains at 26,200 N. The total motor impulse is about 52,400 N·s, which is 32% higher than the original configuration.

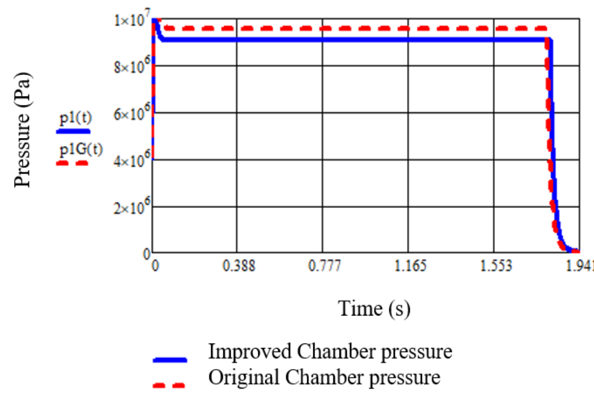


***Figure 3.*** *Combustion chamber pressure profile*

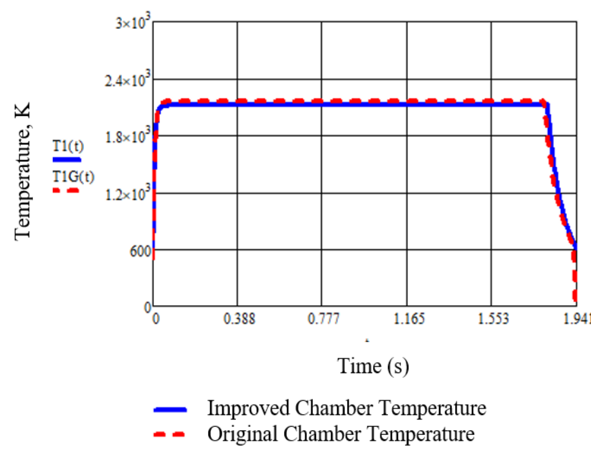


***Figure 4.*** *Combustion chamber temperature profile*

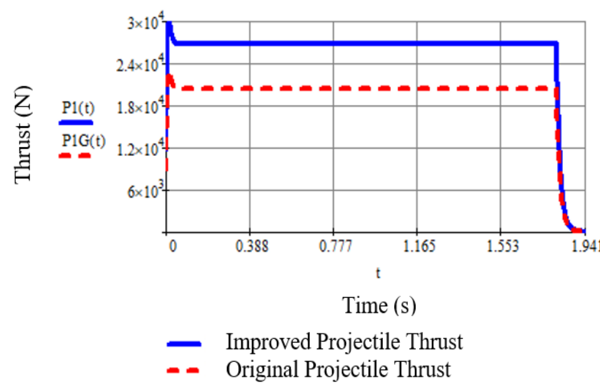


***Figure 5.*** *Motor thrust profile*

### *3.2. External ballistics calculation results*

From the internal ballistics results, thrust, motor operating time, and propellant mass burned over time are determined; these are then used in the external ballistics analysis to verify whether the projectile's flight range meets the requirements. The projectile's dynamic equations are solved numerically using the fourth-order Runge–Kutta method, implemented in a Mathcad program. In the standard configuration, the maximum firing range is 20.4 km at a launch angle of 41°. With the upgraded motor, the range is extended to 41 km at an optimal launch angle of 38–40° (see Figure 6). Notably, the muzzle velocity Vk increases from 690 m/s to 830 m/s, resulting in a higher trajectory curve and a flight time extended by approximately 28%. Programmatic calculations show that variations in aerodynamic drag coefficient Cd within the range of 0.3–0.4 can cause range deviations of up to ±1.2 km, while changes in launch angle of ±2° result in deviations of about ±0.8 km. This highlights the need for further research into the effects of wind, atmospheric density, and aerodynamic oscillations of the projectile.

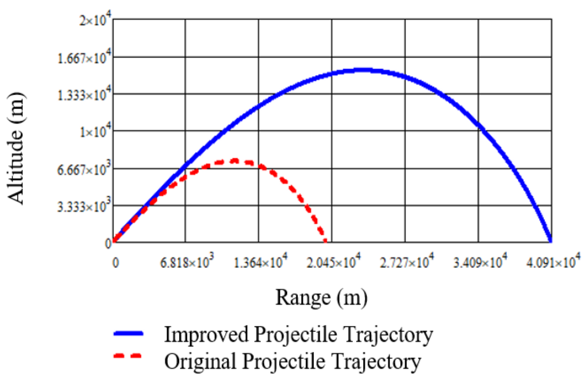


***Figure 6.*** *Flight trajectory of the URP*

Simulation results show that the motor thrust is closely dependent on the relationship between combustion chamber pressure, nozzle throat area, and the geometric dimensions of the propellant grains. When the nozzle throat area decreases, the exhaust gas velocity decreases, leading to an increase in chamber pressure, which in turn accelerates the burning rate according to the governing law, thereby increasing instantaneous thrust. Conversely, an excessively large throat area reduces chamber pressure, resulting in decreased thrust and lower combustion efficiency. The geometric parameters of the propellant grain—including length, diameter, burning area, and core-to-shell ratio—determine the time-dependent variation of the burning area S(t), directly affecting thrust.

The safety limit of the combustion chamber is defined by the peak pressure, which must be less than the material yield strength of the motor shell, with a safety factor of ≥ 1.3–1.5. In this calculation, the peak pressure reaches approximately 8.6–10 MPa, which remains within the strength limits for steel used in the combustion chamber.

Compared to the standard configuration (range 20 km, average thrust about 20,000 N), the upgraded model shows an increase in thrust to 26,200 N, a 32% increase in total impulse, and nearly double the firing range (41 km). These results demonstrate the feasibility and effectiveness of the proposed BM-21 projectile motor upgrade. Compared to modern multiple rocket launcher systems, the 40 km range of this solution is equivalent to the upgraded Russian Grad-2 projectile (range 37–40 km) and the Chinese Type 81 (range 38 km). A key advantage of this solution is that it maintains the standard NATO 122 mm diameter, requiring no major modifications to the BM-21 launcher, and can thus be directly deployed on existing platforms.

It is noteworthy that the average combustion chamber pressure in the upgraded configuration (8.42 MPa) remains within the safety limits compared to the original configuration, indicating that increasing the propellant mass in conjunction with optimizing the nozzle throat area effectively balances the chamber pressure. The pressure and temperature in the combustion chamber of the upgraded projectile do not differ significantly from the original configuration (Figures 3, 4), ensuring structural integrity. The increased thrust is mainly due to the higher exhaust gas flow rate through the nozzle (Figure 5). Additionally, the average chamber temperature of 2,165 K is consistent with the combustion characteristics of RSI-12M propellant, ensuring stable motor operation. However, the current study is limited to theoretical simulation. Practical factors such as manufacturing accuracy, projectile mass distribution, rearward shift of the center of gravity, aerodynamic oscillations, and the effects of wind and air density with altitude have not been experimentally verified. Therefore, the next step should be static firing tests on a test stand to determine actual pressure–thrust curves, as well as field firing tests to compare actual trajectory and range with theoretical models.

## 4. Conclusion

This paper presents a technical solution for upgrading the propellant to extend the range of URP launched from the BM-21 vehicle under domestic technical and technological conditions. A theoretical model was developed to determine the operating characteristics of the URP, employing internal ballistics calculations to compute chamber pressure, temperature, and thrust, as well as external ballistics calculations to determine trajectory and flight range.

According to the calculation results, with the proposed operating parameters for the URP, the combustion chamber has an average operating pressure of 8.45 MPa and an average temperature of 2,165 K. The total motor impulse in the combustion chamber reaches approximately 52,400 N·s, the average motor thrust is 26,200 N, and the flight range is about 41 km.

Further research should include practical experiments, such as manufacturing URPs with the dimensions proposed in this paper, conducting static firing tests on a test stand with sensor-equipped probes to measure chamber pressure, temperature, and motor thrust, and performing field firing tests to verify flight range. Comparing experimental results with theoretical predictions will confirm the accuracy of the methodology.

The research and design improvements of URP provide deeper understanding and mastery of operational principles, design features, and manufacturing technology of URP in general and projectiles for BM-21 in particular. Moreover, this is an opportunity to establish a solid theoretical foundation, allowing for further technical innovations and solutions that help shorten research time and improve the design and manufacturing of URP in Vietnam. These upgrades contribute to enhancing the quality of technical weaponry and equipment, enabling the Vietnam People's Army to better meet the demands of high-tech combat environments.

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