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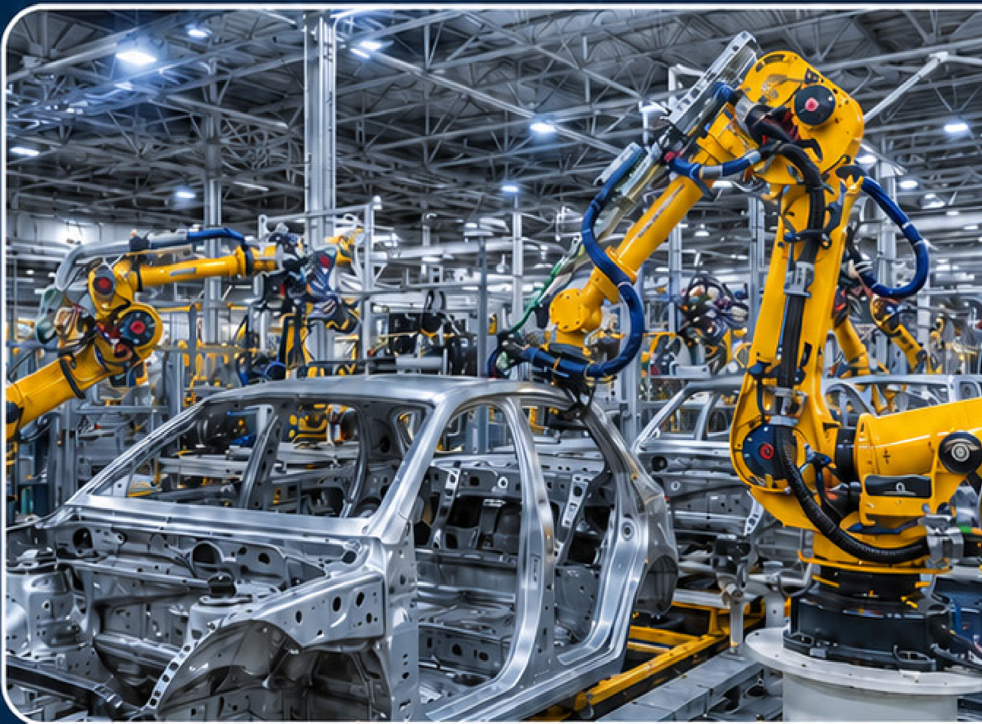

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05.01.00 – Axborot texnologiyalari, boshqaruv va kompyuter grafikasi
05.01.01 – Muhandislik geometriyasi va kompyuter grafikasi. Audio va video texnologiyalari
05.01.02 – Tizimli tahlil, boshqaruv va axborotni qayta ishlash
05.01.03 – Informatikaning nazariy asoslari
05.01.04 – Hisoblash mashinalari, majmualari va kompyuter tarmoqlarining matematik va dasturiy ta'minoti
05.01.05 – Axborotlarni himoyalash usullari va tizimlari. Axborot xavfsizligi
05.01.06 – Hisoblash texnikasi va boshqaruv tizimlarining elementlari va qurilmalari
05.01.07 – Matematik modellashtirish
05.01.11 – Raqamli texnologiyalar va sun'iy intellekt
05.02.00 – Mashinasozlik va mashinashunoslik
05.02.08 – Yer usti majmualari va uchish apparatlari
05.03.02 – Metrologiya va metrologiya ta'minoti
05.04.01 – Telekommunikasiya va kompyuter tizimlari, telekommunikasiya tarmoqlari va qurilmalari. Axborotlarni taqsimlash
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05.05.05 – Issiqlik texnikasining nazariy asoslari
05.05.06 – Qayta tiklanadigan energiya turlari asosidagi energiya qurilmalari
05.06.01 – To'qimachilik va yengil sanoat ishlab chiqarishlari materialshunosligi
05.08.03 – Temir yo'l transportini ishlatish
05.08.06 – "G'ildirakli va gusenisali mashinalar va ularni ishlatish" (texnika fanlari)
05.09.01 – Qurilish konstruksiyalari, bino va inshootlar
05.09.04 – Suv ta'minoti. Kanalizatsiya. Suv havzalarini muhofazalovchi qurilish tizimlari
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08.00.03 – Sanoat iqtisodiyoti
08.00.04 – Qishloq xo'jaligi iqtisodiyoti
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08.00.06 – Ekonometrika va statistika
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08.00.10 – Demografiya. Mehnat iqtisodiyoti
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08.00.16 – Raqamli iqtisodiyot va xalqaro raqamli integratsiya
08.00.17 – Turizm va mehmonxona faoliyati

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MUNDARIJA

MUNDARIJA • СОДЕРЖАНИЕ • CONTENTS

OPTIMIZING CONVERGENT-DIVERGENT ROCKET NOZZLE GEOMETRY (30°/10°) TO ENHANCE THE ALTITUDE PERFORMANCE OF MODEL ROCKETS USING SOLID SUGAR PROPELLANTS

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Abstract. This paper investigates the thermodynamic and gas-dynamic optimization of de Laval nozzle geometry to maximize the flight altitude of model rockets using sugar-based solid propellants. Standard nozzle configurations may experience internal flow separation and divergence losses. To address this issue, a specific convergent-divergent profile featuring a 30° inlet angle and a 10° exit angle was designed and experimentally evaluated. Flight tests were conducted using a standardized 700 g rocket body loaded with a 400 g KNSU/KNSB propellant grain modified with an eco-friendly, waste-derived tobacco ash catalyst rich in K_2CO_3 and $CaCO_3$. While the baseline nozzle configurations consistently achieved peak altitudes of 200 m, the optimized 30°/10° nozzle configuration reached an apogee of 300 m, representing a 50% increase in performance. The findings suggest that optimizing the exit divergence angle may reduce expansion losses and improve the effective axial exhaust velocity.

Keywords: rocket nozzle, de Laval geometry, convergence angle, exit angle, solid propellant, KNSU, flight performance, altitude optimization.

Annotatsiya. Ushbu maqolada shakar asosidagi qattiq raketa yoqilg‘ilaridan foydalanadigan model raketalarning uchish balandligini oshirish maqsadida de Laval soplosi geometriyasini termodinamik va gaz-dinamik jihatdan optimallashtirish masalalari o‘rganilgan. Standart soplo konstruksiyalarida ichki oqimning ajralishi va kengayish bilan bog‘liq yo‘qotishlar yuzaga kelishi mumkin. Ushbu muammoni bartaraf etish maqsadida kirish burchagi 30° va chiqish burchagi 10° bo‘lgan maxsus konvergent-divergent profil ishlab chiqildi hamda tajriba yo‘li bilan baholandi. Uchish sinovlari K_2CO_3 va $CaCO_3$ ga boy, chiqindi tamaki kulidan olingan ekologik toza katalizator qo‘shilgan 400 g KNSU/KNSB yoqilg‘i zaryadi bilan jihozlangan, umumiy massasi 700 g bo‘lgan standart model raketada o‘tkazildi. Bazaviy soplo konfiguratsiyalarida maksimal uchish balandligi muntazam ravishda 200 m ni tashkil etgan bo‘lsa, optimallashtirilgan 30°/10° soplo konfiguratsiyasida apogey 300 m ga yetdi, bu esa samaradorlikning 50% ga oshganini ko‘rsatadi. Natijalar chiqishdagi kengayish burchagini optimallashtirish kengayish yo‘qotishlarini kamaytirishi va chiqindi gazlarning samarali o‘q bo‘ylab tezligini oshirishi mumkinligini ko‘rsatadi.

Kalit so‘zlar: raketa soplosi, de Laval geometriyasi, konvergentsiya burchagi, chiqish burchagi, qattiq yoqilg‘i, KNSU, uchish samaradorligi, balandlikni optimallashtirish.

Аннотация. В статье исследуется термодинамическая и газодинамическая оптимизация геометрии сопла де Лаваля с целью увеличения высоты полёта моделей ракет, использующих твёрдое топливо на основе сахара. В стандартных конструкциях сопел могут возникать отрыв внутреннего потока и потери, связанные с расширением газа. Для решения данной проблемы был разработан и экспериментально оценён специальный сужающе-расширяющийся профиль с углом входа 30° и углом выхода 10°. Лётные испытания проводились с использованием стандартизированного корпуса модели ракеты массой 700 г, оснащённого 400-граммовым зарядом топлива KNSU/KNSB с экологически безопасным катализатором, полученным из отходов табачной золы и содержащим K_2CO_3 и $CaCO_3$. Базовые конфигурации сопел стабильно обеспечивали максимальную высоту полёта 200 м, тогда как оптимизированная конфигурация сопла 30°/10° достигла апогея 300 м, что соответствует увеличению эффективности на 50%. Полученные результаты показывают, что оптимизация угла расширения выходной части сопла может снизить потери при расширении и повысить эффективную осевую скорость истечения газов.

Ключевые слова: ракетное сопло, геометрия де Лаваля, угол сужения, угол выхода, твёрдое топливо, KNSU, лётные характеристики, оптимизация высоты.

INTRODUCTION

Model rocketry serves as a vital testbed for propulsion physics, aerodynamics, and structural design. Among the primary factors determining rocket performance, the thermodynamic efficiency of the supersonic exhaust nozzle is particularly important [1]. Solid sugar propellants—typically formulated from potassium nitrate () combined with sucrose or sorbitol (KNSU/KNSB)—are widely used due to their stability, ease of processing, and reliable combustion kinetics [2].

The primary task of a rocket nozzle—a convergent-divergent de Laval nozzle—is to convert high-pressure, high-temperature combustion chamber gases () into high-velocity directional kinetic energy (However, improper divergence angles cause non-axial velocity vector components, potentially resulting in thrust losses associated with reduced divergence efficiency [3]. Conversely, overly steep entry angles introduce boundary-layer separation and stagnation pressure losses near the nozzle throat [4]. While burn-rate catalysts such as iron(III) oxide () or biomass-derived alkali carbonates () increase the condensed-phase mass consumption rate, energy conversion ultimately depends on exit-flow alignment. This study explores the empirical flight performance of a 700 g model rocket propelled by a 400 g catalyst-enhanced solid grain, comparing the performance of standard nozzle configurations with that of an optimized 30° inlet/10° exit nozzle design.

LITERATURE REVIEW

The theoretical mechanics of supersonic flow through convergent-divergent nozzles are well established in classical gas dynamics [1, 5]. Ideally, exhaust gases expand unidirectionally along the nozzle's central axis. However, in standard conical nozzle designs, the divergence half-angle () induces significant radial dispersion of the exhaust plume, reducing net directional thrust by a geometric efficiency factor defined as:

$$\lambda = \frac{1 + \cos(\alpha)}{2}$$

For standard conical nozzles operating with divergence half-angles between 15° and 20°, radial scattering accounts for a 1.5%–3.0% loss in effective thrust [5]. Sutton and Biblarz argue that reducing the divergence angle below 12° substantially aligns internal flow vectors, thereby reducing expansion penalties [1]. However, Sutton and Biblarz primarily focused on large-scale liquid rocket engines, and boundary-layer friction losses may require additional consideration when these models are applied to small-scale nozzles.

In terms of propellant chemistry, transition-metal oxides—most notably iron(III) oxide () and manganese dioxide ()—have long been established as primary catalysts for lowering the thermal activation energy during decomposition [6, 7]. Recent advances in sustainable energetics have encouraged greater interest in biomass-derived catalytic materials. Tobacco stalk ash contains calcium- and potassium-bearing mineral phases; however, its catalytic effect on KNO_3-based sugar propellants requires direct experimental verification [8]. Existing research has primarily focused on the mineralogical and thermal characteristics of biomass-derived ash, while its behavior under actual model-rocket chamber pressures and in-flight operating conditions remains insufficiently investigated.

From a regional perspective, local researchers such as Tashxodjayev et al. investigated the synthesis and thermal stability of nitrate-carbohydrate solid mixtures, highlighting the hygroscopic vulnerabilities of sugar-based energetic grains [9]. Furthermore, Rustamov and Tursunov analyzed the aerodynamic performance of small-scale educational rockets under local atmospheric conditions [10]. Nevertheless, the present study identifies an area that has received limited attention in the local literature: existing Uzbek studies have generally examined propellant chemistry and aerodynamic airframe design separately, while the interaction between internal nozzle gas dynamics and thrust efficiency in biomass-catalyzed propulsion systems has received comparatively limited consideration.

Therefore, this study bridges these theoretical and empirical gaps by integrating a waste-derived tobacco ash catalyst with a custom 30°/10° de Laval nozzle profile validated through active flight telemetry.

RESEARCH METHODOLOGY

The experimental phase consisted of propellant formulation, nozzle fabrication, static testing, and flight telemetry tracking.

Step 1: Material Preparation and Catalyst Conditioning

Oxidizer: Technical-grade potassium nitrate () was ball-milled to an average particle size of and dried at 105 °C for 4 hours to eliminate residual moisture.

Fuel: Standard sorbitol/sucrose was selected for its favorable melt viscosity and curing characteristics.

Biomass Catalyst: Waste tobacco ash was collected, sieved through a 50 mesh, and thermally conditioned to retain active alkali carbonates ().

Step 2: Propellant Batch Blending

The propellant was formulated using a 65:35 oxidizer-to-fuel ratio and supplemented with 2 wt.% tobacco ash catalyst:

: 63.7%

Sugar/sorbitol: 34.3%

Tobacco ash catalyst: 2.0%

The mixture was thermally cast at 135 °C under continuous mechanical stirring to prevent agglomeration and then vacuum-degassed to eliminate microvoids prior to coring. The total propellant mass per test grain was fixed at exactly .

Step 3: Nozzle Fabrication and Geometry Integration

Two nozzle configurations were precision-machined from mild steel:

1. Control / Baseline Nozzles: Standard commercial geometries (inlet: approximately 45°; e xit: 15°–20°).

2. Optimized Experimental Nozzle: Engineered with a 30° convergence inlet angle, a 10 mm throat diameter, and a smooth 10° divergence exit angle.

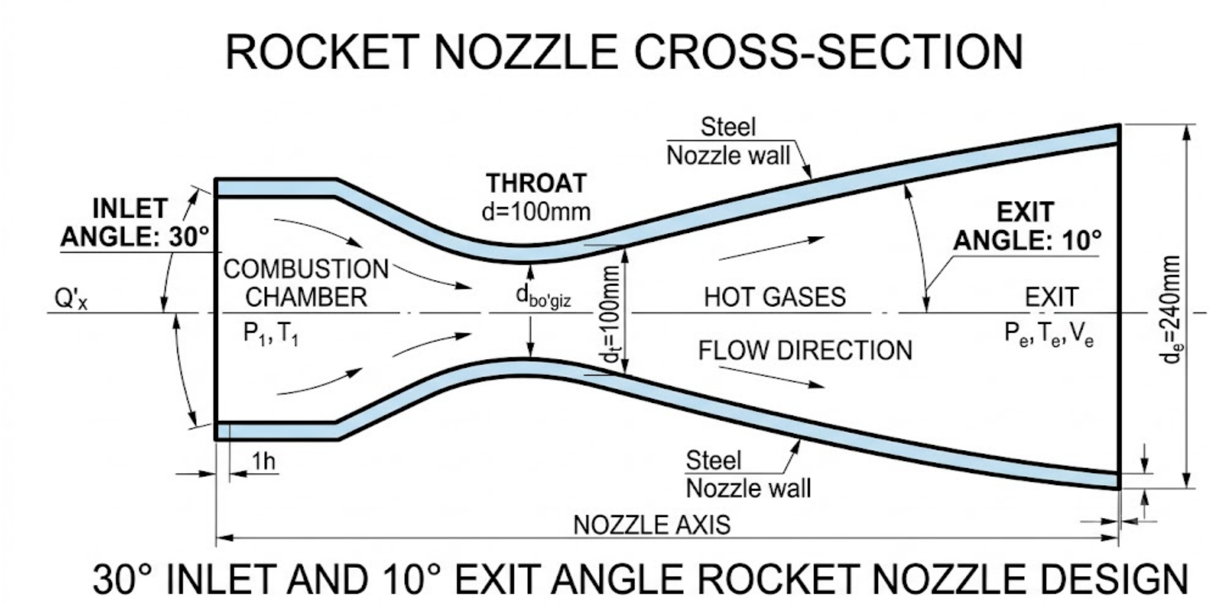

Figure 1. Optimized Nozzle Orifice Design

ANALYSIS AND RESULTS

Flight trials were conducted under identical environmental conditions (wind speed , atmospheric pressure:). The total launch mass of the rocket was maintained at 700 g, comprising a 300 g airframe/telemetry bay and a 400 g propellant grain. Altitude data were recorded using an onboard barometric altimeter combined with ground-based optical tracking.

Flight Telemetry and Performance Comparison

The empirical metrics across the different test groups are summarized in Table 1.

Table 1. Flight Performance Comparison of the Tested Rocket Configurations[1]

Test Parameter / Group	Control Group (Standard Nozzle + Uncatalyzed KNSU)	Baseline Group (Standard Nozzle +Fe2O3)	Experimental Group (30°/10° Nozzle + Tobacco Ash Catalyst)
Total Rocket Mass (g)	700	700	700
Propellant Mass (g)	400	400	400
Nozzle Inlet Angle (°)	45	45	**30**
Nozzle Exit Angle (°)	18	18	**10**
Mean Burn Rate (mm/s)	3.82	4.65	4.71
Specific Impulse, (s)	112	128	**146**
Max Thrust (N)	24.5	31.2	**38.8**
Peak Altitude / Apogee (m)	**200**	**205**	**300**

GAS-DYNAMIC AND CATALYTIC MECHANISM ANALYSIS

The significant performance increase from 200 m to 300 m (a 50% increase in apogee) in the experimental group may be associated with the combined influence of three factors:

Divergence Loss Reduction: Reducing the divergence half-angle from 18° to 10° improves the divergence efficiency factor, λ, from 0.975 to 0.992 [5]. This minimizes radial velocity components, directing a greater proportion of the exhaust kinetic energy along the nozzle axis [1, 3].

Inlet Boundary-Layer Alignment: The 30° entry angle creates a smooth transition toward the throat (), which may help reduce excessive turbulence, flow stagnation, and localized thermal losses prior to supersonic acceleration [4].

Catalytic Enhancement of Combustion: The alkali metal oxides in tobacco ash

() may influence the thermal decomposition of , potentially contributing to an increased burning rate and more stable chamber pressure, P_1 [6, 8].

CONCLUSION AND SUGGESTIONS

This study demonstrates that optimized nozzle exit geometry, together with propellant composition, can make an important contribution to model rocket performance. Implementing a 30° convergence and 10° divergence de Laval nozzle, paired with a biomass-catalyzed (tobacco ash) KNSU propellant grain, yielded a 50% increase in peak flight altitude (from 200 m to 300 m) for a standardized 700 g model rocket carrying 400 g of fuel. Future work will focus on computational fluid dynamics (CFD) modeling of parabolic bell nozzles to further minimize the total nozzle weight while preserving axial flow efficiency.

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1 Source: Author's experimental results.

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