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INCREASING COMBUSTION EFFICIENCY IN FUEL-AIR THERMAL TOOLS WITH EJECTION NOZZLE

The aim of this study is to increase the thermal output of petrol–air burner tools applied to rock breakage during extraction and processing of block stone by intensifying fuel combustion. The research is based on a theoretical framework for shock-wave generation within a perforated ejector nozzle, developed using the conservation laws of continuum mechanics. The methodology includes analysis of supersonic gas flow from the Laval nozzle, as well as calculation of thermodynamic and geometric parameters of the mixing chamber. As a result, the key operational and geometric characteristics of the ejector nozzle were determined, including gas velocity, temperature, outlet cross-sectional area, and jet dimensions. The obtained results demonstrate a significant increase in combustion efficiency and energy characteristics of the thermal tool. The findings are consistent with current studies on supersonic ejector systems and detonation combustion, confirming the effectiveness of the proposed approach.

1. INTRODUCTION

In air-petrol thermal tools equipped with a perforated ejector nozzle, combustion intensification exploits the formation of powerful shock waves in the entry region of the supersonic jet. These shock waves originate when the high-velocity gas exiting the main burner encounters geometric discontinuities inside the cylindrical nozzle — primarily the roughness elements introduced by the entrained cold air stream [1, 2].

At an excess air ratio of $\alpha_T = 0.5$–0.7, the supersonic jet entrains unburned fuel particles that ignite on traversing the shock front, generating an accelerated secondary jet and markedly increasing the burner's total energy output [3, 4, 5]. Research on pressure-gain combustion confirms that detonative combustion can exceed the thermodynamic efficiency of conventional deflagrative combustion by up to 25%, which is particularly advantageous for high-energy thermal applications [6, 7].

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The cylindrical nozzle acts simultaneously as a combustion chamber in which chemical energy is converted into both thermal and kinetic energy. Combustion proceeds in the heterogeneous regime, with fuel distributed across liquid and gaseous phases, so the flow field involves tightly coupled chemical and aero-thermodynamic phenomena in a reactive moving medium. Under these conditions the primary object of analysis is the reacting gas downstream of a strong shock wave. The prevailing combustion mode is detonation, distinguished by propagation velocities far exceeding those of deflagration and accompanied by sharp local rises in pressure and temperature.

Theoretical models of detonation wave (shock wave) development have been formulated and validated in both Russian-language and international scientific literature [8–14], and subsequent investigations have substantially deepened knowledge of the mechanisms governing detonation initiation, propagation, and stabilisation in confined geometries such as combustion chambers and nozzles [7, 15, 16].

2. LITERATURE REVIEW

The problem of combustion intensification in high-speed gas flows and the design of efficient ejector–nozzle systems has attracted considerable research attention in recent years. Below, relevant advances in three interconnected areas are reviewed: (i) detonation wave theory and shock dynamics, (ii) supersonic ejector design and mixing chamber optimization, and (iii) thermal tools for rock destruction.

2.1. DETONATION WAVES AND SHOCK WAVE DYNAMICS

The Rankine–Hugoniot (RH) relations, which describe the conservation of mass, momentum, and energy across a shock front, form the theoretical backbone of detonation analysis. Liberman [16] provides a comprehensive modern treatment of the physics and chemistry of combustion, explosion, and detonation, emphasising the role of the RH conditions in connecting pre- and post-shock thermodynamic states. The limitations of the classical planar-steady RH model for real three-dimensional, unsteady shock waves are discussed in detail by Krehl and Engemann [17], who demonstrate that systematic errors arise when applying idealised jump conditions to practical shock configurations.

Rotating detonation engines (RDEs) represent the most advanced contemporary application of detonation combustion. Sun et al. [7] presented a comprehensive review of research progress in rotating detonation propulsion technology, including the CJ–ZND theoretical framework, triple-point wave structures, and the role of Rayleigh–Hugoniot intersections in determining self-sustained propagation velocity. The authors show that detonative combustion can yield pressure gain ratios significantly exceeding those of conventional deflagrative systems. Practical implementation of pressure-gain combustion across aerospace, power generation, and industrial sectors was reviewed by Rasheed et al. [6], who documented efficiency improvements of up to 25% compared with constant-pressure combustion.

The deflagration-to-detonation transition (DDT) in tubes with cavities – a geometry closely related to the perforated ejector nozzle considered in the present work – was studied by Smirnov et al. [15]. The authors confirmed that surface roughness and geometric discontinuities in a confined tube can initiate DDT at lower initiation energies, supporting the physical mechanism underlying the present ejector design.

2.2. SUPERSONIC EJECTOR DESIGN AND MIXING CHAMBER OPTIMISATION

Supersonic ejectors, in which a high-pressure primary (motive) flow entrains and compresses a secondary flow through momentum exchange in a mixing chamber, share a direct structural and operational analogy with the ejector nozzle of the thermal tool studied here. In a supersonic ejector, the primary flow is accelerated through a converging–diverging (Laval) nozzle, producing a supersonic jet that discharges into the mixing chamber, drags along the secondary flow, and passes through a series of shock waves before entering the diffuser [18].

The entrainment ratio — defined as the ratio of secondary to primary mass flow rate – is the principal performance metric of ejectors. Experimental and numerical studies on supersonic multi-nozzle ejectors (MNEs) by Hu et al. [19] showed that the optimal area ratio R for maximum entrainment ranges from 2.65 to 4.87 under practical working conditions, and that increasing the diameter of the mixing chamber significantly improves entrainment performance. These findings are consistent with the ejector coefficient n derived from the main ejection equation (Eq. 15) in the present work.

The strong sensitivity of ejector performance to mixing chamber geometry was highlighted by Chen et al. [20], who proposed a new curved mixing chamber profile and investigated ten distinct geometries using CFD. The study demonstrated that appropriate shaping of the mixing chamber can substantially increase the entrainment ratio relative to conventional constant-pressure mixing (CPM) designs. A complementary approach based on adjoint-method shape optimisation was applied by Kong et al. [21] to a two-dimensional supersonic ejector: simultaneous modification of the divergent nozzle section, nozzle exit position (NXP), and mixing chamber inlet height resulted in a 37.17% increase in entrainment ratio compared with the baseline geometry.

Large-eddy simulation (LES) of supersonic air ejectors by Metsue et al. [18] provided high-fidelity insight into the turbulent mixing phenomena within the mixing duct, revealing the primary flow shock structures and their interaction with the entrained secondary flow. These results underline the importance of correctly characterising the jet mixing length and shock pattern when designing ejector nozzles for high-temperature applications such as thermal rock-breaking tools.

The influence of nozzle type and geometry on fuel mixing in supersonic combustion chambers was systematically investigated by Li et al. [22]. Three nozzle configurations – rectangular (1:4), rectangular (1:16), and arc (1:16) – were compared at Mach 4 crossflow conditions. The rectangular nozzle with the highest aspect ratio (1:16) delivered the best mixing performance, with mixing efficiency increasing along the streamwise direction due to concentrated injection and enhanced vorticity. These results are directly applicable to the design of ejection bores in the present ejector nozzle.

2.3. THERMAL TOOLS FOR ROCK DESTRUCTION

Thermal tools for rock destruction by high-velocity gas jets have been studied for several decades. The present work builds directly on the prior studies of Povetkin et al. [1, 5, 23], which established the operational and design parameters of petrol-air burners and documented heat flux values and flame-jet parameters for typical block-stone processing conditions. The physical mechanism of rock fragmentation by high-temperature jets – thermal spallation – is driven by thermally induced tensile stresses that exceed the tensile strength of the rock surface layer [1].

Recent international research confirms that thermal spallation remains the most energy-efficient non-contact rock removal mechanism. Rossi et al. [24] demonstrated the feasibility of combined thermo-mechanical drilling (CTMD), where a high-temperature flame jet pre-weakens the rock before mechanical cutting, achieving penetration rates an order of magnitude higher than conventional mechanical drilling in granite. The thermal parameters of the gas jet – its temperature, velocity, and heat flux density – are the controlling variables, in full agreement with the design framework developed in the present article.

The role of ejector-type nozzles in increasing the thermal power and range of the gas jet from a burner was demonstrated by Ndeda et al. [25], who characterised the performance of an FA300A flame jet burner applied to dimension-stone cutting. The authors showed that the jet range and heat flux delivered to the rock surface are directly governed by the fuel flow rate and the ejection ratio — the same parameters that ejection equation (Eq. 13) allows to optimise.

The foregoing review demonstrates that the present work addresses a technologically relevant problem at the intersection of detonation combustion theory, supersonic ejector design, and thermal rock-breaking technology. The key contribution of this paper is the derivation and experimental validation of the main ejection equation for a perforated ejector nozzle operating in the detonation combustion regime, and the determination of the associated kinematic and thermal parameters.

3. SHOCK WAVE MODEL

This section examines the properties of planar shock fronts as used in one-dimensional detonation models. In all such models the detonation wave is represented as a two-zone structure comprising a shock front followed immediately by a reaction zone. The analysis begins with stationary shock waves in non-reacting media and then extends to the case in which chemical energy release occurs behind the shock front.

A planar shock front advances at a constant velocity Ws.The gas state is characterised by pressure, density, and velocity, denoted respectively by ρ, p and u respectively. Transforming to the reference frame co-moving with the shock front, the three conservation relations of continuum mechanics hold exactly (Fig. 1) [11]:

$$\rho_1 W_s = \rho_2 u_2 \text{ (conservation of mass)} \quad (1)$$

$$p_1 + \rho_1 W_s^2 = p_2 + \rho_2 u_2^2 \text{ (conservation of momentum)} \quad (2)$$

$$\rho W_s (h_1 + W_s^2/2) = \rho u_2 (h_2 + u_2^2/2) \text{ (conservation of energy)} \quad (3)$$

where $h = e + pV$ – specific enthalpy, e – internal energy, $V = 1/\rho$ – specific volume.

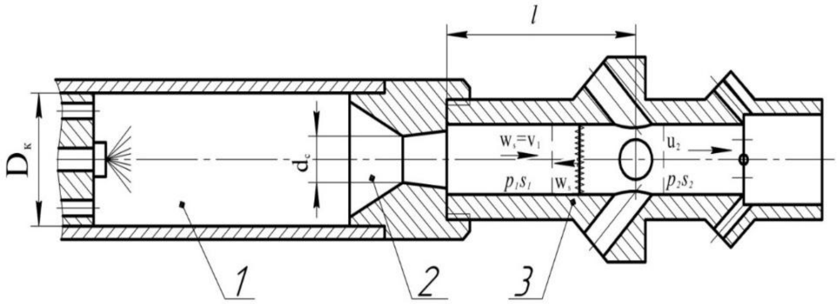

Fig. 1. Schematic of shock wave generation in the ejector nozzle. *1 – combustion chamber; 2 – Laval's nozzle; 3 – ejector nozzle*

The gas is assumed to obey the ideal-gas equation of state [10]:

$$p = \rho RT \tag{4}$$

where R – gas constant, T – temperature. The system of equations (1)–(4) contains five unknowns (W_s, u_2, ρ_2, p_2, T_2), all determinable from the upstream conditions.

Combining Eqs. (1) and (2) yields the mass flux across the shock front:

$$(W_s \rho_1)^2 = (u_2 \rho_2)^2 = (p_2 - p_1) / (V_1 - V_2) \tag{5}$$

Equation (5) is the Rayleigh-line relation in the p–v plane. The Rankine–Hugoniot relation, obtained by combining Eqs. (1)–(3) [11]:

$$e_2 - e_1 = (1/2)(p_2 + p_1)(V_1 - V_2) \tag{6}$$

The analogous expression governing isentropic and adiabatic processes takes the form [13]:

$$d_e = -p_d V \quad or \quad pV = const \tag{7}$$

The ratios of pressure, density, and temperature across the shock front, expressed in terms of upstream Mach number $M_s = W_s/a_1$ (where a_1 is the upstream sound speed):

$$p_2 / p_1 = p_{21} = [2kM_s^2 - (k-1)] / (k+1) \tag{8}$$

$$p_2 / p_1 = p_{21} = (k+1)\, M_s^2 / [(k-1)\, M_s^2 + 2] \tag{9}$$

$$T_2 / T_1 = [2kM_s^2 - (k-1)][(k-1)M_s^2 + 2] / [(k+1)^2 M_s^2] \tag{10}$$

where k — adiabatic index. Incorporating the chemical heat release Q with molecular weight μ [12]:

$$T_2/T_1 = [2kM_s^2 - (k-1)][(k-1)M_s^2 + 2 + 2Q_\mu/RT1] / [(k+1)^2 M_s^2] \tag{11}$$

The post-shock pressure follows from the ideal-gas equation of state at section 2:

$$p_2 = \rho_2 RT_2 \tag{12}$$

The Chapman–Jouguet (CJ) solution, corresponding to the point of tangency between the Rayleigh line and the Hugoniot curve, governs self-sustained detonation propagation velocity [7]; the present ejector nozzle is designed to operate in this detonation regime.

4. EJECTOR NOZZLE CALCULATION

Augmenting the kinetic energy of the unburned-fuel-laden jet is achieved by supplying additional oxidiser through perforation bores distributed along the nozzle wall. Within the resulting oxygen-enriched zone, afterburning of residual fuel components is promoted. This operating principle is structurally analogous to multi-nozzle ejector (MNE) systems reported in the recent literature [19, 22], where secondary-flow entrainment is controlled by the nozzle-exit geometry and mixing-chamber dimensions.

Flow conditions at the primary (ejection) gas inlet carry subscript 1, at the secondary (ejected) gas inlet subscript 2, and at the mixing-chamber exit subscript 3. Applying the integral conservation equations of mass, energy, and momentum following the approach of [9, 26] gives:

$$n \cdot q(\lambda_2) \cdot \sigma_2 + q(\lambda_1) \cdot \sigma 1 = (1+n) \cdot q(\lambda_3) \cdot \sigma_3 \quad (13)$$

Equation (13) is the main ejection equation. It allows determination of the gas-dynamic function q(λ_3) and thereby the mixture velocity λ_3. The ejection coefficient n:

$$n = (p_2^*/p_1^*) \cdot (T_1^*/T_2^*)^\wedge(1/2) \cdot q(\lambda_2)\cdot\sigma_2 / [q(\lambda_1)\cdot\sigma_1] \quad (14)$$

or equivalently:

$$n = \alpha \cdot (F_2/F_1) \cdot q(\lambda_2)/q(\lambda_1) \cdot (T_1^*/T_2^*)^\wedge(1/2) \quad (15)$$

The ejection coefficient n is linked to the nozzle geometric parameter α and the inlet flow conditions through Equation (15). Recent CFD-based studies of supersonic ejectors [18, 20, 21] confirm that the entrainment ratio is highly sensitive to the nozzle exit position and mixing chamber geometry – a result that is consistent with the dependence of n on the ratio F_2/F_1 in Eq. (15). The optimal area ratio for maximum n typically falls in the range 2.65–4.87 according to Hu et al. [19].

The computed ejector nozzle parameters for operating conditions u = 4, P_p = 0.5 MPa, w = 1285 m/s, and T = 2020 K are presented in Table 1 [11].

Table 1. Calculated operational and geometric parameters of the ejector-nozzle thermal tool at fuel flow rates of 17, 25, and 35 L/h

Regime and design parameters	17 L/h air 6 m³/min	25 L/h air 9 m³/min	35 L/h air 12 m³/min
Calculated ejector mass flow rate G_c, kg/s	0.4368	0.684	0.9428
Primary flow mass flux G_p, kg/s	0.1092	0.171	0.2357
Secondary (entrained) flow mass flux G_H, kg/s	0.3276	0.513	0.7071
Throat diameter of the primary nozzle d_{p*}, mm	20	22	26

Laval nozzle exit section d_1, mm	24	30	36
Free jet length l_{c1}, mm	262.5	328.24	393.8
Free jet diameter d_2, mm	148.8	186	223.2

Figure 2 shows the change in stream range of the thermal tool with ejector nozzle as a function of fuel consumption characteristics. The linear increase of range with fuel flow rate is consistent with the ejection coefficient *n* scaling with the primary mass flow rate *Gp*, as described by Eq. (14).

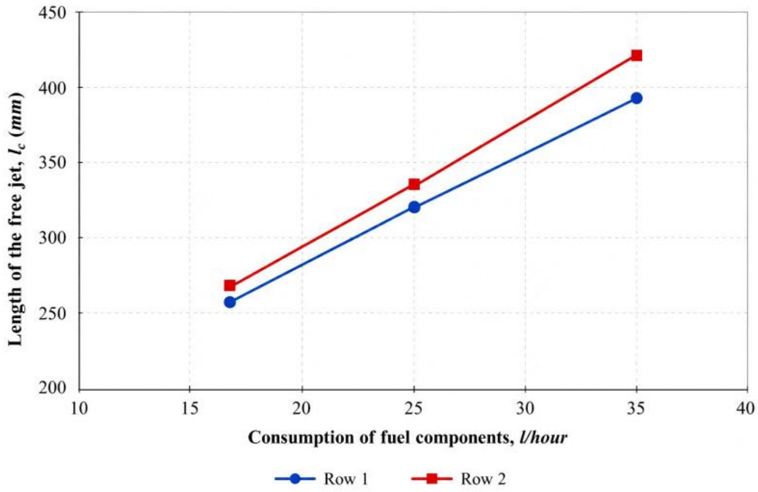

Fig. 2. Jet reach of the ejector-nozzle thermal tool as a function of fuel flow rate,
1 – theoretical, 2 – experimental data

5. HEAT TRANSFER THROUGH THE NOZZLE WALL

Steady-state heat conduction through the homogeneous isotropic nozzle wall is treated using a one-dimensional flat-wall model. A constant heat-flux condition (second-kind boundary condition) $q_c = const$ is imposed at the inner surface ($x = 0$), while a Newton convective condition (third-kind boundary condition) characterised by heat-transfer coefficient α_2 and the external fluid reference temperature t_{a2} applies at the outer surface (Fig. 3). No distributed heat sources are present within the wall.

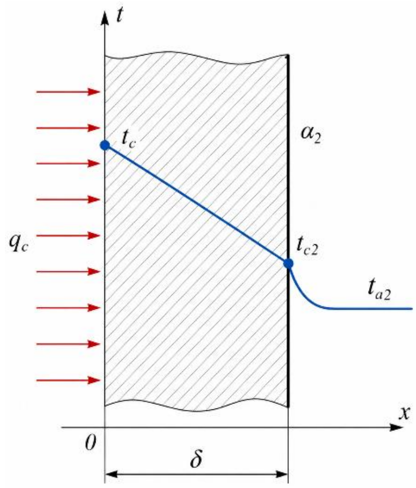

Fig. 3. Heat transfer through a flat wall (mixed boundary conditions)

Under steady-state conditions the temperature field in the wall obeys:

$$d^2t/dx^2 = 0 \quad (16)$$

Integrating with the stated boundary conditions:

$$t_{c1} = t_{c2} + q_c \cdot \delta/\lambda \quad (17)$$

For the ejector nozzle: λ = 35 W/(m·K) (metal thermal conductivity); δ = 0.005 m (wall thickness); t_{c2} = 1473 K (outer wall temperature from Fig. 4 colour assessment).

Pyrometric assessment of the nozzle outer surface by metal colour (Fig. 4) yields $T_н$ = 1100...1200°C (1373...1473 K). Taking into account the increase in working gas temperature due to combustion of unburned fuel and losses to wall heating, the mixed gas stream temperature is taken as $T_н$ = 2000°C [23].

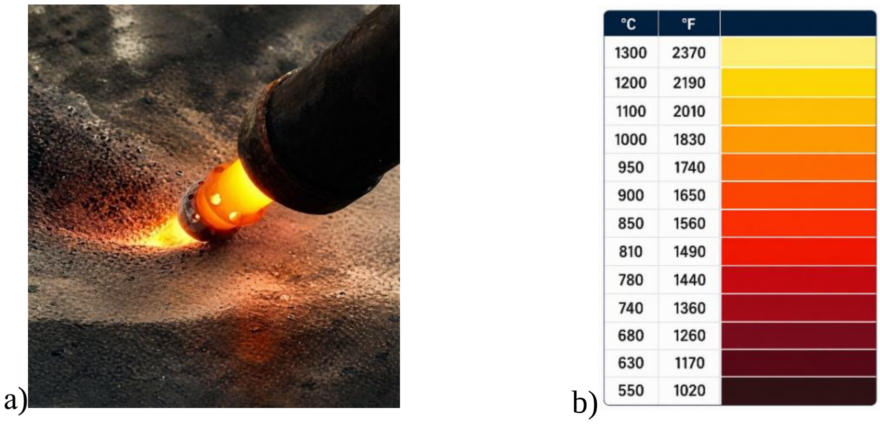

Fig. 4. Nozzle outer surface temperature estimation based on metal colour assessment , a – surface treatment process; b – metal temperature estimation by colour

Solving the inverse heat conduction problem with the measured outer-wall temperature as the known boundary condition determines the inner-wall (combustion-zone) temperature: t_{c1} = 1854 K for all three fuel consumption rates (17, 25, 35 L/h).

6. CONCLUSIONS

1. A shock wave generation model for the gas-dynamic ejector nozzle was established using the three fundamental conservation equations of continuum mechanics (Eqs. 1–3). The results are consistent with modern CJ–ZND detonation theory;
2. The Rankine–Hugoniot relations (Eqs. 6-10) and the detonation adiabatic (Eq. 11) fully determine the post-shock thermodynamic state, enabling calculation of all design parameters from the initial flow conditions;
3. The main ejection equation (Eq. 13) was derived, relating the ejection coefficient n, the nozzle geometric parameter α, and the inlet gas properties. The optimal area ratio F_2/F_1 for maximum entrainment is consistent with the range 2.65-4.87 reported in the recent literature on supersonic ejectors;
4. The temperature of the outer nozzle wall was determined experimentally from metal colour assessment, and the inner-wall (gas-flow) temperature t_{c1} = 1854 K was found by solving the inverse heat conduction problem (Eq. 17);
5. The calculated kinematic and geometric parameters of the new ejector nozzle design (Table 1) demonstrate that increasing the fuel consumption from 17 to 35 L/h raises the free-jet diameter from 148.8 to 223.2 mm and the jet length from 262.5 to 393.8 mm, confirming the scalability of the proposed design;
6. The proposed ejector nozzle concept significantly increases the energy output of petrolair thermal tools for block-stone processing, consistent with the performance gains documented for combined thermo-mechanical drilling in recent field tests.

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REFERENCES

[1] POVETKIN V.V., BUKAYEVA A.Z., KHANDOZHKO A.V., NURYMOV Y.K., 2017, *Study of the Application High Velocity Thermal Spraying Tools Used in Technological Processes and Production*, News of the Academy of Sciences of the Republic of Kazakhstan. Series of Geology and Technical Sciences, 5/425, 190–201, https://doi.org/10.32014/2018.2518-170X.5

[2] NURYMOV Y., BUKAYEVA A., ZHAUYT A., POVETKIN V., ASKAROV Y., 2016, *Study of Thermal Stonecutting Tools*, Journal of Vibroengineering Procedia, 8, 22–27.

[3] RAKISHEV B.R., SHASHENKO A.N., KOVROV A.S., 2018, *Trends of the Rock Failure Conceptions*, Bulletin of National Academy of Sciences of the Republic of Kazakhstan, 6/432, 161–169. https://doi.org/10.32014/2018.2518-170X.46

[4] YANTOVSKY Ye.I., 1988, *Flows of Energy And Exergy*, Moscow: Science, 144 p.

[5] POVETKIN V.V., 1998, *Theoretical Basis for the Calculation of Thermal Energy Flows in the Destruction of Rocks by Thermal Method*, Search Scientific Journal, Ministry of Defense of the Republic of Kazakhstan, 4, 20–25.

[6] RASHEED A., FURMAN A.H., DEAN A.J., 2020, *Advancements in Pressure-Gain Combustion Technologies — Review of Innovations, Methodologies and Practical Applications*, Progress in Aerospace Sciences, 119, 100643. https://doi.org/10.1016/j.paerosci.2020.100643

[7] SUN J., ZHOU J., LIU S., LIN Z., ZOU J., LIU C., 2025, *Research Progress in Rotating Detonation Propulsion Technology*, Acta Astronautica, 232, 1–26. https://doi.org/10.1016/j.actaastro.2025.04.163

[8] SCHELKIN K.I., TROSHIN Ya.K., 1963, *Gas Dynamics of Burning*, Moscow: Academy of Sciences of the USSR, 255 p.

[9] ZELDOVICH Ya.B., 2012, *Detonation Theory*, Moscow: Media, 136 p.

[10] SOLOUKHIN R.I., 1983, *Shock Waves and Detonation in Gases*, Moscow: Fizmatgiz, 321 p.

[11] POVETKIN V.V., BUKAYEVA A.Z., 2020, *Intensification of Combustion Fuel Mixture in Petrol-Air Thermal Tools with Ejector Nozzle*, News of the Academy of Sciences of the Republic of Kazakhstan. Series of Geology and Technical Sciences, 3/441, 40–47. https://doi.org/10.32014/2020.2518-170X.52

[12] ABRAMOVICH G.N., 1991, *Applied Gas Dynamics*, Part 1, 5th ed., Moscow: Science, 600 p.

[13] SHETINKOV Ye.S., 2012, *Physics of Burning Gases*, Moscow: Science, 371 p.

[14] NETLETON M., 1989, *Detonation in Gases*, Moscow: Mir, 280 p.

[15] SMIRNOV N.N., NIKITIN V.F., PHYLIPPOV Yu.G., 2010, *Deflagration-to-Detonation Transition in Gases in Tubes with Cavities*, Journal of Engineering Physics and Thermophysics, 83/6, 1287–1316. https://doi.org/10.1007/s10891-010-0448-6

[16] LIBERMAN M.A., 2021, *Introduction to Physics and Chemistry of Combustion: Explosion*, Flame, Detonation, 2nd ed., Springer, Berlin. https://doi.org/10.1007/978-3-030-78807-9

[17] KREHL P., ENGEMANN S., 2015, *The Classical Rankine–Hugoniot Jump Conditions — an Important Cornerstone of Modern Shock Wave Physics: Ideal Assumptions Vs. Reality*, The European Physical Journal H, 40, 159–230. https://doi.org/10.1140/epjh/e2015-50010-4

[18] METSUE A., VEMULA R., CINNELLA P., 2022, *Large Eddy Simulation of a Supersonic Air Ejector*, Applied Thermal Engineering, 213, 118669. https://doi.org/10.1016/j.applthermaleng.2022.118669

[19] HU K., ZHANG H., WANG C., LI Q., 2024, *Experimental and Numerical Studies on the Performance of Supersonic Multi-Nozzle Ejectors*, Applied Thermal Engineering, 236, 121487. https://doi.org/10.1016/j.applthermaleng.2024.121487

[20] CHEN Y., SUN D., ZHAO H., ZHANG Z., 2024, *A New Mixing Chamber Geometry Design for Supersonic Ejector Performance Optimization Using Computational Fluid Dynamics*, Thermal Science and Engineering Progress, 47, 102321. https://doi.org/10.1016/j.tsep.2024.102321

[21] KONG F., KIM H.D., JIN Y., 2021, *Design Modification of Two-Dimensional Supersonic Ejector Via the Adjoint Method*, Applied Thermal Engineering, 195, 117059. https://doi.org/10.1016/j.applthermaleng.2021.117059

[22] LI Z., ABU-HAMDEH N.H., ABUSORRAH A.M., MUSA A., 2022, *Effects of Nozzle Types on Mass Diffusion Mechanism of Hydrogen Multi-Jets at Supersonic Combustion Chamber*, International Communications in Heat and Mass Transfer, 138, 106358. https://doi.org/10.1016/j.icheatmasstransfer.2022.106358

[23] POVETKIN V.V., BUKAYEVA A.Z., 2018, *Development of Thermal Tools with Combustion Intensifiers for the Destruction of Strong Rocks in the Extraction of Block Stone*, Student Scientific and Technical Journal Engineer, Donetsk, 1/25, 82–85.

[24] ROSSI E., JAMALI S., SAAR M.O., RUDOLF VON ROHR P., 2020, *Field Test of a Combined Thermo-Mechanical Drilling Technology*, Mode I: Thermal spallation drilling, Journal of Petroleum Science and Engineering, 190, 107005. https://doi.org/10.1016/j.petrol.2020.107005

[25] NDEDA R., SEBUSANG E., MARUMO R., OGUR E., 2020, *Flame Jet Burner Application and Performance Characteristics in Cutting Miya Granite for Dimension Stone*, International Journal of Engineering and Technology Research, 4/8, 1–7.

[26] SOKOLOV E.Ya., ZINGER N.M., 1989, *Inkjet Apparatuses*, 3rd ed., Moscow: Energoatomizdat, 352 p.

[27] ISACHENKO V.P., OSIPOVA V.A., SUKOMEL A.S., 1975, *Heat Transfer*, 3rd ed., Moscow: Energy, 488 p.