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# REVIEW OF EJECTOR NOZZLES
# PART 1 – THRUST AUGMENTING EJECTOR NOZZLES

*The **subject of this** article is ejector nozzles, which are intended for the thrust augmentation of jet engines. The **goal** of this study is to analyze the contradictions between technical requirements and the requirements of manufacturability and price, between the required high characteristics of ejectors and compactness, and between the conflicting goals of achieving a high mixing rate with low losses of the total pressure of the primary flow within a short total length. Moreover, this study aims to identify methods for rationally reducing these contradictions by using effective mixers of the primary and secondary flows. The **tasks** to be solved are: development of a classification, revealing the advantages and drawbacks of thrust augmenting ejector nozzles, and analysis of the main directions in ejector nozzle research (theoretical research based on simplified models, experimental research using improved models, and research using computational fluid dynamics models). The **following methods were used**: search of corresponding information sources on the Internet and analysis based on operational experience in the aviation branch. The following **results** were obtained: in terms of information sources, the classification of thrust augmenting ejector nozzles was developed, their advantages and drawbacks were formulated, and the results of available research were analyzed. Investigations of thrust augmenting ejector nozzles for micro-turbojets were analyzed separately. **Conclusions**. The scientific novelty of the results obtained is as follows: 1) information from numerous sources of literature that clarifies classification features, advantages, and drawbacks of thrust augmenting ejector nozzles, development of these nozzles investigations by theoretical and experimental methods were collected; 2) a very limited number of publications and absence (in open-source literature) of methodology as for designing thrust augmenting ejector nozzles for micro-turbojet engines was discovered. Thus, the necessity of developing a design methodology for thrust augmenting ejector nozzles for micro-turbojets has been justified. The goal and challenges of the following research are outlined.*

***Keywords:*** *gas-turbine engine; thrust augmenting ejector nozzle; thrust augmentation; entrainment ratio; primary nozzle; ejector mixing chamber.*

## Introduction

**Subject actuality**. Problem of thrust increase of small turbojets for Unmanned Aerial Vehicles (UAV) is very urgency. UAVs use very small turbojet engines, having static thrust below 1000 N at sea level. All these turbojets are usually similar in design: a single-stage centrifugal or diagonal compressor delivering an overall pressure ratio of up to 4…5, and an uncooled turbine has limited inlet temperature up to 1000 °C [1]. This results in a relatively low thermal efficiency (5…15 %), depending on engine size [1]. Unfortunately, more efficient turbofan engines cannot yet be scaled to this size for reasons of complexity, manufacturability and costs. **Thus, technical requirements come in contradiction with manufacturability requirements and cost**.

A lot of authors (for example W. M. Presz et al. [2], J. Georgi et al. [3]) compared two types of thrust augmenters: a fan with turbine using pressure forces to transfer energy from the primary flow to the secondary one, and an ejector using viscous forces to pump a secondary fluid. Thus the ejector increases mass flow rate, decreasing its speed, which provides static thrust gain and noise reduction.

An **ejector** is a fluid dynamic pump with no moving parts, which pumps a low-energy secondary fluid using the kinetic energy of the primary stream [4]. Shear forces between the primary and secondary flows cause a mixing process of both streams and a static pressure drop below ambient pressure in the mixing zone. Thus, kinetic energy of the primary stream is distributed on a larger mass flow of air. The specific enthalpies of the two streams equalize and the ejector exhaust velocity decreases. For this reason, propulsive efficiency increases. As a result, thrust augmentation can be achieved (comparing with the engine without ejector). Because the ejector reduces static pressure after the primary nozzle, the primary mass flow also increases [3].

In other words, it can be expressed as follows. In an ejector nozzle, the total available energy of the high-velocity, primary exhausting stream is partially recovered through the entrainment of the secondary flow and

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viscous interaction to provide an exhaust at a lower velocity, but with a higher mass flow rate. As a consequence, the momentum flux exiting the ejector becomes greater than that produced by the primary nozzle alone. This difference in the momentum flux can be characterized as the thrust augmentation, which the ejector provides. The levels of thrust augmentation, which can be realized by an ejector, depend on several factors such as: thermodynamic characteristics of the primary and secondary flows, ejector geometry, losses caused by the ejector components, and mixing and diffusion modes [5].

B. Quinn [6] stressed the **contradiction between high performance** (which dramatically depends on mixing perfection and thus requires very long ejectors) **and compactness**. Really, while ejectors have tremendous aircraft potential based on analytical predictions, the ability to implement them in an effective system application remains limited. One major reason is incomplete mixing [4, 7]. Typically, conventional ejectors require a minimum shroud length of 5-7 mixing duct diameters to achieve good mixing and pumping results [8]. Long mixing ducts result in large wall-friction losses, extra weight, and higher costs. S. A. Skebe et al. [9] also noted that for most practical applications, the mining duct length is limited by installation and weight requirements. Therefore, in order to improve ejector efficiency, research efforts have concentrated on developing ejectors that optimize the **conflicting objectives of achieving a high rate of mixing with low primary flow total pressure losses within a short overall length** [9].

An improvement in ejector design has been accomplished through hypermixing nozzles [10]. Alternating flaps or hypermixing nozzles on the primary stream significantly increase ejector mixing for a fixed ejector length. But the same hypermixing nozzles also create high mixing losses.

W. M. Presz et al. [4, 11] presented an alternative approach based on the use of low-loss, **forced mixer lobes** in ejector design. They reported more than 100 % increase in both pumping ratio and thrust augmentation comparing to conventional ejector designs, as well that the forced mixer lobes resulted in nearly complete mixing in very short ejector duct lengths and allowed the use of large diffuser angles (thus giving short length and low friction losses) without resulting in stall (because the lobes generated large-scale streamwise vorticity in the ejector mixing duct, which cause the primary and secondary flows to mix rapidly with low loss); in addition, a velocity profile is created at the diffuser inlet, with high velocities near the diverging walls, which allows high expansion ratios [4].

Povinelli, L. A. & Anderson, B. H. [12] showed that the large-scale secondary flows, not viscous diffusion, are the key to low-loss efficient mixing. The forced mixer lobes use the third dimension to initiate large-scale streamwise vorticity [4]. These vortices rapidly stir the nozzle and external flows together, dramatically increasing the interfacial contact area between the streams, using convective rather than shear mixing, and therefore providing the enhanced mixing to occur [8]. Such convective mixing is rapid and more efficient than shear mixing. The lobe contour shape is the key to generate these low-loss, large-scale (stirring) vortices [4]. Forced mixer ejectors, on the other hand, have been shown to be capable of pumping near-ideal levels of secondary flow with shroud lengths on the order of 1-2 mixing duct diameters. This translates into a significant weight and material savings for aircraft implementation [8].

There are a lot of publications, devoted to both theoretical and experimental investigations of thrust augmenting ejectors. But ejector nozzle application in small turbojets for UAVs has been studied insufficiently (this shows the **scientific actuality of the problem**). As a result, the ejector nozzles, which were widely used in the past for supersonic aircraft and are now used in various fields of engineering, are practically not used in aviation turbojets for UAVs (this determines the **practical actuality**) **Thus, the problem consists in developing the method for ejector nozzle designing, which can considerably increase thrust of small turbojets for UAVs**.

This article reviews publications on theoretical, numerical and experimental research of ejector devices with the aim of finding solutions suitable for use in the field of low-thrust engines.

## 1. Ejector Nozzles: idea appearance, advantages and drawbacks

As it is known, ejector is a device, which uses a high momentum flow and entrains the surrounding secondary flow from environment due to the momentum exchange and shear stresses action between the two flows (when the secondary flow comes from the main air intake of airplane after engine cooling, then the flow, which is captured from environment, is called tertiary one). Ejectors are widely used in various branches of industry, such as fluid transportation [13], mixing [14, 15], refrigeration [16, 17, 18], noise reduction systems, vacuum generation [19], thrust augmentation [3, 20, 21], gas-dynamic lasers [22], fuel cells [23], and even to reduce emission of gas burning jets [24].

Many authors (for example [20, 3]) draw an analogy between a bypass turbojet engine and an ejector nozzle. In both cases a portion of primary flow energy is transmitted to the secondary flow, as a result of which greater total gas flow is accelerated, that allows to increase thrust and to decrease specific fuel consumption.

Although ejector pumps were being used for a variety of applications since the late 1800's [7], it happened so, that the first exploratory tests of ejector augmenters took place only in 1927 [25]. Though, perhaps, these tests were oriented toward showing the feasibility of jet propulsion for airplanes; the first actual application of an ejector augmenter took place in soviet ambulance sled during the Great Patriotic war [26], and it utilized the Coanda Effect. Shortly thereafter the technical community finally realized the potential of these devices by means of von Karman's classical theoretical paper [27] for diffuserless ejector augmenters in incompressible medium.

Ejector nozzles give the following advantages:

1. Reduce noise around the nozzle [2, 28].
2. Increase in thrust [2, 28, 29].
3. Decrease in specific fuel consumption [28].
4. Increase in engine thrust efficiency [2].
5. Reduce the exhaust gas temperature [30].
6. Get simple basic design [7].
7. Minimize the number of the nozzle moving parts [7].
8. Simplify geometric constraints matching [7].
9. Get low mass and dimensions of the structure [7].
10. Cool engine and nozzle [21].

Drawbacks of ejector nozzles are considered as:

1. Additional total pressure losses caused by compression shocks [28].
2. Possible additional external drag caused by flow air intakes [28].

## 2. Ejector Nozzles Classification and Their Main Parameters

Ejector nozzles can be classified according to several features (Fig. 1):

– by cross-section shape: circular and rectangular;

– by primary nozzle duct shape: convergent and convergent-divergent;

– by mixing type: at constant area and at constant pressure;

– by shroud shape: cylindrical, conical and divergent;

– by primary nozzle type: Coanda, central, multiple, hypermixing, lobe and multi-stage.

In addition, ejector nozzles can be subdivided into: static ones (in which the flow parameters do not change with time) and dynamic ones (in which the flow parameters rapidly and periodically change with time).

Three parameters are the most often used to characterize ejector nozzles:

– thrust augmentation, which is the ratio of ejector nozzle thrust ( $F_{ej}$ ) to the thrust of isolated primary nozzle ( $F_{p\,ideal}$ ): $\phi = F_{ej}/F_{p\,ideal}$ ;

– entrainment ratio (or secondary mass flow ratio, or mass flow ratio), which is the secondary mass flow ( $\dot{m}_s$ ) ratio to the primary mass flow ( $\dot{m}_p$ ): $w = \dot{m}_s/\dot{m}_p$ .

– degree of mixing $\beta = \int v_{3s}^2 dA_{3s} \Big/ \left(\bar{v}_{3s}^2 A_{3s}\right)$, where $v_{3s}$ is the velocity, $A_{3s}$ is the area, $\bar{v}_{3s}$ is the average velocity at the ejector shroud exit.

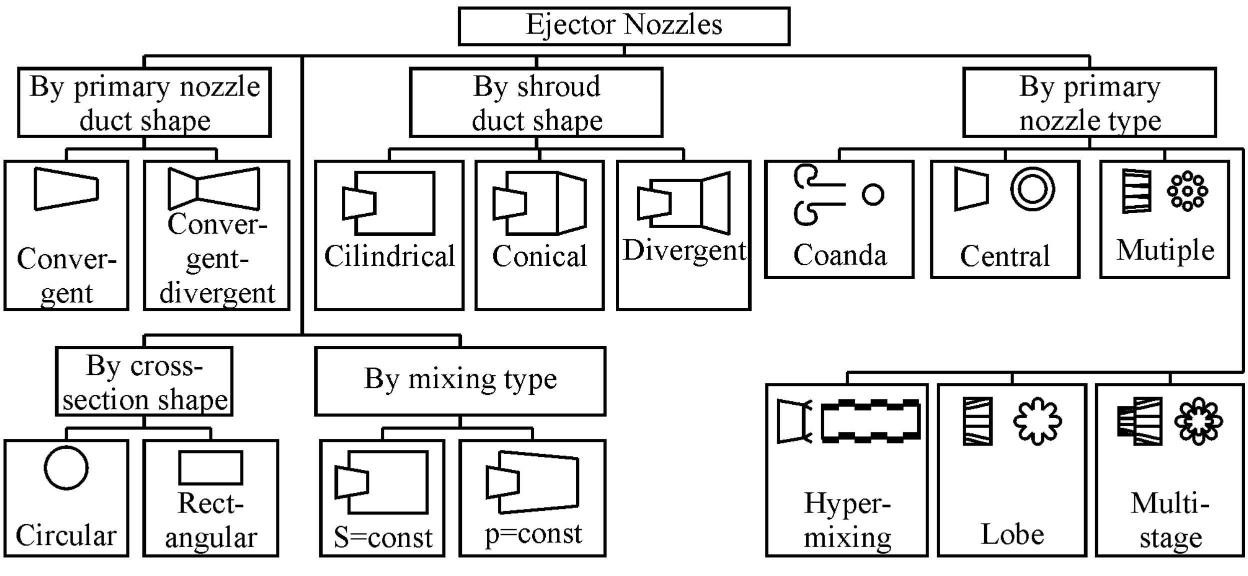


Fig. 1. Ejector Nozzle Classification

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Analysis of literature allows us to distinguish four stages in the study of ejector nozzles:

1. The stage of theoretical researches basing on simplified (usually 1D) models.
2. The stage of wide experimental researches.
3. The stage of theoretical researches based on enhanced (usually 2D) models.
4. The stage of researches with extensive use of computational fluid dynamics (CFD) models.

In addition, to consider development of the aforementioned researches, it will be also useful to briefly review related areas:

– Ejectors from other fields of engineering;
– Additional air intakes and afterbodies;
– Turbofan mixers.

## 3. Analysis of Theoretical Researches Based on Simplified Models

It is assumed that, the first theoretical publication on ejectors became the article of J. H. Keenan et al. [31] (1942), where results of theoretical research of the simplest form of ejector were presented. In 1942 R. Morrison [32] performed an incompressible analysis of an ejector. In 1949, von Karman [27] presented the basic information on cylindrical jet ejectors operating under idealized, incompressible flow conditions. In this analysis, an attempt was made to account for the effect of the non-uniform velocity profile at the secondary flow entrance to the mixing chamber on jet ejector thrust augmentation. In 1949, J. C. Sanders et al. [33] proposed an ejector nozzle thrust calculation method by integration of pressures over the ejector surfaces. The pressures were determined by 1D analysis, assuming complete mixing of two incompressible flows.

In 1950, J. H. Kennan et al. [34] presented a 1D method of ejector analysis and considered mixing of the primary and secondary streams at constant pressure, and mixing of the streams at constant area. It was shown that, better performance can be obtained when constant-pressure mixing is employed. In 1951, F. Kochendorfer et al. [35] came to conclusion that for low values of the primary nozzle pressure ratio (primary stream total pressure at primary nozzle exit ratio to ambient static pressure), the performance of aircraft cooling ejectors could be adequately explained by the methods of nonviscous fluid mechanics, and mixing effects could be neglected. In 1954, F. Kochendorfer et al. [36] showed that for an ejector having a convergent shroud the maximum flow and pressure values can be much less than those for a cylindrical ejector, the discrepancy increasing for larger amounts of convergence. In 1955, B. Szczeniowski et al. [37] presented 1D theory of the jet siphon for nonvicous fluid with curvilinear coordinate.

In 1962, J. Reid [38] considered simplified theoretical analysis for constant area mixing. The analysis indicated that although the system of flow equations formulated can be solved in principle, the numerical solutions are very difficult to obtain. In 1966, A. Bernstein et al. [39] presented 1D theory of compound-compressible streams. The flow in each stream was assumed steady, adiabatic and isentropic flow of a perfect gas with constant thermodynamic properties. Comparison of 1D theory calculations with 3D theory ones and with experimental data showed good agreement. But application of this theory is limited by streams having weak mixing. In 1967, K. Huang et al. [40], presented may be the most perfect collection of 1D theoretical models of thrust augmentation estimation for axisymmetric jet ejectors (Fig. 2). The models include the effects of ejector geometry, flow compressibility, major flow losses, and forward speed. An attempt was done to estimate influence of nonuniform velocity profile at the secondary entrance. Minimal mixing chamber length required for complete mixing of the primary and secondary flows was also estimated.

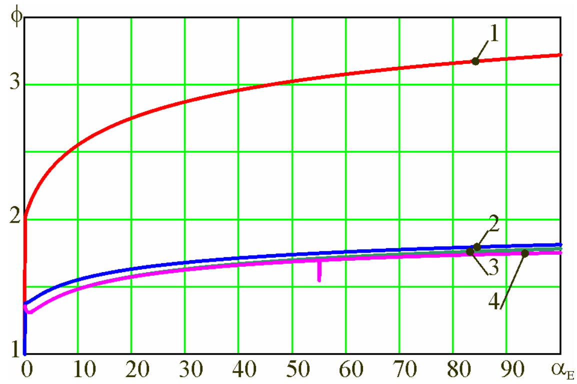


Fig. 2. Thrust augmentation ratios according to [40]: 1 – Ideal; 2 – Accounting losses; 3 – Accounting compressibility; 4 – Accounting entrance irregularity

In 1974, P. M. Bevilaqua [10] proposed flat hypermixing nozzle to increase the rate of jet mixing and improve ejector performance for V/STOL aircraft. It was stressed that, thrust augmentation ratio of short ejector can be increased by better mixing (hypermixing or introducing streamwise vorticity into the jet), even at the expense of some reduction in nozzle efficiency.

In 1975, H. Viets [41] gave a review of some thrust augmenting ejector concepts that have been tested, including the hypermixing nozzle and several unsteady flow ejector designs. In 1977, H. Viets [42] concluded that the efficiency of energy transfer can be improved if the flows are accelerated so that, the velocity difference between them, at collision, is minimized, which is provided by the ejector shroud (which lowers the static pressure within the mixing region and thereby accelerates the ambient air into the device). In 1978, K. S. Nagaraja gave an overview of ejector technology [43]. He noted that, augmentations (which correspond to high inlet area ratios in single-stage ejector) can be achieved in the two-stage ejector with smaller inlet area ratios. In 1979, J. L. Porter et al. [7] considered an ejector as consisting of four distinct components (primary nozzle, secondary inlet, interaction section, and exhaust diffuser) and gave a lot of useful recommendations as for their designing. In 1981, J. L. Porter et al. [44] presented an overview of ejector theory, and mentioned that, the theoretical predictions based on the control volume approach could be improved by introducing corrective terms (taken from experiments) to characterize losses such as skin friction, flow skewness, etc., but they were always configuration-dependent. The physical phenomena approach also required lots of assumptions, which were necessary to close the system of equations, but some of them were empirical and sometimes contradictive. In 1981, K. S. Nagaraja [5] presented an analysis of the relative effects of mixing and expansion on the ejector flow. In 1981, M. Alperin et al. [45, 46, 47] presented analysis of thrust augmenting ejectors taking into account fluid compressibility and assuming complete mixing in a chamber of constant cross-section. There exist two solutions to the equations representing the conservation laws of mass flow and energy as well as the momentum theorem. In 1988, W. M. Presz et al. [48] presented a similarity principle, which allowed to infer the performance of exhaust systems from model testing conducted with uniform stagnation temperatures.

In 1991, W. M. Presz [49] theoretically proved that the ejector system thrust is equal to the lip suction force occurring on the secondary flow inlet, and next that the ejector pumping is independent of the pressure ratio of the primary flow.

In 2010, W. H. Heiser [20] considered unsteady ejector nozzles application for pulse detonation engines and presented formulas for thrust augmentation and entrainment ratio. Unfortunately, these formulas were not provided with any derivation or reference.

## 4. Analysis of Experimental Researches

It is assumed that the earliest experimental studies of ejector nozzles were described in 1932 by E. N. Jacobs et al. [25], who presented the results of tests of annular guides surrounding the jet for use as thrust augmenters. The purpose was to transmit available kinetic energy to the surrounding air to reduce the velocity and increase the momentum of the jet. The Melot type augmenter (four-stage ejector) and two versions of Venturi tubes (with and without the divergent cone) were used in stationary conditions with compressed air at ordinary temperature to estimate the feasibility of jet thrust augmentation. The Melot type augmenter gave the highest thrust among them. The authors concluded that, while the small augmenters had some beneficial effect, the greatest part of the thrust increase is obtained from the Venturi tube action of the diverging cone. It was stressed that the maximum thrust of the Melot type augmenter was at lower primary pressure than for other versions.

In 1942, E. J. Manganiello [50] presented results of experimental researches of suitability of ejectors actuated by the exhaust gases of an air-cooled aircraft radial piston engine to provide air cooling of the engine in the ground conditions.

Starting from 1950$^{th}$, NACA/NASA began conducting systematic experimental studies of ejector nozzles. There are NACA/NASA reports devoted to conical ejectors [51, 52, 53, 54, 55, 56, 57, 58], cylindrical ejectors [35, 59, 60, 57, 61, 62, 63, 2], double-shroud ejectors [64, 65], and divergent ejectors of low divergence angles [56, 66, 67], and also to ejector nozzles with movable shroud flaps [68, 69, 70, 71] or tertiary air flaps [72, 73]. In addition, various ejector configurations have been investigated with external flow [74, 75, 76, 77, 68, 69, 72, 73, 78, 79].

In 1970, in the Internal Aerodynamic Manual [80] experimental data from some NACA reports were consolidated. Some kinds of operation instability of ejector nozzles (high area ratio separation buffeting, low area ratio vibration, subsonic jet acoustic oscillation etc.) and their solutions were reported in the manual.

In 1970$^{th}$, great deal of work was done on ejector nozzles for VTOL aircraft, which used Coanda effect [6, 81, 82]. Since 1980$^{th}$, researches started of forced mixers application to ejector nozzles [11, 4, 83, 84, 9, 85, 86, 87, 88, 49, 8, 89] and 2D ejector nozzles [90, 86, 87, 88, 49, 8].

In 1990, L. Stitt [91] gave an extended outlook on the supersonic nozzle designing from 1950 to 1985. The author made some conclusions: 1) to decrease ejector thrust losses, it is desirable to make rounded shoulder (throat); 2) to reduce boattail drag at high subsonic speeds (increase its critical Mach number), it is desirable to use radius (more than 2.5 diameters of the nacelle) in boattail juncture with cylindrical portion of the nacelle.

In 1999, J. Der [92] proposed to redefine the spacing ratio as a ratio of distance between the trailing edge of the primary nozzle and the end of the ejector shroud to the flow gap between the primary nozzle and the ejector shroud (instead of the distance related to the primary nozzle diameter). It makes graphs for free-mixing layer attachment independent on the ejector area ratio. New coordinates were also proposed for experimental mass flow ratio charts, which made the chocked and unchocked secondary flow regions more visible.

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Since 1990th, investigations started devoted to thrust vectoring ejector nozzles [93]. Since 2010th, investigations began of multi-stage ejectors [94] and ejector applications for pulse detonation engine [20, 95].

## 5. Analysis of Theoretical Researches Using Enhanced Models

In 1942, J. A. Goff et al. [96] made the first attempt to consider the ejector in 2D formulation; although rational structure was not found yet, the results obtained gave direction to the following researches. In 1950, D. R. Chapman [97] presented 2D theory of laminar mixing of a compressible fluid, which allowed calculating of velocity profile for laminar mixing.

Most of the early analytical efforts to analyze ejector nozzles were based on the 1D concepts [35, 61, 39]. In these studies, 1D isentropic relations were applied to both the primary and secondary flows which were considered to coexist within a cylindrical shroud and allowed to have different average pressures. Realizing that such a treatment has limitations, later analyses constructed the primary flow using the method of characteristics, while assuming 1D isentropic flow for the secondary stream [98, 99, 100]. In spite of these refinements, these analyses did not accurately predict the performance of many ejector nozzles of particular design, because they did not account for typical physical phenomena, which occur within ejector nozzles [101].

In 1964, W. L. Chow et al. [99] considered the primary flow by using the method of characteristics, while 1D isentropic theory was used for the secondary stream. In this model, the dissipative effects of the mixing process were not treated as an interaction problem, but rather superimposed on the inviscid jet boundary in the classical boundary-layer approach. In 1965, P. G. Hill [102] presented 2D computational prediction of the mean velocity field of incompressible turbulent jets immersed in secondary streams confined by constant area ducts. The author used jet self-preservation hypothesis for calculation of the mean velocity field of jets surrounded by constant-velocity streams by free-jet data. In 1966, P. Payne [103] presented a 2D theoretical analysis of a jet ejector with constant pressure mixing assuming flows to be incompressible. This analysis indicates that the optimum thrust augmentation is primarily dependent on the diffuser efficiency and that augmentation ratios as high as 4.0 or more are possible with high diffuser efficiencies. This conclusion is based on an infinite secondary-to-primary mass flow ratio which cannot be achieved in practice. In 1966, H. H. Korst et al. [104] presented 2D theory of isobaric turbulent mixing of two compressible non-isoenergetic streams of identical compositions having an effective turbulent Prandtl number of unity based on the continuity and momentum integral methods. In 1967, P. G. Hill [105] presented 2D model to predict the mean velocity field of incompressible turbulent jets immersed in secondary streams in a C-D axisymmetric tube.

In 1972, B. H. Anderson [101] presented computer program, which incorporates several phenomena not previously considered (non-uniformity of primary nozzle inlet flow conditions (spacious sonic line); compressible flow through chocked conical nozzle; streamwise variation in the mixing process) influence on nozzle efficiency (ratio of nozzle thrust without free stream static pressure multiplied by nozzle exit area to sum of the ideal thrusts of the primary and secondary flows) and total pressure ratio. In 1974, B. H. Anderson [106] presented analytical procedure for computing the performance and flow-field characteristics of supersonic ejector nozzles. This 2D theory included the effect of above-mentioned phenomena. In 1974, B. H. Anderson [107] presented results of computational investigations of interrelation between various supersonic ejector nozzle design parameters (primary nozzle lip angle, shroud throat spacing ratio, shroud shoulder (throat) diameter ratio, shroud (exit) diameter ratio) and performance using in-house software [106]. The author stressed two factors that strongly influenced nozzle performance: the primary nozzle inlet flow field and the mixing process between the primary and secondary flow fields.

B. H. Anderson [107] also noted that a continuing problem in the development of exhaust nozzle systems is the large number of design parameters, which the engineer must consider in order to optimize an ejector nozzle (such as: area ratio, length ratio, shroud geometry, shroud shoulder diameter ratio, spacing ratio, primary nozzle geometry, weight flow ratio, temperature ratio, Reynolds number, and so forth).

In 1986, D. Brooke et al. [108] presented an equivalent area developing method for 2D C-D exhaust nozzles with varied ejector flow, using an existing axisymmetric ejector nozzle prediction program.

## 6. Analysis of Researches Based on CFD Models

As authors of publication [17] noted, despite usefulness and the remarkable progress, which 1D models provided for the general understanding of ejector operation, these kinds of studies were unable to reproduce all the flow motion physics inside an ejector (interactions between shocks and boundary layer, vortex generation, mixing and compression rate), that will allow a more reliable and accurate appointing of geometry and parameters of ejector operation. A way of achieving this objective at a reasonable cost is CFD.

In 1978, W. L. Rushmore et al. [109] presented 3D finite element computer code to analyze ejector (for VTOL aircraft) and mixers (for turbofans). Good agreement of computer calculation results with experimental data was reported.

In 1992, J. DeBonis [110] presented results of CFD analysis of rectangular mixer/ejector nozzle for supersonic transport aircraft with the purpose of noise suppression at takeoff mode (M=0.27). The author considered two mixing sections: constant area and diverging and stressed that, the most important attribute of a mixer/ejector nozzle is its mixing effectiveness.

In 2004, E. Jason [111] proposed a calculation method for rocket engine inside cylindrical shroud. It was concluded that, the ejector with single primary flow did not provide desired transfer of kinetic energy from the rocket exhaust to the air stream, but rather transferred the kinetic energy to turbulent energy (thus it showed no significant mixing between the two streams and the decrease in total pressure within the air stream). Two combinations of annular and central jets (50/50 and 75/25) were considered and found that, they improved the mixing process. In 2007, Y.-H. Liu [112] presented results of numerical research of 12-lobed exhauster-ejector mixer (to improve its pumping performance). The highest entrainment ratio appears when the primary flow properly attaches the inner wall of the mixer.

In 2010, S. Khalid et al. [21] considered mechanism responsible for secondary flow entrainment and thrust augmentation of a cylindrical shroud ejector of subsonic mixed flow turbofan using 2D axi-symmetric CFD analysis. In 2011, D. Thirumurthy et al. [113] presented results of CFD investigation of ejector nozzle with chevrons and clamshells for supersonic cruise aircraft. To remove the separation and recirculation zones on the inner surface of the clamshells, the authors used chevrons, which generated streamwise vortexes, promoted mixing and outward spreading and attaching of the shear layer to the inner surface of the clamshells. In 2015, T. Luginsland [114] (for the first time in compressible statement) investigated the role of the nozzle-wall thickness and the nozzle length on the vortex breakdown on swirling-jet flows of a rotating nozzle. In 2019, Z. Hoter et al. [115] presented results of numerical study of a one-sided flat mixer ejector nozzle. The authors varied ejector inlet gap height, ejector flap leading edge radius, streamwise throat location and mixing tabs with the purpose to provide enough thrust during takeoff.

In 2020, Z. Dong et al. [116] considered ejector mode of rocket-based combined-cycle engine operation. The authors numerically investigated the effects of the rectangular cross-section mixer geometrical parameters on the flow structures and mixing characteristics in the converging-diverging mixing duct under no backpressure condition. In 2020, H. Huang et al. [117] considered integrated ejector nozzle with tertiary door under zero flight Mach number and low nozzle pressure ratio (0.9…2.1) using CFD analysis. In 2021, H. Li et al. [118] defined and compared modes of the over-expanded, fully expanded and under-expanded states for a steam ejector using the CFD method. The states influence on mass flow rate and entrainment ratio were analyzed. In 2022, Z. Li et al. [119] considered flat ejector nozzle with tertiary door in full-open and open-close position under transonic Mach number (M=1.2) using CFD analysis. It was concluded that full-open valve configuration generated greater thrust due to greater additional (tertiary plus secondary) flow and due to less losses for vortex formation. In 2023, Z. Li et al. [120] considered the same nozzle and noted that the airflow in such ejector nozzle had the phenomenon of lateral flow, forming a vortex ring, which sizes gradually decrease along the flow direction. In 2023, Z. Li et al. [121] considered four versions of tertiary air inlets (having sector angle 30°, 22.5°, 18°, and 15°) for the same nozzle. As a result of CFD simulation, the authors discovered that the first of them gives the biggest thrust (by 0.5 %), significant lateral flow and multi-pair vortexes, which promote more exchange and transfer of gas energy in the nozzle.

In 2024, F. C. Nwoye et al. [15] presented results of investigation of the shear layer interaction, mixing, and entrainment behavior of an ejector design for the different streamlined shapes of the nozzle. The authors considered four different circular primary nozzles and got almost identical poor mixing. In 2024, A. Vinz et al. [122] presented results of CFD research of boundary layer ingestion engine integration concept. It was discovered about 5.3 % decrease in required shaft power due to embedding comparing with conventional underwing turbofan arrangement. In 2024, Y. He et al. [29] considered numerical simulation of axisymmetric ejector nozzle integrated with the afterbody of an aircraft, using axisymmetric 2D-model at a Mach number of 1.05. It was stressed that factors, which have the most significant influence on the aerodynamic performance of the ejector nozzle, are ejector nozzle throat area ratio to primary nozzle exit area and the ejector nozzle outlet area ratio to the primary nozzle area.

In 2025, S. A. I. Bellary et al. [123] presented results of CFD investigation of a shock train contained within a C-D nozzle duct, with the purpose to isolate the shock wave inside it, so that fuel injection can be done at a supersonic Mach number. In 2025, G. Scarlatella et al. [124] presented results of CFD analysis of advanced reverse-propulsion nozzle conceptsfor vertical take-off and vertical landing reusable launch vehicles, with the aim to evaluate altitude compensation in subsonic counter-flows.

## 7. Analysis of Ejector Nozzles for Micro-Turbojets

In 2010, Y. Shan et al. [125] presented results of experimental and CFD researches of ejector nozzle with

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12-lobed mixer for micro turbojet engine. The authors reported about optimum lobe expansion angles (8.5°…13°), which correspond to the maximum thrust augmentation (1.355…1.351). Experimental data demonstrated that the ejector with lobe mixer provides thrust augmentation of 1.299 comparing to the engine thrust without ejector.

In 2013 J. Georgi et al. [3] presented experimental characteristics of a micro-turbojet engine (having 300 N thrust) with ejector for scaled flight demonstrator having limited Mach number (0.2). The achieved thrust augmentation is at maximum less than or equal 4 %. Its optimum depends on the ejector geometry. A longer ejector resulted in a loss of thrust augmentation because of friction losses; shorter ejectors lead to incomplete mixing and thus again to a loss in thrust augmentation.

In 2019, R. Schmidt et al. [126] presented results of experimental investigation of micro-turbojet engine (180 N) with ejector nozzle. They stated the requirements for the nozzle as: ejector mass flow ratio 1…2; exhaust gas temperature <300 °C; thrust augmentation 10…15 %; reduction in SFC by 10…15 %. Two primary nozzles were investigated: a chevron nozzle and a lob-mixer nozzle with two types of secondary inlets (having large and small gaps). The ejector nozzle with chevron primary nozzle and large gap demonstrated substantial flow irregularity, 4.5 % greater thrust and 5 % lower SFC than the chevron nozzle without ejector. The ejector nozzle with chevron primary nozzle and small gap demonstrated substantial flow irregularity and no thrust or SFC difference comparing to the chevron nozzle without ejector. The ejector nozzle with primary lob mixer nozzle demonstrated better temperature and velocity equalization and 4 % greater thrust at design point. In the same time an engine throttling was detected (only 99 % of maximum rpm was reached), which resulted in SFC increase. The authors concluded that small gap caused more losses in the secondary air inlet; and the lob mixer nozzle can increase the pumping of secondary air through better mixing ability and improved design. The authors also stressed that, significant thrust augmentation is only possible at take-off and low air speed conditions.

In 2021, R. Schmidt et al. [30] presented results of numerical and experimental investigations of mixer application in an ejector nozzle of micro-turbojet for UAVs. The authors note that the lobe mixer nozzle and especially scalloped lobe mixer nozzle achieved higher mixing speeds. But thrust augmentation of these nozzles (9.0 % and 6.5 %) is rather low. Some mixer parameters influence on mixing ability was analyzed. It was found that the mixer cutback angle (varied from 0° to 15°) has minor impact. Increase in the number of lobes resulted in better mixing, but increase in surface area and in friction losses reduced thrust (by 1 % between 6 and 12 lobes). Contoured inner cone did not improve the mixing.

In 2022, R. Schmidt et al. [1] presented results of CFD and experimental investigation of ejector nozzle of micro-turbojet (180 N) for UAV. Some primary nozzles were considered (classic nozzle, 8-, 10-, 12-lobe mixer nozzles and scalloped 8-lobe mixer nozzle). The authors reported that, the maximum thrust augmentation 1.11 was reached for 8-lobe mixer nozzle. High thrust augmentation could be achieved despite a deterioration in the degree of mixing. The mesh influence study showed an increasingly unstable behavior in the convergence of the solution while lowering the element size, at some element sizes, a strong oscillation of the mass flow occurred. The comparison with experiments showed high deviations between the simulation and the measurement results. The simulation assumed uniform inflow conditions. In reality, the inflow conditions into the primary nozzle had strong gradients in the radial and circumferential directions.

In 2023 G. Cican et al. [28] considered ejector integrated with Jet Cat P80 micro-turbojet engine for low subsonic speeds. Results of 3D simulations to get optimal ejector geometry from the condition of maximum thrust showed that, due to the ejector application, the thrust increased (by 2…7 %), and the specific fuel consumption decreased (by 5…12 %) depending on regimes.

In 2025, A. Bogoi et al. [127] presented results of experimental comparative study of noise control in micro-turbojet engines with chevron and circular ejector nozzles. It was noted that chevrons promote higher mixing rates and smaller vortices, generate smaller, controlled vortices near the nozzle, which improve mixing and reduce noise.

## Conclusions

1. Specificity of power plants for UAV defines special requirements, which are made to their thrust in various conditions of practical application.

2. One of the known methods of aviation jet engine thrust increase is based on application of ejector nozzles.

3. Ejectors are also used in multitude of other fields of engineering.

4. This problem was studied by analytical methods, 1D, 2D and 3D numerical simulation methods, as well as by experimental methods, and the results were published in numerous papers.

5. However, results presented in the literature are often contradictory (thus, there is a big divergence between the theoretical estimations of thrust augmentation ratio for low speeds (near 4.0) and its experimental values (below 1.1)). It is caused by presence of great number of factors, influencing on the flow interaction within

an ejector and, particularly, on the thrust generation; consequently, theoretical investigations are based on different initial assumptions and leaded to different results.

6. The review showed that one of the major processes, influencing ejector nozzle thrust, is the flow mixing.

7. Within considered sources, it was not succeeded to find any logically expounded designing method of thrust augmenting ejectors for UAV turbojets. Thus, development of this method is an urgent problem.

8. To reach the stated goal, it is necessary to solve the following problems:

– Develop mathematical model of UAV's power plant with turbojet and ejector nozzle;

– Develop engineering designing method of ejector nozzle for micro-turbojet;

– Verify this method in an existing engine.

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The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, author ship or otherwise, that could affect the research and its results presented in this paper.

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The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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## References

1. Schmidt, R., Hupfer, A., & Gümmer, V. Experimental and Numerical Investigation of Mixer Ejector Nozzles for Small Turbojet Engines. *Proceeding of ISABE 2022*, Ottawa, 25-30 September, 2022, pp. 1-14. Available at: https://www.researchgate.net/publication/372288860/ISABE_2021_036_full.pdf (accessed 28.02.2025).

2. Presz, W., Reynolds, G., & Hunter, C. Thrust Augmentation with Mixer/Ejector Systems. *Proceeding of 40th AIAA Aerospace Sciences Meeting & Exhibit, Reno,* NV, 14-17 January, 2002, pp. 1-10. Available at: https://ntrs.nasa.gov/api/citations/20030003827/downloads/20030003827.pdf (accessed 30.11.2023).

3. Georgi, J., & Staudacher, S. *Characteristics Of Ejectors On Small Gas Turbine Engines*. Deutscher Luft- und Raumfahrtkongress, 2013. pp. 1-7.

4. Presz, W. M., Gousy, R. G., Morin, B. L. Forced Mixer Lobes in Ejector Designs. *Journal of Propulsion*, 1988, vol. 4, iss. 4, pp. 350-355. DOI: 10.2514/3.23073.

5. Nagaraja, K. S. Some Ejector Characteristics. *Proceeding of Aircraft Systems and Technology Conference*, *Dayton*, OH, 11-13 August 1981, pp. 1-9. DOI: 10.2514/6.1981-1679.

6. Quinn, B. Compact Ejector Thrust Augmentation. *Journal of Aircraft*, 1973. vol. 10, no. 8, pp. 481-486. DOI: 10.2514/3.60251.

7. Porter, J. L., & Squyers, R. A. *A Summary/Overview of Ejector Augmentor Theory and Performance: Phase II (Technical Report),* Volume I – Technical Discussion. *ATC Report* No. R-91100/9CR-47A, 1979. 212 p. Available at: https://apps.dtic.mil/sti/tr/pdf/ADA098620.pdf (accessed 06.01.2025).

8. Tillman, G., & Presz, W. Thrust Characteristics of a Supersonic Mixer Ejector. *Proceeding of 15th AIAA Aeroacoustics Conference*, Long Beach, 25-27 October, 1993. pp. 1-9. DOI: 10.2514/6.1993-4345.

9. Skebe, S. A., McCormick, D. C., & Presz, W. M. Parameter effects on mixer-ejector pumping performance. *Proceeding of 26th AIAA Aerospace Sciences Meeting,* Reno, 11-14 January, 1988, pp. 1-14. DOI: 10.2514/6.1988-188.

10. Bevilaqua, P. M. Evaluation of Hypermixing for Thrust Augmenting Ejectors. *Journal of Aircraft*, 1974, vol. 11, pp. 348-354. DOI: 10.2514/3.59257.

11. Presz, W. M., Gousy, R. G., & Morin, B. L. Forced Mixer Lobes in Ejector Designs. *Proceeding of 22nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, Huntsville, 16-18 June, 1986, pp. 1-10. DOI: 10.2514/6.1986-1614.

12. Povinelli, L. A., & Anderson, B. H. Investigation of Mixing in a Turbofan Exhaust Duct, Part II: Computer Code Application and Verification. *AIAA Journal,* vol. 22, iss. 4, 1984, pp. 518-525. DOI: 10.2514/3.8433.

13. Chen, W., Chong, D. Yan, J., & Liu, J. The numerical analysis of the effect of geometrical factors on natural gas ejector performance. *Applied Thermal Engineering,* 2013, vol. 59, pp. 21-29. DOI: 10.1016/j.applthermaleng.2013.04.036.

14. Sun, W., Ma, X., Zhang, Y., Jia, L., & Xue, H. Performance analysis and optimization of a steam ejector through streamlining of the primary nozzle. *Case Studies in Thermal Engineering*, 2021, vol. 27, pp. 1-13. DOI: 10.1016/J.CSITE.2021.101356.

15. Nwoye, F. C., Okoro, H., Okoronkwo, C., Nwaji, G., Nwufo, O., & Emmanuel, A. Changes in Primary Nozzle Contours and Ejector Performance — A Numerical Study. *International Journal of Advantage*

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

*Scientific Engineering*, 2024, vol. 10, no.3 pp. 3495-3507. DOI: 10.29294/IJASE.10.3.2024.3495-3507.

16. Wang, L., Yan, J., Wang, C., & Li, X. Numerical study on optimization of ejector primary nozzle geometries. *International Journal of Refrigeration*. 2017, vol. 76, pp. 219–229. DOI: 10.1016/j.ijrefrig. 2017.02.010.

17. Bartosiewicz, Y., Aidoun, Z., Desevaux, P., & Mercadier, Y. Numerical and experimental investigations on supersonic ejectors. *Int. J. Heat Fluid Flow 2005*, vol. 26, pp. 56–70.

18. Pradeep, G., Srisha, M. V. R., & Pramod, K. Numerical Analysis of Ejector Performance Near the Critical Back Pressure. *Proceeding of the 6th National Symposium on Shock Waves — IITM (NSSW-2020)*, 2020, pp. 1-6. Available at: https://www.researchgate.net/publication/344507428_Numerical_Analysis_of_Ejector_Performance_Near_the_Critical_Back_Pressure#fullTextFileContent (accessed 25.01.2025).

19. Arun, K. R., & Rajesh, G. Physics of vacuum generation in zero-secondary flow ejectors. *Physics of Fluids*. 2018, vol. 30, iss. 6, pp. 1-41. DOI: 10.1063/ 1.5030073.

20. Heiser, W. H. Ejector Thrust Augmentation. *Journal of Propulsion and Power*, 2010, vol. 26, no. 6, pp. 1325–1329. DOI: 10.2514/1.50144.

21. Khalid, S., Sokhey, J., Chakka, P., & Pierluissi, A. Ejector/Engine/Nacelle Integration for Increased Thrust minus Drag. *Proceedings of the 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, Nashville, TN, USA, 25–28 July 2010. pp. 1-11. DOI: 10.2514/6.2010-6501.

22. Mikkelsen, C. D., & Sandberg, M. R., & Addy, A. L. *Theoretical and Experimental Analysis of the Constant-Area, Supersonic-Supersonic Ejector*. University of Illinois Report UILU-ENG-76-4003, 1976. 296 p. Available at: https://apps.dtic.mil/sti/pdfs/ADA033615.pdf (accessed 25.01.2025).

23. Karthick, S. K., Rao, S. M. V., Jagadeesh, G., & Reddy, K. P. J. Parametric experimental studies on mixing characteristics within a low area ratio rectangular supersonic gaseous ejector. *Physics of Fluids*, 2016, no. 28, pp. 1-26. DOI: 10.1063/1.4954669.

24. Qubbaj, A. R. *An Experimental and Numerical Study of Gas Jet Diffusion Flames Enveloped by a Cascade of Venturis. A Dissertation of Doctor of Philosophy*. 1998. Oklahoma. 276 p. Available at: https://research-solution.com/uplode/book/book-89494.pdf?pdf (accessed 25.01.2024).

25. Jacobs, E. N., & Shoemaker, J. M. *Tests on Thrust Augmentors for Jet Propulsion: NACA TN 431*, 1932. 9 p. Available at: https://digital.library.unt.edu/ark:/67531/metadc54078/m2/1/high_res_d/19930081190.pdf (accessed 30.01.2025).

26. Jones, C. N. The Effect of Secondary Flow Velocity Profile on the Static Performance of Low Speed Ejector Thrust Augmenters. *The Aeronautical Journal*, 1975. vol. 79, article no. 779, pp. 510-517, DOI: 10.1017/S0001924000036149.

27. Karman, T. *Theoretical Remarks on Thrust Augmentation. Reissner Anniversary Volume: Contribution to Applied Mechanics*, 1st ed., W. Edwards, Ann Arbor, Michigan, 1949, pp. 461–468.

28. Cican, G., Frigioescu, T.-F., Crunteanu, D.-E., & Cristea, L. Micro Turbojet Engine Nozzle Ejector Impact on the Acoustic Emission, Thrust Force and Fuel Consumption Analysis. *Aerospace*, 2023, no.10, iss. 2, article no. 162, pp. 1-19. DOI: 10.3390/ aerospace10020162.

29. Hi, Y., Shi, X., & Ji, H. Optimal Design of Ejector Nozzle Profile with Internal and External Integrated Flow. *Aerospace*, 2024, vol. 11, iss. 184, pp. 1-17. DOI: 10.3390/aerospace11030184.

30. Schmidt, R., & Hupfer, A. Design and numerical simulation of ejector nozzles for very small turbojet engines. *CEAS Aeronautical Journal*, 2021, no. 12, pp. 923–940. DOI: 10.1007/s13272-021-00537-3.

31. Keenan, J. H., & Neumann, E. P. A simple air ejector. *ASME Journal of Applied Mechanics*, 1942, vol. 9(2), pp. 75–81. DOI: 10.1115/1.4009187.

32. Morrisson, R. *Jet Ejectors and Augmentation. NACA and Aeronautical Research Committee report ARC-6428*, 1942. 40 p. Available at: https://books.google.com.ua/books?id=9XX4xwEACAAJ (accessed 24.01.2025).

33. Sanders, J. C., & Brightwell, V. L. *Analysis of Ejector Thrust by Integration of Calculated Surface Pressures*. TN 1958 NACA, 1949. 36 p. Available at: https://ntrs.nasa.gov/api/citations/19930082636/downloads/19930082636.pdf (accessed 24.01.2025).

34. Keenan, J. H., Neumann, E. P., & Lustwerk, F. An Investigation of Ejector Design by Analysis and Experiment. *Journal of Applied Mechanics*, 1950, vol. 17, no. 3, pp. 299–309. DOI: 10.1115/1.4010131.

35. Kochendorfer, F. D., & Rousso, M. D. *Performance Characteristics of Aircraft Cooling Ejectors Having Short Cylindrical Shrouds: Research memorandum NACA RM E51E01*, 1951. 40 p. Available at: https://core.ac.uk/download/pdf/42799559.pdf (accessed 08.01.2025).

36. Kochendorfer, F. D. *Note on performance of aircraft ejector nozzles at high secondary flows: Research memorandum NASA RM E54F17a*, 1954. 21 p. Available at: https://ntrs.nasa.gov/api/citations/19930088271/downloads/19930088271.pdf. (accessed 08.01.2025).

37. Szczeniowski, B. *Theory of the Jet Syphon*. TN 3385 NACA, 1955. 50 p. Available at: https://ntrs.nasa.gov/api/citations/19930084068/downloads/19930084068.pdf (accessed 24.01.2025).

38. Reid, J. *The Effect of a Cylindrical Shroud on the Performance of a Stationary Convergent Nozzle, R. & M. No. 3320*, Aeronautical Research Council, London, Britain, January 1962.

39. Bernstein, A., Heiser, W., & Hevenor, C. *Compound-Compressible Nozzle Flow. Proceeding of 2nd Propulsion Joint Specialist Conference*, Colorado Springs. 13-17 June, 1966. pp. 1-18. DOI: 10.2514/6.1966-663.

40. Huang, K. P., & Kisielowski, E. *An Investigation of the Thrust Augmentation Characteristics of Jet Ejectors*. USAAVLABS Technical Report 67-8, 1967. 215 p. Available at: https://apps.dtic.mil/sti/tr/pdf/AD0651946.pdf (accessed 08.01.2025).

41. Viets, H. *Thrust Augmenting Ejectors: Aerospace Research Laboratories Report ARL75-0224*, 1975. 196 p. Available at: https://apps.dtic.mil/sti/tr/pdf/ADA017782.pdf. (accessed 08.01.2025).

42. Viets, H. *Thrust augmenting ejector analogy. Journal of Aircraft.* 1977. vol. 14, no. 4, pp. 409–411. DOI: 10.2514/3.44603.

43. Nagaraja, K. S. *Recent Development in Ejector Technology in the Air Force: an Overview. Proceeding of NASA Conference Publication 2093. Workshop on Thrust Augmentation Ejectors*. Dayton, 28-29 June, 1978, pp. 1-22. Available at: https://ntrs.nasa.gov/api/citations/19800001868/downloads/19800001868.pdf (accessed 25.01.2025).

44. Porter, J. L. Squyers, R. A., & Nagaraja, K. S. *An Overview of Ejector Theory. Proceeding of AIAA Aircraft Systems and Technology Conference*, Dayton, Ohio, 11-13 August, 1981, pp. 1-17. DOI: 10.2514/6.1981-1678.

45. Alperin, M., & Wu, J. J. *Thrust Augmenting Ejectors. Proceedings: Ejector Workshop for Aerospace Applications*, AFWAL-TR-82-3059, June 1982, pp. 281-330. Available at: https://apps.dtic.mil/sti/tr/pdf/ADP000513.pdf (accessed 28.02.2025).

46. Alperin, M., & Wu, J.-J. Thrust augmenting ejectors Part I. *AIAA J.*, 1983, vol. 21, iss. 10, pp. 1428–1436. DOI: 10.2514/3.60148.

47. Alperin, M., & Wu, J.-J. Thrust augmenting ejectors Part II. *AIAA J.*, 1983, vol. 21, iss. 12, pp. 1698–1706. DOI: 10.2514/3.8312.

48. Presz, W. M., & Greitzer, E. M. A Useful Similarity Principle for Jet Engine Exhaust System Performance. *Proceeding of 24nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, Boston, Massachusetts, 11-13 July, 1988, pp. 1-10. DOI: 10.2514/6.1988-3001.

49. Presz, W. M. Mixer/Ejector Noise Suppressors. *Proceeding of 27th Joint Propulsion Conference*, Sacramento, 24-26 June, 1991, pp. 1-10. DOI: 10.2514/6.1991-2243.

50. Manganiello, E. J. *A Preliminary Investigation of Exhaust-Gas Ejectors for Ground Cooling.* Wartime Report NACA ACR July 1942. 1942. 28 p. Available at: https://ntrs.nasa.gov/api/citations/19930093264/downloads/19930093264.pdf (accessed 25.01.2025).

51. Huddleston, S. C., Wilsted, H. D., & Ellis, C. W. *Performance of Several Air Ejectors with Conical Mixing Sections and Small Secondary Flow Rates: Research memorandum NACA RM E8D23*, 1948. 76 p. Available at: https://ntrs.nasa.gov/api/citations/19930085446/downloads/19930085446.pdf (accessed 28.02.2025).

52. Ellis, C. W., Hollister, D. P., & Sargent, A. F. *Preliminary Investigation of Cooling-Air Ejector Performance at Pressure Ratios from 1 to 10: Research memorandum NACA RM E51H21*, 1951. 23 p. Available at: https://ntrs.nasa.gov/api/citations/19930086851/downloads/19930086851.pdf (accessed 28.02.2025).

53. Lewis, E., Wallner, & Emmert, T. *Jansen Full-Scale Investigation of Cooling Shroud and Ejector Nozzle for a Turbojet Engine – Afterburner Installation: Research memorandum NASA RM E51J04*, 1951. 43 p. Available at: https://ntrs.nasa.gov/api/citations/19930088192/downloads/19930088192.pdf (accessed 24.12.2024).

54. Greathouse, W. K., & Hollister, D. P. *Preliminary Air-Flow and Thrust Calibrations of Several Conical Cooling-Air Ejectors with a Primary to Secondary Temperature Ratio of 1.0. 1 – Diameter Ratios of 1.21 and 1.10. Research memorandum NACA RM E52E21*, 1952. 26 p. Available at: https://ntrs.nasa.gov/api/citations/19930087173/downloads/19930087173.pdf |(accessed 25.01.2025).

55. Greathouse, W. K., & Hollister, D. P. *Preliminary Air-Flow and Thrust Calibrations of Several Conical Cooling-Air Ejectors with a Primary to Secondary Temperature Ratio of 1.0. I1 – Diameter Ratios of 1.06 and 1.40. Research memorandum NACA RM E52F26*, 1952. 37 p. Available at: https://ntrs.nasa.gov/api/citations/20040040338/downloads/20040040338.pdf (accessed 25.01.2025).

56. Huntley, S. C., & Yanowitz, H. *Pumping and Thrust Characteristics of Several Divergent Cooling-Air Ejectors and Comparison of Performance with Conical and Cylindrical Ejectors: NACA RM E53J13*, 1954. 45 p. Available at: https://ntrs.nasa.gov/api/citations/19930088256/downloads/19930088256.pdf (accessed 28.02.2025).

57. Greathouse, W. K. *Preliminary Investigation of Pumping and Thrust Characteristics of Full-Size Cooling-Air Ejectors at Several Exhaust-Gas Temperatures. Research memorandum NACA RM E54A18*, 1954. 131 p. Available at: https://ntrs.nasa.gov/api/citations/19930088138/downloads/19930088138.pdf (accessed 25.01.2025).

58. Ciepluch, C. C., & Fenn, D. B. *Experimental data for four full-scale conical cooling-air ejectors: Research memorandum NASA RM E54F02*, 1954. 42 p. Available at: https://ntrs.nasa.gov/api/citations/19930088192/downloads/19930088192.pdf. (accessed 08.01.2025).

59. Greathouse, W. K., & Hollister, D. P. *Air-Flow and Thrust Characteristics of Several Cylindrical Cooling-Air Ejectors with a Primary to Secondary Temperature Ratio of 1.0. Research memorandum NACA RM E52L24*, 1953. 83 p. Available at: https://ntrs.nasa.gov/api/citations/19930087598/downloads/19930087598.pdf (accessed 25.01.2025).

60. Kochendorfer, F. D. *Effect of Properties of Primary Fluid on Performance of Cylindrical Shroud Ejectors: Research memorandum NACA RM E53L24a*, 1954. 33 p. Available at: https://ntrs.nasa.gov/api/citations/19930088053/downloads/19930088053.pdf (accessed 28.02.2025).

61. Fabri, J., & Paulon, J. *Theory and Experiments on Supersonic Air-to-Air Ejectors. Technical memoran-*

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

*dum NACA TM-1410*, 1958. 31 p. Available at: https://ntrs.nasa.gov/api/citations/19930090911/downloads/19930090911.pdf (accessed 08.01.2025).

62. Reid, J. *An Experiment on Aerodynamic Nozzles at M=2. Aeronautical Research Council Reports and Memoranda No. 3382*, 1964. 39 p. Available at: https://reports.aerade.cranfield.ac.uk/bitstream/handle/1826.2/3963/arc-rm-3382.pdf?sequence=1&isAllowed=y (accessed 25.01.2025).

63. Samanich, N. E., & Huntley, S. C. *Thrust and Pumping Characteristics of Cylindrical Ejectors Using Afterburning Turbojet Gas Generator: NASA TM X-52565*, 1969. 94 p. Available at: https://ntrs.nasa.gov/api/citations/19730023889/downloads/19730023889.pdf (accessed 28.02.25).

64. Ellis, C. W., Hollister, D. P., & Wilsted, H. D. *Investigation of Performance of Several Double-Shroud Ejectors and Effect of Variable-Area Exhaust Nozzle on Ejector Performance: Research memorandum NACA RM E52D25*, 1952. 28 p. Available at: https://ntrs.nasa.gov/api/citations/19930086983/downloads/19930086983.pdf (accessed 28.02.2025).

65. Reshotko, E. *Performance Characteristics of a Double-Cylindrical-Shroud Ejector Nozzle: Research memorandum NACA RM E53H28*, 1953. 59 p. Available at: https://ntrs.nasa.gov/api/citations/19930088057/downloads/19930088057.pdf (accessed 28.02.2025).

66. Greathouse, W. K., & Beale, W. T. *Performance Characteristics of Several Divergent-Shroud Aircraft Ejectors: Research memorandum NASA RM E55G21a*, 1955. 46 p. Available at: https://ntrs.nasa.gov/api/citations/19930088874/downloads/19930088874.pdf (accessed 08.01.2025).

67. Shillito, T. B., Hearth, D. P., Edgar, M., & Cortright, J. *Exhaust Nozzles for Supersonic Flight with Turbojet Engines, Research memorandum NACA RM E56A18*, 1956. 19 p. Available at: https://ntrs.nasa.gov/api/citations/20090024829/downloads/20090024829.pdf (accessed 08.01.2025).

68. Beke, A., & Simon, P. C. *Thrust and Drag Characteristics of Simulated Variable-Shroud Nozzles with Hot and Cold Primary Flows at Subsonic and Supersonic Speeds: Research memorandum NACA RM E54J26*, 1955. 31 p. Available at: https://ntrs.nasa.gov/api/citations/19930088467/downloads/19930088467.pdf (accessed 28.02.2025).

69. Stitt, L. E., & Valerino, A. S. *Effect of Free-Stream Mach Number on Gross-Foroe and Pumping Characteristics of Several Ejectors. Research memorandum NACA RM E54K23a*, 1955. 38 p. Available at: https://ntrs.nasa.gov/api/citations/19930088528/downloads/19930088528.pdf (accessed 25.01.2025).

70. Steffen, F. W., & Jones, J. R. *Performance of a Wind Tunnel Model of an Aerodynamically Positioned Variable Flap Ejector at Mach Numbers From 0 to 2.0. NASA TM X-1639*, 1968. 38 p. Available at: https://ntrs.nasa.gov/api/citations/19680021127/downloads/19680021127.pdf (accessed 28.02.25).

71. Shrewsbury, G. D., & Jones, J. R. *Static Performance of an Auxiliary Inlet Ejector Nozzle for Supersonic Cruise Aircraft: NASA TM X-1653*, 1968. 42 p. Available at: https://ntrs.nasa.gov/api/citations/19680026292/downloads/19680026292.pdf (accessed 28.02.25).

72. Bresnahan, D. L. *Performance of an Aerodynamically Positioned Auxiliary Inlet Ejector Nozzle at Mach Numbers From 0 to 2.0. NASA TM X-2023*, 1970. 51 p. Available at: https://ntrs.nasa.gov/api/citations/19700018654/downloads/19700018654.pdf (accessed 28.02.25).

73. Samanich, N. E., & Burley, R. R. *Flight Performance of Auxiliary Inlet Ejector and Plug Nozzle at Transonic Speeds. Technical Paper NASA TM-52784*, 1970. 15 p. Available at: https://ntrs.nasa.gov/api/citations/19700016380/downloads/19700016380.pdf (accessed 28.02.2025).

74. Allen, J. L. *Pumping Characteristics for Several Simulated Variable-Geometry Ejectors with Hot and Cold Primary Flow: Research memorandum NACA RM E54G15*, 1954. 26 p. Available at: https://ntrs.nasa.gov/api/citations/19630002650/downloads/19630002650.pdf (accessed 28.02.2025).

75. Vargo, D. J. *Effects of Secondary-Air Flow on Annular Base Force of a Supersonic Airplane: Research memorandum NACA RM E54G28*, 1954. 31 p. Available at: https://ntrs.nasa.gov/api/citations/19630002649/downloads/19630002649.pdf (accessed 28.02.2025).

76. Hearth, D. P., & Valerino, A. S. *Thrust and Pumping Characteristics of a Series of Ejector-Type Exhaust Nozzles at Subsonic and Supersonic Flight Speeds. Research memorandum NACA RM E54H19*, 1954. 37 p. Available at: https://ntrs.nasa.gov/api/citations/19630002630/downloads/19630002630.pdf (accessed 25.01.2025).

77. Salmi, R. J. *Experimental Investigation of Drag of Afterbodies with Exiting Jet at High Subsonic Mach Numbers. Research memorandum NACA RM E54I13*, 1954. 30 p. Available at: https://ntrs.nasa.gov/api/citations/19930088483/downloads/19930088483.pdf (accessed 25.01.2025).

78. Bernal, L., & Sarohia, V. *Entrainment and Mixing in Thrust Augmenting Ejectors. Interim Report AFOSR-TR-1008*. 1982. 102 p. Available at: https://apps.dtic.mil/sti/tr/pdf/ADA121637.pdf (accessed 25.01.2025).

79. Bernal, L., & Sarohia, V. *An Experimental Investigation of Two-Dimensional Thrust Augmenting Ejectors. Final Report, Part I. AFOSR-TR-85-0371*, 1984. 104 p. Available at: https://apps.dtic.mil/sti/tr/pdf/ADA154104.pdf (accessed 25.01.2025).

80. *Internal Aerodynamic Manual. Handbook prepared for Naval Air Systems Command. North American Rockwell Corporation. Columbus*. 1970. 516 p. Available at: https://apps.dtic.mil/sti/tr/pdf/AD0723823.pdf (accessed 25.01.2025).

81. Alperin, M., & Wu, J. J. *End Wall and Corner Flow Improvements ot the Rectangular Alperin Jet-Diffuser Ejector*. Flight Dynamics Research Corpora-

tion, Naval Air Development Center, NADC-77050, 1978. 79 p. Available at: https://apps.dtic.mil/sti/pdfs/ADA057663.pdf (accessed 28.02.2025).

82. Alperin, M., & Wu, J. J. *Recent Development of a Jet-Diffuser Ejector. Journal of Aircraft*, 1981, vol. 18, pp. 1011-1018. DOI: 10.2514/3.57594.

83. Werle, M. J., Paterson, R. W., & Presz, W. M. Flow Structure in a Periodic Axial Vortex Array. *Proceeding of 25th Aerospace Sciences Meeting*, Nevada, 12-15 January, 1987, pp. 1-9. DOI: 10.2514/6.1987-610.

84. Presz, W. M., Blinn, R. F., & Morin, B. L. Short Efficient Ejector Systems. *Proceeding of 23rd AIAA/SAE/ASME/ASEE Joint Propulsion Conference*, San Diego, 29 June-2 July, 1987, pp. 1-9. DOI: 10.2514/6.1987-1837.

85. Tillman, T. G., Patrick, W. P., & Paterson, R. W. Enhanced Mixing of Supersonic Jets. *Proceeding of 24th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, Boston, Massachsetts, 11-13 July, 1988, pp. 1006-1014. DOI: 10.2514/3.23420.

86. Tillman, T. G., & Paterson, R. W. Supersonic Nozzle Mixer Ejector. *Proceeding of 25th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, Monterey, CA, 10-11 July, 1989, pp. 1-9. DOI: 10.2514/6.1989-2925.

87. Tillman, T. G., Paterson, R. W., & Presz, W. M. Supersonic Nozzle Mixer Ejector. *AIAA Journal of Propulsion and Power*, vol. 8, no. 2, 1992, pp. 513-519. DOI: 10.2514/3.23506.

88. Lord, W. K., Jones, C. W., Stern, A. M., Head, V. L., & Krejsa, E. A. Mixer ejector nozzles for jet noise suppression. *Proceeding of 26th AIAA/SAE/ASME/ASEE Joint Propulsion Conference*, Orlando, 16-18 July, 2002, pp. 1–19. DOI: 10.2514/6.1990-1909.

89. Presz, W. M., Reynolds, G., & McCormick, D. Thrust augmentation using mixer-ejector-diffuser systems. *Proceeding of 32th Aerospace Sciences Meeting & Exhibit*, *Reno*, 10-13 January, 1994, pp. 1–10. DOI: 10.2514/6.1994-20.

90. Federspiel, J. E., & Kuchar, A. P. *Performance Evaluation of a Two Dimensional Convergent-Divergent Ejector Exhaust System*, 1988. pp. 1-10. DOI: 10.2514/6.1988-2999.

91. Stitt, L. E. *Exhaust Nozzles for Propulsion Systems with Emphasis on Supersonic Cruise Aircraft. NASA Reference Publication 1235*, 1990. 107 p. Available at: https://ntrs.nasa.gov/api/citations/19900011721/downloads/19900011721.pdf (accessed 08.01.2025).

92. Der, J. Improved methods of characterizing ejector pumping performance. *Journal of Propulsion Power*, 1991, vol. 7, no. 3, pp. 412–419. DOI: 10.2514/3.23342.

93. Lamb, M. *Internal Performance Characteristics of Thrust-Vectored Axisymmetric Ejector Nozzles: NASA Technical Memorandum NASA-TM-4610*, 1998. 232 p. Available at: https://ntrs.nasa.gov/api/citations/19950018918/downloads/19950018918.pdf (accessed 08.01.2025).

94. Presz, Jr. W., & Werle, M. *Multi-stage mixer/ejector systems. Proceeding of 38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Indianapolis*, 2002, pp. 1-11. DOI: 10.2514/6.2002-4064.

95. Huang, X-Q., Lia, M., Guo, Z., & Zheng, L. Experimental Investigation of Thrust Augmentation by Ejectors on a Pulse Detonation Engine. *Thermal Science*, 2015, vol. 19, no. 6, pp. 2105-2114. DOI: 10.2298/TSCI140712066H.

96. Goff, J. A., & Coogan, C. H. Some two-dimensional aspects of the ejector problem. *Journal of Applied Mechanics*, 1942, vol. 9, no. 4, pp. 151-154. DOI: 10.1115/1.4009223.

97. Chapman, D. R. *Laminar Mixing of a Compressible Fluid. NACA Report 958*, 1950. 7 p. Available at: https://ntrs.nasa.gov/api/citations/19930092022/downloads/19930092022.pdf (accessed 28.02.2025).

98. Messing, W. E., & Acker, L. W. *Transonic Free-Flight Drag Results of Full-Scale Models of 16-Inch-Diameter Ram-Jet Engines. Research memorandum NACA RM E52B19*, 1952. 18 p. Available at: https://ntrs.nasa.gov/api/citations/19930090446/downloads/19930090446.pdf (accessed 28.02.2025).

99. Chow, W. L., & Addy, A. L. *Interaction Between Primary and Secondary Streams of Supersonic Ejector Systems and Their Performance Characteristics. AIAA Journal*, 1964, vol. 2, no. 4, pp. 686-695. DOI: 10.2514/3.2403.

100. *Supersonic Ejectors. AGARDograph No. 163* Edited by J. J. Ginoux. Von Karman Institute for Fluid Dynamics. London, 1972. 202 p. Available at: https://www.sto.nato.int/publications/AGARD/AGARD-AG-163/AGARD-AG-163.pdf. (accessed 08.01.2025).

101. Anderson, B. H. *Factors Which Influence the Analysis and Design of Ejector Nozzles. Technical Memorandum NASA TM X-67976*, 1972. 11 p. Available at: https://ntrs.nasa.gov/api/citations/19720006652/downloads/19720006652.pdf (accessed 25.01.2025).

102. Hill, P. G. *Turbulent Jets in Ducted Streams. Journal of Fluid Mechanics*, 1965, vol. 22, iss. 1, pp. 161-186. DOI: 10.1017/S0022112065000654.

103. Payne, P. R. *Steady-State Thrust Augmentors and Jet Pumps. USAAVLABS Technical Report 66-18*, 1966. 134 p. Available at: https://apps.dtic.mil/sti/tr/pdf/AD0632126.pdf (accessed 24.01.2025).

104. Korst, H. H., & Chow, W. L. *Non-Isoenergetic Turbulent ($P_{rt}$ = 1) Jet Mixing Between Two Compressible Streams at Constant Pressure*. NASA CR-419, 1966. 169 p. Available at: https://ntrs.nasa.gov/api/citations/19660013617/downloads/19660013617.pdf (accessed 28.02.2025).

105. Hill, P. G. *Incompressible Jet Mixing in Converging-Diverging Axisymmetric Ducts. Journal of Basic Engineering*, 1967, vol. 89, iss. 1, pp. 210-220. DOI: 10.1115/1.3609555.

106. Anderson, B. H. *Computer Program for Calculating the Flow Field of Supersonic Ejector Nozzles. Technical Note NACA TN-D-7601*, 1974. 90 p. Available at: https://ntrs.nasa.gov/api/citations/19740012321/downloads/19740012321.pdf (accessed 28.02.2025).

107. Anderson, B. H. *Assessment of an Analytical Procedure for Predicting Supersonic Ejector Nozzle Performance. Technical Note NACA TN-D-7601*, 1974. 51 p. Available at: https://ntrs.nasa.gov/api/citations/19740013281/downloads/19740013281.pdf (accessed 28.02.2025).

108. Brooke, D., Dusa, D. J., Kuchar, A. P., & Romine, B. M. *Initial Performance Evaluation of 2DCD Ejector Exhaust Systems — Two Dimensional Convergent-Divergent*. 1986. DOI: 10.2514/6.1986-1615.

109. Rushmore, W. L., & Zelazny, S. W. *A Three Dimensional Turbulent Compressible Flow Model for Ejector and Fluted Mixers: NASA Contractor Report CR-159467*, 1978. 133 p. Available at: https://ntrs.nasa.gov/api/citations/19790006154/downloads/19790006154.pdf (accessed 28.02.2025).

110. DeBonis, J. R. *Full Navier-Stokes analysis of a two-dimensional mixer/ejector nozzle for noise suppression. NASA Technical Memorandum AIAA-92-3570*, 1992. 17 p. Available at: https://ntrs.nasa.gov/api/citations/19920017790/downloads/19920017790.pdf. (accessed 08.01.2025).

111. Jason, E. *Computational Study of Variable Area Ejector Rocket Flowfields*. 2004. 183 p. Available at: https://utoronto.scholaris.ca/server/api/core/bitstreams/00261dd6-7ba9-420d-b2d5-b54c49df6aae/content. (accessed 08.01.2025).

112. Liu, Y.-H. *Experimental and numerical research on high pumping performance mechanism of lobed exhauster-ejector mixer. International Communications in Heat and Mass Transfer*. 2007, no. 34, pp. 197–209. DOI: 10.1016/j.icheatmasstransfer.2006.10.003.

113. Thirumurthy, D., Blaisdell, A. S., Sullivan J. P., Gregory, A., Lyrintzis, L., & Gregory, A., Lyrintzis. Preliminary design and computational analysis of an ejector nozzle with chevrons. *Proceeding of 49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, Orlando, Florida, 2011, pp. 1-17. DOI: https://doi.org/10.2514/6.2011-918

114. Luginsland, T. How the nozzle geometry impacts vortex breakdown in compressible swirling-jet flows. *AIAA Journal*, 2015, vol. 53, iss. 10, pp. 1–15. DOI: 10.2514/1.J053843.

115. Hoter, Z., Castner, R. S., & Zaman, K. Q. CFD Optimization of Ejector Flaps in a One-Sided Mixer Ejector Nozzle. *In Proceedings of the AIAA Scitech 2019 Forum*, San Diego, CA, USA, 7–11 January 2019. pp. 1-12. DOI: 10.2514/6.2019-0544.

116. Dong, Z., Sun, M., Wang, Z., Cai, Z., Yao, Y., & Gu, R. *Numerical investigation on flow and mixing characteristics inside a converging-diverging mixing duct of rocket-based combined-cycle engine in ejector mode. Aerosp. Sci. Technol*. 2020, 106, pp. 1-15. DOI: 10.1016/j.ast.2020.106102.

117. Huang, H., Zhang, K., Tan, H., Lu, S., Zhao, L., Lei, M., & Ling, W. *Flow Characteristics of an Integrated Ejector Nozzle with Tertiary Intake. Journal of Propulsion Technology*. 2020, vol. 41, no. 12, pp. 2729–2738. DOI: 10.13675/j.cnki.tjjs.200170.

118. Li, H., Wang, X., Ning, J., Zhang, P., Hu, H., & Tu, J. Numerical Investigation of the nozzle expansion state and its effect on the performance of the steam ejector based on ideal gas model. *Applied Thermal Engineering*. 2021, vol. 199, pp. 1-32. DOI: 10.1016/j.applthermaleng.2021.117509.

119. Li, Z., & Wang, H. Comparison of the Flow Fields between Nozzles with Full-Open and Open-Close Valves at Transonic Velocity. *Hindawi Journal of Applied Mathematics*, 2022. pp. 1-11. DOI: 10.1155/2022/6875240.

120. Li, Z., Wang, H., & Huang, H. Analysis of Flow Field of Three-Dimensional Ejector Nozzle with Open-close Alternate Intake Valve at Transonic Velocity. *Journal of Aerospace Power*. 2023, vol. 38, no. 12, pp. 2937–2947. DOI: 10.13224/j.cnki.jasp.20210581.

121. Li, Z., & Wang, H. Flow characteristics of ejector nozzles with different auxiliary intake valves. *AIP Advances*, 2024, vol. 14, iss. 1, article no. 015237. pp. 1-9. DOI: 10.1063/5.0187268.

122. Vinz, A., & Raichle, A. Investigation of the effects of boundary layer ingestion engine integration on aircraft thrust requirement. *CEAS Aeronautical Journal*, vol. 15, pp. 1235-1250. DOI: 10.1007/s13272-024-00722-0.

123. Bellary, S. A. I., Dabir, S. A., Khan, S. A., Tamhane, T., Shaikh, J. H., & Khan, A. Computational Analysis of Thrust Generated by Converging Diverging Nozzle at Different Diverging Angle. *Journal of Advanced Research in Numerical Heat Transfer*, 2025, vol. 29, iss. 1, pp. 102-128. DOI: 10.37934/arnht.29.1.102128.

124. Scarlatella, G., Sieder-Katzmann, J., Propst, M., Heutling, T., Petersen, J., Weber, F., Portolani, M., Garutti, M., Bianchi, D., Pastrone, D., Ferrero, A., Tajmar, M., & Bach, C. RANS Simulations of Advanced Nozzle Performance and Retro-Flow Interactions for Vertical Landing of Reusable Launch Vehicles. *Aerospace*, 2025, vol. 12, iss. 124. pp. 1-30. DOI: 10.3390/aerospace12020124.

125. Shan, Y., Zhang, J., & Huang, G. Experimental and Numerical Studies on Lobed Ejector Exhaust System for Micro Turbojet Engine. *Engineering Applications of Computational Fluid Mechanics*, 2011, vol. 5, iss. 1, pp. 141-148. DOI: 10.1080/19942060.2011.11015358.

126. Schmidt, R., Hupfer, A., & Gummer, V. Thrust augmentation for very small jet engines using a mixer-ejector-system. *Proceeding of 24th ISABE Conference*, Canberra, 2019. pp. 1-16. Available at: https://www.researchgate.net/publication/378432229_Thrust_Augmentation_for_very_small_jet_engines_using_a_Mixer-_Ejector-System (accessed 28.02.2025).

127. Bogoi, A., Cican, G., Gall, M., Totu, A., Crunteanu, D. E., & Leventiu, C. Comparative Study of Noise Control in Micro Turbojet Engines with Chevron and Ejector Nozzles Through Statistical, Acoustic and Imaging Insight. *Applied Science*, 2025, vol. 15, iss. 1, article no. 394, pp. 2-28. DOI: 10.3390/app15010394.

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**ОГЛЯД РОБІТ ІЗ ДОСЛІДЖЕННЯ ЕЖЕКТОРНИХ СОПЕЛ.**
**ЧАСТИНА 1 – ЕЖЕКТОРНІ СОПЛА ДЛЯ ПІДВИЩЕННЯ ТЯГИ**

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**Предметом** вивчення в статті є ежекторні сопла, призначені для підвищення тяги реактивних двигунів. **Метою** є аналіз протиріч між технічними вимогами та вимогами технологічності та ціни; між потрібними високими характеристиками ежекторів і компактністю; між суперечливими цілями досягнення високого темпу змішування з малими втратами повного тиску первинного потоку в межах короткої загальної довжини, а також методів раціонального зменшення зазначених протиріч шляхом застосування ефективних змішувачів первинного й вторинного потоків. **Задачі:** розроблення класифікації, виявлення переваг та недоліків ежекторних сопел для підвищення тяги, аналіз головних напрямків дослідження ежекторних сопел (теоретичних досліджень на основі спрощених моделей, експериментальних досліджень, теоретичних досліджень на основі вдосконалених моделей та досліджень з використання моделей обчислювальної гідродинаміки). Використовуваними **методами є:** пошук відповідних джерел у мережі Internet та їх аналіз виходячи з власного досвіду роботи в авіаційній галузі. Отримано наступні **результати.** На основі знайдених джерел інформації розроблено класифікацію ежекторних сопел для підвищення тяги; сформульовано їх переваги та недоліки; проаналізовано результати наявних досліджень. Окремо проаналізовано дослідження ежекторних сопел для підвищення тяги мікро-турбореактивних двигунів. **Висновки.** Наукова новизна отриманих результатів полягає в наступному: зібрано інформацію з багатьох літературних джерел, яка висвітлює класифікаційні особливості, переваги й недоліки ежекторних сопел для підвищення тяги, розвиток дослідження цих сопел теоретичними (на основі аналітичних моделей, а також з використанням обчислювальної гідродинаміки) та експериментальними методами. Виявлено дуже обмежену кількість публікацій і відсутність (у відкритих джерелах) методики щодо проєктування ежекторних сопел для підвищення тяги мікро-турбореактивних двигунів. Таким чином, обґрунтовано потребу в розробленні методики проєктування ежекторного сопла для підвищення тяги мікро-турбореактивних двигунів. Намічено мету та задачі подальших досліджень у цій галузі.

**Ключові слова:** газотурбінний двигун; ежекторне сопло для підвищення тяги; коефіцієнт підвищення тяги; відношення вторинної витрати до первинної; первинне сопло; камера змішування ежектора.

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