


Review

A Critical Review of Supersonic Flow Control for High-Speed Applications

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Abstract: In high-speed fluid dynamics, base pressure controls find many engineering applications, such as in the automobile and defense industries. Several studies have been reported on flow control with sudden expansion duct. Passive control was found to be more beneficial in the last four decades and is used in devices such as cavities, ribs, aerospike, etc., but these need additional control mechanics and objects to control the flow. Therefore, in the last two decades, the active control method has been used via a microjet controller at the base region of the suddenly expanded duct of the convergent–divergent (CD) nozzle to control the flow, which was found to be a cost-efficient and energy-saving method. Hence, in this paper, a systemic literature review is conducted to investigate the research gap by reviewing the exhaustive work on the active control of high-speed aerodynamic flows from the nozzle as the major focus. Additionally, a basic idea about the nozzle and its configuration is discussed, and the passive control method for the control of flow, jet and noise are represented in order to investigate the existing contributions in supersonic speed applications. A critical review of the last two decades considering the challenges and limitations in this field is expressed. As a contribution, some major and minor gaps are introduced, and we plot the research trends in this field. As a result, this review can serve as guidance and an opportunity for scholars who want to use an active control approach via microjets for supersonic flow problems.

Keywords: flow control; de Laval nozzle; CD nozzle; microjet; supersonic flow; CFD; DOE



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1. Introduction

In supersonic vehicles, the flow of exit from the rockets and missile engines has become a significant issue. It has been found that the loss of air inside the high-speed vehicle engines turns to increase the base drag. For example, a nozzle with sudden expansion ducts will form a recirculation zone, increasing base drag. When the base drag increases, the total amount of exit pressure will decrease, and this decrement will result in the loss of the forwarding force or thrust. Hence, many studies have reported controlling the high-speed flows as a passive and active control method. In a passive control method, the duct shape is modified with additional devices/shapes, such as ribs, cavities, cylinders, aerospike, splitter plate, etc. In addition, researchers used different devices of flow formation, such as a nozzle as internal flow control and bluff body, non-circular cylinders, airfoil, and wings as external aerodynamics flow control. On the other hand, the active control of high-speed flow has been studied extensively over the last two decades. Researchers have used a high-speed nozzle with a sudden expansion duct and a microjet controller; a tiny hole in the base area is drilled to control the flow, which was found to be an excellent technique in a supersonic flow problem. Hence, this review is more focused on the active control approach, using a microjet in a CD nozzle.

The abrupt expansion of the external compressible flow over the back of the projectiles and its association to the base pressure has long been the focus of researchers' interest. The

base drag, which accounts for a significant portion of the overall drag, is determined by the base pressure. Generally, the base pressure for a high-speed projectile is lower than the ambient pressure. The vast majority of the ballistics test data were supplied, leading us to presume that the base pressure ratio depends entirely on the flight Mach number. Compared to traditional ballistics testing processes, the experimental investigation of the internal flow apparatus provides several distinguishing benefits. A significant amount of air supply is lowered, which would generally be necessary for the wind tunnel test section to be large enough so that wall interference and other factors do not disrupt the model flow. Internal flows are free of stings and other support devices that are necessary for external flow investigations. The most significant benefit of the internal flow device is that static pressure and surface temperature measurements can be recorded as well as the entry to the expansion and the wake zone (Figure 1). These observations are crucial if the theoretical predictions are to be extensively investigated.

The sudden expansion problems in the subsonic and supersonic flow regimes are found in many applications. We discovered that previous researchers used a system to replicate high altitude conditions in jet and rocket engine test cells, jet discharge results in insufficient, sub-atmospheric discharge pressure. This was found by Khan et al. [1], who used microjets to control the sudden expansion flow (base pressure) from the CD nozzle as an active control method.

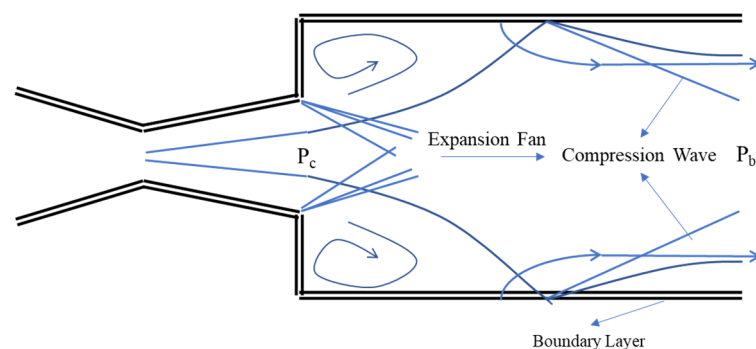


Figure 1. Sudden expansion flow field. Reprinted with permission from ref. [2]. Copyright 2021 Springer.

In this review, the following section explores the fundamental idea about flow development and its types, which gives a basic understanding of this work. Section three illustrates selected studies on the passive control method of high-speed flow, jet, and noise, which provides information about the passive devices and their benefits. Section four is the main objective of this work. Hence, for the detailed investigation, this is split into the different methodologies: experimental, computational fluid dynamics (CFD) and soft computing methods. We reviewed the most relevant papers related to the current work. Section five is the main contribution of this review; based on the existing data in this field, we explore and critically analyze the results. In addition, we propose some research gaps for future work and finally conclude, based on the current existing work.

2. High-Speed Flow Development in Nozzle

For supersonic flow development and investigations, a CD nozzle is utilized in most studies. A nozzle with no expanding part cannot produce supersonic air [3]; the flow is sonic at the throat; therefore, an asterisk denotes conditions at a sonic level. At the throat, the Mach number = 1, ($V = a$) and the throat area (a). Figure 2 illustrates a basic CD nozzle model [4] and the parameters with an asterisk are defined as critical values. If a high-pressure tank is connected to a pipe, then the velocity at the pipe exit changes depending on the backpressure. At any other region of the nozzle, the Mach number velocity and the local area can be derived by the continuity equation [5–7]. Even though it is possible to study one-dimensional flow behavior directly, it is only a particular case of

two-dimensional flow. One of the known one-dimensional flow phenomena is the normal shock and formation of oblique shock waves. The occurrence of oblique shock waves in different flow fields occurs, such as flight at high Mach numbers, aircraft design, diffusers, and supersonic nozzles.

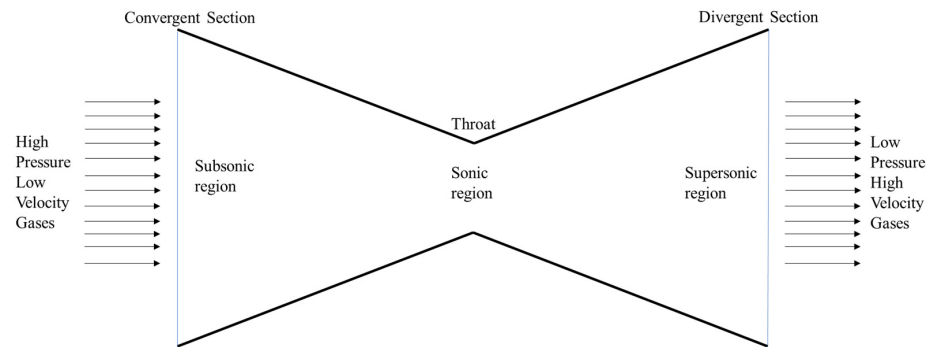


Figure 2. Convergent–divergent (CD) nozzle.

In previous studies, a particular flow rate was solved and analyzed mathematically to solve the energy equations, using a two-dimensional model of a nozzle. The measured iteration method improved the static tension, temperature, and velocity flows. The nozzle is produced and meshed with an automated technique and the sizing of the meshing processes and various values. The CD nozzle with sudden expansion was used to investigate the effect of expansion ratio for creeping expansion flows of fluid in the study of [8–11]. The CD nozzle was used to generate a supersonic flow and was simulated, using the ANSYS fluent software. The generic formula for the nozzle was determined manually, and the results were compared [3,12–14].

Nevertheless, the greatest difficulty in the CD nozzle outflow is in the subsonic and supersonic flow regimes. An abrupt expansion of the problem has various applications in the industry. In jet and rocket engine test cells, we observed that the system is used to simulate high-altitude conditions; the discharging of the jet results in inadequate discharge pressure, which is sub-atmospheric. Khan et al. [15] controlled the base pressure with the active control method, using microjets. In the active control method, the microjets were placed in the base region of the sudden expansion duct, and these microjets were directly connected to the settling chamber with the air directly passing to the duct. The inlet flow of the microjets reduced the recirculation zone, which resulted in decreasing the drag formation. A detailed study on these active flow control can be seen in Section 4.

Usually, the fluid flows are three-dimensional; the terms one, two, or three refer to the amount of coordinated space required to demonstrate the flow. The physical motion usually tends to be three-dimensional. At the same time, these are hard to evaluate and call for the most significant possible simplification. This is done by ignoring the flow variation in any direction, thus simplifying the problem. A three-dimensional problem can be reduced to a two-dimensional one and, subsequently, can be further simplified to one-dimensional one. The continuity equation, Bernoulli's equation, and momentum equation are used to study the one-dimensional flow case as methods of solution [5,16–19]. General classification and examples of flow fields can be seen in Refs. [20,21] which provided the information of 3D flows and sediment transport models for open channel flows [20]. Chong et al. [21] classified the 3D flow, considering the first-order coupled linear differential equation, using three matrix variations for both compressible and incompressible flows. The effect of nozzle geometry on the high-velocity oxygen fuel (HVOF) system was calculated [22]; the nozzle attached inside were adjusted, and they also proved that the cold spray technique influences the HVOF system and applies to the nozzle configuration.

3. Passive Control Methods

This section summarizes some of the passive control approaches of previous researchers, and it is split into three major concerns: flow, jet, and noise control, in order to extract the idea of these methods.

3.1. Flow Control

The examination of abrupt axi-symmetric expansion is a challenging subject that is becoming popular in a range of flow systems in the current scenario. The duct is employed with a smooth inner surface and a low base pressure in most cases. Sudden relief to the shear layer at the nozzle exit is due to the availability of a duct with a larger area. Due to a sudden increase in the duct area, the base pressure and flow-field may be articulated at the base area through the vortex dynamics produced, due to a sudden increase in the duct area. In contrast, the value of the base pressure is almost similar in the base area; however, the mean values are taken for the analysis. As a result of its wide application, abruptly increased flows have been thoroughly investigated.

The investigations were carried out in an abrupt expansion duct in several cases with passive devices such as a rib, cavity, step body, and boattail. Several studies were carried out experimentally to control the flow, and these results serve as the benchmark results. Viswanath [23] studied the impacts of riblets in pressure gradients and three-dimensionality on airfoils, wings, and wing-body combinations in different speed regimes to control the viscous drag in 3M riblets. Ishide and Itazawa [24] tweaked the leading edge flaps to enhance the delta wing design at a low Reynolds number of 1.9105 applied to a chord (geometric mean) of 286 mm as the typical length for micro and crewless air vehicles.

The flow past desired blunt-nosed body with and without spikes was tested in a primary 2D water channel, at a given Reynolds number [25], with spikes of various forms, such as conical, hemispherical, flat, and square nose. Khurana and Suzuki [26] used a forward-facing aerospikes on the nose to examine the heat transfer and its control through the aerospikes for lifting the body configuration in a hypersonic flow. They used experimental techniques and a simplified model of the resulting basic symmetric-delta configuration. A similar study by the same authors [27] was carried out to assess the aerodynamic efficacy for aerospikes on a hypothetical lifting-body in a hypersonic flow at various Mach numbers. In Ref. [28], the experimental research was carried out to determine the importance of the pressure hill height and the zone expansion impact for a flow-through in different forms of spikes with Reynolds numbers ranging from 2278 to 4405 to detect the vortex shedding process. In a prior work, the previous researchers [29] studied a theoretical estimate of the shock standoff distance in a supersonic range with the modified Newtonian impact theory. Based on this passive control strategy, the researchers [30] conducted the tests using a transonic wind tunnel of 38×30 cm in the Mach number ranges of 0.7 to 1.0 and controlled the entire afterbody drag of the outlet flow. In the absence of the jet flow at the base, the same author [31] examined the development of flow management with passive control devices for the axi-symmetric base and afterbody drag reduction in different speed regimes.

Experimentally, [32] studied the control of flow in a sonic jet in a circular convergent nozzle by locating two tabs at the nozzle exit. The effects of annular ribs as a passive control device on the base pressure control was examined, using an experimental technique in a subsonic and sonic nozzle with an abrupt expansion duct [33]. In addition, the researchers investigated the pressure fluctuations in a typical missile base area design at a freestream Mach number of 0.7, with and without a base cavity [34]. The study was discovered in resonant high-speed cavity flows controlled by high frequency pulsed supersonic microjets [35] in addition to CD nozzles. A compression corner calculation model was employed to perform extensive numerical investigations in the supersonic flow field with varied injection pressure ratios, actuation locations, and nozzle types [36]. Figure 3 illustrates the different devices that were used to control the high-speed supersonic flows, particularly in a CD nozzle.

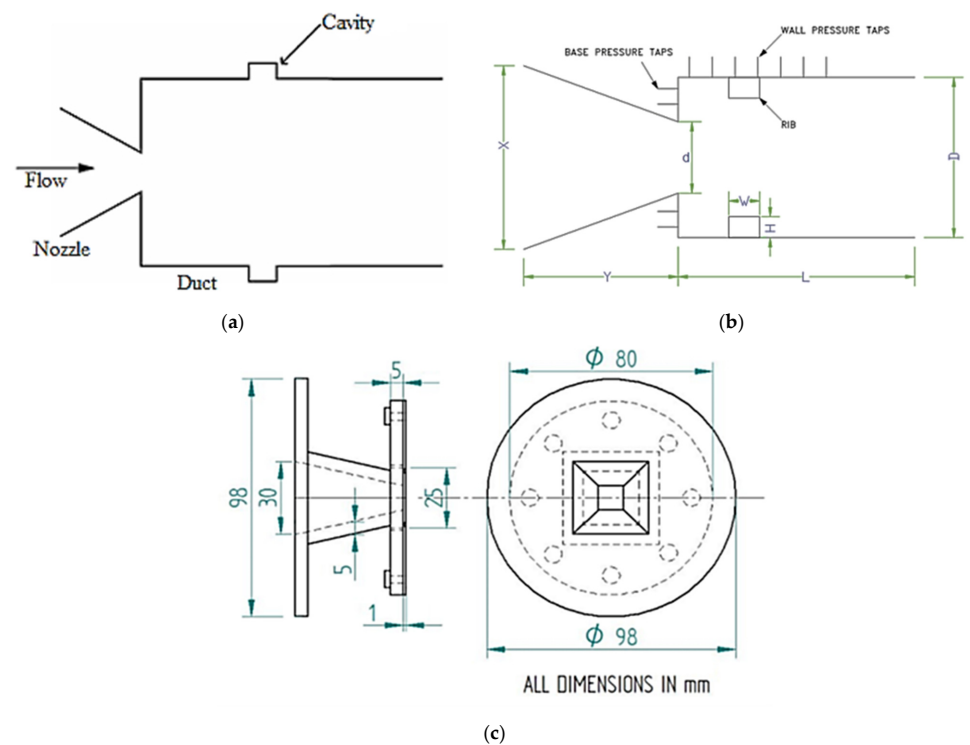


Figure 3. Passive control devices: (a) cavities [37], (b) ribs [38], and (c) cylinders [39,40]. Reprinted under the Creative Commons (CC) License (CC BY 3.0).

3.2. Jet Control

Mixing is required for efficient and effective jet performance in a variety of aerospace applications. Thrust vector control, missile engines, and aircraft propulsion systems are just a few of the technical applications based on jets. To manage the combustion chamber size and improve the vehicle's efficiency, effective mixing is necessary for air-breathing engines. Optimal mixing on a small and big scale is required for combustion cycles to work properly. Small-scale mixing is concerned with molecule mixing, whereas large-scale mixing is concerned with the dismantling of large-scale vortices. Acoustic radiations are caused by the existence of turbulent vortical structures and compressible waves (such as shock waves in supersonic flows), which frequently exceed acceptable levels in practical circumstances such as military and surveillance aircraft [41].

There are several studies that have reported on jet control, and we consider some cases in this review. It was observed that the high-speed flow controlled by the excitation of free shear-layer instabilities [42] uses localized arc filament plasma actuators in jets for different Mach numbers at a supersonic range. Focusing the aspect ratio of the nozzle and nozzle pressure ratio (NPR) with the Mach number variation, the elliptic jet control with limiting tab [43] was investigated and showed that each parameter is important to control the jet flows, similar to the overexpanded plug nozzle jet [44] controlled by the passive method. Additionally, some researchers used ventilated triangular tabs to control the jet [45], control the supersonic elliptic jet with ventilated tabs [46], and to measure the impact of the tab location relative to the nozzle exit on the shock structure of a supersonic jet [47].

Khan et al. [48] experimentally investigated the effect of the extended cowl on the flow field of planar plug nozzles for two different Mach number ranges (1.8 and 2.2) to observe the influence of the cowl length for the pressure distribution. Manigandan and Vijayaraja [49] experimentally investigated the flow-field and acoustic characteristics of the elliptical throat in the CD nozzle. According to the findings, switching from an elliptical to a circular throat alters the shock cell architecture, resulting in a substantial shift in the scream amplitude, owing to wave weakening. The jet controlled for mixing the flow was experimentally studied by Khan et al. [50] for the enhancement of the supersonic

twin-jet mixing by vortex generator to observe the effects and the behavior of the daughter streams. Similarly, an impinging plug nozzle jet using a vortex generator [51] was studied experimentally. Figure 4 shows the nozzle and tab details, CAD drawing (Figure 4a), photographic view without tabs (Figure 4b), schematic sketch of nozzle exits with triangular tabs along the major and minor axes (Figure 4c), and triangular tab dimensions and the photograph of the nozzle with triangular tabs along the major axis (Figure 4d).

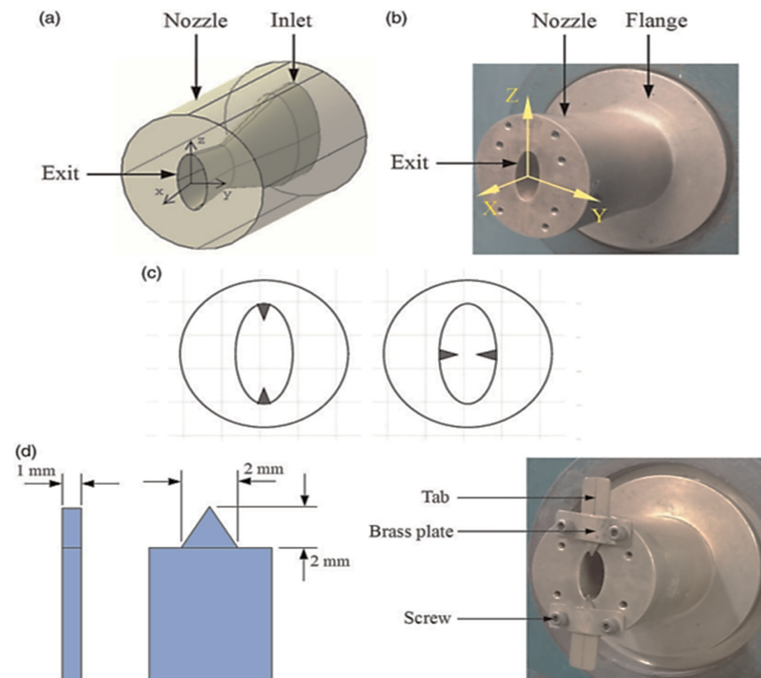


Figure 4. Jet control device, (a) Nozzle drawing, (b) Nozzle image without tabs, (c) Both minor and major tabs on the nozzle drawing (d) Triangular tabs dimension and nozzle image with major tabs [52].

3.3. Noise Control

In the past, the decrease in shock-related noise from aviation engines operating at supercritical nozzle pressure ratio received attention. The fact that shock-related noise occurs on many engines, including the turbofan engines utilized in today's commercial aircrafts, emphasizes its relevance. It has long been known and shown in model scale tests that employing a proper CD nozzle instead of a convergent nozzle, as used in most supersonic aircraft engines, may minimize/remove the shock noise component [53]. However, due to many unsolved issues concerning the noise characteristics of CD nozzles operating under non-design circumstances, the actual application of this idea has been avoided [54]. Although an appropriate CD nozzle may be used to produce a shock-free jet flow at a certain design pressure ratio, the same nozzle can be used for off-design pressure ratios during takeoff and landing operations, resulting in shock noise [55].

The bulk of these noise reduction systems are referred to be passive since they cannot be switched off or changed while in flight and might result in performance losses. Penn State [56] is developing a fluid insert technique for supersonic jet noise reduction. The fluid insert method aims to reduce noise in low bypass ratio turbofans while having minimal impact on engine performance. The fluid inserts blast air into the diverging portion of the nozzle on demand, which may be turned off or adjusted depending on the flight regime. Although significant research has been conducted in the form of noise measurements and Reynolds-averaged Navier–Stokes (RANS) calculations to enhance the fluid insert technology [57,58], the reason why these inserts work is still not understood completely. The correlation of changes in the flow field with corresponding changes in the noise is inadequate, using only existing RANS data [59,60]. It was suggested that unstable scale-

resolving simulations be used to obtain more insight into the flow field and to better understand noise reduction techniques [56]. Additionally, when properly structurally supported, acoustic reflectors of an adequate scale are a suitable noise reduction solution for the high-pressure venting typical of blowdown operations [61]. Due to disadvantages, such as delayed convergence and the complexity of the phase shift mechanism, a unique technique was used that does not use secondary path modeling [62] and the sensitivity of noise to system uncertainties [63]. Fluid inserts reduce the convection speed of wave packets in the jet shear layer, resulting in a reduced Mach wave radiation angle [64].

This interaction is discussed here with a focus on noise creation and reduction when a jet is parallel to or impinging on a solid wall. Various researchers have presented computational methods [65,66] with large-eddy simulations [67–71], high fidelity simulations [72] and 3D simulation [73]. The noise reduction of supersonic jets by nozzle trailing-edge changes was investigated experimentally [74], and hemispherical noise reduction reflectors on transonic jet flows [75] were conducted. Different injection sites, angles, and circumstances were also investigated, resulting in distinct acoustic behavior and flow-field changes [76]. Using steady fluidic injection, researchers conducted an empirical scaling analysis of supersonic jet control [77]. Aft and lateral wall inclinations for a cavity [78] supersonic cavity flow utilizing high-speed upstream injection [79] and cavity dynamics to the introduction of various storage configurations installed at different positions inside the cavity [80] were all numerically modeled for noise reduction. The employment of a single injector as a fluid insert helps break up the large-scale structures of the flow, according to direct cross-correlations of near-field data with far-field microphone signals [81]. Pipe-jet noise is reduced via geometric changes in the form of trailing edge castellations. The interaction between the streamwise vortices is determined by the number of castellations, which changes the sound generated [82]. Figure 5 shows the noise reduction configurations, which are adopted in the nozzle exit region, and represents the baseline nozzle (Figure 5a), nozzle (Figure 5b), schematic of a single fluid inserts in the nozzle (Figure 5c), and designation of different azimuthal planes for the 3FC-2FI nozzle (Figure 5d).

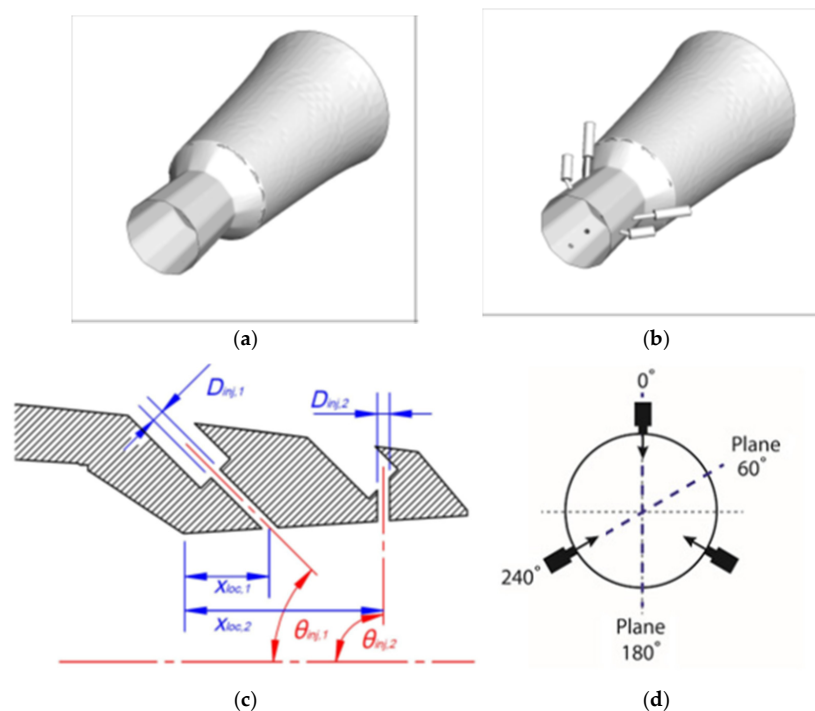


Figure 5. Details of nozzle configurations. Reprinted with permission from ref. [64]. Copyright 2020 Springer.

after measurements for a certain length of pipe were completed. Pressure taps made of stainless steel were used to record the static wall pressure. Because the flow field soon after departing the nozzle is so important, the first nine holes were spaced four millimeters apart, and the remaining holes were spaced eight millimeters apart. The moisture content of the compressed air is absorbed in a dual-tower semi-automatic silica gel dryer. Later the dried air is heated and used to remove the moisture from the air altogether. A regulatory pressure valve operated by a pressure relief pilot permits the dryer to operate; three tanks were used to store the dry air with a total capacity [1].

In previous experimental methods, the NPR was 3 to 11 at various expansion levels and showed that the L/D could be defined for a given Mach number and NPR, resulting in a cumulative increase/decrease in the base pressure [1,83–88]. The experiments were also conducted by [89] for area ratio 2.56 and area ratio 4.84 [90]. The statistical approach aims to verify the experimental data, obtained at the VTI Žarkovo Institute during supersonic wind tunnel tests: free escape and flow with one chosen type of obstacle [91]. The tests were carried out at design NPR with sudden expansion for the duct length $L = 10D$ to $1D$. The considered cross-sectional areas of the tube were 2.56, 3.24, 4.84, and 6.25 [92]. Figure 7 shows the experimental setup for the base and wall pressures.

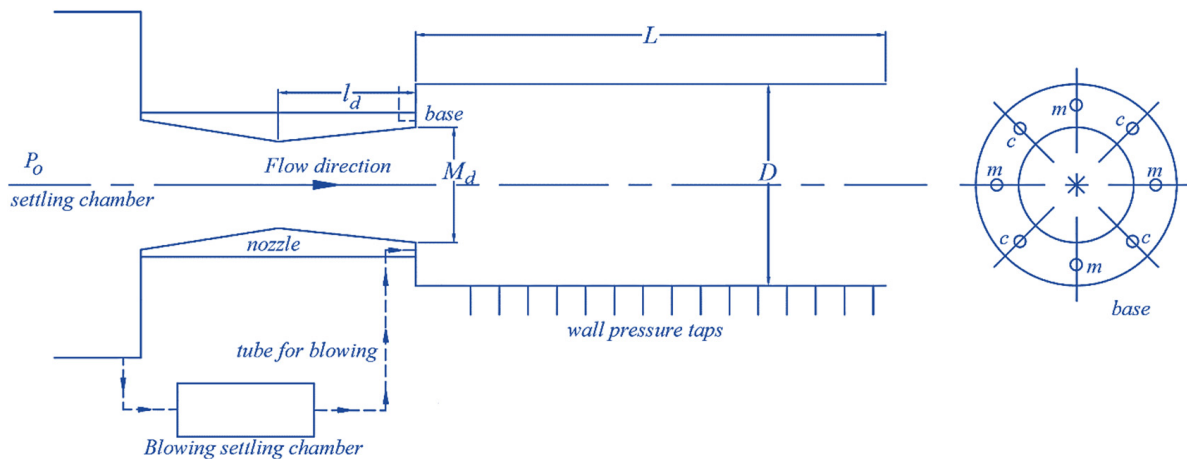


Figure 7. Experimental setup [93]. Reprinted under the Creative Commons (CC) License (CC BY 4.0).

In the presence and absence of a base cavity, the experiments were conducted to analyze the pressure variations in the base region of a conventional missile configuration at a freestream Mach number of 0.7. The authors attempted to identify the variations in pressure and illustrate the influence base cavities have on their behavior. Experiments consisted of unstable calculations of pressure at six azimuthal locations. The disparity in the pressure fluctuations in the azimuthal direction was observed due to a standard axisymmetric, which is significant [35]. For the Mach numbers ranging from 1 to 3, the effect of the microjet control in the CD nozzle with a sudden expansion duct was experimentally tested at supersonic Mach numbers. The research varied nozzle parameters, such as an area ratio of 2.56; NPR ranged from 3 to 11; and L/D ranged from 10 to 1 [94]. They extended their work for Mach 2.5 and 3.0, and cross-sectional areas of 2.56, 3.24, 4.84, and 6.25; the L/D ratio of the duct was 10 to 1, and the NPR used were from 3 and 11 [95].

To control the drag, the researchers [96] worked with base drag and experimentally studied the aerospike behind the base of bluff bodies. A 1 mm thick plate with two spikes at 11.5 mm was mounted between the nozzle as a passive device. The efficacy of the continuous grooved cavity was tested experimentally to control the base flows with specific parameters [97]; in the transonic system, the aerospike effectively control the base pressure [98] without disrupting the main flow, respectively.

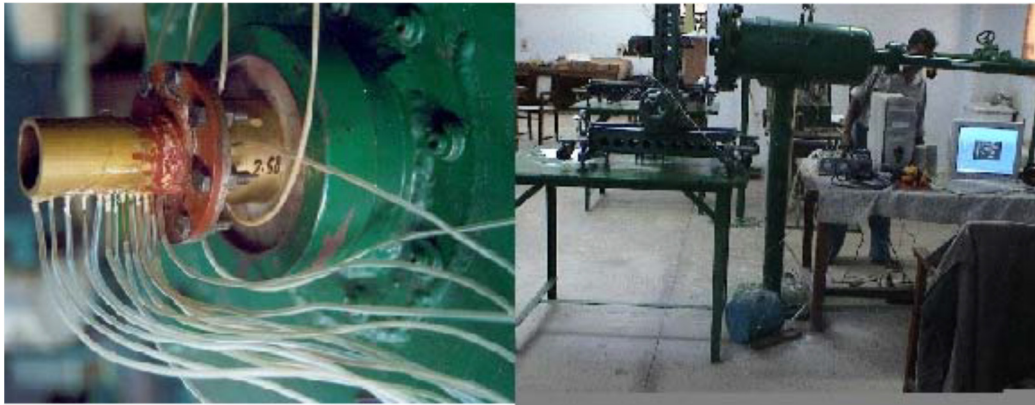


Figure 8. A view of the extended duct with pressure tapings and setup site [97]. Reprinted under the Creative Commons (CC) License (CC BY 3.0).

In summary, Khan et al., investigated the active control of the base pressure [1,15,82–85,99] in which they considered the differed Mach number at various supersonic flow ranges, such as Mach numbers 1.25, 1.30, 1.48, 1.6, 1.8 and 2.0 in [84,85]; 1.87, 2.2 and 2.58 in [15]; and 2.0, 2.5 and 3.0 in [82], respectively. The test area ratio was from 2.56, 3.24, 4.84, and 6.25; the NPR was from 3 to 9; and the duct length for $L = 10D$ until $1D$. More attention was given in the recent study to wall pressure distribution for different inertia levels, relief to the flow, NPR, and the L/D ratio [93,100–107]. After monitoring the flow from the active microjet control, it is also necessary to know whether the flow changes in the duct or not. Hence, recent findings have also shown that several studies are conducted with equivalent or variable Mach number and area ratios with the same NPR and L/D ratios. The majority of wall pressure flows were considered with varying the area ratio, such as 2.56 [93,100], 3.24 [101,102,108,109], 4.84 [103–105,110], and varying the Mach number for the same area ratio 2.56 with Mach 2 and 3 [106], 1.3, 1.9, and 2.4 [111] and for the area ratio 6.25 with Mach 1.1 and 1.5 [112] and 2.1 and 2.8 [113].

4.2. Computational Fluid Dynamics Approach

As the second method of this study on high-speed flow control, a CFD approach was chosen, and a relative work is overviewed to examine the objective and outcomes of the previous investigation.

Apart from experimental studies, a numerical method was employed by various researchers; such studies can be seen in this section. A fluid-structure analysis was found for the delta wing (cropped) [114] based on an aeroelastic solver in the time domain. Two fluidic thrust modulation methods were employed—shock thrust and throat shifting thrust modulation [115]—for the investigation. Initially, the CFD approach examines the supersonic flow through a de Laval nozzle and obtains complete isolation of the thrust flow due to shock waves. The flow was studied for friction, and the temperature of gases at the exit of the combustion chamber [116]. The finite volume model was developed for the estimated two-dimensional and three-dimensional flow formations, using turbulence model efficacies via ANSYS simulation [117]; it was used to investigate the extensive flow field within the supersonic ejector and improved the ejectors mixing chamber wall structure to attain an optimum entrainment ratio to obtain the highest possible capability the ejector can achieve. The ANSYS fluent and ICEM meshing tool was used to conduct the simulation and analyze the ejector performance: k -epsilon realizable and k - ω SST [118] and k - ω [119]. To find the micro-Laval nozzle performance, it was primarily investigated by its machined surface topology, and a circular cross-section micro-Laval nozzle was modeled [120].

Modeling of the nozzle geometry and generating mesh was carried out using the GAMBIT 2.4 program and validated with the findings of the experiment taken from the literature, which are well known [121]. Patel et al. [122] derived the principles of

the de Laval nozzle, using the nozzle operating theory, and examined the experimental approach of evaluating flow for various nozzles; the variance of flow parameters, such as pressure, temperature, velocity, and density, was visualized [123] to investigate the effects of geometry and flow parameters on the thrust force created by the flow from the CD nozzles to a circular duct with a larger cross-section. The study was carried out for all Mach numbers using various area ratios (2–12) and NPR (3 to 11) [124–127]. The researchers optimized the rocket air ejector configuration in AutoCAD, then analyzed it using Ansys CFX using the numerical approach with 3D models [128]. The primary purpose was to optimize the CD nozzle location for each operating circumstance and the influence of reflected shock waves and boundary layers on the ejector performance in the mixing chamber constant zone [129]. To compute the mass flow rate and multiphase sound velocity for a CD nozzle, the equilibrium and homogeneous model that gives rise to no-slip in temperature and velocity between the particle and gas phases was used [130]. Additionally, the mixing noise and shock-related wideband noise [131] in a nozzle was discussed. The CFD methodology was also employed in this definition for varied area ratios, the Mach number, NPR, and L/D, and analyzed the flow region surrounding the base [132].

Meanwhile, it was found that ANSYS fluent was the most appropriate tool to solve this problem. The CFD approach was a dominant concept in ANSYS software and a foundational analysis to settle the problem. It is essential to know the governing equations and the turbulent modeling of the current flow. In this respect, the studies examined and illustrated the testing approach and identified an issue for situations considering the various nozzle parameters and the flow range. In the analysis, the L/D of 10 was used for the conduit. An area ratio between the exit area of the CD nozzle and the duct area was also found and observed in the flow formations (Figure 9). The idea is used by the CFD method for various area ratios, the inertia level, NPR, and the duct length [14,132–137] for the compressible flow.

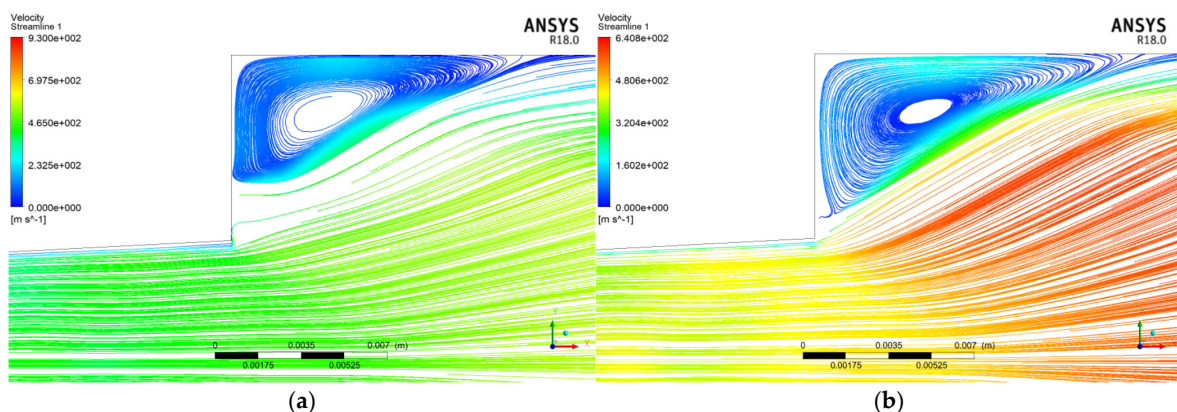


Figure 9. Velocity streamline for area ratio 6.25 (a) with control (b) without control [132]. Reprinted under the Creative Commons (CC) License (CC BY 4.0).

The CFD procedure also used to explore the flow through the wedge [138,139], non-circular cylinder [137,140], splitter plate [141–143], airfoil [144,145] and powered submarine [146] for an incompressible flow range. From the fluent, more studies were found in recent years in which some studies have been utilized with the pressure-based solver, and K-epsilon turbulent modeling was used [134,136]. The fluent results were continued with a change in parameters to investigate the effect of active microjet controller [2,147]. Figure 10 shows the perfect 2D model with the contour received as a result.

4.3. Soft Computing Methods

Soft computing is an emerging technology for discovering these kinds of problems, which parallel the remarkable capacity of the human imagination to target and study in an atmosphere of ambiguity and imprecision. It contains many computer models, including experimental system architecture, fuzzy set theory, neural networks, and approximate reasoning, and it requires intensive computing for learning and reworking.

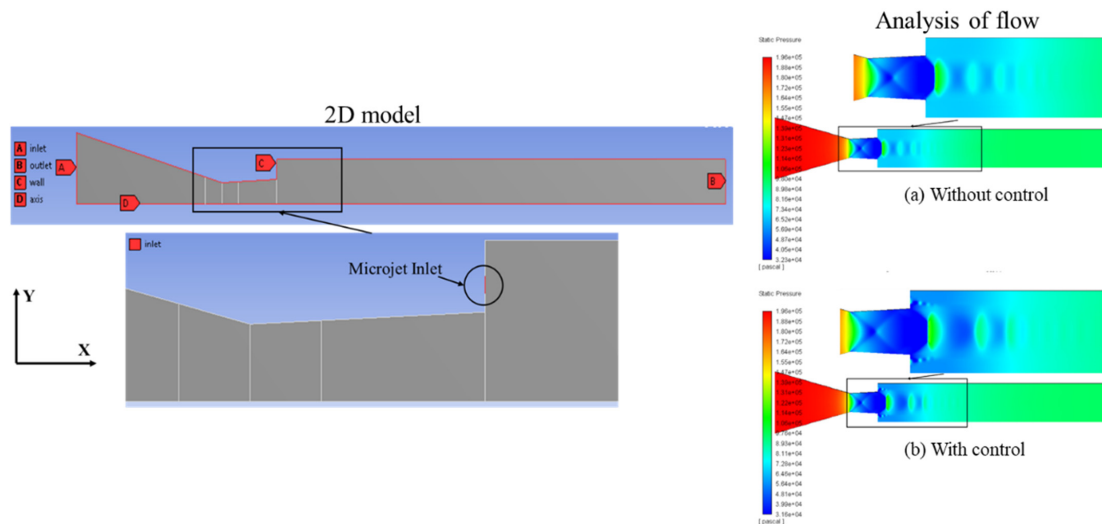


Figure 10. D nozzle with sudden expansion duct and their results. Reprinted with permission from ref. [2]. Copyright 2021 Springer.

4.3.1. Design of Experiments

If one needs to verify scientific predictions properly, these measurements are valuable. In several engineering and medicine implementations, the design of experiments (DOE) method was used to define the variables that are important in the production and optimization phase to accomplish a helpful target. This approach was then used to find the most prevalent strategy for the solution of the current object. The DOE plays a vital role in identifying relevant variables in the development process for industrial uses, such as planning and experimentation [148–150]. These kinds of elements were used successfully with the influence of designer control and changes over two or three stages. The experiments were carried out based on the orthogonal array (OA) to obtain each possible response factor affecting the input variables.

Researchers used the DOE principle based on the current problem and found that this could be an efficient way to achieve the base pressure control with an appropriate parameter. Therefore, to refine the base pressure control, the DOE technique was used. The impact of microjets on control was achieved to obtain base pressure differences of various parameters. The general DOE approach method can be seen in Figure 11.

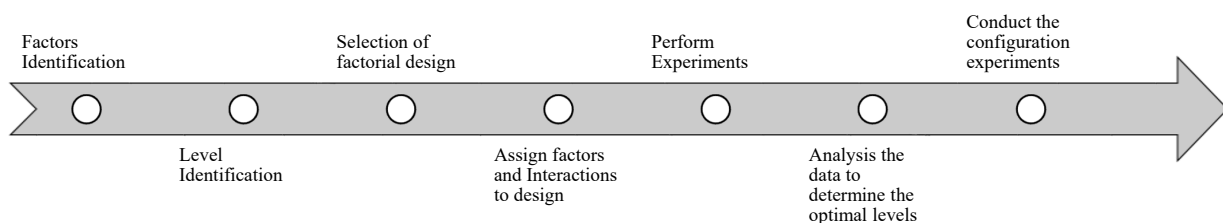


Figure 11. Steps in implementation of DOE approach. Reprinted with permission from ref. [2]. Copyright 2021 Springer.

The experimental study was used for various parametric combinations using microjets to control the base pressure, using a CD nozzle. The data were used to refine the optimal mix of parameters employed to provide precise control of base pressure for improved performance with DOE [151]. A Taguchi design L_9 -OA and variance analysis (ANOVA) was used to analyze the influence of nozzle parameters affecting the base pressure. Multiple linear regression models, confirmation checks, and linear regression equations were performed for accuracy in an optimization. The ANOVA method was also used to obtain the individual parameters statistical significance on the total base pressure variability [152]. The observation on the control becomes effective for lower area ratio, compared to the higher area ratio with the aid of 15 arbitrary test cases; two linear regression model presentations were tested for their estimated accuracy [153]. To optimize the response surface methodology (RSM) of experimental data, non-linear regression models based on the central composite design (CCD) and box-Behnken design (BBD) were developed to simplify the input–output relationships [154]. The DOE with L_{27} -OA and ANOVA was used to determine the feedback (in percentage terms) of various process parameters and their correlations with and without control on the base pressure [155,156]. The optimum nozzle parameters were targeted, such as convergent angle, divergent angle, and the throat radius of the nozzle; the best values were assessed based on the flow parameters [157]. Jaimon et al. [158] used the DOE method to predict the suddenly expanded flow with and without microjets as an active control. To develop the linear model, they used a complete factorial design of the L_{16} orthogonal array (OA). Using Taguchi's L_{27} orthogonal array, a regression analysis was made [159], and optimized results investigated the suitable parameters for base pressure control.

4.3.2. Fuzzy Logic

Jagannath et al. [160] discovered a fuzzy logic methodology for investigating pressure loss in a sudden expansion duct. The authors aimed to notice minor pressure loss when the L/D was 1, as evidenced by the fuzzy logic formulation. According to the authors, this can be a qualitative examination of internal fluid flow through a nozzle with a sudden expansion duct using the fuzzy logic methodology [161]. Because of all other characteristics, such as wall static pressure and loss pressure, including the base pressure, they discovered the best value of L/D . When the Mach number is changed to 1.58 or 2.06, all other parameters remain the same as in the sudden expansion duct with cavities [162]. They found that the fuzzy logic technique L/D of 1 is sufficient for smooth flow growth based on de Laval nozzle and wall static pressure changes in both circumstances. Quadros et al. [163] described the critical aspects of the fuzzy logic technique in turbulent supersonic flow simulations as a cost-effective methodology. The Mamdani-based fuzzy logic methodology was utilized to build connections between input and output in the CFD findings. Triangular, generalized bell shape and Gaussian membership functions were employed in this technique.

4.3.3. Machine Learning

A neural network was employed to examine the predicted floor pressure in a convergent nozzle with shallow cavity internal flows at various subsonic Mach numbers [164]. The authors used feedforward neural networks (NNs) to highlight the modeling problem. A mixed density network was trained using an artificial neural network (ANN) methodology using the updated database of the future flow profile. The ANN [165] was used to learn and train flow characteristics over a transport aircraft configuration to estimate the aerodynamic coefficients using different network sizes. The K-means technique was used to cluster this massive amount of data. According to the RSM, microjets are efficient when a favorable pressure gradient influences the flow. The effect of a lower area ratio and a longer duct length on the base pressure is minimal. Furthermore, the random forest strategy was applied, which belongs to this group and is employed in Bootstrap aggregation employment regression and classification research [166]. Heat maps are used to visualize the massive amount of experimental data generated. Six back-propagation neural network

models (BPMs) based on input and output possibilities are built to forecast pressure in high-speed flows for the first time. The six BPMs with two hidden layers containing four neurons were determined to be the best suited for regression analysis. The very non-linear values of the base and wall pressure are correctly predicted by BPM 5 and BPM 6 [167]. Figure 12 depicts a broad schematic depiction of the back-propagation model (BPM).

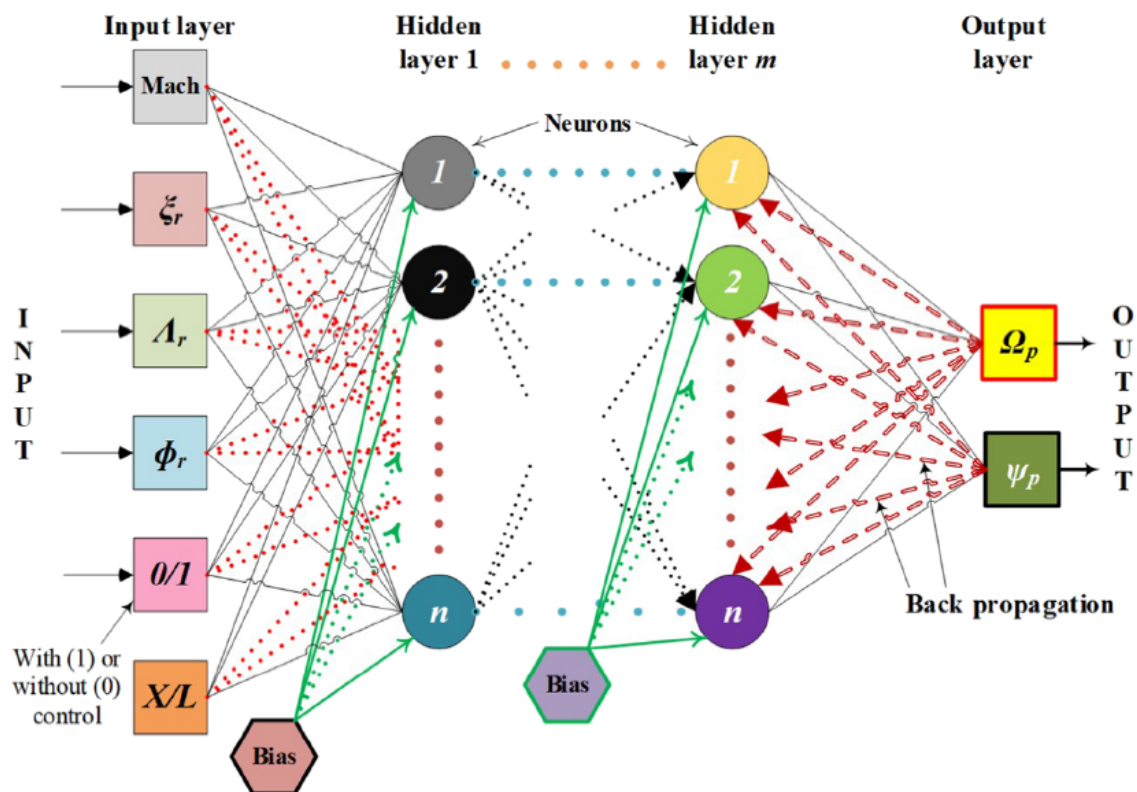


Figure 12. Back-propagation for base pressure modeling. Reprinted with permission from ref. [167]. Copyright 2020 AIP.

5. Critical Analysis of Literature

After conducting an exhaustive review on active flow management by blowing compressed air at the duct base, it was observed that the researchers utilized experimental, CFD and soft computing methods for determining the flow formation inside the nozzle (Figure 13). The experimental method was used in maximum cases for which it was challenging to obtain high-speed flow formations inside the duct, with shadowgraph for clear demonstration. Hence, the researchers utilized the CFD methods; it is easier to obtain the contours for the different variations of the flow parameters. Multiple high-speed supersonic flows were studied well by the researchers. In the CFD, different turbulence models were used to investigate the effectiveness of the aerodynamic flow variations; the limitation found was that there is a lack of three-dimensional modeling and analysis, which can be explored well in future investigation.

Next, a soft computing approach was recently found to optimize the parameters on pressure flows; several studies have been reported via DOE. However, in few cases, machine learning and fuzzy logic methods stated that the optimum results can predict from the standard statical methods. A valuable combination of parameters in the development and optimization of the flow process examines the necessary factors to achieve. Therefore, soft computing minimizes the number of experimental and theoretical workflows for a given situation. That can be more on future work for the researchers to measure the microjet effect on the nozzle pressure control and to find the optimum parameters for controlling

the base pressure. However, there are no studies have been reported in the literature on either theoretical or analytical approaches with fundamental governing equations.

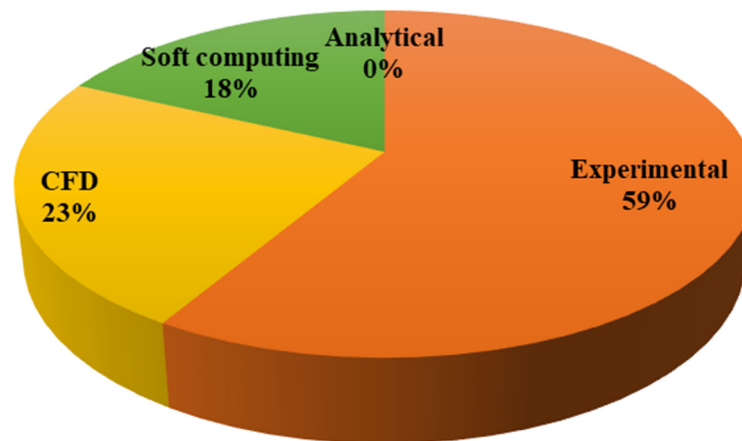


Figure 13. Methodologies used for active flow control.

In contrast, some of the passive control devices are shown in this review to know another type of control method of high-speed flow, jet, and noise. One of the critical issues in passive control is the need for additional energy sources to activate the control mechanism. Indeed, the present literature focuses more on active control and their scenarios. Some of the significant gaps/observations between the methodology related to the present work are shown in Table 1.

Table 1. Major observation for active flow control.

S. No.	Control	Experimental	CFD	Optimization	Remark
1	Active	✓	✓	✓	Very recently, CFD and optimization studies were found, and still a lot of scope in optimization
2	Passive	✓	✓	✓	Several studies have been reported in all approaches
3	Without Control	✓	✓	✓	Several studies have been reported in all approaches

For in-depth analysis of methodologies adopted for the active control method shown by the trends plot, we consider the past two decades. From the graphical view, it has clearly shown that many works have been done with the experimental method in the early years as discussed previously. However, due to recent advanced technologies, such as simulation and data optimization tools, experimental work was reduced in recent years and the soft computing approaches have increased, which have found advantages in research work. Indeed, until now, no mathematical model was made to predict the exact pressure values before and after the microjet controller. The researchers utilized different techniques to predict the results in a flow object. This gives an idea of how the methodologies are increasing in the current scenarios as a scientific approach to solving the respective problem, such as flow control. Figure 14 illustrates the last 20 years of work related to the current study in percentages, considering different techniques used to evaluate the pressure values.

In another consideration, trends in the control of flow are considered a flow model, such as nozzle/jets, bluff body, and airfoil (Figure 15). Nozzle/jets are a type of high-speed configuration that was found in several studies from the past two decades for aerospace applications. Next, the bluff body is also considered to know flow formation, and it is controlled with passive devices, such as splitter plates, for the application of both

automotive and aerospace industries. Lastly, airfoil is found in many studies but in most of the cases, this has been only developed to investigate the aerodynamic forces in some studies where the outer flow control was found.

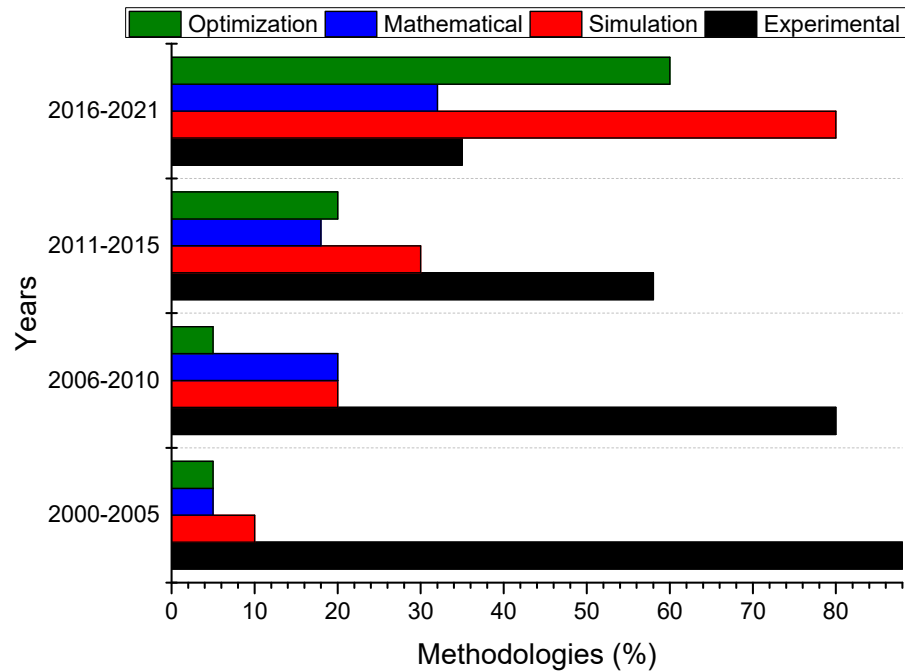


Figure 14. Trends in research methodologies in active control of flow.

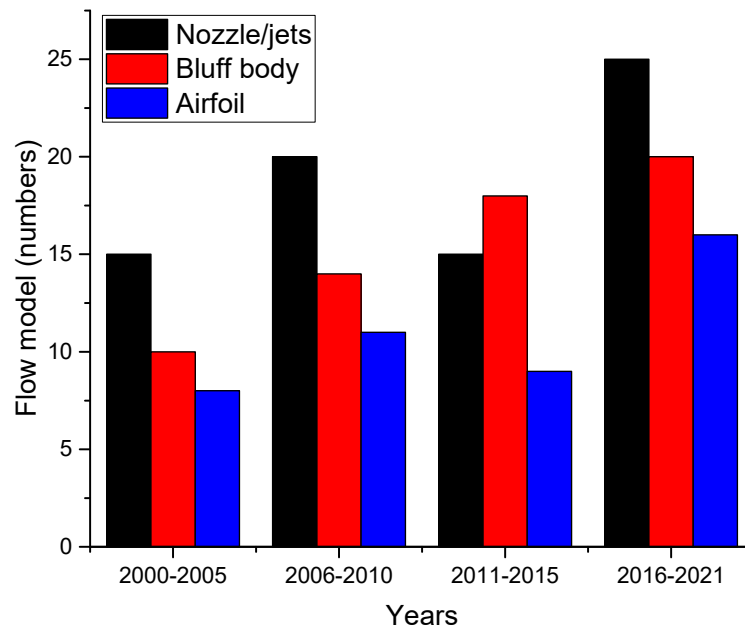


Figure 15. Trend's inflow model and its control.

Apart from the microjet controller for the control of high-speed flow, the researcher utilized different objects, such as smart material (actuator) to control the high-speed flow when focused on the depth of the active control approach. In addition, the devices for the flow control were found in the form of the cavity, corner model, diffuser, bluff body, cylinders, airfoil, wedge, etc. In all studies, some outer flow controlled, and some inner flow controlled was investigated. Table 2 illustrate the summary of the previous work with the limitations in their studies.

Table 2. Summary and limitations of the flow control method.

Type of Object	Technique Adopted	Focused Parameter	Limitations	Reference
Compression corner calculation model	ANSYS Fluent with k- ϵ turbulence model	Numerical investigations in the supersonic flow field with different injection pressure ratios, actuation positions, and nozzle types	The only simulation was used for investigation	[36]
CD nozzle with sudden expansion duct	Experimental, CFD and DOE	Effect of microjet control in a sudden expansion duct with the parametric investigation	Numerical investigation done by 2D model and microjet location is fixed to a single point	[2]
CD nozzle with sudden expansion duct	RSM, clustering, and random forest regression	Pressure in suddenly expanded high-speed aerodynamic flow	Predicting the pressure values using the optimization method with and without microjet controller	[166]
Resonant high-speed cavity	Wind tunnel test with a blowdown-type facility	High-frequency pulsed supersonic microjets to control resonant high-speed cavity flows	The fact that the REM/ SmartREM actuator performance can be enhanced	[35]
Cylindrical cavity structure takes	A computational method based on high-order numerical techniques	Flow physics of a pulsed microjet actuator for high-speed flow control	Efficient and geometrically complicated pulsed actuators were developed for various high-speed flow and noise control	[168]
Ultra-compact serpentine inlet	Experimental work with high-pressure air supply and CFD	Microjet flow control in an ultra-compact serpentine inlet	Mach number of inlet throat between 0.2 to 0.5, and it is varied to a higher number	[169]
Crewless Arial Vehicle	Experimental wind tunnel test	Microjet-based active flow control on a fixed-wing UAV	Experimental results possible to simulate with the CFD model	[170]
Impinging Jet	Experimental work with supersonic jet facility	Control of impinging supersonic jet flows using microjets	A fluent model will be helpful in such an example	[171]
Supersonic Crossflow model	Experimental work in a supersonic wind tunnel	Properties of resonance-enhanced microjets in supersonic crossflow	Limited to experimental work and also the Mach number can be varied	[172]
Ahmed body and NACA 0015 airfoil	An experimental study was conducted in a subsonic wind tunnel	Active flow control by micro-blowing and effects on aerodynamic performances	Experimental work only	[173]
Flap's pressure-side	Experimental approach	Microjet configuration sensitivities for active flow control on multi-element high-lift systems	CFD and data optimization are helpful techniques to predict the multi-element high-lift system	[174]
Flap's pressure-side	Experimental approach	Surface-normal active flow control for lift enhancement and separation mitigation for high-lift standard research model	Other aerodynamic forces	[175]
Spaced jet configurations	Experimental investigation	Control of compression-ramp-induced interaction with steady microjets.	It is advantageous to utilize a control design (MJ6) that functions well	[176]
Double-offset diffuser	Experimental technique	Flow dynamics affected by active flow control in an offset diffuser	Parametric study to predict more accurate results from the experimental data	[177]
Series of cavity flow	Experimental technique	The effects of high-frequency, supersonic microjet injection on a high-speed cavity flow	Specific Mach 1.5	[178]
cylindrical cavity	Simulation and Experimental investigation	Simulations of pulsed actuators for high-speed flow control	The parametric investigation will be effective in changing flow control results	[179]

Table 2. Cont.

Type of Object	Technique Adopted	Focused Parameter	Limitations	Reference
CD Nozzle with sudden expansion duct	CFD approach with 2D model	Base pressure control using microjets	Limited to two-dimensional model	[133,137,147,180]
Wedge	CFD approach with 2D model	Aerodynamics flow control	Limited to two-dimensional model	[137,138]
Bluff body	CFD approach with 2D model	Splitter plate to control flow and non-circular cylinder	Limited to a two-dimensional model	[137,140–142]
Airfoil	CFD approach with 2D model	Analysis of flows and prediction of CH10 airfoil for unmanned aerial vehicle wing design	Only simulation	[150]

Challenges in the Flow Control Method

Some major issues can be found when the active flow control method is used:

- **Experimental test:** One of the major issues during the test is how to reduce the flow disturbances in the connecting pipe from the main settling chamber.
- **Instrumentation:** With its sensing hole facing the flow, the pitot probe mounted on a rigid 3D traverse with a resolution of 0.1 mm was used for pressure measurement. Deficient Reynolds numbers based on the probe diameter significantly influenced the pressures measured by pitot probes. However, this effect is seldom a problem in supersonic streams because a probe of reasonable size will usually have a Reynolds number above 500, which is above the range of troublesome Reynolds numbers.
- **Data accuracy:** Pressure distribution along the jet centerline with a normal to the tab is difficult to measure and needs a proper location and observation.
- **The nozzle calibration:** The measured pitot pressure can determine the Mach number by treating the flow through the nozzle to be isentropic, thus leading to the total pressure at the nozzle exit being the same as the settling chamber pressure.
- **Simulation:** The 2D model was developed in several studies but this can only be suitable when it is uncontrolled or passive controlled. Indeed, a microjet controller needs a 3D model for more accurate results and it is difficult to design, also requiring a supercomputer to simulate/analyze.
- **Base pressure:** Based on the previous result, the base pressure either increases or decreases when it is controlled and also it varies by varying the nozzle parameter. However, it is critical to increasing the supersonic or hypersonic ranges due to high-speed formation in the setup that has a chance to incur breaks/damages; hence, it needs a very high configured/quality setup for testing.
- **Microjet location:** It was found that the microjets were located in the PCD of 13 mm but there is no other location that is reported in the literature; this can be explored well in future studies.
- **Soft computing:** As compared to DOE, only a few studies are reported with machine learning algorithms and the Fuzzy logic approach. These methods can be explored well in future investigations.

6. Conclusions

Throughout this review, the previous work was presented and discussed. The concept of CD nozzle and flow-field was addressed with a fundamental governing equation. The study shows the critical point of view of how researchers utilized the fundamental concepts in the problem solving of high-speed flows, considering active and passive methods. For the passive method, flow, jet, and noise control studies were considered and critically reviewed. Most of the studies in this literature were presented for the active control method; this was the major work of this review. Active control investigation was divided into three powerful techniques: experimental, numerical, and soft computing methods. It was found over the last two decades, the study on active control was done widely with

an experimental approach. In contrast, the CFD study was conducted very recently but needs improvement on its performance with the three-dimensional approach and the proper finite volume method. Moreover, soft computing is well utilized by the design of experiments methods as compared to machine learning and fuzzy logic. Indeed, no analytical investigation has been made on such a problem. Furthermore, a critical analysis and research gaps in this field were discussed.

In summary, guidelines for scientists seeking to control flow with microjets in any high-speed flow development object were introduced. Descriptions, findings, and analyses of the critical literature on supersonic vehicle applications are included in these guidelines. The categorization can provide a quick overview of the microjet controller study topics. Furthermore, researchers may provide comprehensive viewpoints and benchmarks for particular study topics via the difficulties and possibilities. In brief, these recommendations can assist researchers in developing new ideas, especially in the early phases of this field of study.

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