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Regenerative compressor machines: Overview of design parameters and factors affecting their efficiency (literature review)

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Abstract. Increasing demands for energy efficiency in industrial equipment and the need to reduce operating costs highlight the relevance of research into regenerative compressors – a class of turbomachinery that combines the advantages of dynamic and positive-displacement machines and has significant potential for widespread industrial application. Study aimed to systematise and analyse current scientific research in the field of regenerative compressors and pumps to identify the key factors influencing their efficiency. The study was based on analysis and comparison of the results of experimental and numerical studies published in peer-reviewed scientific journals, as well as on the application of computational fluid dynamics (CFD) as a modern digital tool for engineering analysis. Study established that the efficiency of regenerative compressors is determined by a combination of geometric and design parameters. The type and shape of the impeller, as well as the number and profile of the blades,

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influence the degree of pressure increase: the optimal number of blades lies within the range of 30-50, whilst blades of complex shape, despite their higher efficiency, complicate the manufacturing process. The dimensions and configuration of the working channel determine the intensity of circulation and the level of gas-dynamic losses – the height of the channel is a more decisive parameter than its cross-sectional area. The clearances in the flow path are critical: an increase in the axial and radial clearances from 0.15 mm to 0.2 mm leads to a reduction in performance of up to 50 %, which confirms the need to address them at design stage. CFD methods can be used to visualise complex spiral-like flow structures, identify sources of losses and optimise design solutions, thereby reducing costs of physical prototyping. The combination of analytical, experimental and CFD methods provides the basis for developing effective design approaches, which will ensure improved energy efficiency and expand the range of applications for these machines in industrial systems

Keywords: regenerative compressor; regenerative pump; regenerative hypothesis; numerical modelling; Ansys SFX; design optimisation

Introduction

Compressor equipment is an integral part of modern industrial systems and is central in supporting technological processes in the energy sector, the chemical industry, mechanical engineering and related sectors. At the same time, compressors are among the most energy-intensive pieces of equipment: their share of total electricity consumption at industrial enterprises can reach 30-40%. In this context, improving the energy efficiency of compressor equipment is not only an engineering necessity but also an economic and environmental one. A reduction in specific energy consumption by even a few percent can ensure significant resource savings at the level of an enterprise or an industry. Among the wide variety of compressor types, regenerative compressors occupy a special place, combining the characteristics of dynamic and positive-displacement machines. Their distinctive features include a simple design, the absence of surge, compactness and the ability to provide a relatively high degree of pressure increase with low working fluid flow rates. Despite these advantages, regenerative compressors have a comparatively low efficiency – typically in the range of 35-55% – which limits their wider industrial application. The complex flow structure in the flow path, significant sensitivity to geometric parameters and an insufficient methodological basis for comprehensive design optimisation highlight the need for further research in this field. Development of digital tools for engineering analysis, in particular computational fluid dynamics (CFD) methods, creates new opportunities for in-depth study of the operating processes of regenerative compressors and for identifying ways to improve their efficiency.

J.E. Adam *et al.* (2022) substantially contributed to research into the geometric parameters of regenerative compressors, studying the influence of various design parameters on the performance of a side-channel regenerative compressor stage. In particular, the researchers found that the shape of the blades and their angle of attack significantly affect the pressure ratio and isentropic efficiency. The results obtained highlight the significance of carefully selecting the impeller geometry at the initial design stage. Continuing this line of research, J.E. Adam *et al.* (2023) conducted a parametric study of the influence of the working channel geometry on the performance of a regenerative compressor. The authors varied the height, cross-sectional shape and length of the channel and found that the channel height is a more decisive parameter for mass flow than the cross-sectional area. At the same time, the study showed that the influence of individual channel parameters on isentropic efficiency is less pronounced and is mainly evident at high pressure values.

J. Nejadali (2021) applied the response surface method in combination with CFD to optimise the shape of aerodynamic-profile blades for a regenerative compressor. The results of the study showed that aerodynamic-profile blades can deliver higher efficiency compared to standard straight blades. However, the author noted that the complexity of manufacturing such blades may offset the performance advantages in terms of manufacturability and production costs. A. Salimi *et al.* (2023) conducted a multi-criteria optimisation of a regenerative pump with S-shaped blades using the response surface method. The researchers varied several geometric parameters simultaneously and found that the S-shaped blade configuration can provide a better balance between head and efficiency compared to traditional configurations. The results demonstrate the potential of applying multi-criteria optimisation methods to improve the design of regenerative machines. Q.-Q. Li *et al.* (2022) investigated the pressure pulsation characteristics in a regenerative pump as a function of the blade arrangement on the impeller. The authors found that an uneven blade arrangement can significantly reduce amplitude of pressure pulsations without a significant deterioration in head characteristics. This creates opportunities for reducing vibration and acoustic loads on the compressor's structural components under real-world operating conditions. L. Zhou *et al.* (2024) investigated, both numerically and experimentally, the effect of axial clearance on the performance of a regenerative pump. The researchers found that an increase in axial clearance leads to an increase in the intensity of bypass flows and a significant drop in the unit's head characteristics. The results of this study confirm that the axial clearance is one of the most critical parameters in the design of regenerative machines and requires careful monitoring both during manufacture and in operation. J. Zhang *et al.* (2024) conducted a quantitative analysis of energy losses in a regenerative compressor and developed an approach to predicting its operating characteristics. The researchers identified the main sources of losses in the flow path and determined their relative contribution to the machine's overall inefficiency. The proposed methodology can be used for targeted optimisation of design elements with the greatest potential for improving efficiency. W. Li (2025) investigated the effect of wall roughness on the performance of a regenerative pump using CFD modelling. Study determined that increasing the roughness of the internal surfaces of the flow path leads to an increase in hydraulic losses and a reduction in efficiency. The results obtained are of direct practical significance for the selection of materials and manufacturing technologies for the casing components of regenerative compressors, with the aim of minimising friction losses.

An analysis of the studies cited indicates that most of the research focuses on investigating the influence of individual geometric parameters on the performance of regenerative compressors and pumps. At the same time, issue of simultaneous optimisation across multiple parameters remains understudied: most authors vary the parameters sequentially, which prevents them from incorporating their mutual influence and finding the global optimum design. Furthermore, the comprehensive consideration of clearances in conjunction with other geometric parameters in CFD modelling remains an under-researched aspect. These gaps formed the basis for this study. Study aimed to conduct a comprehensive study and systematisation of scientific achievements in the field of regenerative compressors and pumps, to identify the key geometric and design parameters that determine their energy performance, and to justify promising avenues for improving these machines.

Study was conducted in the form of a systematic review. The international scientometric databases Scopus and Web of Science were used to compile the information base, and the search was conducted primarily using English-language queries based on the following key terms: "regenerative compressor", "side channel pump", "vortex compressor", "CFD optimisation" and "impeller geometry". The main criterion for selecting sources was that they had been published between 2020 and 2026, ensuring the relevance of the material considered. In addition, selected fundamental works from an earlier period were included – in particular, classic works on the theory of the regenerative hypothesis and the basic principles of flow component design – without which it is impossible to correctly interpret modern results and trace the evolution of approaches to the design of regenerative machines. A total of 51 scientific publications were analysed, including articles in peer-reviewed journals, proceedings of international conferences and institutional repositories. Sources were selected based on criteria of thematic relevance, scientific novelty and citation frequency in related research.

The study employs a range of general scientific and specialised methods. The method of systems analysis was used to organise the body of literature and identify interrelationships between design parameters and machine characteristics. Comparative analysis was used to compare the results of different research groups and to identify similarities and contradictions in the conclusions regarding the optimal values of geometric parameters. The method of generalisation was applied to formulate comprehensive conclusions based on the body of publications considered. A quantitative analysis of scientific publications determined level of scientific development in specific subject areas and identified gaps in existing research. The material has been organised into thematic sections: impeller design, channel geometry, separator, clearances and CFD modelling – which was used for a systematic coverage of the key aspects of regenerative compressor operation. The evolution of calculation methods has been analysed separately – from one-dimensional analytical models to three-dimensional CFD modelling verified on test benches – to assess their accuracy and limits of applicability at various stages of design.

Design Diagram and Classification of Regenerative Compressors

The design of a single-stage regenerative compressor (Fig. 1) comprises an impeller with blades evenly spaced around its circumference, as well as suction, discharge and working channels. A partition – known as a separator or baffle – is situated between the suction and discharge channels, ensuring they are kept separate. As noted by S. Vanyeyev *et al.* (2010), this design remains the basis for most modern regenerative machines. Despite its structural simplicity, the internal gas-dynamic processes in a regenerative compressor are complex: the working fluid moves along a spatial spiral trajectory, and each cycle between the blades and the channel is accompanied by momentum transfer, mixing and turbulent losses. This physical complexity explains why the accurate analytical prediction of the performance characteristics of regenerative machines remains an open scientific problem to this day. Notably, despite the significant volume of accumulated experimental and numerical data, a single, unified calculation methodology for regenerative machines of various types has not yet been developed – this is one of the key scientific gaps in this field.

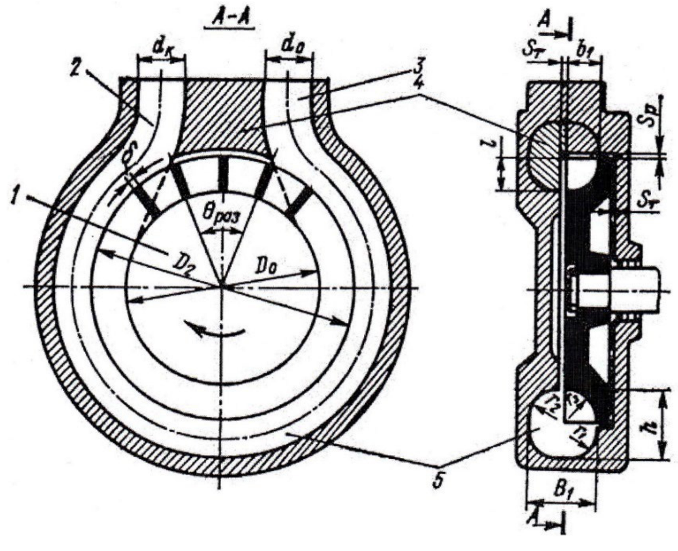
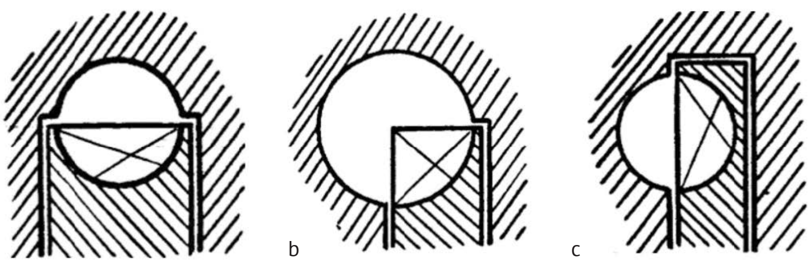


Figure 1. Schematic diagram of a regenerative compressor stage
Notes: 1 – impeller; 2 – discharge channel; 3 – suction duct; 4 – splitter; 5 – operating channel
Source: S.M. Vanyeyev *et al.* (2010)

Depending on the position of the casing's working channel in relation to the impeller blades, the flow paths of regenerative compressors are classified as peripheral, peripheral-lateral and lateral (Fig. 2). Compressors with a lateral channel arrangement have relatively high efficiency but low pressure. Peripheral channels provide higher pressures, although their efficiency is significantly lower. Peripheral-lateral channel arrangement is a compromise option, achieving an efficiency of up to 55% and a pressure coefficient ψ_{ad} = 1.6...3. M. Sreekanth *et al.* (2021), in their systematic review covering over 80 publications spanning 70 years, confirm this conclusion: the authors methodically compared the performance of different types of flow passages and concluded that the peripheral-lateral channel is the most balanced solution for a wide range of industrial applications. This conclusion is relevant: the advantage of the peripheral-lateral channel lies in the fact that the centrifugal effect is actively utilised in the peripheral section, resulting in a significant increase in pressure, whilst the lateral component facilitates the effective re-entry of the working fluid into the inter-blade space – thus ensuring that the entire channel area is utilised more uniformly in the energy exchange. At the same time, there is an absence in the literature of systematic comparative studies in which all three types of channels would be analysed under identical conditions using a single geometry; this complicates the quantitative justification of the advantages of the peripheral-lateral variant and represents a promising area for further research.



a b c

Figure 2. Main types of flow components in regenerative compressors
Notes: a – peripheral canal; b – peripheral-lateral canal; c – lateral canal
Source: S.M. Vanyeyev *et al.* (2010)

The shape of the flow section's profile in the meridional cross-section can be rectangular, circular or curved (Fig. 3). A rectangular cross-section is the simplest to manufacture, but is characterised by increased losses in the corner regions, where stagnation zones form. A circular cross-section ensures a smoother redistribution of velocities and a lower tendency for separation zones to form, which, according to W. Li (2025), has a positive effect on the level of hydraulic losses when operating under high-pressure conditions. A curved profile is an attempt to combine the advantages of both options. Thus, a common pattern emerges regarding the choice of cross-sectional shape: an increase in the aerodynamic efficiency of the channel shape is accompanied by greater manufacturing complexity, and each of the three options occupies a specific niche depending on the priorities: efficiency, manufacturability or compactness. M.M. Raheel & A. Engeda (2005), in their systematic study on the design of radial-bladed regenerative turbomachines, emphasise that the number of channels is increased primarily to boost capacity and flow rate, as well as to increase power output in turbine modes. Multi-channel flow sections are most easily implemented using a stage with an external peripheral channel; however, as the number of channels increases, the design of the separator becomes significantly more complex and the risk of cross-flow increases. It is worth noting the limited availability of quantitative data in the literature regarding the impact of the number of channels on performance – most publications focus on single-channel configurations, which represents a gap for applications with high performance requirements.

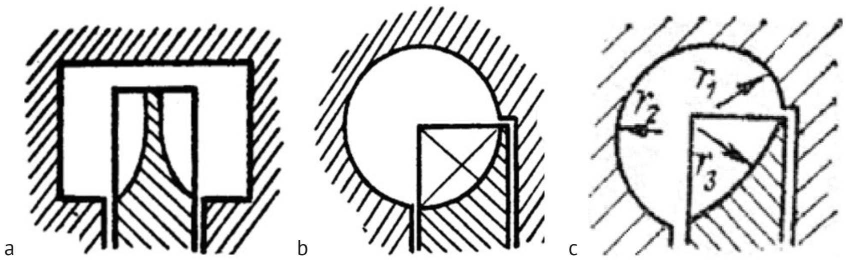


Figure 3. Shapes of the flow section profile in a meridional cross-section

Notes: a – rectangular duct; b – circular duct; c – curved duct

Source: S.M. Vanyeyev *et al.* (2010)

Regenerative turbomachines can be designed as single-flow, double-flow or multi-flow types. N.D. Karlsen-Davies & G.A. Aggidis (2016), in their fundamental review of regenerative annular pumps based on an analysis of over 120 sources, established that the use of double or multi-flow configurations makes it possible to relieve the rotor of radial forces and reduce the vibration load on the bearings. S. Münsterjohann *et al.* (2017) expanded on this idea by applying psychoacoustic evaluation criteria to the design of a low-noise side blower: the authors demonstrated that a symmetrical multi-flow blower configuration not only balances the force load but also significantly reduces the tonal components of noise, which is critical for medical and laboratory equipment. M. Raheel *et al.* (2003), whilst investigating the characteristics of single- and multi-stage regenerative compressors for natural gas transport, demonstrated that regenerative machines are competitive with centrifugal compressors in the range of low flow rates and high pressures: the measured pressure, for the same geometric parameters, increases proportionally with the number of stages in a multi-stage configuration, whilst efficiency decreases due to the accumulation of losses. Comparing the findings of these three research groups, a common pattern emerges: the transition from single-flow to multi-flow and multi-stage configurations expands the machine's functional capabilities, but is inevitably accompanied by either a reduction in efficiency or increased design complexity. This trade-off between productivity and efficiency in multi-stage designs remains unresolved and requires targeted research using multi-criteria optimisation methods. Thus, the choice of flow configuration and the number of stages is a complex design decision that simultaneously affects the mechanical reliability, hydraulic efficiency and acoustic characteristics of the machine.

The amount of energy transferred depends on the geometry and design parameters of the impeller and the casing components. M. Badami & M. Mura (2011), in the study on the development and validation of a one-dimensional model of a regenerative compressor for various devices, established that accurate consideration of geometric parameters – including the shape, arrangement and number of blades, as well as the dimensions of the annular channel – is crucial for adequate prediction of performance characteristics. The 1D model they developed demonstrated satisfactory agreement with experimental data for a wide range of geometries, confirming the validity of using simplified models in the early stages of design. At the same time, the authors note that the model exhibits systematic deviations at low flow rates, where non-linear effects become dominant. In the authors' view, this highlights the need to use three-dimensional CFD modelling to verify the results, particularly under non-standard operating conditions. To summarise the findings of this section, it should be emphasised that the structural layout and the type of flow path are the primary design decisions that determine the entire scope for further optimisation: the choice of channel type, cross-sectional shape and flow configuration effectively sets the upper limit of achievable efficiency, which cannot be significantly exceeded solely by optimising the geometry of the blades or clearances.

Effect of Impeller Geometry on Compressor Performance

Type and geometry of the blades directly affect the compressor's efficiency and determine the degree of pressure increase, as energy is transferred specifically from the impeller to the gas or liquid. G. Grabow (1975) established a fundamental relationship between the number of blades, their angle and the suction characteristics of regenerative pumps. Despite the age of these studies, the patterns identified by G. Grabow (1975) remain relevant and are used by contemporary researchers as a starting point. This indicates that the basic physics of momentum transfer in a regenerative machine is relatively stable and has not undergone any fundamental revision over the past five decades. It is worth noting that most contemporary studies of impeller geometry are highly specialised – they optimise one or two parameters for a specific geometry, without establishing generalised patterns suitable for use at the conceptual design stage.

Blade shape is one of the most debated parameters in the literature. J.E. Adam *et al.* (2022), using a systematic numerical experiment design that varied several geometric parameters simultaneously, found that blade geometry significantly influences the shape of the pressure characteristic: backwards-curved blades provide a more uniform pressure distribution and a wider range of stable operation, whilst straight blades have a steeper characteristic curve with a higher peak head at the design point. J. Nejadali (2021), using the response surface method in combination with three-dimensional CFD modelling to optimise airfoil-type blades, achieved an increase in isentropic efficiency of up to 8% compared with the baseline design featuring straight blades. The author systematically varied the angle of attack, profile thickness and curvature, and found that the angle of attack is the dominant parameter compared to the other variables. A. Salimi *et al.* (2023), building on this approach, applied multi-objective optimisation using the response surface method to a compressor with S-shaped blades and concluded that a simultaneous increase in pressure and efficiency is possible but requires a trade-off: maximum pressure is achieved at installation angles that slightly reduce efficiency, and vice versa. A common finding in the studies by J. Nejadali (2021), J.E. Adam *et al.* (2022) and A. Salimi *et al.* (2023) is that all three studies confirm the dominant role of the blade installation angle amongst the geometric parameters of the blade shape – this is a sufficiently reliable conclusion, as it has been obtained using three independent methods.

S.-Y. Jeon *et al.* (2019) adopted a different approach and developed a fundamentally new type of S-shaped blade, optimised for a microbubble pump. The research methodology was based on a combination of CFD modelling with an optimisation algorithm and verification using a physical prototype. The authors demonstrated that the S-shaped form helps to reduce cavitation and extend the operating range, although it does decrease the peak efficiency at the design point slightly compared with standard blades. Comparing the results of S.-Y. Jeon *et al.* (2019) and A. Salimi *et al.* (2023), a contradiction can be observed: both studies demonstrated the advantages of the S-shaped profile, but in different aspects – S.-Y. Jeon *et al.* (2019) addressed cavitation resistance, whilst A. Salimi (2023) emphasised simultaneous increase in head and efficiency. This is explained by the different operating conditions: the first study focused on pumping applications with a liquid medium, whilst the second focused on compressor applications with a gaseous medium. It is reasonable to assume that a direct comparison of these results is not valid without covering differences in Reynolds and Mach numbers. This circumstance highlights a significant scientific gap: the literature lacks studies that systematically compare the efficiency of different blade profiles under identical dimensionless similarity parameters, which makes it impossible to directly transfer results between applications.

K. Chen *et al.* (2022) investigated the effect of the blade tip undercut angle using three-dimensional unsteady CFD modelling, verified on a test bench. The researchers found that an increase in the undercut angle from 0° to 30° leads to a redistribution of high-velocity zones within the side channel and a change in secondary vortex structures. At angles of 15-20°, an optimal balance is observed between the level of turbulent losses and energy transfer efficiency, manifested in a 3-5% increase in isentropic efficiency. Although complex-shaped blades are generally more efficient, one of the main advantages of regenerative compressors – their structural simplicity – should be considered. Q.-Q. Li *et al.* (2022), based on an analysis of the match between the impeller and the duct, emphasise the need for a balance between geometric complexity and manufacturability; consequently, from a practical design perspective, the straight blade (Fig. 4) remains a sensible choice for most industrial applications, where manufacturability and cost take precedence over maximising efficiency. In the authors' view, the optimal strategy for selecting the blade shape should be determined as early as the technical specification stage: if maximum efficiency is the priority, the use of profiled blades verified via CFD is justified; if cost and service life are the priorities, straight blade with an optimised installation angle should be preferred.

The number of impeller blades is another key parameter. Q.-Q. Li *et al.* (2022), using unsteady CFD modelling and analysis of pressure pulsations via the fast Fourier transform, found that increasing the number of blades from 24 to 48 leads to a significant reduction in the amplitude of the dominant pressure pulsation frequencies, which is beneficial in terms of vibration reliability. At the same time, the contact surface area increases and, consequently, so do friction losses. J. Nejadrajabali *et al.* (2016), using flow pattern analysis and comparative CFD modelling, recommend a range of 30-50 blades as the optimal compromise. J. Pei *et al.* (2019), in their study of the effect of the side channel wrap angle, arrived at a similar optimum – 36 blades for the geometry under investigation. The agreement between the recommendations of these two independent research groups regarding the optimal range of blade count provides significant confirmation of the reliability of the results obtained, although it should be noted that the specific optimal number of blades depends on the wheel dimensions, channel height and operating mode. Notably, Q.-Q. Li *et al.* (2022) approached this issue from the perspective of dynamic characteristics, whilst J. Nejadrajabali *et al.* (2016) and J. Pei *et al.* (2019) – from perspective of static efficiency, and all three groups converge on the same range. This is one of the most reliable quantitative results in this field, suitable for direct application in engineering practice.

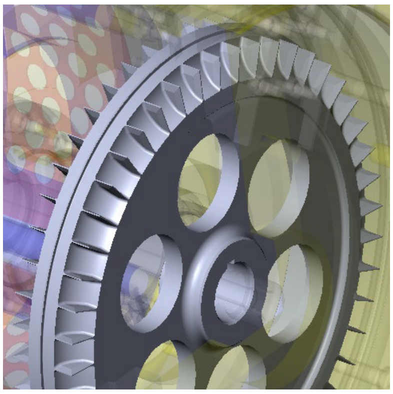


Figure 4. Straight peripheral-lateral blades
Source: compiled by the authors

The size of the impeller (outer diameter) determines the pressure increase within the machine via the tip speed of the blades. M.-W. Heo *et al.* (2016), using multi-objective optimisation that simultaneously accounts for aerodynamic and aeroacoustic criteria, demonstrated that increasing the diameter increases the pressure head but simultaneously increases the level of broadband noise due to the rise in circumferential velocity. In their study, the optimal diameter was determined as a compromise between these two criteria. F. Zhang *et al.* (2021), applying vortex identification methods to the results of CFD modelling, showed that reducing the impeller diameter whilst keeping other parameters constant leads to a decrease in the intensity of circulation vortices in the side channel, which reduces the efficiency of mass transfer between the impeller and the channel. Thus, the impeller size affects not only the kinematics but also the qualitative structure of the internal flow. When comparing studies by M.-W. Heo *et al.* (2016) and F. Zhang *et al.* (2021), it is worth noting that both studies reveal a mutually reinforcing effect: an increase in diameter simultaneously improves the hydraulic characteristics and worsens the acoustic characteristics; that is, diameter is a parameter with a clearly defined conflict of objectives. This makes it a natural candidate for multi-criteria optimisation rather than single-parameter tuning.

Methods for the systematic optimisation of impeller geometry are becoming increasingly widespread. H. Quan *et al.* (2020), applying an orthogonal design of experiments method to a regenerative pump, simultaneously varied the blade angle, the number of blades and the impeller diameter, and determined their relative importance: the number of blades is the most influential parameter (42% contribution), followed by the blade angle (35%) and the impeller diameter, which has the least influence (23%). The orthogonal approach can significantly reduce the number of CFD calculations required compared with a full factorial design, whilst maintaining the statistical validity of the conclusions. Building on this methodology, J. Yang *et al.* (2025) applied the orthogonal method to the numerical optimisation of a regenerative pump impeller design and found that the optimal combination of geometric parameters increases head by 7.3% and efficiency by 4.1% compared with the original design. When comparing the two studies, it is worth noting the methodological continuity and convergence of conclusions regarding the priority of parameters, which enhances confidence in the recommendations obtained. Notavly, the hierarchy of parameter influence established by H. Quan *et al.* (2020) – number of blades, angle, diameter – is consistent with the general conclusion regarding the dominant role of the number of blades, as derived from an analysis of the works by J. Nejadrajabali *et al.* (2016) and J. Pei *et al.* (2019). Such consistency in the results obtained using different methods and by different research groups suggests that this hierarchy has been reliably established. At the same time, it is worth noting that all the optimisation studies considered were conducted for specific geometries and operating conditions, and the question of whether the optimal values obtained can be extrapolated to other scales and conditions remains open.

Geometric Parameters of the Working Channel and Their Impact on Efficiency

The working fluid enters the impeller housing's working channel via the suction pipe and then flows into the inter-blade channels of the impeller. In the inter-blade channels, the mechanical energy of the drive is converted into the kinetic and potential energy of the gas. Centrifugal forces direct the gas particles predominantly in a radial direction from the inter-blade space into the working channel of the casing, where the kinetic energy of the flow is subsequently converted into pressure energy. The blade suction angle significantly influences the degree of symmetry of the secondary vortex motion in the channel: at angles close to 90°, the most uniform velocity distribution and the lowest losses in the recirculation zone are observed. This result is a substantial guideline for design; however, it is worth noting that there is a lack of studies in the literature that systematically vary the suction angle over a wide range for different types of channels, which limits the possibility of generalising this conclusion.

Mechanism of the spiral trajectory of the working body is a defining feature of the regenerative compressor, distinguishing it from all other classes of dynamic machines. W. Li (2025), in a CFD modelling of a regenerative pump taking into account the roughness of the channel walls, quantitatively assessed the influence of this mechanism: the repeated interaction of the blades with the same working fluid particles results in the regenerative compressor developing 3-5 times greater pressure than a centrifugal compressor of the same dimensions at the same rotational speed. This result is consistent with the classical theoretical estimates by W.A. Wilson *et al.* (1955); however, W. Li (2025) further demonstrated that the roughness of the channel walls can reduce this effect by 10-18%, depending on the Reynolds number and relative roughness. This is a substantial practical finding for manufacturers, as it highlights the significance of the quality of the channel surface finish. Despite practical significance of this parameter, the influence of roughness on the performance of regenerative machines remains under-researched in the literature – W. Li (2025) is, in fact, the only modern publication on this topic, indicating a significant scientific gap.

The parameters of the working channel – height, cross-sectional shape, length and curvature – directly influence the intensity of the working fluid circulation and the level of gas-dynamic losses. J.E. Adam *et al.* (2022), applying a systematic Design of Experiments (DoE) approach to a regenerative compressor and simultaneously varying the height, width and cross-sectional shape of the channel, established that the influence of channel geometry on performance is complex and non-linear: individual parameters exhibit significant interaction with one another, meaning that the optimal value of one parameter depends on the value of another. In particular, the authors found that the optimal channel height is a function of the number of blades: as the number of blades increases, the optimal channel height also increases. This interaction explains why attempts to optimise the channel geometry by varying just one parameter often yield conflicting results across different studies. This conclusion is substantial from a methodological point of view: it means that single-parameter studies of channel geometry, which constitute most publications in this field, are of limited value for practical design.

Working channel height is more substantial in determining mass flow rate than its cross-sectional area. J. Zhang *et al.* (2024), whilst conducting a quantitative analysis of energy losses in a regenerative compressor using the entropy production method, found that reducing the channel height whilst maintaining the cross-sectional area leads to an increase in local entropy dissipation in the secondary circulation zone, which is the primary mechanism of energy transfer. This is explained by the fact that a reduction in the duct height increases the velocity gradient in the vertical direction and, consequently, increases viscous losses. The authors quantitatively established that losses in the secondary circulation zone account for 35-45% of the compressor's total losses, confirming their dominant role. This result is substantial from a design perspective, as it indicates that optimisation efforts should primarily be directed towards minimising losses specifically in the secondary circulation zone. J. Wang *et al.* (2023) independently confirm this conclusion: in their comparative study, the lowest efficiency values are also observed for configurations with the minimum channel height. The consistency of the results obtained by J. Zhang *et al.* (2024) and J. Wang *et al.* (2023) – using different methods and for different machine configurations – suggests that the channel height is the most critical geometric parameter of the flow section among all those considered.

Cross-sectional shape of the working channel affects the compressor's performance through the distribution of velocities and the structure of secondary vortices. W. Li (2025) found that a circular cross-section provides more favourable flow conditions due to a more uniform velocity distribution and reduced local losses compared to a rectangular channel; the difference in efficiency between these two cross-sectional shapes, for the same channel height, is 2-4% at the design point. Q. Li *et al.* (2024), applying the Proper Orthogonal Decomposition (POD) method to the results of unsteady CFD simulations, demonstrated that the cross-sectional shape significantly influences the spatial structure of the dominant pressure pulsation modes: in channels with a circular cross-section, the dominant modes are more symmetrical and have a lower amplitude, which helps to reduce the vibration load. Comparing these results with the data from J.E. Adam *et al.* (2023), a general conclusion can be drawn: the cross-sectional shape is a substantial parameter, but its influence on static efficiency is less significant than that of the duct height, whilst it has a more significant impact on dynamic characteristics (pressure pulsations, noise). Thus, the choice of cross-sectional shape should be made addressing priorities of the specific application: if noise or vibration levels are critical, a circular cross-section is preferable; if manufacturability and production cost are the priority, a rectangular cross-section remains a reasonable choice.

The isentropic efficiency of a regenerative compressor exhibits a more complex dependence on the geometric parameters of the channel. J. Wang *et* *al.* (2023), comparing single- and multi-stage configurations of side-channel pumps at different channel heights, confirmed that the lowest efficiency values are observed for variants with the minimum side-channel height, whilst an increase in height leads to an increase in efficiency. Notably, in multi-stage configurations this effect is amplified, as losses in each stage accumulate. M. Badami & M. Mura (2012), based on a comparison of 1D and 3D CFD models of a regenerative blower for fuel cells, noted that three-dimensional modelling is relevant for accurate prediction of performance characteristics under non-design operating conditions. This highlights the fundamental limitations of one-dimensional models when analysing the influence of channel geometry – they may yield satisfactory results at the design point, but systematically fail at low and high flow rates, where three-dimensional effects are dominant. To summarise the findings of this section, a key pattern should be emphasised: of all the channel's geometric parameters, height has the greatest influence on static characteristics, whilst the cross-sectional shape determines the machine's dynamic behaviour. This hierarchy of parameter influence serves as a substantial guide for setting priorities when designing and optimising regenerative compressors; however, it must be acknowledged that most existing studies were conducted for a limited range of geometries and do not provide a complete picture of the interaction of all channel parameters simultaneously.

Design Features of the Separator and Their Impact on the Working Process

The separator (Fig. 5) is an essential structural component of the flow path in a centrifugal compressor; its function is to separate the discharge zone from the suction zone and to prevent the compressed gas from flowing in the opposite direction. However, a certain amount of gas inevitably penetrates the suction zone through the gaps between the rotor and the casing and through the inter-blade space, which is a source of volumetric losses. An analysis of existing research identified three interrelated areas of study concerning the separator: the influence of the wrap angle on hydraulic characteristics, the physics of "dead zone" formation, and the effect of the separator on transient force loads. These areas have developed to some extent in parallel and have only begun to be considered comprehensively in the latest studies. F. Zhang *et al.* (2020), using the entropy production method to quantitatively analyse energy losses in a side-channel pump at different channel wrap angles, found that the amount of leakage through the separator decreases as the radial clearance between the separator and the impeller decreases and as the separator wrap angle increases. However, the authors also demonstrated that increasing the separator angle simultaneously reduces the effective working section of the channel and leads to an 8-12% drop-in mass flow rate for every 15° increase in the angle. Thus, optimisation of separator angle is a problem with two mutually conflicting objectives.

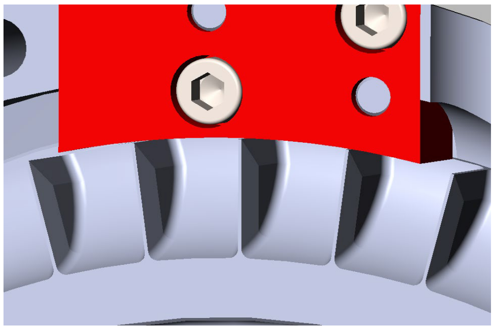


Figure 5. Separator (cutter)
Source: compiled by the authors

J. Pei *et al.* (2019), in a study of effect of the side channel coverage angle, modelled three geometric variants of the pump with separator angles of 15°, 30° and 45°, using unsteady three-dimensional CFD modelling with the results verified on a test bench. A comparative analysis showed that a 15° angle ensures the most intense mass transfer throughout the flow path: the authors quantitatively measured the intensity of secondary circulation by analysing the velocity vector field and found that at a 15° angle it is 18% higher than at a 45° angle. The 15° and 30° configurations demonstrate higher static pressure values in the outlet region – by 6-9% respectively – due to the greater length of the side channel and a longer duration of energy exchange. These results can be considered reliable and well-founded, as the authors conducted parallel measurements on a physical test rig, and the discrepancy between the CFD results and the experiment does not exceed 4%. A comparison of the approaches by F. Zhang *et al.* (2020) and J. Pei *et al.* (2019) reveals methodological complementarity: the former work quantitatively describes the mechanism of losses using the entropy method, whilst the latter quantitatively determines the optimum by comparing specific geometric variants. Together, they provide a sufficiently comprehensive picture to inform practical recommendations regarding the choice of the separator angle.

A. Fleder & M. Böhle (2012), based on the results of a systematic study of the internal flow structure in a side-channel pump using particle image velocimetry (PIV) and CFD, confirmed that minimum static pressure values are recorded in the separator zone for all geometric variants. The authors explained this phenomenon by the fact that, in the separator zone, the exchange of kinetic and potential energy between the blade channels and the annular channel is interrupted, with the result that energy which was not transferred in the preceding zone is irretrievably dissipated. A substantial contribution by A. Fleder & M. Böhle (2012) was that they were the first to quantitatively describe the minimum-pressure zone as a "dead zone" with zero net energy exchange – this is conceptually relevant for determination of why reducing the separator angle generally increases the machine's efficiency. Notably, study by A. Fleder & M. Böhle (2012) is one of the few studies in which the PIV method has been applied to the investigation of regenerative machines, which was used for verification of CFD results at the level of the velocity field, rather than merely integral characteristics. Expanding the use of such verification is a substantial methodological task for future research.

K.A. Adu-Poku *et al.* (2022), whilst investigating the internal flow mechanisms and transient force distribution in a side-channel pump using transient CFD with regenerative structure analysis, demonstrated that the design of the separator significantly influences the transient hydrodynamic forces acting on the impeller. In particular, the authors found that sharp pressure gradients arise in the separator region, which are the source of variable forces with a frequency that is a multiple of the number of blades and the rotational frequency. These forces can cause resonant phenomena if their frequency matches the natural frequencies of the structure. A. Javadi *et al.* (2026), using the Large Eddy Simulation (LES) method – which is a significantly more accurate but also much more resource-intensive approach compared to RANS – confirmed and elaborated on this result: the separator is a zone of heightened turbulent activity, where the kinetic energy of large eddies is actively transferred to smaller scales and dissipated as heat. According to estimates by A. Javadi *et al.* (2026), between 15 and 22% of the compressor's total losses are dissipated in the separator zone, depending on the operating mode. A comparison of the results of K.A. Adu-Poku *et al.* (2022) and A. Javadi *et al.* (2026) reveals complete qualitative agreement, whilst LES modelling provides a more detailed picture of the distribution of dissipation within the separator zone. A gap in the research remains: there are no studies dedicated to the targeted profiling of the separator edges as a means of reducing turbulent losses; although the physical nature of the losses in this zone has already been well described, the question of the optimal shape of the edges is scarcely addressed in the literature.

According to the authors, combination of the results of these studies provides a substantial design conclusion: the angle of the separator should be selected as the minimum permissible from a structural point of view (2-3 blade pitches), whilst the geometry of the separator's leading and trailing edges must be carefully profiled to reduce the intensity of separation phenomena and the associated losses. Reducing the wrap angle from 45° to 15° results in more intense flow exchange, higher static pressure values and lower hydraulic losses, which ultimately improves the machine's hydraulic performance. The findings of K.A. Adu-Poku *et al.* (2022) raise a substantial point: an excessive reduction in the separator angle without corresponding profiling of its edges may exacerbate transient force loads on the wheel due to the sharpening of pressure gradients at the boundary of the "dead zone". Consequently, the final choice of angle must be made addressing overall impact on all characteristics, including vibrational and acoustic ones.

Effect of Clearances in the Flow Path on Compressor Performance

Clearances in the flow path of a regenerative compressor are among the most sensitive design parameters, significantly affecting performance, compression efficiency and energy losses. Analysis of existing research has identified three main areas of focus: the quantitative determination of the proportion of losses due to clearances in the overall loss balance; the influence of clearances on the machine's dynamic characteristics; and the specific characteristics of clearances in hydrogen applications. It is noteworthy that all three areas have developed in parallel and are only now beginning to be considered in relation to one another. L. Zhou *et al.* (2024), using a combination of three-dimensional unsteady CFD modelling and experimental measurements on a test bench for a regenerative pump with five different axial clearance values in the range of 0.1-0.5 mm, demonstrated that the relationship between performance and clearance is non-linear: in the range of small clearances (0.1-0.2 mm), the increase in performance as the clearance decreases is significant (up to 15% for every 0.05 mm), whilst for large clearances (over 0.3 mm) this sensitivity decreases. The authors also found that a change in the axial clearance affects not only the volumetric efficiency but also the shape of the pressure characteristic: as the clearance increases, the steepness of the characteristic decreases, which may lead to unstable operation in a parallel configuration with other blowers.

J. Zhang *et al.* (2024), in a quantitative analysis of energy losses in a regenerative compressor using entropy method for various values of axial and radial clearances, found that losses due to clearances account for 28-40% of total hydrodynamic losses depending on the operating mode, and that this proportion increases with rising rotational speed. Notably, the authors were able to quantify the contributions of the axial and radial clearances: the axial clearance accounts for 70-75% of the total losses due to clearances, whilst the radial clearance contributes only 25-30%. This result provides a substantial practical guideline: during design and manufacture, the axial clearance must be controlled as the dominant factor. W.-Y. Zhang & Z.-H. Li (1991) established an analytical relationship between the magnitude of the axial clearance and the characteristics of a regenerative pump, which is generally consistent with modern CFD results, indicating the reliability of classical analytical approaches as a first approximation.

J. Wang *et al.* (2023), when comparing single-stage and multi-stage configurations of side-channel pumps, found that in multi-stage configurations the effect of clearances on head pulsations is significantly more pronounced than in single-stage ones: for the same clearance value, the amplitude of pulsations in a two-stage configuration is 40-60% higher than in a single-stage one. This is because, in a multi-stage configuration, flow through the clearances of the first stage disturbs the inlet field of the second stage, amplifying transient phenomena. Z.C. Zhu *et al.* (2001), in their early theoretical and experimental study of low-flow regenerative pumps, reached a similar conclusion regarding the significant influence of the gap on external characteristics, confirming that this pattern is not specific to a particular type of machine or operating mode, but is common to the class of regenerative machines. When comparing the results of J. Wang *et al.* (2023) and Z.C. Zhu *et al.* (2001), it is worth noting a substantial pattern: despite differences in methodology and a gap of more than twenty years between the publications, both studies confirm the general nature of the effect of clearances, which gives this conclusion the status of a well-established fact, suitable for direct use in design.

V.S. Sitalo & S.M. Vanieiev (2025) conducted a comprehensive analysis of the effect of the magnitude of the axial and radial clearances along the entire length of the flow path between the impeller and the compressor casing, which had an outer diameter of 250 mm, using three-dimensional CFD modelling in ANSYS CFX. The authors modelled two clearance options – 0.15 mm and 0.2 mm – and compared them with an idealised case with no clearances. The results are revealing: with a clearance of 0.15 mm, the compressor's performance decreases by 23% compared with the idealised case, and with a clearance of 0.2 mm, by 50% (Fig. 6). Such a sharp drop in performance with an increase in the clearance of just 0.05 mm is evidence of high sensitivity of regenerative machines to manufacturing precision. A comparison with the results of L. Zhou *et al.* (2024) shows qualitative agreement – both studies reveal a non-linear dependence with increased sensitivity at small clearances – which confirms the general nature of this pattern regardless of the type of working medium (liquid or gas). Notably, both studies – L. Zhou *et al.* (2024) and V.S. Sitalo & S.M. Vanyeyev (2025) – were conducted for specific geometries and do not cover the full range of impeller diameters, which limits the generalisability of the results. The development of generalised dimensionless relationships between the relative clearance and the relative reduction in performance is a promising area for further research.

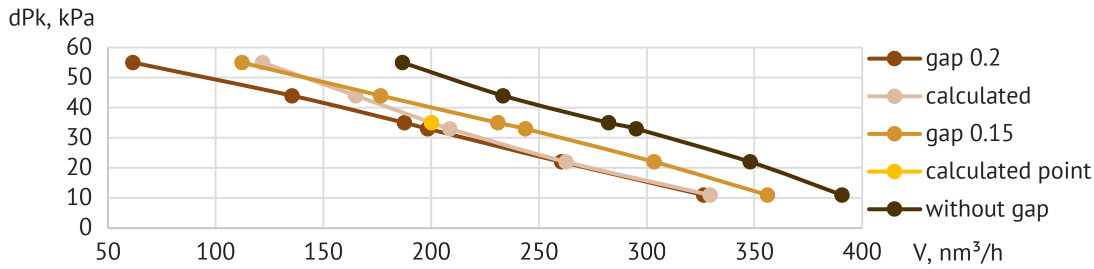


Figure 6. Compressor performance at different clearances in the flow path

Source: V.S. Sitalo & S.M. Vanyeyev (2025

Studies on regenerative machines for fuel cell systems emphasise issue of clearances. X. Yu *et al.* (2022), whilst conducting an experimental study into the effect of hydrogen recirculation on the performance of a PEMFC fuel cell, found that the accuracy with which the recirculation blower maintains the set hydrogen flow rate is critical for stable stack operation: a deviation in the recirculation flow rate of more than 8% from the calculated value leads to a significant reduction in fuel cell efficiency and an uneven distribution of membrane moisture. Since cross-flow through the gaps is the main source of flow instability, the results of X. Yu *et al.* (2022) indirectly confirm the need for strict control of the gaps in hydrogen pumps. Y. Chen *et al.* (2024), investigating the influence of the geometric parameters of a regenerative hydrogen pump in a PEMFC system using three-dimensional CFD with variations in the axial gap, quantitatively confirmed this conclusion: an increase in the axial clearance of 0.05 mm reduces the hydrogen recirculation coefficient by 11-15%, which is unacceptable for fuel cell systems with stringent stability requirements. Comparing the results of Y. Chen *et al.* (2024) with the data from V.S. Sitalo & S.M. Vanyeyev (2025) for an air compressor, it was found that hydrogen blowers are twice as sensitive to the gap size, which further justifies the need to establish separate, stricter tolerances for this class of machines.

X. Liang *et al.* (2024), whilst investigating the influence of design parameters on the efficiency of a regenerative blower for hydrogen recirculation in PEMFC fuel cells using transient CFD simulations verified on a test bench, found that the issue of clearances is particularly critical in hydrogen blowers: due to low dynamic viscosity of hydrogen (14 times lower than that of air), flow through gaps is proportionally greater for the same absolute gap values. Y. Chen *et al.* (2025) confirmed this finding, demonstrating that when switching from air to hydrogen, the efficiency of a regenerative compressor decreases by 8-12% with the same design clearances, and recommended reducing the permissible axial clearance for hydrogen blowers to 0.05-0.08 mm. The convergence of the findings by X. Liang *et al.* (2024) and Y. Chen *et al.* (2025), obtained independently and using different methods, lends these recommendations a high degree of credibility. It is appropriate to regard this result as substantial from a practical point of view: it means that design standards for clearances developed for air compressors cannot be automatically applied to hydrogen applications without revision. This is a fundamental caveat for design engineers in the field of hydrogen energy.

Thus, optimisation of clearances in the flow path is a complex task exceeding the scope of clearance reduction. It is necessary to address type of working medium, operating mode, design constraints on manufacturing accuracy, thermal deformation due to heating, as well as the risk of jamming at small clearances. To summarise the findings of this section, it is worth noting that clearances are the only parameter among those considered where the effect on the machine's performance is both the most significant and the least controllable in practice – due to the influence of wear, thermal deformations and manufacturing tolerances. Incorporation of clearances is an essential step in the creation of CFD models: calculations without clearances consistently yield overly optimistic results and cannot be used to quantitatively predict the performance of a real machine.

CFD Studies of Regenerative Flow Machines

Research into the operation of regenerative compressors began with a theoretical analysis of their gas dynamics. W.A. Wilson *et al.* (1955) proposed a theoretical model of the fluid-dynamic mechanism of regenerative pumps based on a pulsation approach, which became the first mathematically rigorous attempt to describe the circulation of the working fluid between the blades and the channel. Despite its age, this work is still cited in contemporary literature as a conceptual foundation, which attests to its fundamental significance. T. Meakhail *et al.* (2003), continuing this line of research, conducted a systematic study of the circulation flow in a regenerative pump using the PIV method and steady-state CFD modelling. The authors were the first to quantitatively describe the three-dimensional structure of the circulation and established that the actual trajectory of fluid particles is more complex than predicted by the simple spiral model proposed by W.A. Wilson *et al.* (1955): within a single blade pitch, the fluid undergoes not one but 1.5-2 complete circulations, which explains the more efficient energy transfer compared with theoretical estimates. In parallel, one-dimensional models based on the theory of angular momentum were developed – M. Badami & M. Mura (2011) demonstrated that such models are capable of reproducing the general shape of the pressure-flow characteristic with acceptable accuracy (an error of up to 10% at the design point), but systematically deviate in non-design operating conditions. The fundamental limitation of one-dimensional approaches is determined by the fact that they are unable to reproduce the three-dimensional structure of secondary circulation and, consequently, cannot quantitatively assess the influence of the channel's geometric parameters on local losses. Thus, the evolution of computational methods from the impulse theory of W.A. Wilson *et al.* (1955) through 1D models to three-dimensional CFD represents a sequential increase in the level of physical detail, whereby each new approach does not supersede previous one, but rather defines the limits of its applicability.

F.J. Quail *et al.* (2010; 2011) were among the first to systematically apply CFD to regenerative pumps. In their 2010 paper, the authors used three-dimensional CFD to analyse the flow structure and verified the results by comparing them with PIV measurements of the circulation. They found that CFD modelling qualitatively reproduces the main regenerative structures, but quantitative agreement depends on the choice of turbulence model. In their paper, F.J. Quail *et al.* (2011) developed a one-dimensional analytical model of torque exchange and compared it with three-dimensional CFD: the one-dimensional model showed satisfactory accuracy at the calculation point (a deviation of 5-8%) but was significantly inaccurate at low flow rates. M. Insinna *et al.* (2018) expanded on this comparison, demonstrating that for engineering design at the conceptual stage, the one-dimensional model is appropriate due to its speed, whilst at the detailed design stage, three-dimensional CFD is relevant. It is worth agreeing with this conclusion: a rational design strategy lies in the sequential application of both approaches – 1D for rapid parametric analysis and 3D CFD for final verification and optimisation. Notably, conclusion regarding the appropriateness of a two-stage approach has been confirmed by three independent research groups – F.J. Quail *et al.* (2011), M. Badami & M. Mura (2012), and M. Insinna *et al.* (2018) – which lends it the status of a sufficiently reliable methodological recommendation.

M. Badami & M. Mura (2012) conducted an in-depth comparison of 1D and 3D approaches for a regenerative blower for fuel cells. The methodology involved developing a proprietary 1D model, comparing it with three-dimensional CFD simulations, and verifying both approaches on a test bench. The authors emphasised that 3D CFD is essential for accurately predicting performance at low flow rates, where separation phenomena and reverse flows determine the behaviour of the machine. D. Griffini *et al.* (2015), using CFD to develop the design of a regenerative flow compressor, made a substantial observation: the Mach numbers in various elements of the compressor are around 0.5, and neglecting the compressibility effect leads to a systematic error of up to 7% in predicting the pressure rise. This is a fundamental caveat for researchers using incompressible CFD solvers to model regenerative compressors, a common practice due to its simplicity. Notably, despite the obviousness of this caveat, a significant proportion of publications appearing since the work by D. Griffini *et al.* (2015) continue to apply incompressible models without proper justification – this is a systemic methodological problem within the field that requires the attention of peer reviewers and journal editors.

C.-M. Jang & H.-J. Jeon (2014), whilst investigating the effect of blade pitch angle and tip thickness using steady-state CFD with bench testing, examined three different angles (14°, 18° and 22°) and found that an angle of 18° provides the best compromise between pressure increase and efficiency. Regarding tip thickness: 1 mm provides a better pressure increase than 2 mm and 3 mm. C. Lee & H.G. Kil (2014), whilst investigating a regenerative blower for a fuel cell system using CFD, found that when designing such machines, it is necessary to align the blower's aerodynamic characteristics with the dynamics of the fuel cell: the blower must provide the required flow rate across a wide range of back-pressure values, which is a more stringent requirement than in conventional industrial applications. The authors demonstrated that standard geometric recommendations for industrial blowers are not always optimal for fuel cell applications, and recommended separate CFD optimisation for each type of application. M. Sreekanth *et al.* (2021), in their comprehensive review, systematised the results of CFD studies and emphasised that the existing CFD data set for regenerative machines is heterogeneous: different research groups use different turbulence models, meshes and boundary conditions, which complicates a direct comparison of results.

One substantial area of application for regenerative blowers is life support systems. M.G. Izenson *et al.* (2011) developed and investigated a regenerative blower for ventilating an EVA (extravehicular activity) spacesuit, where a regenerative machine is the only technically viable option due to the combination of requirements for low mass, compactness and the ability to operate in microgravity conditions. The methodology included analytical design, CFD verification and testing of the prototype under conditions simulating extravehicular activity. It was established that the developed blower provides the required flow rates of CO_2 and O_2 across the range of mission conditions, whilst weighing less than 0.5 kg. M.G. Izenson *et al.* (2012) continued this research and conducted endurance and parametric tests on the EVA blower, establishing that the unit maintains satisfactory performance after 500 hours of operation without maintenance. Comparing the two studies, it is noted that they cover the full cycle from design to endurance validation – this is an example of a methodologically comprehensive study that provides a reliable basis for the implementation of regenerative blowers in mission-critical systems. Together with the findings of C. Lee & H.G. Kil (2014) and M. Badami & M. Mura (2012), these studies convincingly demonstrate that regenerative compressors are a competitive solution not only for industrial applications but also for systems with heightened requirements for reliability and compactness. At the same time, it must be acknowledged that research into the resource characteristics of regenerative machines is limited in the literature – studies by M.G. Izenson *et al.* (2011; 2012) remain only publications presenting a full cycle of reliability validation, which constitutes a significant gap for applications with heightened reliability requirements.

A. Javadi *et al.* (2026) improved the accuracy of CFD modelling by applying the Large Eddy Simulation (LES) method to a side-channel pump under several operating conditions. Compared with traditional RANS models (SST k-ω), LES modelling yielded significantly more accurate results in non-design operating conditions: the deviation from the experimental data for head did not exceed 2% (compared with 8-12% for RANS). The authors demonstrated that RANS models systematically underestimate the level of turbulent kinetic energy in flow separation zones (the separator zone and the outlet of the blade channel), which is the cause of their systematic errors. At the same time, the authors note that LES modelling requires 50-100 times more computational resources than RANS, which limits its practical application in engineering calculations. Q. Li *et al.* (2024), applying the POD method to the results of unsteady CFD simulations of a regenerative pump, found that the first three eigenmodes account for over 85% of pressure pulsation energy. This information is beneficial for design of active pulsation damping systems and for fault diagnosis. K.A. Adu-Poku *et al.* (2022), applying vortex identification methods (Q-criterion, λ2-criterion) to the results of unsteady CFD simulations, found that the structure of vortex formations in a side-channel pump depends significantly on the blade shape and directly determines the nature of the unsteady forces. T.-G. Lim *et al.* (2015) combined CFD modelling with aeroacoustic noise analysis and established a link between the vortex structures arising in the separator region and the dominant frequencies of the blower's acoustic noise. This study is one of the few to establish a quantitative correlation between CFD results and acoustic characteristics, which is relevant for applications with stringent noise requirements. M. Kumar *et al.* (2022), in a coupled fluid-structure interaction (FSI) analysis of a regenerative compressor and pump, demonstrated that the regions of maximum mechanical stresses in the impeller correlate with the regions of elevated hydrodynamic pressure identified by CFD modelling. This highlights the need to address FSI effects when designing compressors for applications with stringent service life requirements.

A general analysis of the evolution of CFD research into regenerative compressors formed several relevant conclusions. Firstly, CFD methods have progressed from qualitative visualisation of the flow to quantitative prediction of performance characteristics with an accuracy approaching that of physical experiments. Secondly, the choice of turbulence model is critical: RANS models are acceptable for steady-state conditions, but LES or hybrid RANS-LES approaches are necessary for unsteady conditions and the accurate analysis of transient phenomena. Thirdly, accounting for compressibility is essential even for subsonic flows at Mach numbers above 0.3. Fourthly, lack of standardised CFD verification protocols for regenerative machines significantly limits the ability to accumulate generalised knowledge in the field – since results obtained under different boundary conditions, meshes and turbulence models are fundamentally incomparable. According to the authors, further progress in CFD research into regenerative compressors lies in the application of machine learning methods to accelerate parametric optimisation and in the development of hybrid models that combine the accuracy of LES with acceptable computational costs.

Conclusions

An analysis of scientific research in the field of regenerative compressors and pumps systematised key factors determining their efficiency and formed following conclusions. The geometry of the impeller is a determining factor in energy transfer. The optimum number of blades lies within the range of 30-50: fewer blades reduce circulation intensity, whilst more blades increase friction losses. Complex blade profiles (airfoil, S-shaped) provide a 3-8% increase in isentropic efficiency compared with straight blades, but complicate the manufacturing process. For most industrial applications, the straight blade remains a sound choice in terms of manufacturability and production cost. Orthogonal optimisation methods confirm that the number of blades is the most influential parameter among the impeller's geometric characteristics.

Geometry of the working channel determines the intensity of secondary circulation and the level of irreversible losses. The height of the channel is a more significant parameter than its cross-sectional area: reducing the height whilst maintaining the area increases local entropy dissipation in the secondary circulation zone, which accounts for 35-45% of total losses. The optimum channel height depends on the number of blades, confirming the non-linear nature of the interaction between geometric parameters. The separator angle has a dual effect on performance: reducing the angle from 45° to 15° increases the mass transfer rate by 18% and the static outlet pressure by 6-9%, but at the same time reduces the effective working length of the channel. The separator zone accounts for 15-22% of the compressor's total losses, and incorrect profiling of this zone leads to resonant vibration phenomena.

The clearances in the flow path proved to be the most critical design parameter: increasing the axial clearance from 0.15 mm to 0.2 mm reduces performance by up to 50%. The axial clearance dominates the radial clearance, accounting for 70-75% of losses due to bypass flow. In hydrogen blowers for fuel cells, this sensitivity is twice as high as in air-driven machines, requiring the establishment of separate, tighter tolerances. CFD methods have evolved from qualitative visualisation to quantitative prediction of performance characteristics with an error of less than 2% when using the LES approach. RANS models are acceptable in design operating conditions but systematically produce errors in non-design regions. Compressibility must be addressed for Mach numbers above 0.3. The optimal design strategy involves a sequential combination of 1D analysis at the concept stage and 3D CFD at the detailed design stage. Further research should address development and verification of proprietary CFD models of a regenerative compressor, covering clearances and the actual properties of the gas; the parametric optimisation of the flow path geometry using machine learning methods; and experimental investigation of the effect of clearances on compressor performance when operating with different working fluids, in particular hydrogen.

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Conflict of Interest

None.

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Вихрові компресорні машини: огляд конструктивних параметрів та чинників, що визначають їх ефективність (огляд літератури)

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Анотація. Зростання вимог до енергоефективності промислового обладнання та необхідність зниження експлуатаційних витрат актуалізують дослідження вихрових компресорів – класу турбомашин, що поєднують переваги динамічних та об'ємних машин і мають значний потенціал для широкого промислового застосування. Метою роботи були систематизація та аналіз сучасних наукових досліджень у галузі вихрових компресорів і насосів з метою визначення ключових чинників, що впливають на їх ефективність. Дослідження базувалося на аналізі та порівнянні результатів експериментальних і чисельних робіт, опублікованих у реферованих наукових виданнях, а також на застосуванні методів обчислювальної гідродинаміки (CFD) як сучасного цифрового інструменту інженерного аналізу. Встановлено, що ефективність вихрових компресорів визначається комплексом геометричних та конструктивних параметрів. Тип і форма робочого колеса, кількість і профіль лопаток впливають на ступінь підвищення тиску: оптимальна кількість лопаток перебуває в діапазоні 30-50, а лопатки складної форми, попри вищу ефективність, ускладнюють виготовлення. Розміри та конфігурація робочого каналу визначають інтенсивність циркуляції та рівень газодинамічних втрат – висота каналу є більш визначальним параметром, ніж площа його поперечного перерізу. Критичними є зазори в проточній частині: збільшення торцевого та радіального зазору з 0,15 мм до 0,2 мм призводить до зниження продуктивності до 50 %, що підтверджує необхідність їх обов'язкового врахування на етапі проектування. Застосування CFD-методів дозволяє візуалізувати складну спіралеподібну структуру потоку, виявляти джерела втрат та оптимізувати конструктивні рішення, скорочуючи витрати на фізичне прототипування. Поєднання аналітичних, експериментальних і CFD-методів створює основу для формування ефективних підходів до проектування, що забезпечить підвищення енергетичної ефективності та розширення галузей застосування цих машин у промислових системах

Ключові слова: вихровий компресор; вихровий насос; регенеративна гіпотеза; чисельне моделювання; Ansys SFX; оптимізація конструкції