EFFECT OF VANED AND VANELESS DIFFUSER ON THE PERFORMANCE OF TURBO BLOWERS

Pinar Demircioglu[1,2*] – Ismail Bogrekci[2] – Berkay Sert[2,3] – Mujtaba Abbakar[3] – Ahmet Gogebakan[2,3]

[1]Institute of Materials Science, TUM School of Engineering and Design, Technical University of Munich, Garching, 85748, Germany
[2]Department of Mechanical Engineering, Faculty of Engineering, Aydin Adnan Menderes University, Aydin, 09100, Turkey
[3]HAUS Centrifuge Technologies R&D Center, Aydin, 09100, Turkey

ARTICLE INFO

***Article history*:**
Received: 23.05.2024.
Received in revised form: 08.10.2024.
Accepted: 09.12.2024.

Keywords:
Diffuser type
VGD system
Flow efficiency
Performance tests
Volume flow rate

DOI: https://doi.org/10.30765/er.2532

Abstract:

The design of the diffuser significantly impacts the efficiency and overall performance of turbo blowers. The choice of diffuser type in centrifugal compressors and turbo blowers impacts efficiency. Vaned diffusers perform best at high flow rates but lose efficiency at lower flows due to their fixed design. Vaneless diffusers, without fixed blades, adapt better to varying flow rates and excel at part-load conditions. Therefore, vaned diffusers are ideal for applications with constant high flow rates, while vaneless diffusers offer efficiency advantages in variable flow rate applications. HAUS Centrifugal technology's XMP 122 Turbo blower will be employed in performance tests with both vaned and vaneless diffusers. The blower features an automatic variable geometry diffuser (VGD) system that optimizes flow efficiency. During testing, the blower operated within a speed range of 19,000 to 33,000 rpm. Analysis of the obtained data revealed a noticeable enhancement in volume flow rate.

1 Introduction

Recently, turbochargers have required higher performance centrifugal compressors, leading to a demand for increased flow and pressure [1,2]. Additionally, the need for compact designs has become important for cost-effectiveness and easy installation. The diffuser is essential for centrifugal compressors, as it slows down the fluid coming from the impeller, converting its kinetic energy into pressure. As the need for better compressor performance grows, researchers focus on studying and optimizing different diffuser types. Centrifugal compressor diffusers come in two main types: Vaned Diffusers (VD) usually have higher efficiency and deliver more static pressure, but they have a smaller operating range. Vaneless Diffusers (VLD) offer a wider and more stable operating range. However, they tend to have lower efficiency than vaned diffusers in centrifugal compressors. Compressors with vaned diffusers offer better pressure recovery but a narrower operating range. In contrast, vaneless diffusers are more affordable and tolerant of fluctuating inlet flow without sacrificing much performance. However, using vaned diffusers in industrial applications increases the potential for performance issues [3,4]. Enhancing centrifugal compressor performance focuses on cutting electricity usage, thereby reducing emissions in power generation. In industries such as wastewater treatment, a wider operating range is preferred to eliminate the need for additional compressors. Vaneless diffusers are selected for their simplicity and reduced size, leading to favourable costs and a broad operational range. Energy efficiency is crucial in such applications, with diffuser width significantly influencing the critical flow angle. Maintaining this angle is essential in preventing compressor stalling, and key design considerations include channel width and the ratio between impeller outlet and diffuser outlet radii [5].

The choice between vaned and vaneless diffusers in centrifugal compressors and turbo blowers significantly impacts efficiency. Vaned diffusers provide high efficiency at high flow rates but may face losses

* Corresponding author
E-mail address: pinar.demircioglu@tum.de

at lower flows due to their fixed structure. In contrast, vaneless diffusers lack stationary blades, allowing for better adaptability and efficiency across a wider operating range, especially at part-load conditions. The decision between these diffuser types depends on specific application needs: vaned diffusers are ideal for applications with constant high flow rates, while vaneless diffusers offer efficiency advantages for applications with varying flow rates. This study aims to investigate the effects of vaned and vaneless diffusers on the performance of turbo blowers, with a particular emphasis on the XMP 122 Turbo blower developed by HAUS Centrifugal technology. An evaluation and comparison of the efficiency and operational performance of both diffuser types will be conducted under varying conditions. The blower's Variable Geometry Diffuser (VGD) mechanism, designed to automatically adjust the flow for optimal efficiency, will be employed during tests carried out at speeds ranging from 19,000 to 33,000 rpm. The data obtained will be analyzed to determine the influence of diffuser selection on volume flow and overall performance. Ultimately, it is anticipated that valuable insights will be generated to inform the design and application of centrifugal compressors in diverse industrial contexts.

2 Literature Review

A comprehensive study of existing research on vaned and vaneless diffusers helps us grasp the complexities and progress in designing turbo blowers. By combining existing knowledge, we contribute to the current understanding and pinpoint potential areas for future research and improvement in centrifugal compressor technology. Researchers [5] investigated the effects of diffuser vanes on the stability of centrifugal compressors. They studied high-pressure ratio compressors, with and without diffuser vanes, to determine the impact of the diffuser on compressor stability. Advanced testing techniques, such as dynamic pressure measurements and Fourier analysis, were used to examine and interpret the intricate instability phenomena that occurred in both the time and frequency ranges.

The diffuser vanes effectively prevented rotating stall in the diffuser at high speeds, while not significantly affecting rotating instability in the impeller at lower speeds. These vanes also delayed the onset of compressor surge at high speeds. The experimental observations and theoretical analysis suggest that the vanes create a more negative diffuser pressure rise slope. This improves the stability of the compressor stage, allowing it to operate at a lower mass flow rate before experiencing surge. Some experimental studies [6-9] investigated the stability of the last stage in a high-pressure centrifugal compressor. Researchers tested different vaneless diffusers with varying radius ratios, width ratios, and contraction shapes. They found that narrowing the width ratio enlarged the stable operating range for the compressor. Although this reduced the diffuser's energy efficiency slightly, it had a negligible impact on the compressor's overall performance. Additionally, modifying the width contraction shape at the vaneless diffuser's inlet affected the critical stall angle by approximately 5 degrees. To adjust to evolving needs, engineers need to modify internal passages and configure suction and discharge pipes despite space limitations. This design change, however, introduces challenges such as elevated flow speeds within the passages and increased curvature. As a result, improving efficiency and extending the operational range becomes more difficult. A significant issue arises from the increased distortion in the flow around the pipes, particularly in non-symmetrical areas like bent suction pipes and scrolls. This trend raises the possibility of reduced efficiency and limits the operating range [10]. When the compressor is running, it takes in air through the inlet, sending it through the rotating blades known as the impeller. This pressurization process exposes the impeller to various forces, such as heat, fluid flow, and rotation (centrifugal forces). If these forces become too strong, they can bend or break the impeller blades. Thus, it's crucial to fully understand the stresses acting on the impeller to ensure the turbo compressor works well and lasts [11].

The performance of the designs is evaluated based on various factors, including full-load efficiency, pressure ratio, flow capacity, power consumption, operational range, stall angle, reliability, installation flexibility, and cost. Studies [1-9] have highlighted substantial differences between the two designs across different operating conditions through qualitative analysis. Computational Fluid Dynamics (CFD) simulations [12-14] have been widely used in studies examining the performance of turbo blowers with different diffuser designs (vaned and vaneless). These simulations provide valuable information about the fluid flow behavior, efficiency, and other essential aspects of these devices. Researchers have investigated flow patterns, pressure distributions, and efficiency maps to gain insights into the aerodynamic characteristics of turbo blowers in various operating conditions. These CFD-powered investigations have advanced our understanding of turbo blower design and optimization, leading to more efficient and dependable systems. Studies using both physical tests and computer simulations have shown that diffusers without guide vanes have a higher likelihood of flow separation within a wide range of widths. This is especially true when the angle of the airflow leaving the impeller at its intended flow rate is very small. To reduce this risk, the part of the diffuser that is closest to the impeller is made with a width that slowly gets narrower as it moves away from the impeller's center [15]. The experimental study [16] examines the effects of a vaned diffuser on a centrifugal compressor's performance. By comparing a compressor with a vaneless diffuser to two with vaned diffusers, the research finds that the vaned diffusers narrow the operating range and reduce flow rates at stall and choke points. However, at lower flow rates, they increase the total pressure ratio and efficiency. The vaned diffuser plays a key role in setting the choke point flow rate, resulting in the impeller operating consistently at low flow rates and ensuring a steady pressure increase from the impeller inlet to the main blade's leading edge.

3 Materials and Methods

3.1 Test Bench Setup

The HAUS test facility adheres to the ISO 5167 standard for pipe layout and sensor placement. Conforming to this standard, sensors must be positioned at a minimum distance equal to or exceeding the pipe diameter. This practice ensures that the flow undergoes a transition to laminar flow before reaching the sensors, aligning with established guidelines for accurate and reliable measurements within the facility.

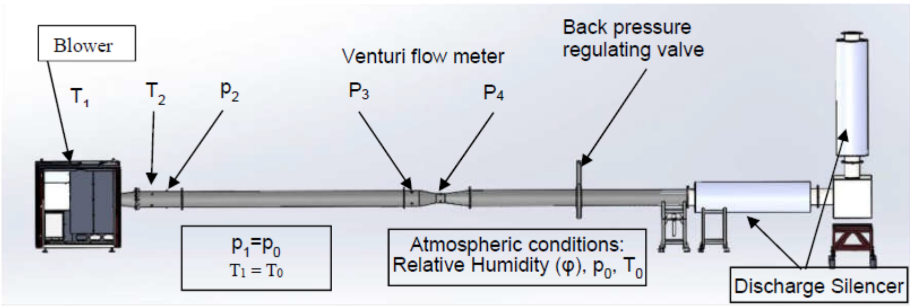

Figure 1. HAUS test bench setup.

For quantifying the mass flow of the air, a venturi tube is employed, as depicted in Figure 1. Two pressure sensors are positioned within the venturi tube (Figure 2). Utilizing Bernoulli's equation, the pressure difference between two points in the flow stream is correlated to the fluid velocity at those points. This application, particularly to specialized flow elements such as Venturi tubes or orifice plates, enables the derivation of expressions facilitating the calculation of mass flow rate.

$$P + \frac{1}{2}\rho v^2 + \rho g h = \text{constant} \qquad (1)$$

where:

- P is pressure (Pa)
- ρ is density (kg/m^3)
- v is velocity (m/s)
- g is acceleration due to gravity (m/s^2)
- h is elevation

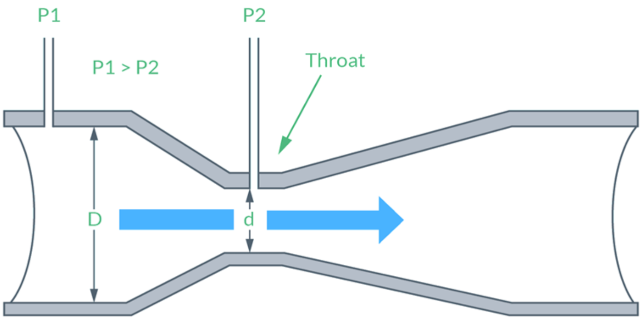

Figure 2. Schematic of venturi tube.

The mass flow rate through a Venturi tube can be calculated using Equation 2.

$$\dot{m} = \frac{C}{\sqrt{1-\beta^4}}\varepsilon\frac{\pi}{4}d^2\sqrt{2\Delta P\rho_1} \tag{2}$$

where:

- ṁ is mass flow rate (kg/s)
- C is the discharge Represents the discharge coefficient, a dimensionless factor that accounts for energy losses due to friction and other factors within the Venturi tube. It typically ranges from 0.9 to 0.98 (dimensionless)
- ß is the diameter ratio, defined as the ratio of the diameter of the orifice to the diameter of the pipe
- ε is the expansibility factor
- ρ is the fluid density (kg/m³)
- ΔP is the pressure difference across the orifice (Pa)
- d is the diameter of pipe

Two distinct tests were done on the turbo blowers, utilizing vaned diffusers in the first test and vaneless diffusers in the second. The machines were operated at rotational speeds of 19,000, 23,000, 27,000, 30,000, and 33,000 rpm respectively, with corresponding performance graphs created for both diffuser configurations. The HAUS XMP 122 integrates a VGD mechanism, dynamically adjusting diffuser attack angles for each operating point according to the rotational velocity. Recorded data with varied pressure and temperature points was used to create performance graphs for both vaned and vaneless diffusers. In the second test, vanes were removed from the VGD system while maintaining identical operating points for data collection.

3.2 CFD Setup

The die parts are employed in cutting ventilation holes for the disc component. The ventilation hole cutting die consists of five punches and five matrices, with the punch and matrix components experiencing the most wear in this operation. The high volume of mass production results in significant wear on die parts, leading to both time wastage and increased die costs. The ventilation hole cutting die operates on a 1000T eccentric press. Wear on the material can cause burrs on the ventilation hole of the disc. Table 3 presents die properties along with their respective hardness values, while Table 4 outlines the chemical composition percentages of the material in relation to die properties.

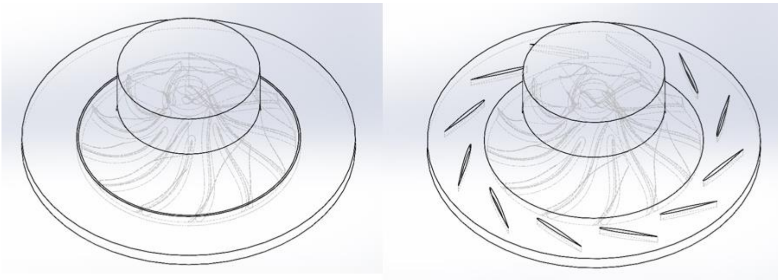

Figure 3. Fluid domain of vane and vaneless diffuser CFD setup.

Table 1. Boundary conditions for CFD setup.

P1	**1 bar**
P2	1.85 bar
T1	20 °C
Ω	33,000 rpm
Fluid model	SST

4 Results and Discussion

4.1 Test Bench Results

The discussion section interprets performance test data, exploring the effectiveness of vaneless versus vaned diffusers in centrifugal compressors. Drawing insights from literature and theories, differences were found in the results, offering a comprehensive understanding of the implications associated with these divergent diffuser types. For data comprehension, a performance graph is plotted, depicting diverse operating points. The graph outlines the interplay of key parameters influencing compressor performance, with volume flow on the x-axis and pressure rise on the y-axis. Curves are generated through interpolation of operating points at identical rotational speeds. The surge, denoting the minimum stable flow, serves as a critical threshold. Operating beneath this threshold induces unstable flows, pressure fluctuations, and potential impeller damage, highlighting the pivotal role of the surge phenomenon. Figure 4 illustrates the vaned and vaneless operating points on a single graph for comparative analysis.

The absence of vanes in the diffuser diminishes flow separation effects, thereby affecting the efficiency of the compression stage. A study by Michael M. Cui et al. documented an average increase of 5%, while the current design shows a 15% efficiency improvement, showcasing notable advancements in this investigation [17]. Nevertheless, vaneless diffusers commonly feature broader flow passages, necessitated for attaining equivalent pressure recovery as vaned diffusers. This increased passage width may induce heightened flow instability and susceptibility to surge, as illustrated in Figure 4. The vaneless diffuser plot indicates the onset of surge at elevated volume flows compared to the vaned counterpart. Simultaneously, the expanded passage allows the machine to operate at flow rates surpassing those attainable with the vaned diffuser.

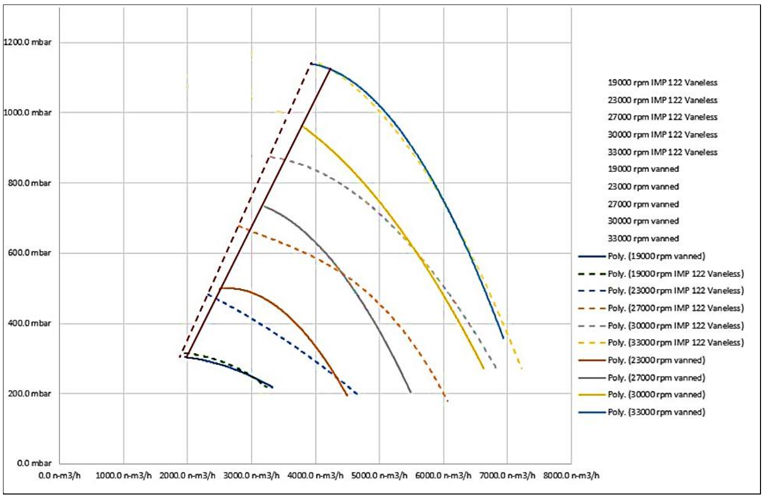

Figure 4. Vaned and vaneless diffuser performance graph.

As highlighted earlier, the absence of vaneless diffusers mitigates the impact of flow separation which is a phenomenon predominantly induced by vortices in centrifugal compressors. The creation of vortices in these compressors is attributed to various factors, with flow instabilities, forced rotation by the impeller, and velocity differentials at the air foil tips. According to Michael M. Cui et al., flow instabilities stem from pressure fluctuations. In the context of vaneless diffusers, the dominant influence is exerted by wakes and jets originating from the impeller, resulting in a distinctive stripe-like pattern along the flow direction. Conversely, in vaned diffusers, the presence of diffuser vanes significantly shapes the pressure distribution, giving rise to stationary waves [18].

4.2 CFD Results

Table 2 presents CFD results that compare the performance of centrifugal compressor diffusers with vanes and without vanes. These results provide valuable information on parameters that influence compressor efficiency and flow characteristics, including inlet and outlet pressure, flow rates, pressure differences, temperature, density, efficiency, and power consumption. By comparing the performance of vaned and vaneless diffusers, the analysis reveals how diffuser configuration affects compressor efficiency and flow behaviour.

Table 2. CFD results of vaned and vaneless diffuser.

Diffuser Type	Vaned	Vaneless
PTOTAL1	100,019 Pa	100,011 Pa
PTOTAL2	184,964 Pa	184,986 Pa
Mass flow	1.804 kg/s	1.864 kg/s
Volume flow	5,114.5 m^3/h	5,284.9 m^3/h
P2-P1	84,945 Pa	84,975 Pa
P2-P1	849.45 mbar	849.75 mbar
T1	13.82 °C	13.34 °C
T2	83.33 °C	81.29 °C
T2/T1	1.242	1.237
Density	1.2698 kg/m^3	1.2697 kg/m^3
Polytropic eff η	80.98%	82.56%
Shaft power	126.00 kW	127.26 kW

The main goal was to examine and acquire a nuanced understanding of the intricate flow dynamics within the diffuser section. Using ANSYS CFX, a detailed CFD analysis, provided a thorough exploration of how the fluid reacts to the impeller and diffuser configurations in the compressor. This analytical approach provided detailed insights into the complex interactions governing the flow patterns in these critical sections of the compressor. Table 2 contains data gathered from diffusers with and without vanes, operating at a pressure increase of 1.85 bar. The analysis results align with accepted theories and industry literature on centrifugal compressors, which supports the reliability and accuracy of this research. The consistency between the findings and existing theoretical frameworks helps confirm the credibility of the study, indicating that the observed results accurately reflect the established knowledge in the area of centrifugal compressor operation.

The initial observation of significance involves the volume flow characteristics. As presented in Table 2, the utilization of vaned diffusers leads to a reduction in the compressor's volume flow. This reduction is attributed to various factors, as previously mentioned. A study conducted by Hideto Hiramatsu et al. delves into the phenomenon of rotating stall induced by vaned diffusers [19]. Rotating stall is instigated by the separation of flow between the leading edge and trailing edge of the diffuser. This separation occurs when the boundary layer along the diffuser walls detaches from the surface, disrupting the smooth flow of the working fluid. Consequently, vortices are generated within the diffuser, blocking the passage of flow, and diminishing the overall flow exiting the discharge. In Figure 5, the magnitude of vortices generated by vaned diffusers is visually visible. It is noteworthy that flow separation effects can also manifest within vaneless diffusers, albeit with smaller vortex dimensions compared to their vaned counterparts. Additionally, a striking observation is the significantly smaller size of vortices within vaneless diffusers, leading to a substantially reduced loss in overall volume flow.

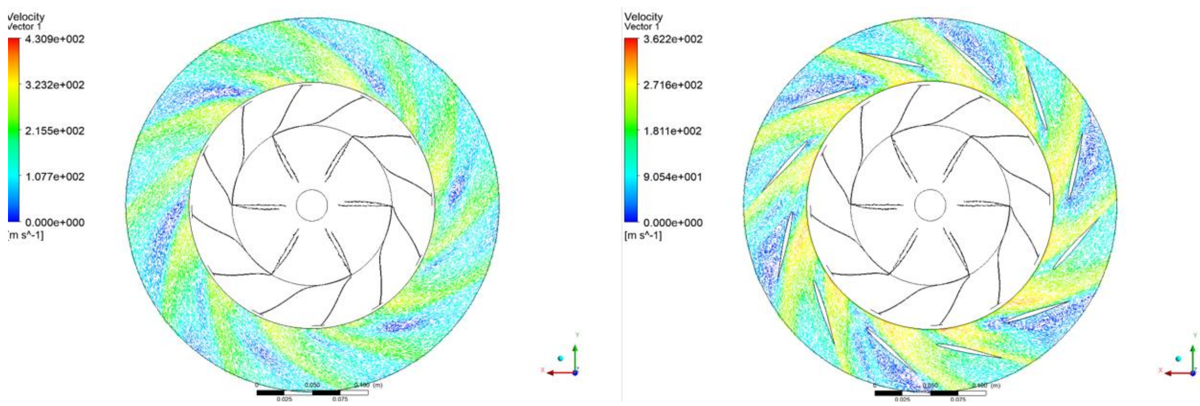

Figure 5. Velocity vectors of vaneless and vaned diffusers.

Inspection of the data from Table 2 also shows a small rise in the discharge temperature associated with the vaned diffuser as opposed to its vaneless counterpart. Variations in temperature discharge among diffusers stem from factors such as impeller design, inlet conditions, and compressor operating conditions. Within the framework of this CFD study, where the analysis was conducted under uniform conditions with the sole distinction being the diffuser type, the predominant contributor to discharge temperature emerges as the friction generated within the boundaries of the diffuser blades. Despite the presence of these frictional elements, the noted temperature difference remains small, signifying relatively low friction losses within the diffuser and contributing to the marginal temperature differential.

The data indicates a marginal superiority in polytropic efficiency for the vaneless diffuser. The efficiency of turbomachinery is influenced by a multitude of factors. The vaneless diffuser's enhanced efficiency is principally attributed to the absence of vanes, mitigating frictional losses inherent to surfaces. This phenomenon results in diminished energy dissipation through frictional heating, consequently elevating overall efficiency. Moreover, the vaneless diffuser's inherently simpler design allows for a smoother flow path, thereby further enhancing efficiency through the reduction of turbulence and disturbances. Notably, the overall aerodynamic simplicity intrinsic to the vaneless diffuser design concurrently contributes to efficiency improvements by minimizing losses compared to the more complex vaned diffuser counterparts. Taher Halawa et al. extensively investigated the losses associated with vaned diffusers, concluding that the vaneless diffuser configuration affords a more balanced pressure distribution on blades. The balanced distribution across blades is confirmed to be a sign of decreased unbalance forces resulting from stall cell formation. This emphasizes the expected superiority in the overall balance of the vaneless diffuser compared to the vaned diffuser configuration. [20].

5 Conclusion

Recent advancements in vaneless diffuser designs have made a significant impact on compressor efficiency. One exciting development is the adaptive vaneless diffuser, which can adjust its shape based on changing operating conditions. This adaptability helps optimize flow paths, improve pressure recovery, and reduce energy losses. The use of 3D printing technology has also opened up new possibilities by allowing the creation of complex geometries that enable smoother flow transitions, which in turn reduces drag and weight. Additionally, incorporating Computational Fluid Dynamics (CFD) allows engineers to simulate and refine designs before building them, leading to better choices regarding channel widths and angles. Finally, multistage vaneless diffusers are gaining traction as they can enhance performance across a wider range of conditions, effectively managing flow fluctuations and minimizing disturbances. Together, these innovations are making centrifugal compressors more efficient and adaptable, meeting the growing demands for performance in various industries [21].

This study aimed to determine and assess the differences in performance between diffusers with and without vanes. This research investigated whether the lower manufacturing costs and time of the vaneless diffuser impact the compressor's performance. The results provide valuable insights into the understanding and optimization of these diffuser configurations.

- Increasing the maximum volume flow of the vaneless diffuser benefits the turbo blower. The higher volume flow allows the machine to handle greater capacities without requiring a larger motor. However, the lack of vanes makes the blower more prone to stalling at higher volume flows compared to vaned diffusers. This can be a potential issue if the blower needs to operate at lower volumes.
- Without vanes, the diffuser shows lower exhaust temperatures. This means that the vaneless diffuser design can work well even when the outside temperature is a bit higher than usual. The lower exhaust temperature shows that the diffuser works better and can handle changes in the environment better. This makes the vaneless diffuser more versatile and thermally efficient, making it a good choice for systems that need to work well in different temperatures.
- Eliminating vanes in the diffuser design leads to increased polytropic efficiency, which directly translates to lower operating costs. Additionally, this efficiency improvement reduces wear and tear on the equipment, contributing to its long-term durability. These combined benefits enhance the financial viability of the machinery and allow it to operate effectively for a more extended period. Machines with vaneless diffusers have higher efficiency. This makes them more reliable and durable when working in different conditions. They can be used for longer periods, ensuring efficient blower operation.
- Eliminating the VGD system not only lowers production costs but also significantly reduces overall manufacturing expenses thanks to streamlined processes and a simplified design. The vaneless diffuser's inherent simplicity, compared to the complexities of the VGD system, saves both time and money. This cost-efficiency makes the transition to a vaneless diffuser configuration economically viable and feasible, providing further motivation for its adoption.

In conclusion, our study shows that the benefits of removing the VGD system and using a vaneless diffuser design are much greater than the disadvantages. The data and analysis show that removing the VGD system makes the design simpler and also significantly improves efficiency, stability, and performance. This improved reliability and cost-effectiveness strongly support the use of a vaneless diffuser instead of a VGD system in the scope of this study. To improve the performance of the vaned diffuser, future research should focus on refining the design of the vanes. By making small adjustments to their shape and orientation, it may be possible to overcome the challenges identified in this study. This approach will involve carefully evaluating design modifications to enhance the efficiency and stability of the compressor.

Acknowledgements

We are sincerely grateful to the HAUS Centrifuge Technologies R&D Center for their invaluable contributions to the experimental aspects of this study. Their steady support and collaborative efforts were crucial to the successful execution and completion of this research.

References

[1] Krain, H., Hoffmann, B., Rohne, K., Eisenlohr, G., & Richter, F. Improved High Pressure Ratio Centrifugal Compressor. Proceedings of the ASME Turbo Expo 2007: Power for Land, Sea, and Air. Volume 6: Turbo Expo 2007, Parts A and B. Montreal, Canada. May 14-17, 2007. pp. 967-975. ASME. doi: 10.1115/GT2007-27100.

[2] Xu, C. Design Experience and Considerations for Centrifugal Compressor Development. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering. 2007. 221(2):273-287. doi:10.1243/09544100JAERO103.

[3] Issac, J.M., Sitaram, N., Govardhan, M. Effect of diffuser vane height and position on the performance of a centrifugal compressor. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy. 2004, 218(8):647-654. doi:10.1243/0957650042584320.

[4] Zhao, H., Lu, X., Huang, W. Experiment study of vaned diffuser effects on overall performance and flow field of a centrifugal compressor. IOP Conference Series: Earth and Environmental Science 310 (032043), pp. 1-8, 2019. doi: 10.1088/1755-1315/310/3/032043.

[5] Zou, W., He, X., Zhang, W., Niu, Z., Zheng, X. Roles of vanes in diffuser on stability of centrifugal compressor. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering. 2019. 233(14):5380-5392. doi:10.1177/0954410019844433.

[6] Jaatinen-Värri, A., Grönman, A., Turunen-Saaresti, T., Roytta, P. Effect of vaneless diffuser width on the overall performance of a centrifugal compressor. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy. 225, pp. 665-673. 2011. doi: 10.1177/0957650911399828.

[7] Ferrara, G., Ferrari, L., Mengoni, C.P., De Lucia M., Baldassarre L. Experimental Investigation and Characterization of the Rotating Stall in a High Pressure Centrifugal Compressor: Part I - Influence of Diffuser Geometry on Stall Inception, pp. 1-8, 2002. doi: 10.1115/GT2002-30389.

[8] Ferrara, G., Ferrari, L., Mengoni, C.P., De Lucia, M., Baldassarre L. Experimental Investigation and Characterization of the Rotating Stall in a High Pressure Centrifugal Compressor: Part II - Influence of Diffuser Geometry on Stage Performance, pp. 1-8, 2002. doi: 10.1115/GT2002-30390.

[9] Cellai, A., Ferrara, G., Ferrari, L., Mengoni, C.P., Baldassarre, L. Experimental Investigation and Characterization of the Rotating Stall in a High Pressure Centrifugal Compressor: Part III - Influence of Diffuser Geometry on Stall Inception and Performance (2nd Impeller Tested), pp. 1-9, 2003. doi: 10.1115/GT2003-38390.

[10] Zheng, X., Lin, Y., Kawakubo, T., Tamaki, H. Extension of Operating Range of a Centrifugal Compressor by Use of a Non-Axisymmetric Diffuser. IHI Engineering Review. 2018. 51(1): 43-56.

[11] Bogrekci, I., Demircioglu, P., Sert, B., Gogebakan, A., Abbakar, M., "Effect of Stresses Acting on Impeller Blades", Journal of Thermal Sciences, Vol. 27, No. 4B, pp. 3113-3121, 2023. doi: 10.2298/TSCI2304113B.

[12] Kozaka, E.O., Demircioglu, P., Bogrekci, I., Ornek, T., Kose, U., "3D Optimization of an Axial Mixer Propeller through High Fidelity Simulations", Journal of Thermal Sciences, Vol. 27, No. 4B, pp. 3281-3289, 2023. doi: 10.2298/TSCI2304281K.

[13] Zhang, Q., Huo, Q., Zhang, L., Song, L., Yang, J. Effect of Vaneless Diffuser Shape on Performance of Centrifugal Compressor. Applied Sciences. 2020; 10(6):1936. doi: 10.3390/app10061936.

[14] Petukhov, E., Galerkin, Y., Rekstin, A. CFD-calculation method for vane diffusers of a centrifugal compressor stage. IOP Conference Series: Materials Science and Engineering. 604 (012051), pp. 1-10, 2019. doi: 10.1088/1757-899X/604/1/012051.

[15] Solovyeva, O., Galerkin, Y, Drozdov, A. Vaneless diffuser for low flow rate centrifugal compressor stage. Proceedings of 13th European Conference on Turbomachinery Fluid dynamics & Thermodynamics ETC13, April 8-12, 2019, Lausanne, Switzerland, pp. 1-11, 2019. doi: 10.29008/ETC2019-329.

[16] Zhao, H., Lu, X., Huang, W. Experiment study of vaned diffuser effects on overall performance and flow field of a centrifugal compressor. IOP Conference Series: Earth and Environmental Science 310 (032043), pp. 1-7, 2019. doi: 10.1088/1755-1315/310/3/032043.

[17] Cui, M.M. (2000). Comparative Study of Vaneless and Vaned Diffusers in a Transonic Centrifugal Compressor with Real Gas. Volume 1: Aircraft Engine; Marine; Turbomachinery; Microturbines and Small Turbomachinery. doi:10.1115/2000-gt-0450.

[18] Cui, M.M. (2005). Comparative Study of Unsteady Flows in a Transonic Centrifugal Compressor with Vaneless and Vaned Diffusers. International Journal of Rotating Machinery, 2005(1), 90-103. doi:10.1155/ijrm.2005.90.

[19] Hiramatsu, H., Shibata, A., Komaki, S., Miyagawa, K., & Sano, T. (2015). Flow Instability in Off Design Condition of Vaned and Vaneless Diffuser Centrifugal Pump. Volume 1A: Symposia, Part 2. doi:10.1115/ajkfluids2015.

[20] Halawa, T., Alqaradawi, M., Gadala, M. S., Shahin, I., & Badr, O. (2015). Numerical investigation of rotating stall in centrifugal compressor with vaned and vaneless diffuser. Journal of Thermal Science, 24(4), 323-333. doi:10.1007/s11630-015-0791-1.

[21] Gasparin, E., Mattos, V., Saltara, F., Mello, P.E., Dezan, D., Yanagihara, J., & Salviano, L. (2023). Parametric optimization applied to design a high-performance vaneless-diffuser for CO_2 centrifugal compressor. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 46(1), 111-130. https://doi.org/10.1080/15567036.2023.2279265.