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Numerical Investigation of Aerodynamic and Acoustic Performance of a Centrifugal Blower

Zaid Paloba[1], Jayahar Sivasubramanian[2]

[1,2] Department of Aerospace and Automotive Engineering, M. S. Ramaiah University of Applied Sciences, Bangalore, India

Abstract

A detailed numerical evaluation of a centrifugal blower's aerodynamic and acoustic performance is presented. In particular, the impact of the blade chord length and trailing edge configurations on the performance is explored. The blower has a forward-curved type blade impeller with 32 blades on each side that operates at 3000 rpm. The computational domain was methodically modelled and rigorously analyzed using the Multiple Reference Frame (MRF) approach and the SST k-ω turbulence model. Variations in blade chord lengths (-5%, +5%, and +10% of the initial length) relative to the original chord length (OCL), as well as modifications to the trailing edge design, for example Rounded Trailing Edge (RTE) and Sharp Trailing Edge (STE), indicated significant impacts on performance characteristics. Parametric study was performed for varying mass flow rates at the outflow (ranging from 100 m^3/hr. to 250 m^3/hr.) to evaluate the blower's static pressure under various operating conditions. Variations in aerodynamic efficiency and acoustic behavior were observed in the simulations, which were attributed to the change in the curved surface area of blades and due to differences in von-Karman vortex sizes caused by changes in blade chord length and trailing edge arrangement, respectively. These findings give useful information for improving blower performance and efficiency in real-world applications.

Keywords: Centrifugal Blower, Aerodynamic Performance, Acoustic Performance, Von-Karman Vortices, Vortex Shedding

1. Introduction

Centrifugal blowers are essential components in a wide range of industrial applications, such as air conditioning, ventilation, and pneumatic conveying systems. It is vital that their aerodynamic performance be optimized in order to improve energy efficiency and operational costs. Furthermore, minimizing noise emissions is crucial due to stringent environmental laws and the need to establish a safe working environment for employees. This research aims to investigate the effects of blade chord length and trailing edge configurations on the aerodynamic and acoustic performance of an industrial centrifugal blower, with a particular interest in vortex shedding and decibel levels. Centrifugal blowers establish airflow through an impeller, which is the single component responsible for fluid movement from the input to the output.

Recently, Moczko, Przemyslaw, et al. demonstrated that changing the aerodynamic design of the centrifugal blowers may significantly improve efficiency and performance. Blade adjustment mechanism has been identified as a relevant parameter for adjusting blower performance for diverse applications [1]. Cui, Baoling, et al and Mansour et al emphasized the significance of trailing edge design in centrifugal blower performance. Aerodynamic losses and airflow patterns may be significantly impacted by the switch from an RTE to a STE. Sharp trailing edge tend to minimize flow separation in comparison to their smooth or rounded counterparts, which improves efficiency and reduces turbulence [2, 3]. Blower blades interacts with the fluid around them to create von Kármán vortices. The size and intensity of these vortices directly affect the aerodynamic efficiency and noise levels of the blower. Aerodynamic losses and turbulent flow regions, that contribute to noise production, are projected to be reduced by STE. Industrial blowers must function well in terms of aeroacoustics. Excessive noise emissions affect worker productivity and health in addition to the environment. According to Oddo, Remy, et al., the aeroacoustics performance in industrial fans and blowers is crucial. Solutions for noise reduction are essential to ensuring good performance while adhering to strict noise rules [4]. The goal of the present study is to ascertain how the RTE and STE arrangement affect the blower's decibel output. Advanced numerical simulations are utilized to investigate these complex flow dynamics by employing the Multiple Reference Frame (MRF) technique, which is extensively used for modelling rotating machinery, and the SST k-ω turbulence model, which successfully predicts turbulent flow characteristics [5].

2. Literature Review and Objective

Centrifugal blowers have become crucial components in a wide range of industrial applications in recent years, necessitating design and performance improvements. Several studies have helped to improve our understanding of centrifugal blower baseline behavior [7]. However, the impact of blade chord length variations and trailing edge designs on the aerodynamic and aeroacoustics performance of blowers has received little attention. Baloni et al. investigated the design, development, and analysis of a centrifugal blower in depth, providing insight into its overall performance characteristics. There are certain parameters which are very crucial in the role of efficiency of the machine and its losses: a) Diameter Ratio of Impeller b) Inlet and Outlet Blade Angle c) Blade Number and d) Solidity [7]. Santosh et al. investigated the effect of blade number on centrifugal fan performance, highlighting the importance of this parameter in fan behavior. It is understood that increasing the number of blades from 11 to 14 alone increases the effectiveness of the centrifugal fan system by 5.74% with minimal pressure decrease in the casing [8]. Zhang et al. explored the design and performance of an ultra-low specific speed centrifugal blower, resulting in the development of an optimization design technique based on artificial neural networks (ANN) and hierarchical fair competition genetic algorithms with dynamic niche (HFCDN-GAs). The method builds the ideal blade by incremental profile adjustments using Bezier parameterization and the FINE/TURBO solver. The study focuses on an industrial ultra-low specific speed centrifugal blower with parallel hub and shroud as a reference case for optimization. The performance of centrifugal blowers with various types of blades is investigated. The results show a considerable performance boost in the optimized blade, giving support for the use of optimization based design for blower blade [9]. Barhatte et al. employed experimental and computational methods to study and increase the performance of a centrifugal blower, offering practical insights. The Volute Tongue has a significant impact on centrifugal blower performance, impacting pressure distribution around the impeller, maximum efficiency discharge, and noise levels. The suggested new design increased volume flow rate by 6.29%, efficiency by 2.67%, and noise by 0.04% for the same 120W power input. [10]. Jiao et al. numerically modelled the airflow through turbocharger compressors, taking dual volute design into account, and offered important information for improving compressor efficiency. The optimal geometry scenario leads in a pressure ratio gain of 0.04 bar, which decreases stator losses from 0.05 to 0.01 bar. Flow irregularities are observed in the meridional plane, particularly in the old stator, where a zone near the leading edge accelerates the flow. The stator's behavior varies depending on where the blade is located [11]. Fang et al. proposed a study approach for centrifugal blower design and optimization completely based on mean camber line optimization and computational fluid dynamics (CFD) analysis. The results reveal an improvement in stall margin of about 8.5% and an increase in efficiency of 1.5%. The overall pressure ratio remains consistent. Mean camber lines that have been optimized efficiently manage Mach number and flow separation, increasing blower capacity [12]. Dieh's work on compressor noise control contributed to a better understanding of noise reduction strategies in turbomachinery. A compressor's noise is multifaceted, with components coming from a number of sources. Turbulence is the most major source of noise in centrifugal compressors. This is a result of two phenomena: (a) vortex shedding and (b) upstream turbulence [13]. Jeon's numerical study of the acoustic parameters of a centrifugal impeller with a splitter provided crucial insights into noise generation in centrifugal blowers Lowson's equation is used to forecast the acoustic field by the fan. The author's splitter impeller, which features double splitters, showed better acoustic properties than the original impeller [14]. Sinayoko, M. Kingan, and A. Agarwal investigated trailing edge noise theory for spinning blades in uniform flow. Turbulent eddies convecting within an airfoil’s boundary layer are dispersed into sound at the trailing edge (TE) [15]. Their study focuses on the noise production mechanisms connected with rotating blades, with a particular emphasis on trailing edge shapes and their effect on noise levels. This paper gives important theoretical insights into the aeroacoustics behavior of rotating blades and lays the groundwork for understanding the influence of trailing edge geometry on noise decibel levels. Several more research, in addition to the ones mentioned above, have investigated the influence of trailing edge arrangement on noise levels in various turbomachinery applications. Ye and Zheng, for example, evaluated the effect of blade trailing edge design on the noise emission of axial flow fans. This study investigated the use of innovative serrated trailing-edges on axial fan blades to improve acoustics. Simulations revealed that STEs greatly decreased aerodynamic noise over the frequency range, notably at low and intermediate frequencies, attaining a 6.7 dB reduction relative to the baseline [16]. Their findings emphasized the significance of trailing edge treatment in lowering fan noise. Furthermore, Mansour and Thévenin investigated the acoustic impact of various trailing edge designs in a centrifugal pump. Their research indicated that the trailing edge layout might have a significant influence on the noise levels produced by the turbine [17]. These studies highlight the importance of trailing edge arrangement in reducing noise emissions in turbomachinery, especially centrifugal blowers. The present study intends to investigate the effect of different chord lengths of impeller blades on performance, which requires additional examination. Furthermore, the study also intends to investigate the magnitude of von Karman Vortices created from an impeller's Rounded Trailing Edge (RTE) to Sharp Trailing Edge (STE) and their impact on noise levels.

3. Simulation Setup and Numerical Methods

A. Computational Methodology

Numerical simulations using ANSYS Fluent 2022 R1 were used to analyze the aerodynamic and acoustic performance of an industrial centrifugal blower. The centrifugal blower's original geometry is displayed in Figure 1.1, and an inside view of the centrifugal blower is given in Figure 1.2. The computational domain of the original blower was utilized for the simulations (see Figure 2.1), it has inlets and outlet boundary surfaces extruded (see Figure 2.2) for improved flow physics capturing ability. There are many significant advantages to widening or extruding a blower geometry's inlets and outlets before running a simulation. When the flow enters and exits the simulation region, extensions ensure that it develops completely. A uniform velocity profile along the inlet and outflow boundaries facilitates numerical convergence and yields more accurate results. It is necessary to put the outflow boundary condition far enough downstream from sharp bends. Otherwise, the simulation might diverge and generate incorrect findings. Figure 3.1 shows a 2D image of the original blower's blades with RTE, whereas Figure 3.2 shows a 2D view of the original blower's blades with TTE. To provide an accurate depiction of the blower's shape, the polyhedral type of volume mesh was generated (Figure 4.1) and the Surface Mesh of the Impeller is shown in Figure 4.2. For accurately capturing the boundary layer, three prism layers with 0.1 mm height of the first layer were added to the blade and the casing (see Figure 5) with a growth rate of 20%. The Shear Stress Transport (SST) k-ω turbulence model was used for the simulations, which is known for its capability to capture turbulent flows accurately Four different mass flow rates at the blower's outlet were used to evaluate its performance, ranging from 100 m^3/hr to 250 m^3/hr. To accurately reflect the blower's interaction with the surrounding fluid, all free-stream walls were given a viscous (no-slip) condition. This extensive computational setup, combined with visualisation of the original blower and various blade chord lengths, ensures a thorough analysis of the blower's performance characteristics, and provides insightful information on the effects of different blade configurations on aerodynamics and acoustics.

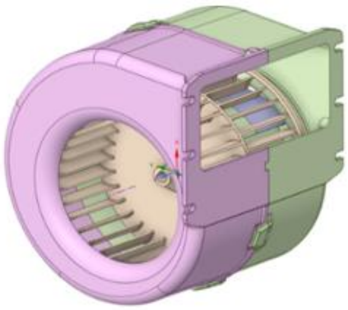

Figure 1.1: Centrifugal Blower.

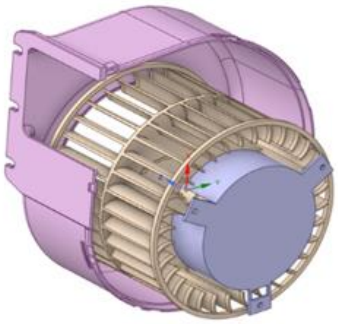

Figure 1.2: Inside View of the Centrifugal Blower.

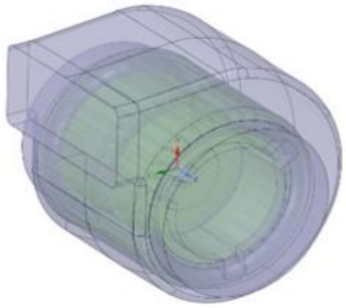

Figure 2.1: Volume Region Extracted.

Figure 2.2: Inlets and Outlet Surfaces Extruded.

Figure 3.1: 2D view of original blade with RTE.

Figure 3.2: 2D view of original blade with TTE.

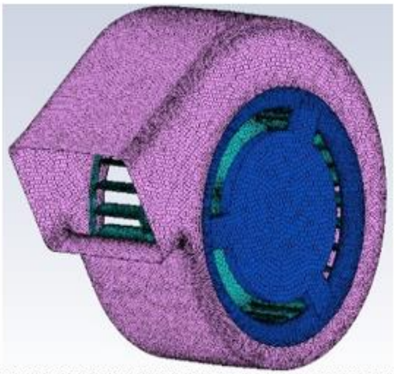

Fig. 4.1: Surface Mesh of the Blower.

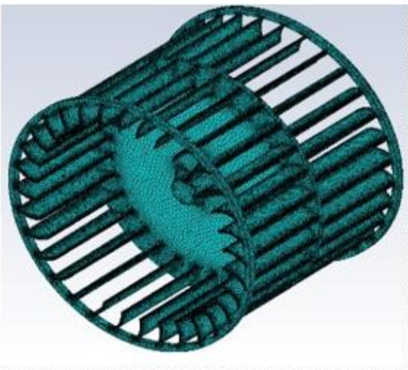

Fig. 4.2: Surface Mesh of the Blower.

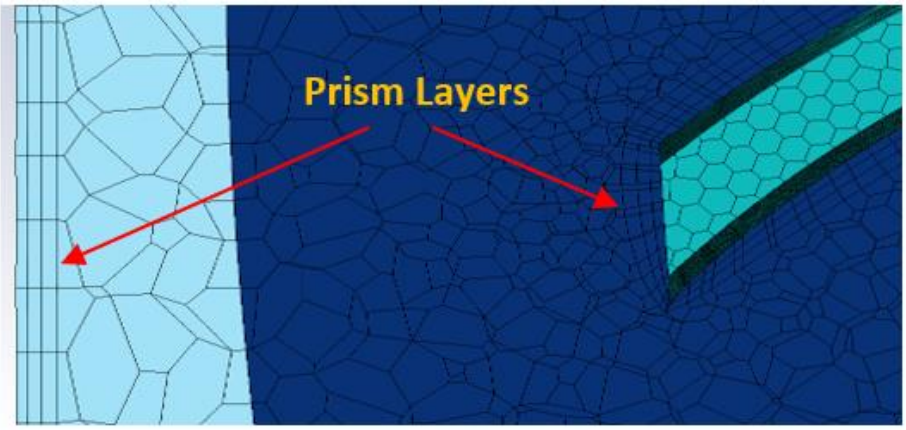

Figure 5: Prism Layers on Blade and Wall

B. Grid Convergence Study

To ensure the validity and reliability of the numerical simulations, a grid convergence study was performed on the blower with impeller with 5% decrement in the initial chord length. The pressure drop across the blower's inlets and outlet was compared using different grid resolutions. Five unstructured meshes with polyhedral cells were developed for the current investigation. The polyhedral mesh is the most resource-efficient since it has less than half the hexahedral mesh's cell numbers and around a quarter of the tetrahedral mesh's cell numbers [18]. The polyhedral mesh type has additional benefits such as fewer iterations, convergence to lower residual values, and shorter runtimes for solutions all contribute to a quicker convergence [19]. In order to get the value of y^+ smaller than 5, the prism layers with an initial height of 0.1 mm and a 20% growth rate were chosen. The y^+ values were maintained below 5 to preserve an adequate resolution near the walls. The study discovered that the change in wall pressure was marginally sensitive to cell number, implying the necessity for a grid with appropriate resolution for good forecasts. The variation of static pressure (Pa) drop at the outlet with mesh count is shown in Figure 6. The pressure drop obtained is almost the same for grids with more than 11467965 cell count. Therefore, all the case studies were performed with the same number of mesh count.

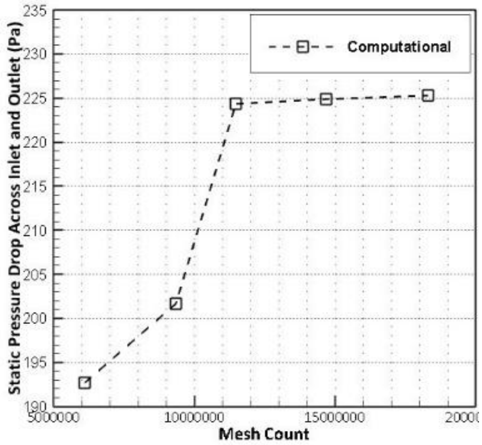

Figure 6: Grid Convergence Study.

C. Validation Study

For validation purposes, experimental data for the centrifugal blower model MB 840 [19] from Oriental Motors was used. Pressure and mass flow rate from the blower performance data were compared with the results from the numerical simulations (see Figure 7). The good agreement between the simulation results and experimental data confirms the numerical model's reliability and accuracy in predicting the centrifugal blower's performance under various operating conditions.

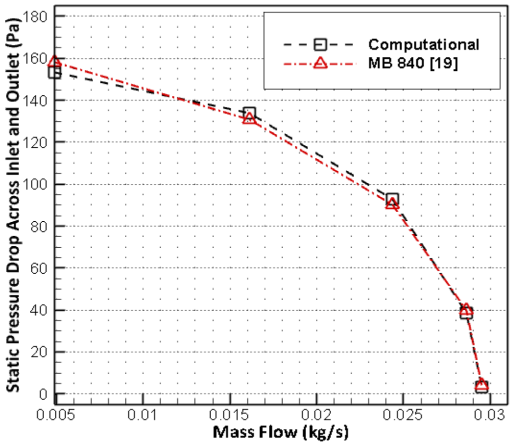

Figure 6: Grid Convergence Study.

4. Results and Discussion

A. Aerodynamics Evaluation

Examining the fan curves for various blade chord lengths, especially with smooth/round or sharp trailing edge configurations, is a part of this investigation of the industrial centrifugal blower's aerodynamic performance (see Figures 8 and 9). Both trailing edge variants demonstrated consistent reductions in pressure drop as the mass flow rate increased for the original blade chord length. However, the sharp trailing edge arrangement produced somewhat lower pressure drop values than the round trailing edge. The round trailing edge pressure drop at 100 m^3/hr was 369.3683 Pa, whereas the sharp trailing edge pressure drop was 280.785 Pa. The consistent trend of decrease in pressure drop was observed for both setups at 150 m^3/hr, 200 m^3/hr, and 250 m^3/hr. Similar observations were made for blade chord length variations of -5%, +5%, and +10%. When compared to the round trailing edge, the sharp trailing edge arrangement consistently displayed reduced pressure drops. The results suggested that the sharp trailing edge exhibited improved aerodynamic performance, the same can be inferred from the decrease in the pressure drop values for mass flow rate range considered in this study. In terms of pressure drop reduction, the aerodynamic results show that the sharp trailing edge design outperforms the round trailing edge configuration. The +10% chord length case with a sharp trailing edge displayed the lowest pressure drops for all mass flow rates, making it the best choice in terms of improved aerodynamic efficiency.

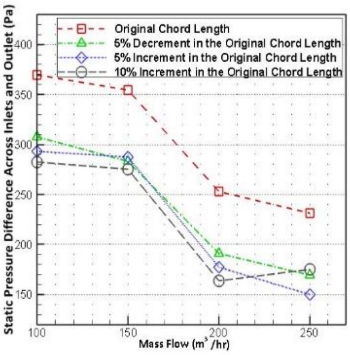

Figure 8: Fan Curve for Blades with RTE.

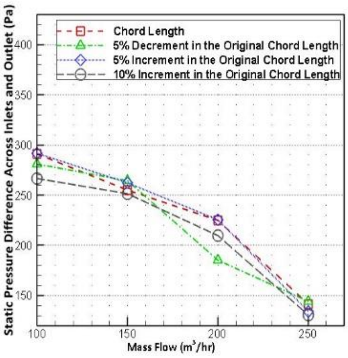

Figure 9: Fan Curve for Blades with STE.

B. Acoustics Evaluation

The acoustic performance of the industrial centrifugal blower was investigated by assessing the acoustic power levels (in dB) for various blade chord lengths with both round and sharp trailing edge configurations. Acoustic power levels were tested for each arrangement at varied mass flow rates (in m^3/hr) using area-weighted sound pressure level (OASPL) technique. Acoustic power levels varied when the mass flow rate changed for the initial/original blade chord length with a round trailing edge. The acoustic power level was reported at 20.275358 dB for 100 m^3/hr and at 15.056256 dB for 150 m^3/hr. For 200 m^3/hr, the acoustic power level climbed to 19.007399 dB, and for 250 m^3/hr, it further increased to 22.947419 dB. Similarly, when the mass flow rate increased, so did the acoustic power levels with a sharp trailing edge and the original blade chord length. For mass flow rate of 100 m^3/hr, the acoustic power level was 16.529959 dB, dropping to 17.442667 dB for 150 m^3/hr. The acoustic power level increased to 19.207926 dB for 200 m^3/hr and 20.621444 dB for 250 m^3/hr. For blade chord length adjustments of -5%, +5%, and +10%, the sharp trailing edge arrangement consistently demonstrated lower acoustic power levels than the smooth/round trailing edge configuration. The results demonstrated that a sharp trailing edge increased acoustic performance, as seen by lower acoustic power level values for all the mass flow rates considered. Overall, the sharp trailing edge arrangement is superior in terms of acoustic performance, as it consistently demonstrated reduced acoustic power levels across several blade chord length variations and mass flow rates. In particular, the +10% chord length variation with a sharp trailing edge displayed the lowest acoustic power levels for all mass flow rates, making it the best choice for decreasing noise emissions and ensuring quieter operation.

C. Efficiency Analysis

Efficiency is a critical parameter in finding the appropriate centrifugal blower designs for diverse industrial applications. When the performance patterns of the Sharp Trailing Edge (STE) and Rounded Trailing Edge (RTE) variations are compared, it is clear that the latter provides substantial advantages in terms of efficiency (see Figures 10 and 11). The RTE configuration consistently beats the STE design in terms of efficiency across several blade chord length variations. This difference in performance is inherent in the flow physics that governs both designs.

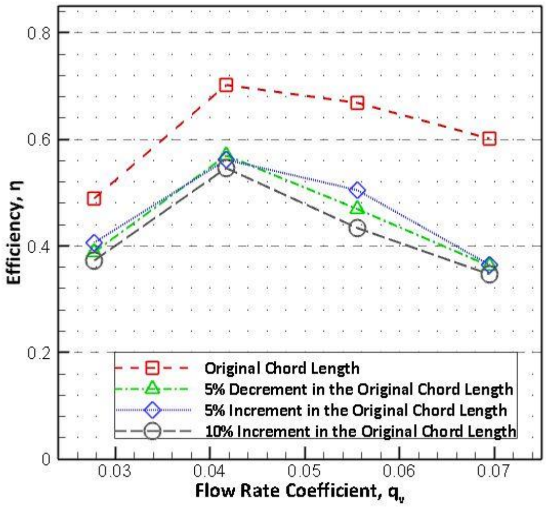

Figure 10: Efficiency Curve for RTE.

This efficiency disparity can be explained by the fact that the STE impeller is more prone to gas accumulation inside blade channels, especially at lower gas volume fractions [17]. This vulnerability is owing to its reduced performance in such settings. The STE configuration's intrinsical geometry adds to gas collection and flow disturbances, eventually impeding efficient flow patterns and energy conversion.

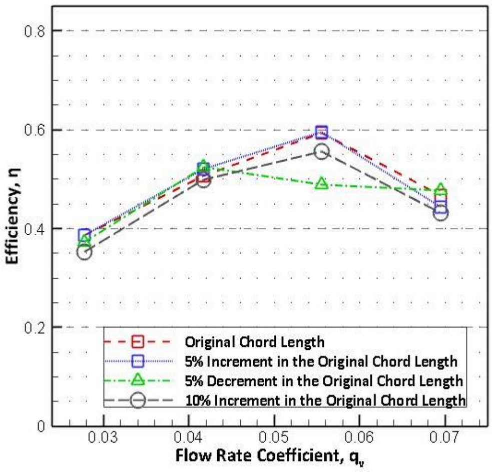

Figure 11: Efficiency Curve for STE.

D. Flow Visualization Study

The static pressure contours reveal areas of high pressure and flow separation at the trailing edge in the Rounded Trailing Edge (RTE) case with a 5% reduction of the original chord length (Fig. 12.1). This indicates the possibility of aerodynamic inefficiencies and increased noise generation. The Sharp Trailing Edge (STE) arrangement (Fig. 12.2), on the other hand, has a more streamlined flow pattern, suggesting improved aerodynamic efficiency and lower noise levels, which improves acoustic performance. The static pressure contour for the initial chord length of the blade (Fig. 13.1) reveals pressure drop dynamics in the region beyond the blades. The interaction of the flow with the blades causes acceleration and turbulence, resulting in vortices or whirling flow patterns that might affect the operation of the blower. Similarly, pressure changes over the blade surface (Fig. 14.1) suggest the possibility of flow separations and turbulence, which might reduce overall aerodynamic efficiency. The STE design (Fig. 14.2) shows increased pressure on the bottom side of the blades, implying greater flow uniformity and performance. In comparison to the STE design, the static pressure contour for the RTE configuration with a 10% increase of the original chord length (Fig. 15.1) shows a more uniform pressure distribution over the blades' surface. Similarly, the STE arrangement (Fig. 15.2) shows a modest low-pressure zone near the volute, prompting more examination for efficiency optimization. Velocity contours in Figs. 16.1 and 16.2 show the effect of trailing edge design on flow behaviour for a 5% reduction in chord length. Localized low-velocity zones around the center of the impeller in the RTE design (Fig. 16.1) indicate probable flow separation and turbulence. The Sharp Trailing Edge (STE) design (Fig. 16.2) shows a more consistent flow pattern around the blades, indicating improved flow uniformity and less turbulence. The velocity contours corresponding to the original chord length (Figs. 17.1 and 17.2) provide information on flow behaviour. Higher velocity zones near trailing edges in the RTE design (Fig. 17.1) suggest streamlined flow with the possibility of acceleration. In contrast, Fig. 17.2 (STE) shows a more uniform distribution, assuming less turbulence and improved aerodynamic efficiency. Figures 18.1 and 18.2 show velocity contours for the RTE and STE designs with a 5% increase of the original chord length. Fig. 18.1 shows higher velocity zones along the blades, although there are pockets of lower velocity near the trailing edge, indicating the possibility of turbulence. In Fig. 18.2, a vortex is seen at the outlet region, which might impair pressure distribution and acoustic performance. Figs. 19.1 and 19.2 show velocity contours for a 5% increase in chord length, with separate flow patterns for RTE and STE designs. Fig. 19.1 highlights higher velocity locations with turbulence along the trailing edge. In contrast, Fig. 19.2 shows a vortex at the volute tongue, indicating possible reverse flow that might affect pressure differential between inlets and outputs, as well as the acoustic performance of the blower.

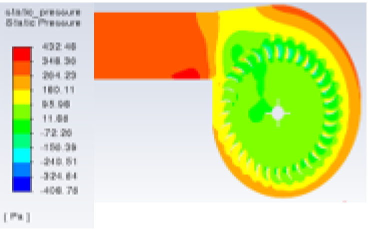	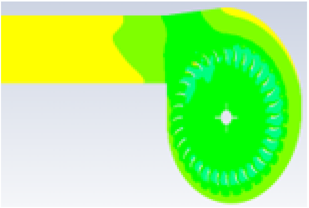
Fig. 12.1: Static Pressure plot for 5% Decrement in OCL, RTE.	Fig.12.2: Static Pressure plot for 5% Decrement in OCL, STE.
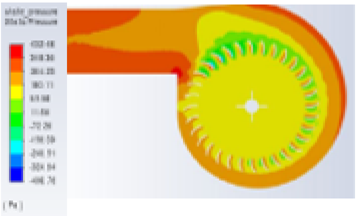	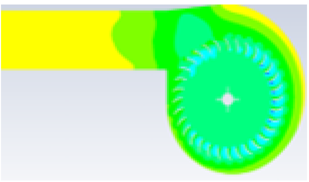
Fig. 13.1: Static Pressure Plot for OCL, RTE	Fig. 13.2: Static Pressure plot for OCL, STE.
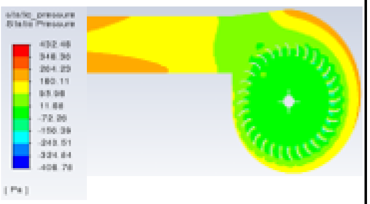	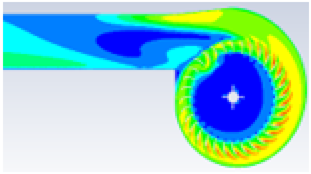
Fig. 14.1: Static Pressure Plot for 5% Increment in OCL, RTE.	Fig. 14.2: Static Pressure plot for 5% Increment in OCL, STE.
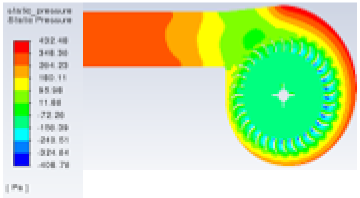	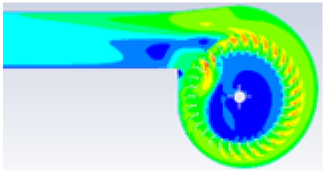
Fig. 15.1: Static Pressure Plot for 10% Increment in OCL, RTE.	Fig. 15.2: Static Pressure plot for 10% Increment in OCL, STE.

5. Conclusions

The study of the aerodynamic and acoustic performance of an industrial centrifugal blower revealed a complex interplay between efficiency, flow behaviour, and acoustic factors. According to the results obtained for efficiency, the RTE configuration outperforms STE in terms of numerical efficiency. However, a thorough examination reveals that the efficiency alone does not reflect the entire picture. Flow visualisation investigation has revealed the underlying physics governing the performance of various arrangements. Superior flow characteristics are demonstrated in terms of uniform pressure distribution, decreased turbulence, and minimised high-pressure zones in the case of STE. While the RTE arrangement is efficient, its flow behaviour shows areas of concern, such as flow separations along the trailing edge. When it comes to acoustic performance, the STE configuration's smoother flow pattern helps to reduce noise emission. While the RTE design may be more efficient, the additional turbulence and flow separation may lead to greater noise levels.

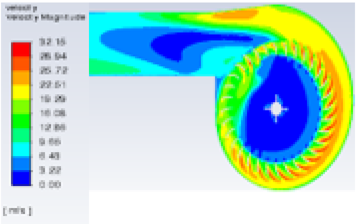	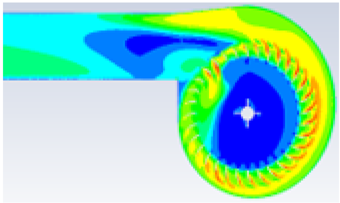
Fig. 16.1: Static Pressure plot for 5% Decrement in OCL, RTE.	Fig.16.2: Static Pressure plot for 5% Decrement in OCL, STE.
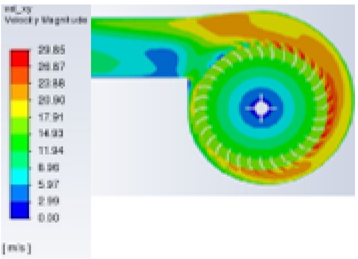	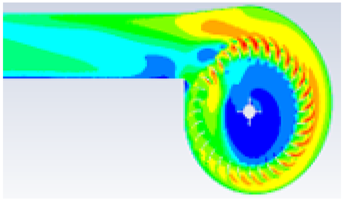
Fig. 17.1: Static Pressure Plot for OCL, RTE	Fig. 17.2: Static Pressure plot for OCL, STE.
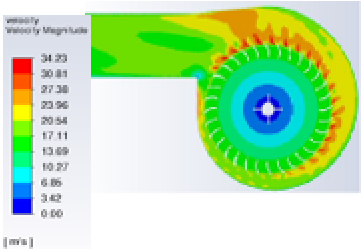	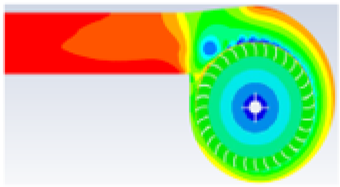
Fig. 18.1: Static Pressure Plot for 5% Increment in OCL, RTE.	Fig. 18.2: Static Pressure plot for 5% Increment in OCL, STE.
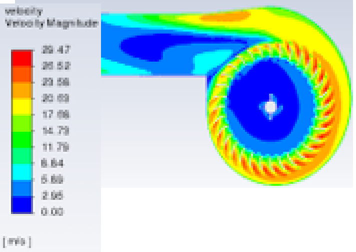	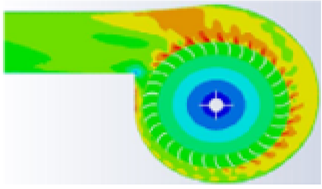
Fig. 19.1: Static Pressure Plot for 10% Increment in OCL, RTE.	Fig. 19.2: Static Pressure plot for 10% Increment in OCL, STE.

As a result, striking a compromise between efficiency and acoustic comfort becomes critical, with the STE design favoured due to its greater flow-induced noise reduction capability. When these findings are balanced, the decision between efficiency, flow behaviour, and acoustics becomes more complicated. The STE configuration not only has better flow characteristics, but it also shows promise in terms of noise reduction. This dual benefit strengthens the STE design's popularity, since it fulfils not just efficiency requirements but also the need for quieter operation.

References

1. Moczko, Przemyslaw, et al. (2022) "*Enhancing Efficiency of Industrial Centrifugal Fans Using Blade Adjustment Mechanism*." *Energies*, vol. 15, no. 3, 26 Jan. 2022, p. 893.
2. Cui, Baoling, et al. (2020) "*Influence of Cutting Angle of Blade Trailing Edge on Unsteady Flow in a Centrifugal Pump under Off-Design Conditions*." *Applied Sciences*, vol. 10, no. 2, 13 Jan. 2020, p. 580.
3. Mansour, Michael; Thévenin, Dominique; Parikh, Trupen (2020). "*Influence of the Shape of the Impeller Blade Trailing Edge on Single and Two-Phase Air-water Flows in a Centrifugal Pump*". Turbomachinery Laboratory, Texas A&M Engineering Experiment Station; Texas A & M University.
4. Oddo, Remy, et al. (2013), "*Industrial Fan Noise Control Using Flow Obstructions*". *Proceedings of Meetings on Acoustics*, Vol. 19, 030010, 2 June 2013.
5. Gullberg, P. and Sengupta, R. (2011). "*Axial Fan Performance Predictions in CFD, Comparison of MRF and Sliding Mesh with Experiment*". *SAE Technical Paper*, 2011.
6. Subramanya, Shreyasu. (2020). "*Modelling and Simulation of Fan Performance Using CFD Group*". Thesis, Linköpings universitet, Mekanisk värmeteori och strömningslära, 2020
7. Baloni, B.D., Channiwala, S.A. & Harsha, S.N.R. (2018). "*Design, Development and Analysis of Centrifugal Blower*''. *Journal of Institute of Engineers*. India Ser. C 99, 277–284 (2018).
8. Santosh., Anantharaman, K. and Rajasekaran, G. (2022) "*Effect of Blade Number on the Performance of Centrifugal Fan*," *Materials Proceedings*, Elsevier, pg. 1143–1152.
9. Zhang, B. et al. (2011) "*Blade Optimization Design and Performance Investigations of an Ultra-Low Specific Speed Centrifugal Blower*," *Science China-technological Sciences*.
10. Barhatte, S., Chopade, M. and Walimbe, A. (2021) "*Performance Enhancement of a Centrifugal Blower using Experimental and Computational Techniques*," Proceedings of 3rd International Conference on Recent Trends in Engineering & Technology (2014).
11. Jiao, K. et al. (2009) "*Numerical Simulation of Air Flow Through Turbocharger Compressors with Dual Volute Design*," *Applied Energy*, Elsevier, 86(11), pp. 2494–2506.
12. Fang, J. et al. (2023) "*Research on Centrifugal Blower Design and Optimization Method Based on Mean Camber Line Optimization and CFD*," *Journal of Physics*, 2419(1), p. 012062.
13. G. M. Dieh., (1972) '*'Compressor Noise Control*'', International Compressor Engineering Conference.
14. Jeon, W.-H. (2005). "*A Numerical Study on the Acoustic Characteristics of a Centrifugal Impeller with a Splitter*", International Transactions on Computer Science and Engineering
15. Sinayoko, M., Kingan, A., & Agarwal, A. (2013). "*Trailing Edge Noise Theory for Rotating Blades in Uniform Flow*". *Proc. A* (2013) 469 (2157): 20130065
16. Ye, X., Zheng, N., Zhang, R. and Li, C. (2022). "*Effect of Serrated Trailing-Edge Blades on Aerodynamic Noise of an Axial Fan*". *Journal of Mechanical Science and Technology*, 36(6).
17. Mansour, Michael, and Dominique Thévenin. (2020). "*Influence of the Shape of the Impeller Blade Trailing Edge on Single and Two-Phase Air-Water Flows in a Centrifugal Pump*". Turbomachinery and Pump Symposia, Texas A&M Engineering, 7 Dec. 2020.

18. Peng, W., Li, G., Geng, J. and Yan, W. (2019). "*A strategy for the partition of MRF zones in axial fan simulation*". *International Journal of Ventilation*, Vol. 18, 2019.
19. Wang, W., Cao, Y. and Okaze, T. (2021) "*Comparison of hexahedral, tetrahedral and polyhedral cells for reproducing the wind field around an isolated building by LES*," *Building and Environment*, 195, p. 107717.
20. *Oriental Motor General Catalog*. (2013). Pg. F-88.