



# JOURNAL ON COMMUNICATIONS

ISSN:1000-436X

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## Design, Analysis and Optimization of Centrifugal Fans: A Comprehensive Review

Akshay Sanap<sup>1</sup>, Vijaykumar Shep<sup>1</sup>, Sudarshan Sanap<sup>1</sup>

<sup>1</sup>Department of Mechanical Engineering

MIT Art, Design & Technology University, Pune, India

**Abstract**— Centrifugal fans are used extensively in industries where their aerodynamics play an important role in affecting the efficiency of the process and energy consumed. This paper reviews the state of the art related to centrifugal fan design, aerodynamics, CFD analyses, optimization methods, experimentation, structure, and noise. Analysis of the effect of important geometric variables, such as blades profile, impeller arrangement, and volute shape, is done to determine their impact on performance. Effectiveness of numerical models, especially Computational Fluid Dynamics (CFD), in simulating flow, pressure, and losses in the fan is evaluated. Several optimization methods, such as Response Surface Methodology (RSM), Genetic Algorithm (GA), Artificial Neural Network (ANN), and multi-objective optimization, are discussed. The significance of experiments and structural analysis for reliable and durable systems is also explored. The key trends, research areas, and recommendations have been developed based on the comparative analysis of the existing literature to provide insights into the design of efficient centrifugal fans.

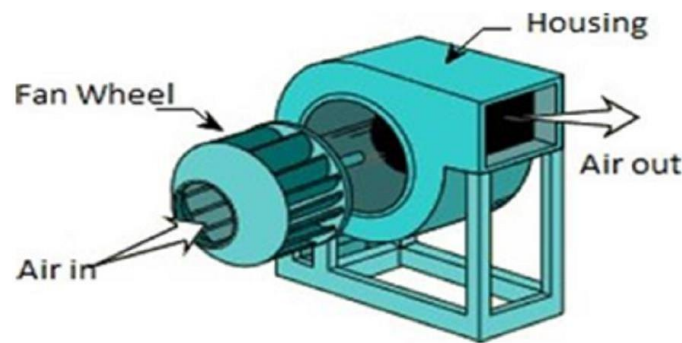
**Keywords**—Centrifugal Fan, Computational Fluid Dynamics (CFD), Aerodynamic Performance, Optimization Techniques, Energy Efficiency, Structural Analysis

### 1. Introduction

Centrifugal fans find wide applications in engineering profession in HVAC, industries, thermal power and electronic cooling devices as they can be used to produce large amounts of air using relatively low pressures. They form a significant part of the fluid mechanics systems and their functioning is characterized by efficiency and effectiveness. A typical centrifugal fan system consists of various components such as the impeller, volute, inlet and others.

The working principle of centrifugal fans is heavily reliant on the geometry parameters involved such as the shape of the blades, the shape of the impellers and the shape of the volutes. The modern processes of designing that incorporate inverse designs are useful in ensuring better flow and pressure control thereby leading to better aerodynamic functioning [1]. Geometric design provides that there are no flow separation and energy losses besides providing uniform flow.

Air Flow is as illustrated in Fig. 1. Fan air flow takes place axially through the inlet and is powered by spinning radially through the outlet.



**Figure 1. Schematic diagram of a centrifugal fan illustrating its components (adapted from [2]).**

Computational Fluid Dynamics (CFD) has become a useful method to examine the flow behavior within centrifugal fans. This method can be used to examine the distribution of velocity, pressure, and even complex flow processes, such as the formation of vortices and separating the flow. CFD analysis has been seen to yield accurate results in terms of fan performance and losses incurred, thus avoiding the need for conducting elaborate experiments [3].

On the other hand, the study of unsteady flows has shown how rotating stall and vortices affect performance [4]. Optimization methods have been employed extensively for improving performance of centrifugal fans through systematic manipulation of design variables. Optimization approaches like Response Surface Methodology (RSM) and multi-objective optimization methods can help investigate design space efficiently while improving both efficiency and pressure ratio [5], [6].

The importance of experiments in verifying numerical forecasts is very important since they are key to confirming practical feasibility. Real-world studies have shown that with proper optimization of fans, considerable gains can be made in efficiency and reduction of energy consumption. The good correlation achieved through both experiments and simulations shows the soundness of current design procedures [7].

Most literature only focuses on a single area out of these areas despite the fact that there have been tremendous developments in certain fields such as geometry, CFD analysis, optimization and validating it through experimentation. Hence, a holistic approach to integrate all these areas to understand their impacts is lacking. It is therefore necessary that an extensive assessment of the existing literature available on the subject matter is carried out.

With this regard, the current study offers an extensive review on various aspects related to centrifugal fans such as design issues, aerodynamics, CFD simulation, optimization techniques, experimental analyses, structural issues, and noise and vibration. The purpose of this review is to investigate some of the key trends, compare various methods, find any potential gaps in the literature, and make recommendations on future work.

## 2. Methodology

The present literature review was done through a critical analysis of the relevant research articles related to the study design and performance analysis of centrifugal fans. Both the traditional and current nature of the topic area were obtained by having 126 research articles retrieved through journals, conferences, and literature review on the subject matter.

The accumulated literature was then subjected to a systematic multistep screening process on its relevancy, credibility, and validity. In the first step of the filtering process, publications on subjects outside the scope of research like axial flow fans, centrifugal compressors, and other turbomachinery were weeded out. The second step involved the identification and exclusion of duplicate works.

Further screening involved ensuring that there was adequate technical information available for review. Any paper that lacked details such as methodology, results, or analysis was not considered. Other papers whose sources could not be reliably cited academically were also omitted. The same applies to papers that could not be related to the design and operation of centrifugal fans.

The total number of studies that were excluded was 56 studies. These studies included 25 studies because of their irrelevancy to the domain, six studies because of duplication or overlap, ten studies because of a lack of technical data, five studies because of unavailability or unreliability of references, and ten studies because of their low applicability to the objectives of the study. After using these exclusion criteria, 70 high-quality papers remained for further analysis.

The papers selected have been classified according to their main area of research into design and geometrical optimization, CFD and numerical methods, optimization algorithms, experimental investigations, structural and FEA analysis, noise and vibration analysis, and case studies on applications.

Review of each investigation was done based on its methodology framework and design requirements and its critical performance measures such as efficiency, pressure increase, flow, structural and noise performance. A comparison review was conducted to identify patterns, strengths, weaknesses and knowledge gaps in the literature reviewed. This method makes it easy to conduct an intensive and unbiased examination of the literature on centrifugal fans.

### **3. Literature Review**

#### **3.1. Design and Geometric Analysis**

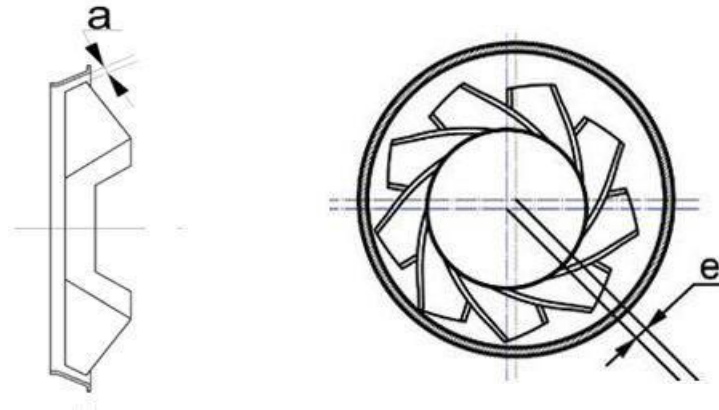
The aerodynamic performance of the centrifugal fan is influenced by the geometrical and design considerations of the centrifugal fan. Different geometrical characteristics including geometry of the blade, shape of a volute casing, and shape of a diffuser among others have a significant influence on the pressure generation, quality of the flow, and losses. These geometrical properties can be effectively optimized to yield higher performance and can be employed as a platform to carry out aerodynamic and numerical studies.

An inverse approach for designing impeller blades is discussed in [1], which involves creation of blade profiles using a desired distribution of velocity and angular momentum. With this approach, blades of different curvatures, including backwards curved, radial, and forwards curved blades can be designed to obtain better aerodynamic characteristics. Similarly, airfoil-like blades that were investigated in the article [8] have demonstrated that the optimal shapes of the blades can lead to a decreased separation and vortex, which increases efficiency by approximately 3-7 percent and extends the working range.

Geometry of volute is believed to be a significant factor that influences pressure recovery and uniform flow. As indicated in [9], the proper design of the volute geometry can avoid the losses in the flows due to geometric discontinuity. In addition, any variation in the impeller position, such as radial displacement as discussed in [10], causes non-uniformity of the pressure distribution and induces instability of the flow, thereby adversely affecting the efficiency of the flow due to the formation of vortices and the reversal of the flow.

The geometric characteristics of the number of blades, the thickness of the blades, and the size of the impeller have a significant influence on the flow characteristics and efficiency. Based on the study by [11], it is clear that tip clearance develops a leakage flow, whereas studies such as [12] indicate that tip clearance produces a leakage flow.

The blade configuration of the impeller as depicted in Figure 2(a) demonstrates how the curvature and positioning of the blades direct the air flow, whereas the clearance at the blade tip as presented in Figure 2(b) controls the leakage losses.



**Figure 2. (a) Impeller blade arrangement; (b) Tip clearance between blade tip and casing (adapted from [12]).**

Geometric parameters vs. Performance is further studied in [13] and [14] by analyzing how changes in design can enhance flow distribution and pressure gain. Other than traditional geometric factors, there have also been studies related to the effects of blade numbers and blade thicknesses on the performance of the fan. It can be seen that changes in blade numbers do not affect the performance very much, but the circulation between the blades changes the velocity distribution without causing any energy losses. On the other hand, blade thickness affects the velocity diagram and the aerodynamic performance of the fan[15].

Parametric optimization approaches have been widely utilized in many works to find the most appropriate combinations of design variables. As seen from the application of Taguchi methodology in [16], parameters like number of blades, impeller diameter, and volute shape greatly affect the performance by increasing it up to 23%. With the optimization of the blade by Bezier curves in [17] the blade curvature is better controlled and good pressure distribution is achieved with no separation. Likewise, optimization of the diffuser using DOE in [18] indicates that the angle at which the air leaves diffuser is a key factor in achieving good pressure recovery.

New geometric optimization methods, such as mean camber line optimization in [19], may provide better control of the incidence losses inside the impeller and increase efficiency. The success of geometrical optimization is also proven by the fact that it is integrated as part of the design process where several variables are optimized simultaneously to attain an overall development as shown in [20].

As a result, it may be observed that the functionality of centrifugal fans greatly depends upon their significant geometrical design parameters. The essential influence on the enhancement of aerodynamic performance can be attributed to optimization of blade profiles, volutes and diffusers that may reduce energy loss and the separation of flows. Moreover, the use of modern technologies in the design of fans, including parameter, profile optimization, etc., contributes to enhancing the uniformity of flows. Thus, one of the simplest processes that

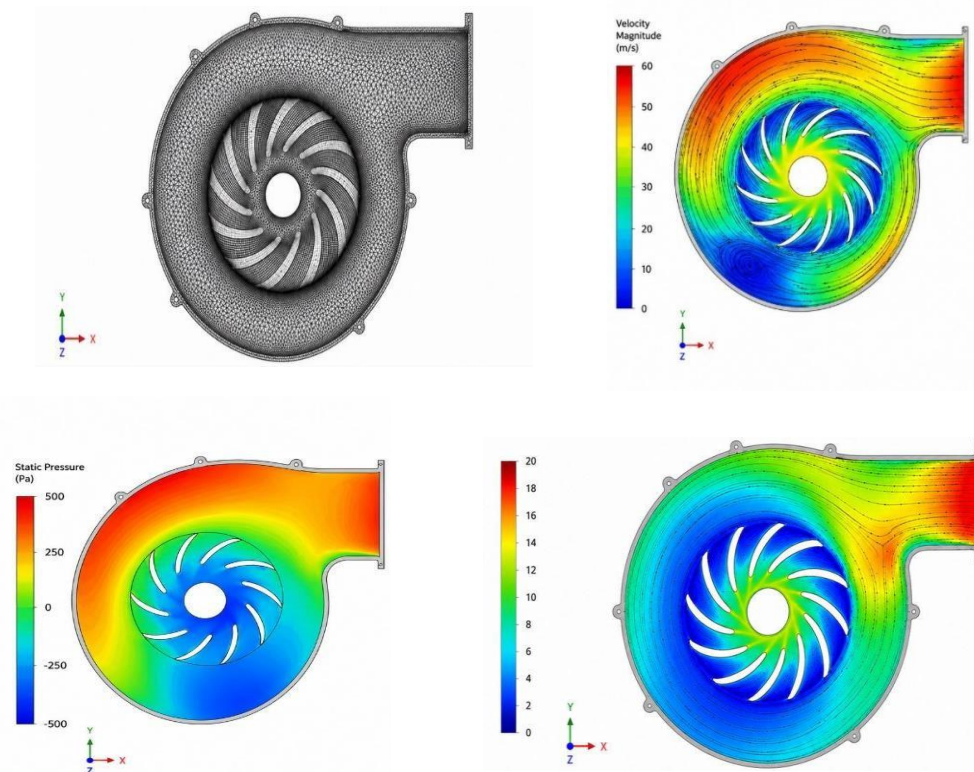
must be conducted to come up with efficient centrifugal fans is called the geometric optimization of fans.

### 3.2. CFD Analysis and Numerical Studies

The role of Computational Fluid Dynamics (CFD) and numerical techniques cannot be understated when analyzing the aerodynamic performance of centrifugal fans. Various elements such as the internal flow characteristics, pressure distribution, velocity distribution, and energy loss can be easily investigated through these techniques. It is essential to note that a numerical analysis will provide vital insights into the complex flow phenomenon.

There are several studies conducted in the analysis of flow fields, which seek to provide insights into the internal aerodynamics of the centrifugal fan. The studies look into the velocity and pressure field, vortex formation and flow separation in the impeller and volute. In these studies, it is evident that stall rotation, flow circulation, and leakage flow are responsible for the major losses and non-uniform pressure distribution. Additionally, it is discovered that the characteristics of the flow field rely heavily on geometry, inlet conditions, and operation regimes [3], [4], [21], [22].

Typical contour plots of the centrifugal fan using CFD simulation are shown in figure 3, including the computational mesh and the distributions of velocity, pressure, and turbulence intensity. The contours show significant flow features including recirculation areas, flow separation, pressure gradients and areas of turbulence within the fan volute and impeller passages.



**Figure 3. CFD results of a centrifugal fan showing (a) computational mesh, (b) velocity distribution with streamlines, (c) pressure distribution, and (d) turbulence intensity contours. (author's illustration).**

The influence of operation parameters and scale geometries is analyzed further by means of numerical analysis, in which parameters such as Reynolds numbers, aspect ratios, and thermal conditions play a crucial role in influencing flow characteristics and heat transfer properties. Flow distribution changes occur within the impeller, and efficiency gains are only achieved up to a certain level, after which efficiency declines due to unstable flow behavior [23]. Apart from standard aerodynamic studies, CFD has also been used in optimizing the overall flow behavior. This shows that CFD is an effective tool for the prediction of airflow behavior in complicated cases, such as those involving the generators cooling systems. The results show that the change in structure has considerably improved the airflow behavior [24].

Some other numerical analyses explore the effect of the design variables on the flow inside and on the performance. Changes in blade shape, impeller size, and inlet parameters affect the pressure field, the discharge rate, and efficiency. Design flaws cause flow separation and development of secondary flows, whereas optimum design variables enhance flow homogeneity and efficiency [25], [26], [27].

The reliability of CFD based performance predictions can be proven by comparing the predictions with those obtained experimentally, which show very good agreement. This proves that numerical modeling can reliably simulate actual fan performance, thus reducing the need for prototype testing considerably [28].

Coupled fluid-structure analysis is also conducted by certain research works besides fluid dynamic analysis to examine not only flow behavior but also the structure. It is found that the flow behavior like velocity non-uniformity and the generation of eddies have strong relations with the loading of the structure and heat effect [29],[30].

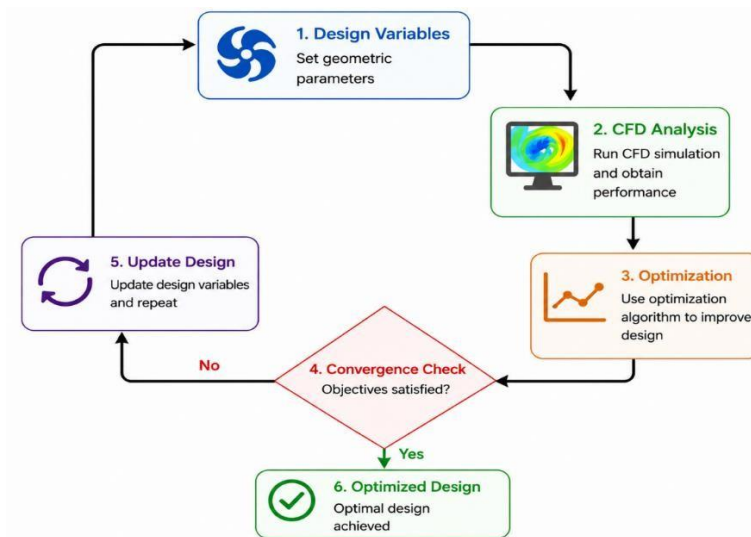
Furthermore, in advanced studies based on computational fluid dynamics, the capability of numerical methods in simulating fan characteristics, including pressure distribution, velocity, and performance curves, has been emphasized based on turbomachinery principles. The findings acquired by employing such numerical models have been confirmed in comparison with theoretical predictions [31].

The studies reviewed show that CFD is an efficient tool for predicting the behavior of centrifugal fans. Computational fluid dynamics provides valuable insight into the flow phenomena taking place within the fan and makes it possible to detect areas of losses, such as vortices, leakage flow, and flow separation. In addition, the high level of correlation achieved between computed results and experimental data indicates that computational fluid dynamics can be efficiently applied to predict fan behavior.

### **3.3. Optimization Techniques**

Implementation of optimization methods plays an important role for improving the efficiency of centrifugal fans. Implementation of different optimization methods such as Response Surface Methodology (RSM), Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Artificial Neural Network (ANN), surrogate model optimization, topology optimization, and multi-objective optimization has become a common phenomenon.

Figure 4 shows the optimization loop of a simplified process that illustrates the repeated design and assessment process of centrifugal fan optimization



**Fig. 4. Simplified optimization loop for centrifugal fan design shows iterative interaction between design variables, CFD analysis, optimization, and convergence process (author's illustration).**

The optimization techniques used in [5], [6], [32] utilize statistical and surrogated based techniques to relate geometrical parameters to performance criteria. Such techniques allow for effective optimization of the design process by lowering computational efforts. The use of RSM and surrogated models, for example, shows increased efficiency and flow stability, among other benefits.

The use of machine learning methods with evolutionary methods improves the process of optimization in terms of speed and precision. The use of surrogate models like artificial neural networks and extreme learning machines with optimization methods provides fast predictions of the performance characteristics without relying heavily on CFD computations [33].

Optimization techniques based on multiple objectives are used to achieve a balance between conflicting objectives like efficiency, pressure ratio, and noise level. NSGA-II's evolutionary methods facilitate optimization of multiple parameters at once, leading to higher performance levels and compromises[34], [35].

Parametric optimization focuses on the importance of significant design parameters such as the blade design, diffuser design, and volute shape. The Taguchi method may help select the most significant design parameters, while the splitter blades have a crucial role in reducing energy losses in the impeller [36], [37], [38].

It is used for the improvement of fan performance as well. Improvement of housing geometry and system design improves the efficiency of air flow, which stresses the significance of an integrated approach[39], [40].

Optimization methods like topology optimization can help in the redistribution of material inside the casing to minimize losses and ensure uniform flow[41]. More advanced optimization methodologies contribute to increased stability by minimizing the impact of parameter changes [42]. Design adaptations help blade shapes vary with changes in operating conditions, thus broadening the operating range and enhancing aerodynamic efficiency [43].

Current research emphasizes the optimization of aerodynamics and energy efficiency via design changes in the blades, tips, and airfoils, leading to enhanced pressure rise, efficiency, and flow performance [44], [45], [46], [47]. The surrogate-based evolutionary optimization methodologies presented in [48], [49] enables rapid assessment of different design concepts,

especially in multi-criteria design problems, at a greatly reduced computational cost relative to traditional CFD optimization techniques.

The optimization algorithms in general turn out to be highly significant in increasing the efficiency of centrifugal fans through efficient analysis of parameters and acquiring improved aerodynamic characteristics.

### **3.4. Experimental Studies**

It is important to note that experimental research is needed to confirm numerical forecasting and determine the true performance of centrifugal fans. These tests are aimed at testing prototypes, measuring performance, industrial testing, and the study of aerodynamic and acoustic behaviour under realistic operating conditions.

Prototyping and experimentation show that the appropriate testing conditions are necessary to accurately evaluate the performance. Prototypes show that better fan designs can be done in practice with practical positive results in terms of flow rate and effectiveness. This highlights the validity of a combined theoretical and experimental approach [50].

The fact that it is at industrial level that it is validated further points to the reality that optimized designs have been shown to apply under real operating conditions. Experimental studies have shown that with design changes, it is possible to achieve enormous efficiency and energy savings under realistic constraints such as system resistance, and environmental variation [7].

The experimental studies of dynamic behavior are concerned with the vibration nature of centrifugal fan parts. The investigations demonstrate that aerodynamic forces and structural properties are strongly influential on the impeller vibration, and thus the mechanical reliability and structural integrity of impellers is also significantly affected by aerodynamic forces and structural characteristics [51].

The study of the causes and the nature of sound generation in centrifugal fans have been studied through experimental investigations of noise taking place in centrifugal fans. It is deduced that aerodynamic mechanisms, especially the flow separation and turbulence are critical in the production of sound. It is also discovered that any modifications on geometry and clearance design can contribute to minimizing the noise emitted [52], [53].

Moreover, analysis of geometric features of hubs conducted experimentally has shown that geometric changes have a major impact on the distribution and efficiency of flows. The appropriate arrangement of the hubs leads to improvement of the conditions of the inlet flow, diminishes distortion, and also improves the overall performance of the fans [54].

Overall, experiments carried out have proved the importance of validation in proving that CFD and optimization analyses are indeed correct. Experimental data can help shed light on many aspects of real systems, such as their performance and vibrations, among others. As can be seen based on the obtained results through experiments, there is consistency between the numerical and experimental results.

### **3.5. Structural and Material Analysis**

Structural strength and material considerations are the key areas that should be investigated when determining the reliability and safety of centrifugal fan systems. Some of the analytical techniques that are commonly used include FEA, Fluid-Structure Interaction (FSI), and material evaluation analysis of various loadings of stresses, deformations, vibrational behaviour and fatigue life.

Research that focuses on structural response measures the impacts of loads on the stress and deformations caused by loads. The studies reveal that areas like blade roots and shaft joints are extremely prone to stress concentrations, whereas centrifugal and aerodynamic forces play an important role in structural behavior [2].

Another important consideration, in the analysis of structures, is that of material selection; particularly when dealing with conditions where corrosion and erosion may be common. In a comparative analysis of different materials, it is demonstrated that stainless steel is better compared to the traditional materials like mild steel in respect to corrosion resistance and durability [55], [56].

Fatigue is another phenomenon that emerges to be a critical consideration in the design of centrifugal fans. Recent research on the fatigue resistance of fan components demonstrates that cyclic loads associated with the rotation of the fan component and the aerodynamic stresses could be taken seriously regarding their effect on the fatigue resistance of fan components. Critical stress areas are determined, which allows foreseeing failures and proves the importance of studying aerodynamic-structural interaction [57].

The vibration nature of various components of the centrifugal fan is studied dynamically when the centrifugal fan is running. Based on these analyses, it is evident that fan imbalance, aerodynamic loads, and stiffness have a significant contribution towards vibrations. In case there is too much vibration, it might result in noise production and reduced efficiency [58].

High-level techniques of material and structure optimization explore the possibility of employing composite materials to enhance efficiency. As can be seen, composite materials have a variety of advantages such as reduction of weight and increased damping of vibrations which has led to higher efficiency in fan systems [59], [60].

Other research on structure optimization establishes that geometry and material arrangement can be changed to eliminate stress concentrations and to enhance strength without incurring any loss of functionality. Besides that, the assessment of the influence exerted on the parts of fans by thermal, centrifugal, and aerodynamic forces is performed using the multi-physics approach [61], [62]. In addition to that, multi-physics approach is used in the assessment of the influence exerted by thermal, centrifugal, and aerodynamic forces on fans' parts. This demonstrates the importance of considering a number of parameters which are interrelated in order to come up with an estimate of the structural performance [63].

Based on the above study, it is important to note that centrifugal fans structural analysis, and FEA is very crucial in safe and proper functioning of the centrifugal fans. The hybridization of FEA and FSI, as well as the optimization of materials, can be used to learn the behavior and vibration modes of the system and the behavior of stress and fatigue.

### **3.6. Noise and Vibration Analysis**

The performance characteristics of noise and vibrations are very significant in centrifugal fans. Noise and vibration in the centrifugal fan are investigated using research related to identification of noise sources, vibration analysis, and noise reduction methods.

Research conducted in the area of blade arrangement indicates that unequal spacing of blades greatly affects noise behavior, reducing noise through changing blade passage frequency and interfering with pressure fluctuations, without affecting aerodynamics at all [64]. Basic research on aerodynamic noise generation indicates that there is an increase in the level of broadband noise owing to the effect of blade configuration, separation of flow, and turbulence [65].

Moreover, design-based noise reduction measures prove yet again that optimization of the blade shape, volute design, and flow control devices is an effective way to lower noise levels without much impact on performance [66]. In addition to this, noise attenuation by means of open cell metal foams has proved itself rather efficient but at the same time is characterized by a penalty in pressure drop[67].

In addition to aerodynamic noise, vibration analysis is also an important consideration with respect to the dynamics of centrifugal fans. The vibration analysis of shaft and bearing components reveals that imbalance, misalignment, and aerodynamic excitations are some of

the main factors responsible for causing instabilities in the fan, and modal analysis becomes quite significant here[68]. Moreover, vibro-acoustic optimization techniques have been developed to combine structural and acoustic analysis methods and show that proper casing design can effectively lower noise level. It proves that coupled analysis is required in order to achieve vibration and acoustic performance simultaneously [69].

As mentioned above, aerodynamic properties, as well as the geometrical shapes of fan blades, significantly influence noise production and vibrations within centrifugal fans. An effective solution for reducing noise production is based on the integration of various aspects in combination with the consideration of the relationship between the aerodynamic and acoustic parameters of such devices.

### 3.7. Application Based Case Studies

Studies based on the application of fans are important because they offer useful information about how the fans behave when used in particular situations. The fans are applied to unique applications, such as medical applications and high-temperature processes, to show that the use of numerical analysis and experimental testing is a suitable technique.

The effect of temperature variation on the performance of centrifugal fans is analyzed, paying specific attention to changes in the physical properties of the air like density and viscosity and how these factors influence the performance. It is determined that when the temperature increases, the density of the air decreases while its viscosity increases, thereby causing the Reynolds number and efficiency to reduce. In addition, due to change in temperatures, the fan's performance curve will be affected, meaning that operation at BEP is necessary to maximize energy efficiency [70].

It is obvious that the functioning of the centrifugal fans is conditioned by a number of conditions and parameters which are related to the practical implementation. The designers are able to develop effective design alternatives by using CFD, optimization procedures as well as experimental studies depending on the purpose of use. It is necessary to note that the performance of fans also depends on the conditions of the surroundings and other factors.

## 4. Comparative Analysis

Table 1 shows the comparative analysis of the reviewed literature, which includes methodologies, parameters, and key findings from various fields of study.

**Table 1. Comparative Analysis of Centrifugal Fan Studies on Basis of Methodology, Parameters, and Significant Results.**

| Design and Geometric Analysis |                       |                 |                                |
|-------------------------------|-----------------------|-----------------|--------------------------------|
| Ref.                          | Method                | Parameters      | Key Outcome                    |
| [1]                           | Inverse design        | Blade profile   | Improved aerodynamic control   |
| [8]                           | CFD +<br>Experimental | Airfoil blade   | Efficiency improvement (3–7%)  |
| [9]                           | Analytical            | Volute shape    | Reduction in flow losses       |
| [10]                          | CFD                   | Impeller offset | Flow instability identified    |
| [11]                          | Analytical            | Blade geometry  | Improved velocity distribution |

|   |                          |                         |  |
|---|--------------------------|-------------------------|--|
| [12]                                      | CFD                      | Tip clearance           | Efficiency reduction due to leakage        |
| [13]                                      | CFD                      | Geometry variation      | Pressure increase                          |
| [14]                                      | CFD                      | Impeller design         | Improved flow uniformity                   |
| [15]                                      | Experimental + Numerical | Blade number, thickness | Significant effect of blade thickness      |
| [16]                                      | CFD + Taguchi            | Geometry parameters     | Performance improvement ( $\approx 23\%$ ) |
| [17]                                      | CFD + GA                 | Blade curvature         | Pressure increase                          |
| [18]                                      | CFD + DOE                | Diffuser angle          | Efficiency improvement                     |
| [19]                                      | CFD + ANN                | Camber line             | Efficiency improvement                     |
| [20]                                      | CFD + NSGA-II            | Geometry, noise         | Efficiency improvement and noise reduction |
| <b>CFD Analysis and Numerical Studies</b> |                          |                         |  |
| [3]                                       | CFD                      | Flow field              | Accurate performance prediction            |
| [4]                                       | Unsteady CFD             | Vortex, stall           | Identification of loss mechanisms          |
| [21]                                      | CFD                      | Internal flow           | Influence of geometry on flow              |
| [22]                                      | CFD                      | Wind field              | Flow field characterization                |
| [23]                                      | Numerical + Experimental | Scaling effects         | Flow dependency on geometry                |
| [24]                                      | CFD                      | Cooling flow            | Improved thermal performance               |
| [25]                                      | CFD                      | Internal flow           | Flow separation analysis                   |
| [26]                                      | CFD + Experimental       | Geometry                | Performance improvement                    |
| [27]                                      | Numerical                | Pressure, velocity      | Distribution analysis                      |
| [28]                                      | CFD + Experimental       | Prototype               | Validation of numerical model              |
| [29]                                      | CFD + FEA                | Flow and structure      | Coupled behavior analysis                  |
| [30]                                      | Coupled analysis         | Aeromechanics           | Interaction between flow and structure     |
| [31]                                      | CFD (RANS)               | Pressure, velocity      | Reliable flow modeling                     |
| <b>Optimization Techniques</b>            |                          |                         |  |
| [32]                                      | ANN + CFD                | Geometry                | Improved prediction accuracy               |
| [5]                                       | CFD + RSM                | Blade angle             | Efficiency improvement                     |
| [6]                                       | NSGA-II                  | Multi-objective         | Optimized performance trade-off            |
| [33]                                      | PSO + ELM                | Multi-blade             | Performance improvement                    |

|   |                          |                     |   |
|---|--------------------------|---------------------|---|
| [34]                                    | Multi-objective          | Aero + noise        | Balanced design improvement                 |
| [35]                                    | Multi-point optimization | Geometry            | Performance improvement                     |
| [36]                                    | Parametric               | Blade design        | Efficiency improvement                      |
| [37]                                    | Taguchi                  | Volute              | Performance improvement                     |
| [38]                                    | CFD + Design             | Splitter blade      | Improved flow characteristics               |
| [39]                                    | CFD + GA                 | Industrial blower   | Efficiency improvement                      |
| [40]                                    | CFD + DOE                | Housing             | Improved flow distribution                  |
| [41]                                    | Topology optimization    | Casing              | Reduction in losses                         |
| [42]                                    | Robust design            | Guide vane          | Improved stability                          |
| [43]                                    | CFD + FEM                | Adjustable blade    | Expanded operating range                    |
| [44]                                    | CFD + Experimental       | Impeller parameters | Increased flow rate                         |
| [45]                                    | CFD + Experimental       | Sirocco fan         | Improved energy efficiency                  |
| [46]                                    | CFD + Taguchi            | Tip geometry        | Pressure increase                           |
| [47]                                    | CFD + Experimental       | Airfoil blade       | Efficiency improvement                      |
| [48]                                    | CST + NSGA-II            | Blade design        | Efficiency improvement                      |
| [49]                                    | Surrogate + NSGA-II      | Aero + noise        | Reduced cost and improved accuracy          |
| <b>Experimental Studies</b>             |                          |                     |   |
| [50]                                    | Experimental + CFD       | Prototype           | Validation of results                       |
| [7]                                     | Industrial testing       | System              | Efficiency improvement ( $\approx 19.6\%$ ) |
| [51]                                    | Vibration testing        | Impeller            | Dynamic behavior analysis                   |
| [52]                                    | Noise testing            | Flow interaction    | Identification of noise sources             |
| [53]                                    | Experimental             | Blade design        | Noise reduction                             |
| [54]                                    | Experimental             | Hub geometry        | Efficiency improvement                      |
| <b>Structural and Material Analysis</b> |                          |                     |   |
| [2]                                     | FEA                      | Stress, deformation | Structural behavior analysis                |
| [55]                                    | CFD + FEA                | Material            | Improved durability                         |
| [56]                                    | FEA                      | Corrosion           | Strength improvement                        |
| [57]                                    | FSI                      | Fatigue             | Fatigue life prediction                     |

|                                       |                         |                    |   |
|---------------------------------------|-------------------------|--------------------|---|
| [58]                                  | Modal + fatigue         | Stress cycles      | Failure prediction                            |
| [59]                                  | FEM + CFD               | Composite material | Weight reduction                              |
| [60]                                  | FEA                     | Damping            | Vibration reduction                           |
| [61]                                  | Structural optimization | Stress             | Stress reduction                              |
| [62]                                  | FEA                     | Strength           | Improved structural strength                  |
| [63]                                  | Multi-physics           | Thermal + load     | Improved prediction accuracy                  |
| <b>Noise and Vibration Analysis</b>   |                         |                    |   |
| [64]                                  | Experimental            | Blade spacing      | Noise reduction                               |
| [65]                                  | Analytical              | Blade design       | Noise mechanism analysis                      |
| [66]                                  | Design method           | Aerodynamic noise  | Noise reduction                               |
| [67]                                  | Passive control         | Foam               | Noise reduction ( $\approx 5$ dB)             |
| [68]                                  | FEM                     | Shaft system       | Improved stability                            |
| [69]                                  | Vibro-acoustic          | Casing             | Noise reduction ( $\approx 7.3$ dB)           |
| <b>Application-Based Case Studies</b> |                         |                    |   |
| [70]                                  | CFD + Experimental      | Temperature        | Efficiency reduction at elevated temperatures |

Comparative analysis of all the literature reviewed suggests that performance of centrifugal fans is dependent on design features, flow dynamics, optimization methods, and physical properties. Studies based on design and geometry have established multiple factors that influence the performance of fans including the shape of the blade, volute design, diffusion angle and tip clearance. Whereas the basic knowledge of the problem is provided by analytical methods, the design-based CFD studies provide the understanding of the aspect of flow dynamics in the fan performance.

Numerical studies show that CFD analysis has the potential to predict flow behavior inside a system. Moreover, it aids in the identification of the origin of losses and therefore, more design accuracy and less expensive trials. Moreover, coupled and multi-physics studies emphasize the importance of considering the interaction between aerodynamics and mechanics.

Research studies focused on optimization prove that it is possible to achieve significant improvement in performance with the help of design optimization. Surrogated modeling, surrogated genetic algorithms, genetic algorithms, NSGA-II, and response surface methodology (RSM) are some of the methods that enable a person to effectively explore the design space and economically optimize different performance measures simultaneously. Multi-objective optimization is a particular technique that works well in the case of conflicting objectives.

The importance of experimental research is to establish the validity of numerical and optimization solutions in actual operations. This kind of research will give a deeper insight into

issues such as resistance, vibration, and noise that may not be fully simulated by the use of computational techniques.

The distribution of stress, choice of materials, and the ability to resist fatigue become very important in structural analysis. Recent software is available, such as finite element analysis and fluid structure interaction, that can be used to reliably predict deformation and vibrations. Moreover, the use of composite materials is also significant in terms of minimizing weight and enhancing the damping properties.

Aerodynamics, the design of blades, and structure dynamics have a severe impact on the sound produced by wind turbines based on research about noise and vibration. Though design and passive control measures could be used effectively to reduce noise, they may be accompanied by negative pressure drop.

Application research has revealed that the operating parameters including the temperature differences have a tremendous impact on the performance of fans as they affect fluid characteristics.

In conclusion, the comparative study has proved the importance of all the research methods in developing and improving the performance of centrifugal fans. An integrated approach that involves design, CFD, experiments, structural analysis, and the acoustics tests is indispensable in the achievement of maximum efficiency and performance of centrifugal fans.

## 5. Key Limitations

Following a thorough examination of the selected references, certain critical gaps in the research of centrifugal fans design, analysis, and optimization become apparent even though significant progress is made in the field.

To begin with, a significant body of research has been developed on the various designs of fans that include the shape of the impeller, the shape of the volute and the shape of the diffuser. But there has been little emphasis in terms of optimization of the entire fan system.

Moreover, although CFD and analysis of structures are relatively common facilities, they are typically done independently. A coupled method of multi-physics analysis that incorporates Fluid-Structure Interaction (FSI) is a very uncommon approach since it provides the simultaneous study of aerodynamics, structure and fatigue performance.

However, the other major limitation is the computational cost imposed by complicated optimization processes. Others of them are Genetic Algorithm (GA), surrogate modeling, and multi-objective optimization. These methods require a lot of repetitions, hence resulting in more computation time. Therefore, the necessity to develop better optimization algorithms emerged, which will be able to reduce the cost of computations without reducing the accuracy.

Also, the problem of attaining a compromise between aerodynamic efficiency and noise suppression is still a very critical issue. Although certain design changes or passive control strategies can be useful in reducing noise emissions, they can result in increased pressure loss or inefficiencies.

Furthermore, although experimental studies are conducted with the purpose of verifying the study, they are typically conducted under controlled laboratory conditions, which are not necessarily a reflection of the actual operating conditions. Large-scale experimental studies that are application specific are not yet to be conducted.

The above discussion can be summed up as follows: all the weaknesses above described justify using an integrated approach to enhancing the efficiency of the centrifugal fan system.

## 6. Conclusions

The design considerations of a centrifugal fan are discussed in detail, as are aspects of aerodynamics, CFD studies, optimizations, experiments, structural mechanics and noise. It demonstrates that the efficiency of the centrifugal fan strongly depends on the geometrical features, such as the shape of the blades, volute casing, diffuser, and impeller sizes.

CFD has been an excellent and robust method of studying the internal flow characteristics which is a good way of investigating the distribution of these velocity and pressure fields as well as separation within the flow. The capability of the simulation is indicated by the high correlation between the simulation and the experimental results.

Optimization techniques, including statistics, evolution and multi-objective optimization have also resulted in increased aerodynamic efficiency achieved by minimizing losses and maximizing the flow. Experimental activity proves this and gives much valuable information about the applications in real time. The structural optimization is concerned with the contribution of stress distribution, vibration and choice of material in the establishment of dependable design. Besides this, optimization of noise and vibration indicates that there is a close connection between aerodynamics and acoustics.

Application-based studies have revealed that operating conditions and in particular temperature variations impact the efficiency of fans significantly due to alterations in the fluid characteristics.

Overall, the findings of this review show that to design effective centrifugal fans, one will have to employ a holistic approach, which involves elements of design optimization, computational fluid dynamics analysis, experimental testing, structural analysis, and acoustics. The future research in this area should focus on multi-physics modeling, effective optimization techniques, and real experimental studies.

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