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Optimizing and Analyzing a Centrifugal Compressor Impeller for 50,000 rpm: Performance Enhancement and Structural Integrity Assessment †

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Abstract: The centrifugal compressor impeller is a critical component in enhancing the energy of working fluid, endowing the compressor with its characteristic centrifugal nature. This study focuses on optimizing a radial impeller in a shark-like configuration, specifically a dorsal fin shape, without modifying the remaining blades, aiming to improve performance and assess the impeller's structural integrity at high rotational speeds of 50,000 rpm. The enhanced design is anticipated to increase the efficiency of the combustor significantly. Utilizing Solid Works 2019 for modeling and ANSYS for Computational Fluid Dynamics (CFD) simulations, this study examines the overall deformation and von Mises stress experienced by the impeller. Structural analyses are performed on two distinct materials: aluminum alloy 2618 and Ti 6-2-4-6 alloy, to determine the optimal material choice for various applications. The findings delineate crucial design parameters and material selection criteria that could lead to substantial advancements in compressor technology.

Keywords: von Mises stress; impeller; aluminum alloy 2618; Ti 6-2-4-6 alloy; CFD analysis

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1. Introduction

Centrifugal compressors, also known as radial compressors, are dynamic turbomachines that ideally increase fluid pressure by accelerating a continuous flow through a rotor or impeller [1]. This acceleration imparts kinetic energy to the fluid, which is subsequently converted into potential energy or static pressure as the fluid decelerates in a diffuser. Generally, the pressure rise in the diffuser is commensurate with that in the impeller [2]. The design of the impeller is paramount in determining the performance of a centrifugal compressor. A well-designed impeller optimizes flow, minimizes turbulence, and enhances efficiency [3]. Impellers are categorized into open and closed types; each has its own advantages and limitations. Closed or shrouded impellers are characterized by two solid plates attached to the vane sides, enhancing the structure's robustness [4]. Fluid is drawn into the impeller via a nozzle, moves through the vanes, and enters the diffuser from the eye of the impeller [5]. The efficiency of closed impellers is partly attributed to the use of wear rings which prevent the recirculation of media back to the eye, eliminating the need for tight vane/casing tolerances [6]. The velocity of the impeller is crucial to avoid flow blockages, particularly at the blade throat, where high velocity may induce vibrations [7]. The impeller's rotational speed is a key factor in the selection of vane profiles, with radial vanes being preferred for high-speed applications [8]. For the turbofan engine under consideration in this study, an operational speed of 50,000 rpm was selected to investigate the performance [9]. Additionally, real-time issues such as external loads and pressures were analyzed, leading to the recommendation of cost-effective materials [10].

2. Modelling of Impeller

Solid Works, a solid modeling computer program that operates on Microsoft Windows, is utilized for both Computer-Aided Design (CAD) and Computer-Aided Engineering (CAE). The process of creating a model in Solid Works typically begins with a 2D sketch, although 3D sketches are available for advanced users. The sketch encompasses geometric elements such as points, lines, arcs, conics (excluding hyperbolas), and splines. Dimensions are applied to the sketch to define the size and location of the geometry [11]. Various relationships, such as tangency, parallelism, perpendicularity, and concentricity, are established to delineate attributes. The parametric nature of Solid Works enables independent control over dimensions within the sketch or through relations to other parameters, both internal and external to the sketch. This parametric design capability facilitates optimal design and is equally applicable to the design of turbines [12]. A radial impeller is characterized by the flow leaving the impeller radially, perpendicular to the pump shaft. The specifications of the impeller modeled for this study are given in Table 1. These specifications will be referenced during the subsequent analysis and discussion.

Table 1. Specifications of the radial impeller.

Parameter	Value
Height of the impeller (h)	100 mm
Width of the impeller	0.5 m
Rotational speed	50,000 rpm
Eye tip diameter	0.175 m

3. Optimal Impeller Design

While a backward-curved impeller is known for its higher efficiency, the concept of modifying a forward-curved blade to achieve a greater efficiency rate, in conjunction with other impellers, assists in compressing the air into a more pressurized state suitable for combustion. The primary objective of this study, however, is to optimize the design of a radial impeller with a shark fin-like configuration for the dorsal fin shape without altering the remaining blades. SOLIDWORKS serves as the tool for modeling the impeller, and ANSYS Fluent 23 is employed to import the modeled impeller to analyze the airflow through the blades. The process involves the development of a radial single-sided impeller blade vane and determining the channel depth of the impeller. The impeller design calculations and the methodology for crafting a single-sided centrifugal impeller are focused on evaluating the impeller depth and pinpointing the angular positions of the root and tip. The overarching aim of the design procedure is to amplify the efficiency rate of combustion. A new design is instrumental in managing flow separation, which is a critical factor in the performance of combustion systems.

4. Method

The evaluation of the von Mises stress, total deformation, and von Mises strain on the impeller geometry is conducted through thermal–static stress analysis using ANSYS 23 for various materials. ANSYS Mechanical is capable of addressing a range of structural issues, whether linear, nonlinear, or dynamic. The suite provided by ANSYS also includes Fluent and CFX for computational fluid dynamics (CFD) problems, offering a comprehensive virtual environment for such analyses. The impeller is subjected to both structural and thermal loads. Structurally, an angular velocity of 50,000 rpm is applied along the global z-axis [13]. Thermal loads involve metal temperatures at different heights along the blade, acknowledging the temperature gradient from the root's minimum to the highest at the hub's cessation. Fixed support locations are designated at the impeller's hub, serving as a boundary condition [14]. The centrifugal impeller may incorporate one of three vane types: backward, forward, or radial. The preliminary phase included a comparative analysis of these vane types based on the existing literature.

For instance, backward-facing blades propel fluid with their convex side, while the concave side of forward-facing blades directs the flow. Radial vanes process the fluid uniformly from any direction. This study's design optimization is conducted on a radial blade. To design a radial single-sided impeller blade vane, the channel depth of the impeller is estimated. Computations primarily focus on identifying the angular positions of the root and tip and assessing the impeller depth for a single-sided centrifugal impeller. The design's objective is to enhance the overall efficiency rate of combustion. Refer to Figure 1 for an illustration of the dorsal fin. The impeller vane's design is predicated on achieving favorable flow characteristics and preventing flow separation within the blade passage, as indicated in Figure 1. The design calculations were instrumental in optimizing the impeller and are given in Table 2.

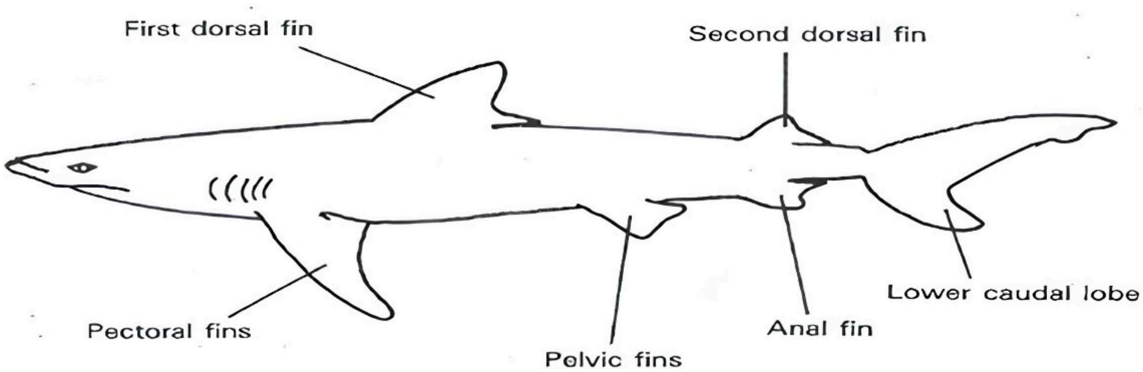

Figure 1. Dorsal fin.

Table 2. Design Calculations for the Impeller.

Design Parameter	Value
Impeller tip speed, U	1308.2 m/s
Temperature increase, $T03$–$T01$	159 K
Pressure ratio, $P03/P01$	3.50
Power required	1438.1 kW
Area of an impeller eye, $A1$	0.01768 m^2
Density at inlet, $p1$	1.32 kg/m^3
Axial velocity, $Ca1$	192.82 m/s
Dynamic temperature equivalent, $C1^2/2Cp$	18.3402 K
Temperature, $T1$	276.66 K
Pressure, $P1$	0.8939713 bar
Density, $p1$	1.12613 kg/m^3
Updated axial velocity, $Ca1$	200.98 m/s
Radial velocity, $Cr2$	200.98 m/s
Tangential velocity, $Cw2$	1177.4 m/s
Pressure ratio, $P02/P01$	3.99
Temperature, $T02 = T03$	454 K
Temperature, $T2$	427 K
Pressure, $P2$	101.2 bar

To ascertain the von Mises stress, total deformation, and velocity, the aforementioned thermal and static analysis boundary conditions are applied to the imported and meshed geometry [14]. The tetrahedral meshing technique is employed to discretize the critical geometry, customizing the element size to 6.5×10^{-3} m, which results in a mesh consisting of 164,400 elements and 240,099 nodes [15]. Refer to Figure 2 for the Solid Works model of the impeller with the dorsal fin configuration.

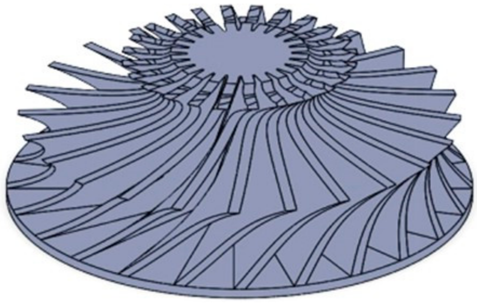

Figure 2. Impeller solid work model with dorsal fin configuration.

To determine the von Mises stress, total deformation, and velocity as depicted in Figure 1, the aforementioned thermal and static analysis boundary conditions are applied to the imported and meshed geometry [14]. The tetrahedral technique is employed for meshing the critical geometry, with the body size customized to set the element size at 6.5×10^{-3} m. This results in a mesh consisting of 164,400 elements and 240,099 nodes [15].

The mechanical properties of the materials, aluminum Alloy 2618 and Ti 6246, which are integral to the study, are tabulated in Table 3.

Table 3. Mechanical properties of aluminum alloy 2618 and Ti 6246.

Property	Aluminum Alloy 2618	Ti 6246
Young's Modulus (GPa)	80	114
Density (kg/m^3)	2700	4650
Ultimate Strength (MPa)	440	1200

5. Results and Discussion

The boundary conditions for thermal and static analysis were applied to the imported and meshed geometry to compute von Mises stress, total deformation, and velocity [16]. Initially, thermal analysis was conducted on the solution, which was then transitioned to static structural analysis [17]. The static analysis considers that temperature is maximum at the exit due to the energy conversion [18]. Both materials, aluminum 2618 alloy and Ti 6-2-4-6, were evaluated under specified inlet and exit temperatures, and the resultant pressure loads were integrated into the static structural analysis [19]. Isentropic relations were utilized to derive design parameters such as impeller eye diameter, vane angle, air mass flow rate, and pressure ratio, which are intrinsic to the internal flow dynamics [20]. The maximum pressure observed was 0.6045 Pa, indicated in red on the pressure-distribution map (see Figure 3).

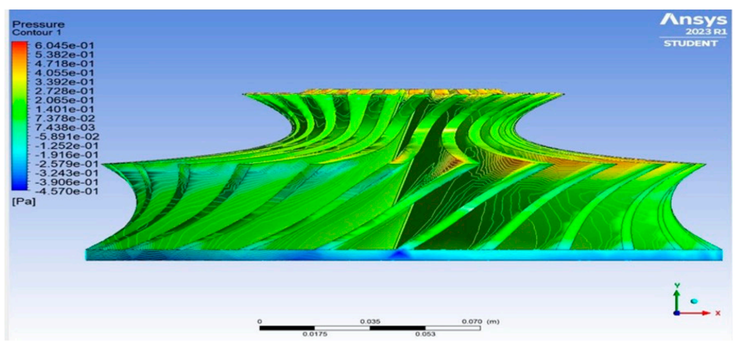

Figure 3. Pressure distribution for impeller with dorsal fin.

Velocity distribution ranged from 0 to 1.155 m/s, as shown in Figure 4. The CFD analysis confirms the absence of flow separation, which is essential to the structural integrity of the impeller during its operational lifespan.

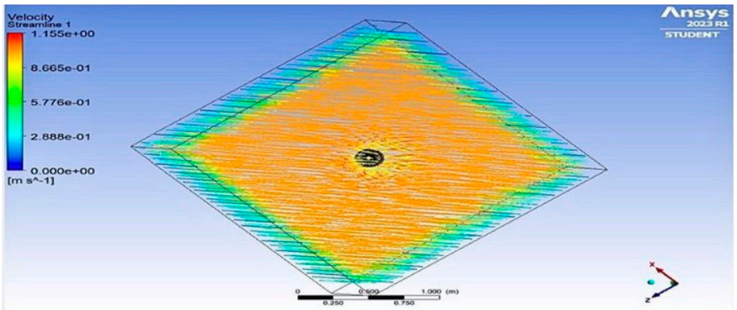

Figure 4. Velocity distribution for impeller with dorsal fin.

The impeller exhibited a maximum deformation of 4.51 × 10^{-7} m, as depicted in Figure 5, confirming the component's structural integrity and highlighting the variation in deformation across different parts. Comparative studies indicate that the maximum von Mises stress for Ti-6Al-4V in an impeller with radial vanes is 3.56 × 10^8 Pa, and the deformation is 0.186 m [7]. It was noted that the load ratio of Ti-6Al-4V is lower than that of aluminum 2618 alloy, but the stress amplitude for Ti-6Al-4V is higher.

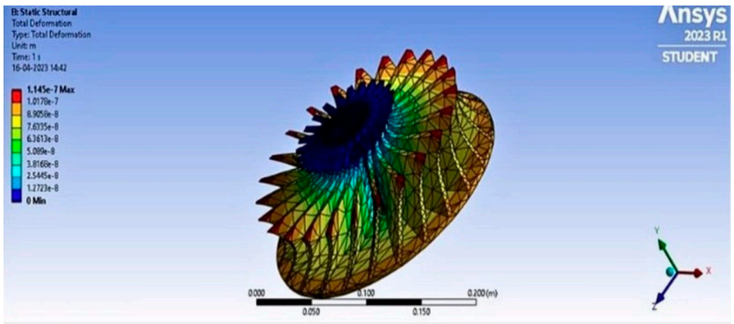

Figure 5. Total deformation of the impeller with dorsal fin.

Analysis suggests that Ti 6-2-4-6 alloy is the superior material choice for centrifugal compressor impellers (refer to Figure 6). This conclusion is based on the alloy's lower von Mises stress in comparison to its ultimate strength, reduced density, and minimal deformation when subjected to a rotational speed of 50,000 rpm. Notably, the von Mises stress values peak at the hub and near the blade regions. The mechanical behavior of the two materials was rigorously analyzed to determine their suitability for the impeller design.

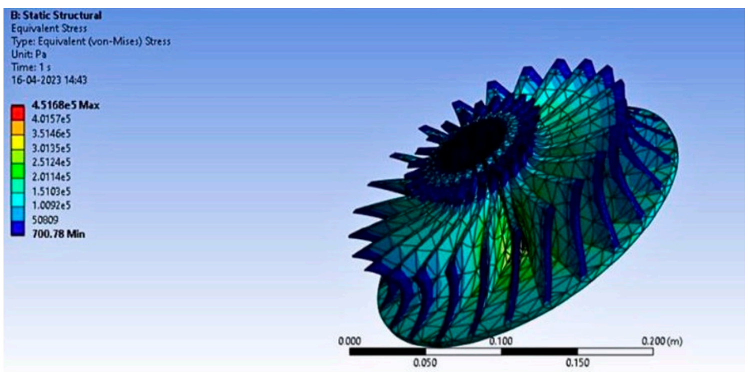

Figure 6. Von Mises stress distribution for impeller with dorsal fin.

Aluminum and titanium alloys are commonly used in the gas turbine engine's cold section due to their favorable properties. The study's findings have been summarized in Table 4, which presents a comparison between Aluminum 2618 alloy and Ti 6-2-4-6.

Table 4. Comparison of mechanical behavior: Al 2618 Alloy vs. Ti 6-2-4-6.

Alloy	von Mises Stress (Pa)	Deformation (m)	Velocity (m/s)	Pressure (Pa)
Al 2618 alloy	4.5168×10^8	1.145×10^{-7}	1.132	4.718
Ti 6-2-4-6	6.7561×10^8	1.392×10^{-3}	2.124	5.819

The structural integrity analysis focused on the geometry of the impeller vane with the dorsal fin configuration. It was found that the Ti 6-2-4-6 alloy demonstrated superior strength compared to the aluminum 2618 alloy, as well as better performance in terms of total deformation, velocity, and pressure. A significant pressure rise of 3.66 was observed, which surpasses the earlier design's pressure ratio of 3.25 [7]. The aluminum 2618 alloy, while not as strong as Ti 6-2-4-6, was noted for its cost-effectiveness and lower density, which contribute to reducing the overall engine weight. These findings underscore the importance of material selection in the design of centrifugal compressor impellers operating at high speeds. The comprehensive analysis provided by this study not only informs material selection for high-performance impellers but also sets the stage for future research into vibration analysis due to centrifugal loading, which will aim to predict natural frequencies and their effects on the impeller's operational integrity.

6. Conclusions

This study presented a comprehensive analysis of a newly designed impeller vane with a dorsal fin configuration, utilizing numerical tools to assess its structural integrity and performance characteristics. This research contributes to the ongoing efforts to improve the efficiency of centrifugal compressors, which are preferred due to their simplicity and high output pressure. Drawing inspiration from nature, particularly the dorsal fin concept, has proven beneficial in minimizing aerodynamic losses and preventing flow separation. The computational fluid dynamics (CFD) analysis provided a deep understanding of the flow dynamics within the compressor, leading to insights into the reduction of various forms of losses. The mechanical behavior of two materials, Ti 6-2-4-6 alloy and aluminum 2618 alloy, was examined, highlighting the superior strength and performance of the Ti 6-2-4-6 alloy under operational stress conditions as per the Ansys software simulations. Ultimately, the study concluded that while Ti 6-2-4-6 exhibits higher strength, the aluminum 2618 alloy offers cost-effectiveness and contributes to weight reduction in gas turbine engines, making it a viable option for the impeller design. Future work will focus on vibration analysis under centrifugal loading to predict natural frequencies and their potential impacts, furthering the understanding of impeller dynamics at high rotational speeds.

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