



Aerodynamic and Thermomechanical Optimization of Turbocharger Compressor Wheels for Improving Energy Conversion Efficiency

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Abstract

This study addresses the engineering problem that turbocharger compressor-wheel performance is often optimized through separate aerodynamic, geometric, structural, thermal, and material analyses, although these factors interact directly in determining useful pressure development, irreversible loss, structural stability, and energy conversion efficiency. The purpose of the research was to quantify the individual and combined effects of Aerodynamic Flow Optimization (AFO), Geometric Configuration Optimization (GCO), Thermomechanical Structural Optimization (TSO), and Thermal Deformation and Material Optimization (TDMO) on Energy Conversion Efficiency (ECE) in high-speed automotive turbocharger compressor wheels. A quantitative, cross-sectional, case-study-based design was adopted, using purposive expert sampling and a structured five-point Likert questionnaire administered to technically qualified engineering professionals. Of 320 questionnaires distributed, 298 were returned and 286 valid responses were retained, yielding an effective response rate of 89.4%. Data analysis included descriptive statistics, reliability and validity assessment, Pearson correlation, and multiple linear regression, with significance evaluated at $p < .05$. ECE recorded the highest mean score ($M = 4.22$, $SD = 0.50$), while AFO, GCO, TSO, and TDMO achieved means of 4.18, 4.15, 4.12, and 4.09, respectively. All predictors were positively associated with ECE, with correlations of $r = .74$ for AFO, $r = .71$ for GCO, $r = .68$ for TSO, and $r = .65$ for TDMO, all $p < .001$. The combined model explained 71.2% of the variance in ECE ($R^2 = .712$, adjusted $R^2 = .708$, $F(4,281) = 173.69$, $p < .001$). AFO was the strongest predictor ($\beta = .31$), followed by GCO ($\beta = .28$), TSO ($\beta = .24$), and TDMO ($\beta = .21$), all $p < .001$. The findings indicate that compressor-wheel efficiency is best understood through an integrated optimization framework in which aerodynamic loss reduction is reinforced by geometric refinement, structural integrity, thermal stability, and material performance, offering practical guidance for energy-efficient and reliable turbocharger design.

Keywords

Turbocharger Compressor Wheels; Aerodynamic Flow Optimization; Geometric Configuration Optimization; Thermomechanical Optimization; Energy Conversion Efficiency;

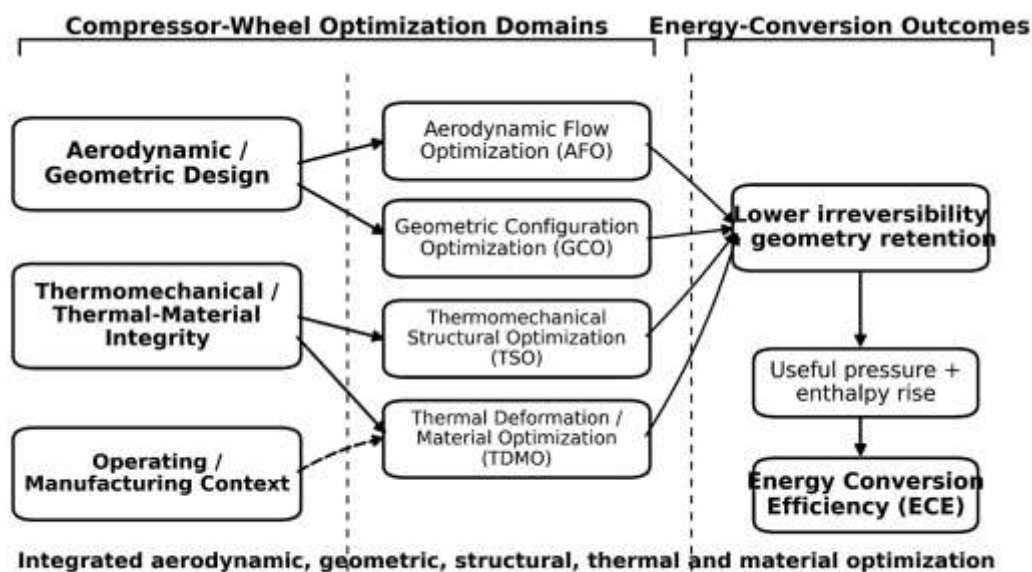
INTRODUCTION

A turbocharger is an exhaust-energy recovery and air-compression system in which the turbine extracts energy from the engine exhaust stream and transfers mechanical shaft power to a centrifugal compressor, while the compressor wheel converts this rotational work into increased airflow pressure and enthalpy. Within this system, the compressor wheel, or centrifugal impeller, is the principal rotating aerodynamic component responsible for accelerating inlet air through its blade passages before part of the kinetic energy is converted into static-pressure rise through diffusion. Energy conversion efficiency in a turbocharger compressor can consequently be understood through measures such as isentropic or polytropic efficiency, pressure ratio, useful compression work, aerodynamic loss, and the ability of the wheel to maintain efficient compression over its intended operating range. Compressor maps and experimental operating behavior have demonstrated that the thermodynamic interpretation of compressor efficiency is sensitive to both operating condition and the validity of the conventional adiabatic assumption ([Bontempo et al., 2015](#)). The international significance of this problem extends across automotive engines, marine propulsion, distributed power systems, industrial machinery, and other applications requiring compact and high-pressure-ratio air compression. Micro-scale automotive compressor research has shown that relatively small geometric changes to the impeller can measurably alter isentropic efficiency, making wheel design a direct engineering concern in turbocharger energy utilization ([Atac et al., 2018](#)). Component-loss analysis has similarly identified skin friction, diffusion, blade loading, recirculation, slip, and blockage as important mechanisms governing pressure ratio and efficiency across varying compressor speeds and mass-flow conditions ([Khoshkalam et al., 2019](#)). Thermodynamic measurement becomes particularly important because compressor operation is not universally adiabatic. Heat transfer from the turbine, bearing housing, lubricant, and surrounding structure can modify compressor outlet temperature and distort efficiency calculations, especially at lower turbocharger speeds ([Casey & Fesich, 2010](#); [Shaaban & Seume, 2012](#)). Experimental thermal analysis has further demonstrated measurable heat transfer through turbocharger components and associated deterioration in observed compressor performance under non-adiabatic conditions ([Romagnoli & Martinez-Botas, 2012](#)). At the aerodynamic level, high-speed centrifugal compressor development simultaneously involves pressure ratio, choke flow, surge margin, efficiency, and mechanical integrity, which makes compressor-wheel performance an energy-conversion problem rather than a purely geometric design exercise ([Pakle & Jiang, 2018](#)). Flow instability near surge and other off-design operating states also alters the internal aerodynamic field and pressure behavior of automotive centrifugal compressors ([Broatch et al., 2016](#)).

Aerodynamic optimization of a turbocharger compressor wheel concerns the systematic modification of blade and flow-path geometry to reduce irreversible aerodynamic losses while maintaining pressure-rise capability, mass-flow capacity, and stable operation. Important geometric variables include inducer and exducer dimensions, blade inlet and outlet angles, blade-angle distribution, backsweep, splitter-blade location, hub and shroud contours, blade height, blade thickness, blade number, and tip clearance. Computational optimization has demonstrated the usefulness of combining computational fluid dynamics, regression analysis, and genetic algorithms to identify blade configurations associated with higher isentropic efficiency ([Shu et al., 2008](#)). Numerical comparison of impellers having different blade-angle distributions has also demonstrated that changes in channel geometry and blade-angle development can produce meaningful differences in compressor efficiency even when major dimensional characteristics remain unchanged ([Roytta et al., 2009](#)). Multi-objective optimization has treated isentropic efficiency and total pressure ratio as simultaneous objectives, while hub and shroud contour variables have been incorporated into evolutionary optimization supported by RANS calculations and experimental validation ([Kim et al., 2010](#)). Turbocharger-specific studies have further established that splitter blades should not automatically be treated as shortened copies of full blades because secondary flows and incidence at the splitter leading edge can introduce substantial aerodynamic losses. Modification of splitter leading-edge position and inclination has increased nominal-point efficiency while improving surge margin ([Moussavi et al., 2017](#)). Geometric parameterization of a micro radial turbocharger compressor has likewise produced efficiency enhancement through optimization of full-blade beta distribution and splitter leading-edge location ([Atac et al., 2018](#)). Meridional-plane geometry also affects compressor operation because hub-line

modification changes the internal flow passage, stall characteristics, pressure ratio, and efficiency distribution (Xie et al., 2018). Three-dimensional CFD combined with genetic algorithms has been used to optimize leading-edge and trailing-edge blade angles and splitter starting locations, reinforcing the sensitivity of compressor performance to interacting geometric parameters rather than a single isolated dimension (Omid et al., 2019). Three-dimensional optimization of a transonic centrifugal impeller has further shown that blade-angle distribution can be manipulated to improve isentropic efficiency while constraining pressure ratio and mass flow (Ekradi & Madadi, 2020). Gradient-based optimization has also improved impeller aerodynamic efficiency while preserving required flow capacity, demonstrating the central role of geometric sensitivity in turbocharger compressor design (Honda et al., 2021).

Figure 1: Integrated Overview of Turbocharger Compressor-Wheel Optimization and Energy Conversion



Aerodynamic improvement alone cannot adequately characterize compressor-wheel optimization because the wheel operates as a very high-speed rotating structure subjected simultaneously to centrifugal force, aerodynamic pressure, temperature gradients, cyclic loading, and geometrically induced stress concentrations. Thermomechanical optimization consequently concerns the control of stress, strain, deformation, thermal expansion, stiffness, fatigue loading, and structural safety while retaining the aerodynamic geometry needed for effective compression. Aero-thermo-mechanical analysis has demonstrated that centrifugal force, aerodynamic pressure, and thermal loading deform the impeller during operation, producing a nonuniform running tip-clearance profile and measurable changes in polytropic efficiency (Kim et al., 2016). Such coupling is particularly important because tip clearance is both an aerodynamic loss mechanism and a structural-dimensional outcome. Combined centrifugal and aerodynamic loading has also been used to identify stress concentrations and estimate impeller fatigue life through finite-element analysis and experimentally supported S-N relationships (Liu et al., 2016). Turbocharger compressor wheels experience repeated changes in rotational speed, creating cyclic mechanical loading that can produce low-cycle fatigue and eventual fracture. Duty-cycle speed histories, finite-element stress analysis, and cumulative damage concepts have therefore been applied directly to wheel redesign for improved fatigue performance (Raja et al., 2019). Material selection adds another thermomechanical dimension because density, elastic response, thermal expansion, yield strength, fatigue characteristics, and temperature-dependent behavior affect both wheel displacement and durability. Comparative evaluation of aluminum and titanium compressor-wheel materials under centrifugal, aerodynamic, and thermal loads has shown substantial material-dependent differences in stress, deformation, and fatigue-life behavior (Emara et al., 2020). Multidisciplinary optimization has addressed this aerodynamic-structural interaction more directly. Aero-mechanical optimization of a high-speed centrifugal impeller has produced Pareto solutions that

increased isentropic efficiency while reducing maximum stress (Li et al., 2019). A separate multidisciplinary framework has combined aerodynamic efficiency, structural integrity, blade number, and processing considerations within centrifugal compressor optimization (Zhang et al., 2018). Preliminary compressor design research has also integrated aero-thermodynamic prediction with impeller-strength prediction rather than postponing structural evaluation until after aerodynamic geometry has been established (Sun et al., 2019). Thermal conditions additionally change rotor-shaft material properties and structural stiffness, making temperature relevant to the dynamic behavior of turbocharger rotating assemblies (Liu et al., 2020).

The interaction among aerodynamic geometry, thermomechanical loading, manufacturing variation, and operating condition makes compressor-wheel optimization a multivariable engineering problem in which a nominally high-performing geometry may respond differently when rotational speed, boundary conditions, dimensional tolerances, or blade profiles vary. Aerodynamic robustness research has consequently moved beyond optimization at a single deterministic operating point. Uncertainty-quantification-based optimization has shown that rotor-speed variation and geometric variables such as inlet angle, outlet angle, envelope angle, and tip clearance can influence compressor pressure ratio and efficiency, requiring performance sensitivity to be considered together with nominal aerodynamic performance (Tang et al., 2020). Robustness optimization under combined operational and geometric uncertainties has also demonstrated measurable relationships among design variables, mean pressure ratio, isentropic efficiency, performance variability, and acoustic behavior (Tang et al., 2021). Manufacturing errors introduce another layer of complexity because the manufactured compressor blade may not reproduce its intended aerodynamic surface exactly. Statistical analysis of machined impellers has demonstrated that camber and thickness deviations can modify separation behavior and degrade aerodynamic performance, especially when positive blade-thickness errors occur near critical leading-edge regions (Ju et al., 2021). The relevance of manufacturing to optimization has been reinforced by experimental work in which additively manufactured compressor wheels have been subjected to high-speed operation and compared with conventional wheel configurations, linking prototype manufacturing with numerical and experimental compressor assessment (Andrearczyk et al., 2020). These findings are closely connected to component-level energy losses. An automotive turbocharger compressor does not lose efficiency through one mechanism alone; skin friction, diffusion, recirculation, blade loading, incidence, leakage, and blockage contribute differently as rotational speed and flow rate change (Khoshkalam et al., 2019). Thermal conditions can simultaneously alter the apparent efficiency obtained from temperature measurements, making purely aerodynamic interpretation incomplete when heat transfer is appreciable (Casey & Fesich, 2010). Experimental automotive testing has reported relative errors in compressor-efficiency estimation when the classical adiabatic assumption is applied under conditions where heat transfer affects the measured thermodynamic state (Bontempo et al., 2015). The wheel is consequently positioned at the intersection of fluid mechanics, thermodynamics, heat transfer, structural mechanics, materials engineering, and high-speed rotor dynamics, with each domain contributing measurable factors to the amount of shaft energy converted into useful compressed-air pressure and enthalpy.

Within the reviewed literature, aerodynamic performance has predominantly been investigated through CFD, experimental compressor mapping, response-surface methods, evolutionary algorithms, adjoint optimization, and uncertainty-based numerical optimization, whereas structural and thermomechanical performance has primarily been evaluated through finite-element stress analysis, fatigue assessment, coupled aero-thermo-mechanical calculation, thermal analysis, and multidisciplinary optimization. This separation creates a specific empirical problem for a study concerned with the combined aerodynamic and thermomechanical optimization of turbocharger compressor wheels. Aerodynamic studies consistently identify blade-angle distribution, splitter configuration, meridional contours, tip clearance, and internal loss mechanisms as important determinants of compressor efficiency and pressure development (Ekradi & Madadi, 2020; Moussavi et al., 2017). Structural studies identify centrifugal stress, blade-root stress, cyclic loading, deformation, fatigue resistance, and material behavior as central limits on compressor-wheel operation (Emara et al., 2020; S. Liu et al., 2016). Multidisciplinary investigations confirm that aerodynamic efficiency and mechanical stress can respond differently to the same geometric modifications, creating a requirement

to evaluate both performance domains within one analytical structure rather than treating wheel geometry as an exclusively aerodynamic variable (Li et al., 2019; Sun et al., 2019). Manufacturing and operating uncertainties add further variation because geometric deviation and stochastic boundary conditions can alter pressure ratio, efficiency, and aerodynamic robustness even when the nominal wheel design remains unchanged (Ju et al., 2021; Tang et al., 2020). The present research therefore defines four measurable optimization dimensions: Aerodynamic Flow Optimization, Geometric Configuration Optimization, Thermomechanical Structural Optimization, and Thermal Deformation and Material Optimization. Energy Conversion Efficiency is treated as the dependent performance construct, expressed through the engineering logic of efficient pressure and enthalpy rise, reduced aerodynamic loss, effective compression work, and sustained compressor performance. The study adopts a quantitative, cross-sectional, case-study-based approach in which technically qualified respondents evaluate these defined engineering dimensions through a five-point Likert instrument, followed by descriptive statistics, Pearson correlation analysis, and multiple regression modeling. This structure permits the individual relationships of the four optimization dimensions with Energy Conversion Efficiency and their combined statistical contribution to be examined within one coherent compressor-wheel research model.

Background of the Study

Turbocharger compressor wheels are critical rotating components in modern forced-induction systems because they determine how effectively mechanical energy transmitted from the turbine shaft is converted into useful pressure and enthalpy increases in the intake airflow. During operation, the compressor wheel rotates at extremely high speeds and draws ambient air through the inducer region before accelerating it through curved blade passages toward the exducer. The resulting increase in fluid velocity is subsequently transformed into pressure through diffusion, allowing a greater mass of air to enter the engine or associated energy-conversion system. The effectiveness of this process depends strongly on compressor-wheel geometry, internal flow behavior, rotational loading, material characteristics, thermal conditions, and the interaction among these factors. Aerodynamic losses caused by flow separation, incidence, tip leakage, secondary flows, recirculation, blade loading, surface friction, and nonuniform pressure distribution can reduce the fraction of shaft work that is converted into useful compression. Geometric parameters such as blade inlet and outlet angles, backsweep, inducer diameter, exducer diameter, blade thickness, splitter-blade configuration, hub and shroud contours, and tip clearance directly influence these aerodynamic mechanisms. At the same time, the compressor wheel must withstand substantial centrifugal forces, cyclic speed variations, aerodynamic pressure loads, thermal gradients, and material deformation. Structural optimization is therefore closely connected with aerodynamic optimization because modifications intended to improve flow behavior may alter stress concentration, stiffness, deformation, fatigue resistance, or running tip clearance. Thermal expansion can further modify the effective blade-to-shroud clearance and consequently influence leakage and compressor efficiency. The research problem is therefore inherently multidisciplinary and requires aerodynamic, geometric, structural, thermal, and material considerations to be examined within a unified performance framework. This study focuses on four principal optimization dimensions, namely Aerodynamic Flow Optimization, Geometric Configuration Optimization, Thermomechanical Structural Optimization, and Thermal Deformation and Material Optimization, and evaluates their relationships with Energy Conversion Efficiency. By adopting a quantitative, cross-sectional, case-study-based engineering approach, the research treats these dimensions as measurable constructs and analyzes their individual and combined associations with compressor-wheel energy-conversion performance.

Problem Statement

The aerodynamic and thermomechanical performance of turbocharger compressor wheels remains a complex engineering problem because improvements in one performance dimension can interact with or constrain other dimensions. Compressor-wheel development has traditionally placed strong emphasis on aerodynamic quantities such as pressure ratio, mass-flow capacity, compressor efficiency, surge margin, and internal flow losses. However, the wheel simultaneously operates under severe mechanical and thermal conditions generated by very high rotational speeds, repeated acceleration and deceleration, centrifugal loading, aerodynamic pressure, temperature gradients, and material-

dependent deformation. A blade geometry that produces favorable aerodynamic characteristics may also create undesirable stress concentrations, excessive deformation, reduced fatigue resistance, or temperature-sensitive dimensional changes. Similarly, structural modifications intended to increase mechanical strength may increase mass, alter flow passages, change blade loading, or affect tip-clearance behavior. This creates a need for an integrated assessment rather than isolated aerodynamic or structural evaluation. Another problem concerns the fragmented way in which relevant optimization factors are frequently evaluated. Aerodynamic flow behavior, geometric configuration, structural response, thermal deformation, material selection, and energy efficiency are often considered through separate analytical procedures, making it difficult to determine their relative and collective influence on compressor-wheel performance within one empirical model. Moreover, compressor performance can be affected by manufacturing variation, operating-condition changes, and thermally induced dimensional variation, meaning that nominal design characteristics alone may not fully represent actual operating behavior. There is therefore a clear research need to quantify how major aerodynamic and thermomechanical optimization factors relate to Energy Conversion Efficiency and to determine which factors provide the strongest statistical contribution when examined together. The present study addresses this problem by establishing a structured quantitative model in which Aerodynamic Flow Optimization, Geometric Configuration Optimization, Thermomechanical Structural Optimization, and Thermal Deformation and Material Optimization serve as explanatory variables for Energy Conversion Efficiency. Descriptive statistics, Pearson correlation analysis, and multiple regression modeling are used to examine the relationships systematically within a defined turbocharger compressor-wheel case-study environment.

Purpose and Objectives of the Study

The principal purpose of this study is to quantitatively examine how aerodynamic and thermomechanical optimization factors influence the Energy Conversion Efficiency of turbocharger compressor wheels within a defined engineering case-study context. The study is designed to move beyond the examination of compressor-wheel performance as a single-dimensional aerodynamic issue by evaluating the combined role of airflow characteristics, geometric configuration, structural behavior, thermal deformation, and material characteristics. The first objective is to determine the relationship between Aerodynamic Flow Optimization and Energy Conversion Efficiency by examining factors associated with reduced flow separation, controlled incidence, minimized tip-leakage losses, improved blade loading, enhanced flow uniformity, and reduced secondary-flow losses. The second objective is to assess the influence of Geometric Configuration Optimization on Energy Conversion Efficiency through the evaluation of blade-angle configuration, backsweep, inducer and exducer dimensions, hub and shroud profiles, splitter-blade arrangement, blade thickness, and tip-clearance control. The third objective is to evaluate the relationship between Thermomechanical Structural Optimization and Energy Conversion Efficiency by considering centrifugal stress, blade-root stress, deformation, stiffness, fatigue resistance, structural stability, and high-speed operational integrity. The fourth objective is to determine how Thermal Deformation and Material Optimization affects Energy Conversion Efficiency by examining thermal expansion, thermal stress, temperature-induced dimensional variation, material strength, density, fatigue behavior, and thermal stability. The fifth objective is to determine the collective predictive effect of the four optimization dimensions on Energy Conversion Efficiency using multiple regression analysis. In fulfilling these objectives, the study applies a structured five-point Likert instrument to data obtained from technically qualified respondents and uses descriptive statistics, reliability and validity assessment, Pearson correlation analysis, and multiple regression modeling to establish the magnitude, direction, and statistical significance of the identified relationships.

Research Hypotheses

The hypotheses of this study are formulated to test the statistical relationships between the four identified aerodynamic and thermomechanical optimization dimensions and Energy Conversion Efficiency in turbocharger compressor wheels. H1 proposes that Aerodynamic Flow Optimization has a significant positive effect on Energy Conversion Efficiency. H2 proposes that Geometric Configuration Optimization has a significant positive effect on Energy Conversion Efficiency. H3 states that Thermomechanical Structural Optimization has a significant positive effect on Energy Conversion

Efficiency. H4 proposes that Thermal Deformation and Material Optimization has a significant positive effect on Energy Conversion Efficiency. H5 proposes that Aerodynamic Flow Optimization, Geometric Configuration Optimization, Thermomechanical Structural Optimization, and Thermal Deformation and Material Optimization jointly exert a significant predictive effect on Energy Conversion Efficiency. These hypotheses reflect the engineering expectation that reducing separation, incidence loss, leakage and secondary-flow losses, refining blade and passage geometry, controlling structural stress and deformation, and maintaining thermal-material stability will be associated with more effective conversion of shaft work into useful compressed-air pressure and enthalpy. The hypotheses establish the statistical structure of the study and provide the basis for correlation analysis, regression modeling, coefficient interpretation, significance testing, and evaluation of the relative contribution of each optimization dimension.

LITERATURE REVIEW

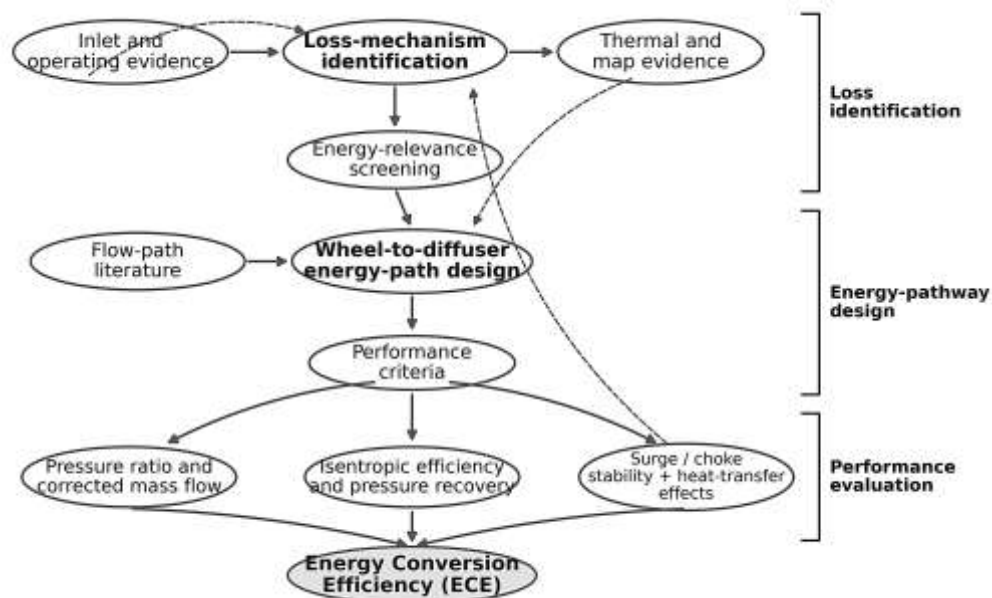
Turbocharger compressor-wheel research occupies an interdisciplinary area involving fluid mechanics, thermodynamics, turbomachinery aerodynamics, structural mechanics, heat transfer, materials engineering, manufacturing accuracy, and high-speed rotating machinery. The compressor wheel performs the fundamental task of transferring rotational shaft energy to the working fluid, increasing air velocity and enabling subsequent pressure development through centrifugal action and diffusion. Its efficiency is therefore determined by both the aerodynamic effectiveness of the flow passages and the ability of the physical wheel to maintain its intended geometry during high-speed operation. Aerodynamic research has consequently examined internal flow separation, blade incidence, tip-leakage vortices, secondary flows, recirculation, blockage, blade loading, surface friction, choke behavior, surge characteristics, pressure ratio, and isentropic efficiency. Geometric optimization studies have focused on blade inlet and outlet angles, backsweep, inducer and exducer dimensions, meridional contours, splitter-blade configurations, blade thickness, blade number, and tip-clearance characteristics. Alongside these aerodynamic concerns, thermomechanical research has investigated centrifugal stress, aerodynamic loading, deformation, thermal gradients, thermal expansion, material strength, fatigue behavior, structural stiffness, and failure mechanisms. These fields become closely interconnected because deformation and temperature can alter the effective tip clearance and blade geometry, while aerodynamic modifications can influence mechanical loading and stress distribution. Compressor-wheel performance must therefore be interpreted through an integrated design perspective in which aerodynamic efficiency cannot be separated completely from structural and thermal operating conditions. The literature relevant to this study is organized around six major areas: turbocharger compressor-wheel aerodynamics and energy conversion, aerodynamic flow optimization, geometric configuration optimization, thermomechanical and material optimization, the theoretical foundation based on Second-Law Thermodynamics and Exergy Theory, and a conceptual framework linking Aerodynamic Flow Optimization, Geometric Configuration Optimization, Thermomechanical Structural Optimization, and Thermal Deformation and Material Optimization with Energy Conversion Efficiency.

Turbocharger Compressor-Wheel Aerodynamics and Energy Conversion Efficiency

Turbocharger compressor-wheel aerodynamics is governed by the transfer of mechanical shaft work into fluid kinetic energy and then into useful pressure rise as air moves from the inducer through the rotating impeller, diffuser, and downstream housing. The compressor wheel therefore operates as the primary energy-transfer element of the centrifugal compressor stage, and its aerodynamic quality is reflected in pressure ratio, corrected mass flow, isentropic efficiency, choke behavior, surge margin, and the distribution of losses through the flow path. At the wheel inlet, the incoming velocity field must meet the blade leading edges with an incidence compatible with the local blade angle; excessive positive or negative incidence can generate separation and additional entropy production. Inside the impeller, blade curvature, rotation, Coriolis effects, pressure gradients, secondary motion, boundary-layer development, and tip leakage interact to create a highly three-dimensional flow field. Downstream of the wheel, residual kinetic energy must be recovered through diffusion without producing excessive separation or instability. In "Investigation of the flow in a small-scale turbocharger centrifugal compressor" (pp. 3-13), particle-image velocimetry and CFD were combined on a full-scale automotive turbocharger compressor, showing that measured diffuser-flow structures and overall

stage behavior can be reproduced with numerical methods and used to explain performance variations across the compressor map (Ashik & Shabbir, 2022; Hazby et al., 2017). The aerodynamic state upstream of the wheel is equally important because inlet geometry changes the velocity distribution and incidence presented to the rotating blades. In "Effect of the inlet geometry on performance, surge margin and noise emission of an automotive turbocharger compressor" (pp. 875-882), alternative inlet configurations altered isentropic efficiency, pressure ratio, and surge behavior, demonstrating that compressor-wheel performance depends on the complete inlet-to-diffuser flow system rather than on impeller geometry alone (Galindo et al., 2017; Hasan & Adnan, 2022). These mechanisms establish aerodynamic efficiency as the outcome of interacting local flow phenomena rather than a single geometric property.

Figure 2: Aerodynamic Energy-Conversion Pathway and Performance Evaluation Framework



Energy-conversion efficiency in a turbocharger compressor is commonly evaluated by comparing the actual compression process with an ideal isentropic process for the same pressure ratio, although the measured value is influenced by operating conditions and thermal exchange as well as aerodynamic losses. Shaft power delivered to the compressor is consumed in raising the stagnation enthalpy of the air, overcoming viscous friction, sustaining secondary and leakage flows, and compensating for losses produced by incidence, separation, wake mixing, diffusion, and nonuniform pressure fields. Consequently, a compressor wheel can achieve the required pressure ratio while still exhibiting inefficient energy conversion if a large proportion of supplied work is dissipated through irreversible mechanisms. The position of an operating point on the compressor map is therefore important. Near the peak-efficiency region, incidence and diffusion are generally better matched to the geometry, whereas movement toward low-flow or high-flow limits can increase instability, recirculation, blockage, or choking losses. In "An experimental investigation of internal heat transfer in an automotive turbocharger compressor" (pp. 531-539), infrared thermography and quasi-adiabatic testing showed that heat transferred internally from hotter turbocharger regions can distort the apparent diabatic compressor efficiency and that corrected efficiency maps better isolate compressor performance from thermal contamination (Mahbubul et al., 2022; Tanda et al., 2017). This distinction is especially important for energy-conversion analysis because outlet-temperature measurements enter directly into compressor-efficiency calculations. Performance mapping also requires a physically meaningful representation of flow, work, and efficiency over speeds and operating points. In "A new method for performance map prediction of automotive turbocharger compressors with both vaneless and vaned diffusers" (pp. 1734-1747), relationships among flow coefficient, work coefficient, impeller outlet

conditions, pressure ratio, and efficiency were organized into a predictive framework validated on multiple automotive turbocharger compressors (Li et al., 2021; Mashfiqur & Md, 2022). Thus, compressor-wheel efficiency should be interpreted as a coupled aerodynamic and thermodynamic quantity whose measured value depends on both internal loss generation and the conditions under which the compressor map is obtained.

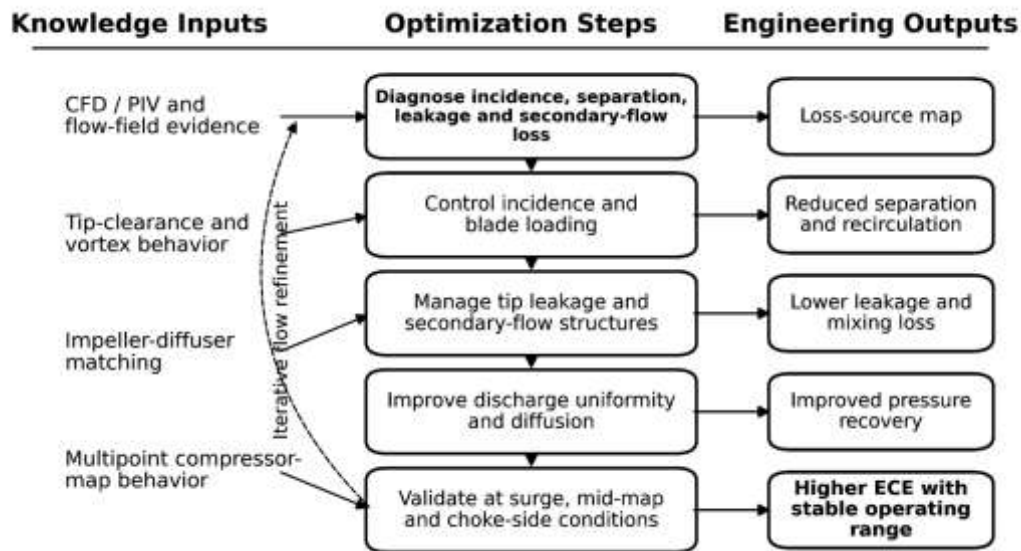
The aerodynamic contribution of the compressor wheel to total stage efficiency is inseparable from geometric matching among the impeller, diffuser, and volute because energy leaving the wheel remains partly in kinetic form and must be converted into static pressure with limited additional loss. Blade number, blade spacing, exit flow angle, backsweep, slip, blockage, wake structure, and tip-clearance leakage determine the velocity and pressure field delivered by the wheel, while the diffuser and volute determine how effectively that discharge is recovered. Greater blade guidance can reduce slip and improve control of relative flow, yet greater solidity can also enlarge wetted area, friction, and blockage, so efficient wheel design requires a balance among competing loss mechanisms. The wheel exit condition is particularly important because a nonuniform or excessively swirling discharge increases the burden placed on downstream pressure-recovery components. In "Effect of housing size on the performance of a centrifugal compressor for turbocharger application: An experimental and numerical study" (pp. 2153-2172), scaled housing configurations were tested with the same impeller, and reductions in housing size produced higher meridional and swirl velocities, greater pressure losses, and measurable efficiency penalties near choke, while increased surface roughness introduced additional wall-shear losses (Karunakaran & Mallikarjuna, 2022; Ashfaq & Mohammad, 2022). The findings illustrate that wheel efficiency cannot be interpreted independently from the aerodynamic environment into which the impeller discharges. Optimization must therefore consider the complete energy pathway, beginning with inlet incidence and relative velocity, continuing through blade work transfer, secondary flow, leakage, and wake formation, and ending with diffusion and volute pressure recovery. For the present research, this sequence supports treating Energy Conversion Efficiency as a measurable performance construct associated with useful pressure development, reduced irreversible loss, effective compression work, and stable operation over the intended compressor map. Aerodynamic Flow Optimization and Geometric Configuration Optimization are consequently treated as related but distinct explanatory constructs, permitting flow-quality mechanisms and wheel-design parameters to be examined separately while preserving their combined relationship with compressor energy conversion.

Aerodynamic Flow Optimization in Turbocharger Compressor Wheels

Aerodynamic Flow Optimization in turbocharger compressor wheels concerns the systematic control of the internal flow field so that a greater proportion of shaft work is converted into useful pressure rise with lower irreversible losses. The optimization problem extends beyond maximizing a single design-point efficiency because the wheel must preserve favorable incidence, loading, diffusion, and flow stability over a meaningful operating range. Inside a centrifugal impeller, Coriolis effects, curvature, pressure gradients, boundary-layer growth, and blade-to-blade loading generate cross-passage motion that redistributes low-momentum fluid and produces secondary-flow structures. These structures thicken wake regions, increase nonuniformity at the impeller outlet, promote local separation, and reduce the useful head delivered by the wheel. In "Analysis of Secondary Flows in Centrifugal Impellers" (pp. 45-52), a vorticity-based description showed that secondary flows directly contribute to head loss, nonuniform meridional velocity profiles, flow separation or stall, and impeller slip, while also indicating that impeller flow shapes can be designed to suppress these losses at their source (Brun & Kurz, 2005; Sadia & Mostari, 2022). This establishes secondary-flow management as a central component of aerodynamic optimization rather than a secondary correction after the wheel geometry has been selected. The optimization process must therefore control how blade curvature, loading distribution, passage width, and local pressure gradients influence the migration of low-momentum fluid between the hub, shroud, pressure surface, and suction surface. Numerical optimization provides one means of coordinating these interacting variables. In "Numerical Optimization on a Centrifugal Turbocharger Compressor" (pp. 1175-1180), computational fluid dynamics and an artificial neural network were combined while varying stacking laws, end-wall geometry, and blade-section camber, with total-to-total efficiency and total pressure ratio used as

performance outputs (Qi et al., 2009; Shaiful et al., 2022). Such control is especially important in compact turbocharger wheels, where high rotational speed intensifies three-dimensional flow interactions.

Figure 3: Aerodynamic Flow Optimization Process for Turbocharger Compressor Wheels



Tip-region flow is another major target of Aerodynamic Flow Optimization because the pressure difference between blade pressure and suction surfaces drives leakage through the clearance between the rotating blade tip and stationary shroud. The resulting leakage jet interacts with the primary passage flow, rolls into a vortex, increases mixing loss, changes blade loading, and can create blockage close to the shroud. As mass flow is reduced toward the low-flow boundary, these structures can migrate upstream and interact with inlet flow, increasing the complexity of stall inception and limiting the usable compressor map. Optimization therefore requires more than simply reducing clearance to its smallest geometric value; it requires controlling leakage strength, vortex trajectory, mixing location, and the interaction between tip flow and the main passage stream. In "Performance Improvement of a Centrifugal Compressor by Passive Means" (Article 727259, pp. 1-9), multiple tip-clearance levels were examined together with turbulence generators and partial shrouds, with a partial shroud producing the strongest performance improvement because the extended leakage path reduced tip-leakage flow and associated losses, while turbulence generation mainly affected operating range (Sitaram & Swamy, 2012; Stabak & Shahid, 2022). This evidence shows that flow control at the blade tip can alter both efficiency and stability without requiring complete redesign of the entire compressor stage. Tip-leakage behavior can also have a more complex relationship with stability than a simple loss model suggests. In "The Effect of Tip Leakage Vortex for Operating Range Enhancement of Centrifugal Compressor" (Article 051020), experimental and computational analysis showed that tip-leakage-vortex breakdown and the resulting blockage could participate in stabilizing low-flow operation in a wider-range configuration (Mohammad, 2023; Tomita et al., 2013). Consequently, Aerodynamic Flow Optimization should control the structure and position of leakage vortices rather than treating every tip-region vortex as an identical loss source.

The downstream flow leaving the compressor wheel is equally important because the kinetic energy produced by the impeller must be recovered efficiently as static pressure in the diffuser and volute. Impeller-exit flow is characteristically nonuniform because wakes, jet-wake structures, residual swirl, tip-leakage effects, secondary motion, and blade-to-blade pressure gradients persist beyond the trailing edge. Poor matching between wheel discharge and diffuser geometry increases diffusion loss, separation, blockage, and sensitivity to off-design operation, which means that aerodynamic optimization must consider the complete flow path rather than the rotating wheel in isolation. Diffuser optimization is particularly relevant to turbocharger compressors because compact packaging, wide operating requirements, and rapidly changing engine demand require acceptable efficiency from near-surge conditions through mid-flow operation toward choke. In "Numerical Optimisation of the Diffuser in a Typical Turbocharger Compressor Using the Adjoint Method" (pp. 179-196), adjoint-based

shape optimization was applied across six operating cases covering surge-side, stable-midpoint, and choke-side conditions on two speed lines, with an efficiency improvement reaching approximately 2.6% for a representative mid-stable condition ([Adnan & Iftekhar, 2023](#); [Hazizi et al., 2022](#)). The study demonstrates the value of multipoint optimization because a geometry optimized at only one map location may redistribute losses unfavorably elsewhere. For the present research, Aerodynamic Flow Optimization therefore represents coordinated improvement of incidence control, secondary-flow suppression, leakage management, blade loading, wake reduction, diffusion quality, and operating-range stability. These mechanisms provide a physically grounded basis for evaluating the construct through expert assessment because they describe recognizable aerodynamic practices used in compressor development. Within the proposed quantitative model, higher levels of Aerodynamic Flow Optimization are expected to correspond with lower irreversible flow losses, more uniform impeller-discharge conditions, improved pressure recovery, and stronger Energy Conversion Efficiency, while correlation and regression analysis determine the magnitude and statistical significance of that relationship within the selected case-study context.

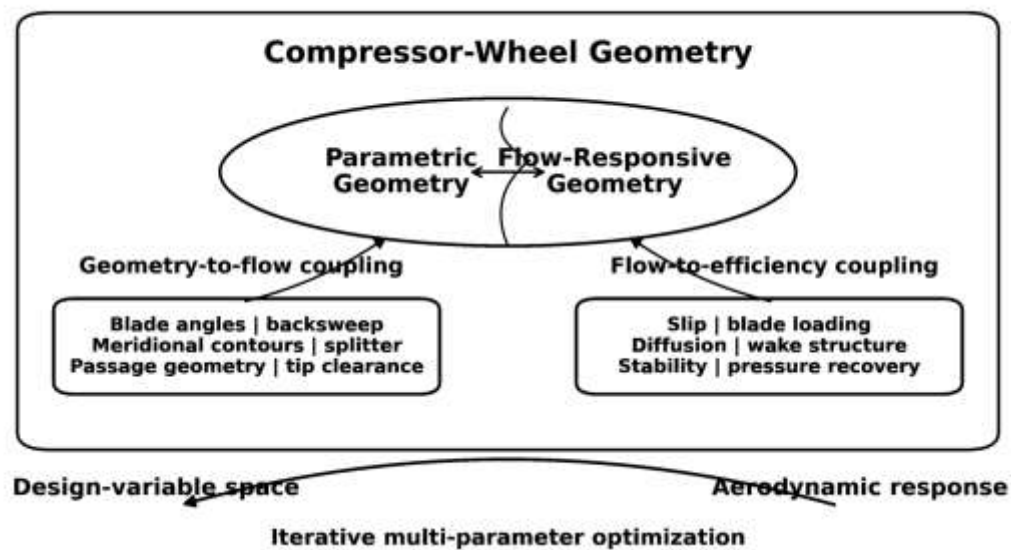
Geometric Configuration Optimization of Compressor Wheels

Geometric Configuration Optimization constitutes one of the most influential design activities in centrifugal compressor development because the three-dimensional shape of the impeller directly governs velocity triangles, blade loading, slip, diffusion, flow-path curvature, pressure development, and aerodynamic loss. Important geometric variables include inducer and exducer diameters, blade inlet and exit angles, backsweep angle, blade height, passage width, blade thickness, meridional hub and shroud contours, and the spatial distribution of blade angles between the leading and trailing edges. Changes in these parameters modify both the amount of work transferred to the airflow and the manner in which the resulting flow leaves the rotating impeller. In "Numerical Investigation of the Effect of Different Back Sweep Angle and Exducer Width on the Impeller Outlet Flow Pattern of a Centrifugal Compressor with Vaneless Diffuser" (pp. 421-433), variations in backsweep and exducer width were shown to influence wake position, relative velocity, flow-deviation angle, and the uniformity of the impeller discharge, with increased backsweep producing a more uniform outlet-flow field and improved conditions for downstream diffusion ([Hildebrandt & Genrup, 2007](#); [Rahman, 2023](#)). This relationship demonstrates that backsweep cannot be selected solely from a mechanical or dimensional perspective because its aerodynamic consequences extend into the diffuser and affect overall stage pressure recovery. Meridional geometry is similarly important because modification of the hub and shroud contours changes passage area, streamwise acceleration, local diffusion, and the distribution of low-momentum fluid. In "A Numerical Study on Shape Design Optimization for an Impeller of a Centrifugal Compressor" (pp. 5-12), the meridional profile and blade-angle distribution were parameterized through control points and optimized using design-of-experiments and response-surface methods, while specific overall efficiency served as the primary objective function and optimized geometries were evaluated under design and off-design conditions ([Sheak & Tahmedur, 2023](#); [Seo et al., 2014](#)). Geometric Configuration Optimization therefore requires simultaneous consideration of dimensions and curvature because individual parameters modify the complete three-dimensional flow passage rather than functioning as isolated design characteristics.

The complexity of compressor-wheel geometry makes multi-parameter optimization particularly important because improving one geometric characteristic can negatively alter another performance measure. Increasing backsweep, for example, can modify exit velocity and diffusion behavior while reducing work input for a fixed tip speed, whereas enlarging passage dimensions can influence mass-flow capacity but simultaneously modify diffusion rates, blockage, and blade loading. Blade-angle distributions also determine how aerodynamic loading develops from inducer to exducer and therefore influence local acceleration, separation tendencies, relative Mach number, and entropy generation. In "Multi-objective Optimization for Centrifugal Compressor of Mini Turbojet Engine" (pp. 414-425), geometric parameters were treated as optimization inputs within a design-of-experiments and response-surface framework, and the resulting configurations were assessed simultaneously against efficiency, pressure ratio, and compressor input-power objectives rather than against one isolated performance indicator ([Guo et al., 2014](#); [Kaïum, 2023](#)). Such an approach is directly relevant to turbocharger compressor wheels because geometric design requires balancing pressure-generation

capability with energy consumption and aerodynamic efficiency. Shape optimization becomes even more important near the low-flow stability boundary, where inappropriate blade curvature or passage geometry can strengthen separation and reduce stall margin. In "Surrogate-Based Shape Optimization of Stall Margin and Efficiency of a Centrifugal Compressor" (pp. 1607-1620), blade curvature, impeller-shroud curvature, and diffuser-hub curvature were selected as design parameters in a multi-objective optimization process intended to improve both efficiency and stall margin, with the optimized geometry suppressing separation mechanisms associated with unstable operation (Khalfallah et al., 2015; Pervaz, 2023). These findings show that compressor-wheel geometry determines more than nominal design-point efficiency. It also influences the width and stability of the usable operating region, making geometrical optimization particularly important for turbocharger applications in which compressor operating conditions can move substantially across the performance map.

Figure 4: Geometric Configuration Optimization and Aerodynamic Response Framework



Advanced compressor-wheel optimization further requires three-dimensional geometric features to be considered because conventional two-dimensional blade-angle adjustment cannot completely control shock structure, tip-region loading, wake formation, and spanwise redistribution of aerodynamic forces in highly loaded or transonic impellers. Blade camber determines the progression of turning and loading along the passage, while sweep alters the axial position of blade sections and can redistribute loading between the hub and shroud. Lean changes circumferential stacking and modifies spanwise pressure gradients, whereas leading-edge and trailing-edge shapes influence incidence, shock interaction, wake thickness, and local separation. These geometric variables can therefore interact, meaning that the optimum compressor wheel may depend on combinations of geometric features rather than on the independent optimum value of each parameter. In "Performance Improvement of Transonic Centrifugal Compressors by Optimization of Complex Three-Dimensional Features" (pp. 2723-2738), camber curves, sweep, and lean were examined through multipoint and multi-objective optimization; optimization of camber reduced shock strength, sweep modification reduced the wake region, and the combined optimized configuration increased peak efficiency and choke mass-flow capacity relative to the baseline impeller (He & Zheng, 2017; Badrul & Mominul, 2023). Such evidence demonstrates that Geometric Configuration Optimization should be interpreted as a coordinated manipulation of blade and passage characteristics rather than simple dimensional refinement. For the present research, the construct therefore encompasses optimization of blade angles, backsweep, inducer and exducer dimensions, meridional hub-shroud profiles, blade curvature, blade thickness, splitter arrangement, passage dimensions, and clearance-sensitive geometry. These features provide technically meaningful indicators for examining whether improved geometric configuration is

associated with higher Energy Conversion Efficiency. Within the quantitative model of this study, the construct is treated independently from Aerodynamic Flow Optimization because geometry represents controllable design characteristics, whereas aerodynamic optimization represents the resulting management of flow phenomena such as separation, leakage, wake development, incidence, and loss generation.

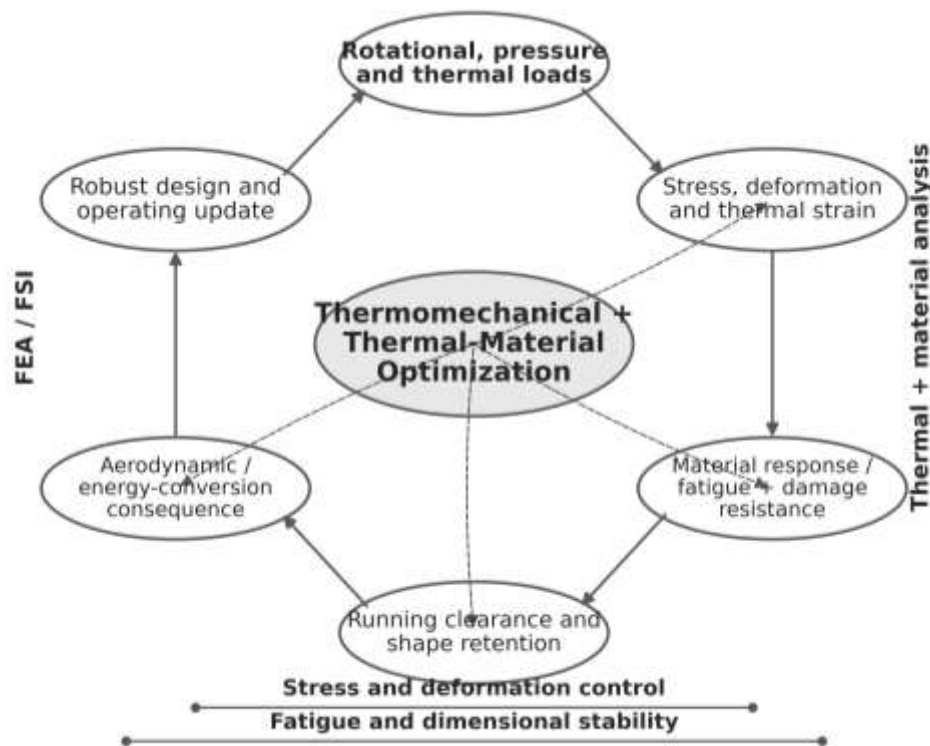
Material Optimization of Compressor Wheels

Thermomechanical optimization of turbocharger compressor wheels requires simultaneous control of centrifugal stress, thermal gradients, elastic-plastic deformation, creep, relaxation, fatigue, and material stability because the wheel operates at extremely high rotational speed while experiencing repeated thermal and mechanical transients. Rotational loading produces tensile and equivalent stresses that generally increase with angular velocity and radial distance, whereas nonuniform temperature distributions create thermal expansion and additional stress fields that can alter blade and back-disk deformation. These mechanisms are coupled because temperature changes the elastic modulus, yield strength, hardening response, and time-dependent deformation behavior of the wheel material. In "Thermomechanical Behaviour of Turbocharger Compressor Wheels" (pp. 1089-1098), transient conjugate heat-transfer boundary conditions and finite-element calculations were used to characterize temperature distribution, deformation, relaxation, creep, and low-cycle fatigue behavior of 2618-T6 aluminum compressor wheels under different operating points and thermal shock cycles, demonstrating the importance of time-dependent material response in highly stressed regions (Makarenko et al., 2012; Rakib & Towhidul, 2023). Material microstructure adds another source of thermomechanical variability because forged compressor-wheel blanks can develop nonuniform grain structures during heat treatment. In "Influence of Microstructure on the Quasistatic and Low Cycle Fatigue Behaviour of an AA2618 Aluminium Alloy" (pp. 1339-1347), specimens taken from different locations within a forged AA2618 slug showed differences in yield strength, tensile strength, cyclic response, and fatigue life, with local microstructure influencing both quasistatic properties and low-cycle fatigue behavior at elevated temperatures (Khalil & Lang, 2011; Kanti, 2023). These findings establish that compressor-wheel optimization should incorporate not only global stress limits but also spatial variations in temperature, strain, microstructure, and material properties. A thermomechanically optimized wheel must retain sufficient stiffness and fatigue resistance while limiting deformation that could modify critical aerodynamic dimensions such as blade-tip clearance, exducer geometry, and the alignment of rotating and stationary surfaces during high-speed operation throughout repeated acceleration and deceleration operating cycles.

Structural durability is important because compressor wheels are subjected to cyclic loading that can initiate cracks at high stress concentrations and propagate those cracks under repeated cycles. Centrifugal force is normally the dominant mechanical load, but aerodynamic pressure, thermal stress, vibration, overspeed, residual stress, and geometric discontinuities can combine to change the stress state. Optimization must therefore address where peak stresses occur, how those stresses vary through a duty cycle, and whether the material can tolerate repeated loading without progressive damage. In "Fatigue Life Assessment of the Centrifugal Compressor Impeller with Cracks Based on the Properties of FV520B" (pp. 177-186), finite-element analysis was combined with material testing and fracture-mechanics concepts to establish relationships between local stress and crack size and to predict the remaining fatigue life of compressor impellers containing specified cracks (Liu et al., 2016; Nishat, 2023). This approach demonstrates why crack-sensitive regions should be incorporated into structural optimization rather than evaluated after a design has been completed. Surface condition and environmental exposure also affect structural reliability because defects can provide sites for fatigue initiation. In "Failure Analysis in Aluminium Turbocharger Wheels" (pp. 108-118), premature failures of machined AA2618-T652 compressor wheels were traced to fatigue initiated by intergranular corrosion on the upper camber surface, even though the investigated wheel material met specified composition and hardness requirements (Moreira, 2016; Risha & Shurovi, 2023). Material optimization must consequently include resistance to damage initiation as well as measures of yield and ultimate strength. For turbocharger applications, a compressor-wheel material should combine low density with high specific strength, fracture resistance, corrosion resistance, thermal stability, fatigue endurance, manufacturability, and predictable behavior under centrifugal and thermal loading. These

requirements connect thermomechanical optimization directly to operational reliability because reduced wheel mass can decrease centrifugal stress while inadequate microstructural or environmental resistance can shorten service life even when static stresses remain below limits.

Figure 5: Thermomechanical, Thermal, and Material Optimization Cycle



Material and thermal optimization further determine whether a compressor wheel can preserve aerodynamic shape and structural integrity throughout its service envelope. Aluminum alloys are widely used because their low density reduces rotational inertia and centrifugal loading, while precipitation strengthening provides useful mechanical strength at moderate temperatures. Their suitability, however, depends on fatigue resistance, temperature sensitivity, creep response, microstructural stability, corrosion behavior, and the manufacturing condition of the finished wheel. Titanium alloys can offer greater specific strength and thermal capability for demanding applications, but their higher density relative to aluminum, processing difficulty, and cost can change the overall design tradeoff. Material selection should therefore be linked to actual thermomechanical loading rather than based on a single room-temperature strength value. In "Fatigue Behavior of 2618-T851 Aluminum Alloy under Uniaxial and Multiaxial Loadings" (Article 105322), extensive fatigue testing showed that fatigue resistance of 2618-T851 aluminum is sensitive to mean tensile and shear stresses and that cracks repeatedly initiated at coarse Al₃FeNi intermetallic particles, emphasizing the importance of microstructural features under complex cyclic loading (Benaissa et al., 2020; Stabak & Siam, 2023). For compressor-wheel optimization, these observations are important because rotating blades experience combined stress components whose amplitudes change with speed, pressure loading, temperature, and vibration. Thermal deformation must also remain controlled to prevent excessive changes in tip clearance, blade alignment, and back-disk geometry that can increase leakage or disturb the designed aerodynamic flow field. The Thermal Deformation and Material Optimization construct in this study therefore encompasses control of thermal gradients, dimensional stability, material density, high-temperature strength, cyclic fatigue resistance, creep resistance, fracture behavior, and microstructural reliability. When assessed together with Thermomechanical Structural Optimization, these characteristics provide a coherent basis for examining whether structurally stable, thermally resistant compressor-wheel designs are associated with greater Energy Conversion Efficiency under the operating conditions represented by the selected engineering case study.

Theoretical Framework

Second-Law Thermodynamics and Exergy Theory provide the principal theoretical foundation for evaluating how aerodynamic and thermomechanical optimization can improve the Energy Conversion Efficiency of turbocharger compressor wheels. The First Law establishes that energy is conserved, whereas the Second Law distinguishes between energy quantity and the quality or useful work potential of that energy. This distinction is particularly relevant to centrifugal compressors because the mechanical power supplied to the compressor wheel is not converted completely into useful pressure and enthalpy increase. Part of that available work is degraded through friction, turbulence, flow separation, tip leakage, shock formation, secondary flows, heat transfer, mixing, and other irreversible processes. Exergy represents the maximum theoretical useful work that can be obtained as a system approaches equilibrium with a specified reference environment. For a flowing fluid, neglecting kinetic and potential terms when they are comparatively small, the specific physical exergy can be expressed as follows. In "Application of Exergy Balances for the Optimization of Non-Adiabatic Small Turbomachines Operation" (pp. 2924-2936), exergy analysis was applied specifically to small turbomachinery, including turbochargers, and showed that conventional adiabatic performance evaluation can overestimate actual turbomachine performance when internal heat transfer is significant (Diango et al., 2011; Feroz, 2023). The theoretical connection with compressor-wheel optimization is therefore direct: any aerodynamic, thermal, or structural mechanism that increases irreversibility reduces the useful-work potential retained by the compressed airflow. In "Second-Law Analysis of Irreversible Losses in Gas Turbines" (Article 470), entropy and exergy equations were formulated for compressible turbulent flows in rotating and stationary components, while compressor-cascade analysis demonstrated that Second-Law quantities can identify local irreversible-loss behavior that conventional overall performance parameters cannot fully describe (Jin et al., 2017; Tahmedur & Rifat, 2023).

$$ex = (h - h_0) - T_0(s - s_0)$$

The central quantitative principle connecting Exergy Theory to compressor-wheel design is the Gouy-Stodola relationship, which links entropy generation directly to destroyed useful-work potential. For the compressor wheel, entropy generation arises from viscous dissipation, turbulent mixing, tip-leakage interaction, boundary-layer growth, separation, nonuniform diffusion, heat transfer across finite temperature differences, and other non-ideal processes. Consequently, aerodynamic optimization can theoretically improve energy conversion by reducing entropy generation, while thermomechanical optimization can support this reduction by maintaining the intended blade geometry, clearance, and material dimensional stability under operating loads. For an ideal-gas approximation, the entropy change between compressor inlet and outlet connects temperature rise and pressure ratio directly to the Second-Law evaluation. In "Experimental and Numerical Investigation of a Turbocharger Turbine Using Exergy Analysis at Non-Adiabatic Conditions", three-dimensional CFD and experimental measurements were combined with flow-exergy analysis to separate useful energy transformation, heat-transfer effects, and irreversible losses in a turbocharger environment, demonstrating that First-Law energy accounting alone does not fully characterize aerothermodynamic loss mechanisms (Asheke, 2024; Lim et al., 2020). Exergy-based interpretation is also sensitive to compressor pressure ratio and thermodynamic operating conditions. In "Exergetic Effects of Some Design Parameters on the Small Turbojet Engine for Unmanned Air Vehicle Applications" (pp. 51-61), compressor pressure ratio was treated as a principal design parameter affecting component and system exergy performance, illustrating that compression characteristics directly influence useful energy utilization within turbomachinery cycles (Ashrafuzzaman 2024; Turan, 2012).

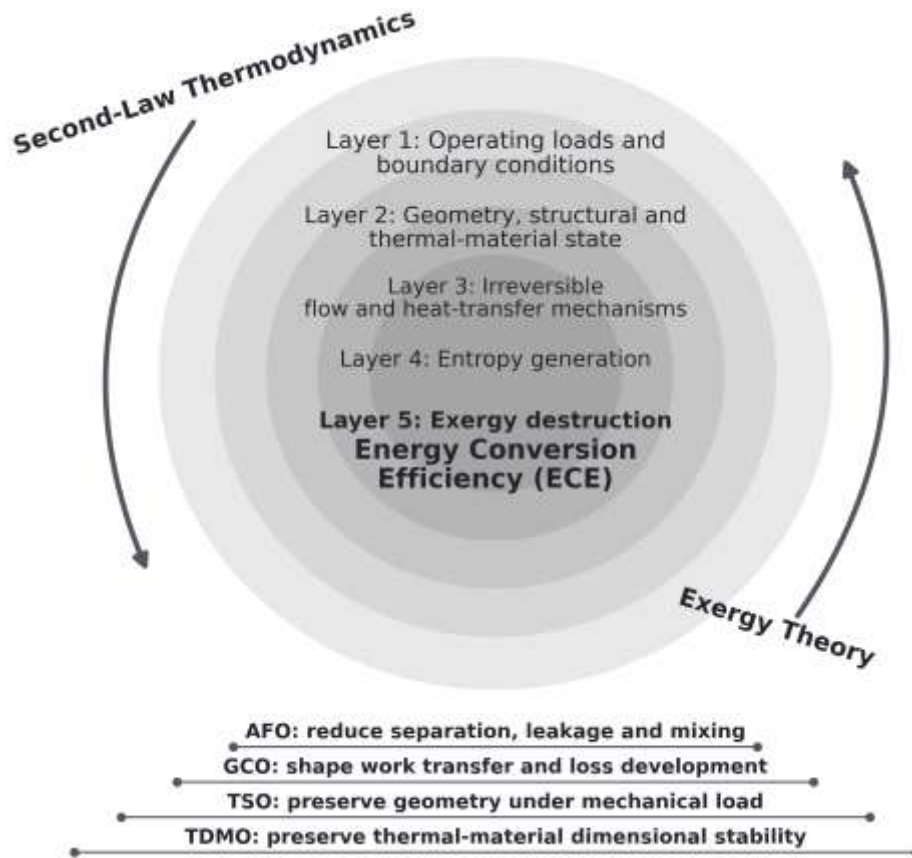
$$E_D = T_0 S_{gen}$$

$$s_2 - s_1 = c_p \ln(T_2/T_1) - R \ln(p_2/p_1)$$

For the present study, the most useful whole-study expression is the Second-Law or exergy efficiency because it provides the theoretical link between the four optimization constructs and Energy Conversion Efficiency. Compressor exergy efficiency may be represented generally as the ratio of the useful increase in flow exergy to the mechanical exergy supplied to the compressor. This formulation is particularly suitable for the study because increased useful pressure and enthalpy development raise the productive portion of compressor work, whereas increasing entropy generation lowers the useful

exergy retained in the airflow.

Figure 6: Second-Law Thermodynamics and Exergy-Theory Framework for Compressor-Wheel Optimization



Aerodynamic Flow Optimization theoretically reduces entropy production caused by leakage, separation, incidence, mixing, and secondary flow. Geometric Configuration Optimization modifies blade and passage characteristics that determine work transfer and loss development. Thermomechanical Structural Optimization helps preserve the designed aerodynamic geometry under centrifugal and pressure loading, while Thermal Deformation and Material Optimization controls temperature-dependent dimensional change and material response that can affect blade clearance and flow quality. In "Energy and Exergy Analysis of a Novel Turbo-Compounding System for Supercharging and Mild Hybridization of a Gasoline Engine" (pp. 817-828), energy and exergy balances were applied to compression and expansion components to quantify useful energy conversion, component losses, and overall thermodynamic performance within a forced-induction and waste-energy-recovery system (Mashiat, 2024; Salek et al., 2021). Accordingly, Second-Law Thermodynamics and Exergy Theory provide the physical logic underlying the statistical model of this research, in which AFO, GCO, TSO, and TDMO are evaluated as determinants of Energy Conversion Efficiency.

$$\eta_{ex, c} = \frac{\dot{m}[(h_2 - h_1) - T_0(s_2 - s_1)]}{W_c}$$

Conceptual Framework for Aerodynamic

The conceptual framework of this study integrates four engineering optimization constructs, namely Aerodynamic Flow Optimization (AFO), Geometric Configuration Optimization (GCO), Thermomechanical Structural Optimization (TSO), and Thermal Deformation and Material Optimization (TDMO), as explanatory variables of Energy Conversion Efficiency (ECE) in turbocharger compressor wheels. The framework is based on the premise that compressor efficiency does not depend on one isolated design parameter, because the energy transferred from the rotating shaft to the airflow

is influenced simultaneously by internal-flow quality, blade and passage geometry, structural deformation, and temperature-dependent material behavior. AFO represents the control of aerodynamic phenomena including incidence, separation, tip leakage, wake formation, secondary flow, flow nonuniformity, and diffusion losses. GCO represents controllable geometric characteristics such as blade-angle distribution, backsweep, splitter position, blade stacking, meridional contours, passage dimensions, and tip-clearance configuration. In "Multi-objective optimization and design rule mining for an aerodynamically efficient and stable centrifugal impeller with a vaned diffuser" (pp. 271-293), simultaneous optimization of impeller shape, aerodynamic efficiency, and outlet-flow uniformity demonstrated that design variables can influence efficiency and stability through interacting aerodynamic mechanisms rather than through independent effects (Kaium, 2024; Sugimura et al., 2010). The relationship between geometry and broader compressor performance is also supported by "Multipoint and Multiobjective Optimization of a Centrifugal Compressor Impeller Based on Genetic Algorithm" (Article 6263274), where geometric parameterization and multiobjective optimization produced simultaneous changes in pressure ratio, isentropic efficiency, surge margin, and choke mass flow across the operating range (Li et al., 2017; Kanti, 2024). These relationships provide the basis for representing AFO and GCO as direct explanatory constructs of ECE.

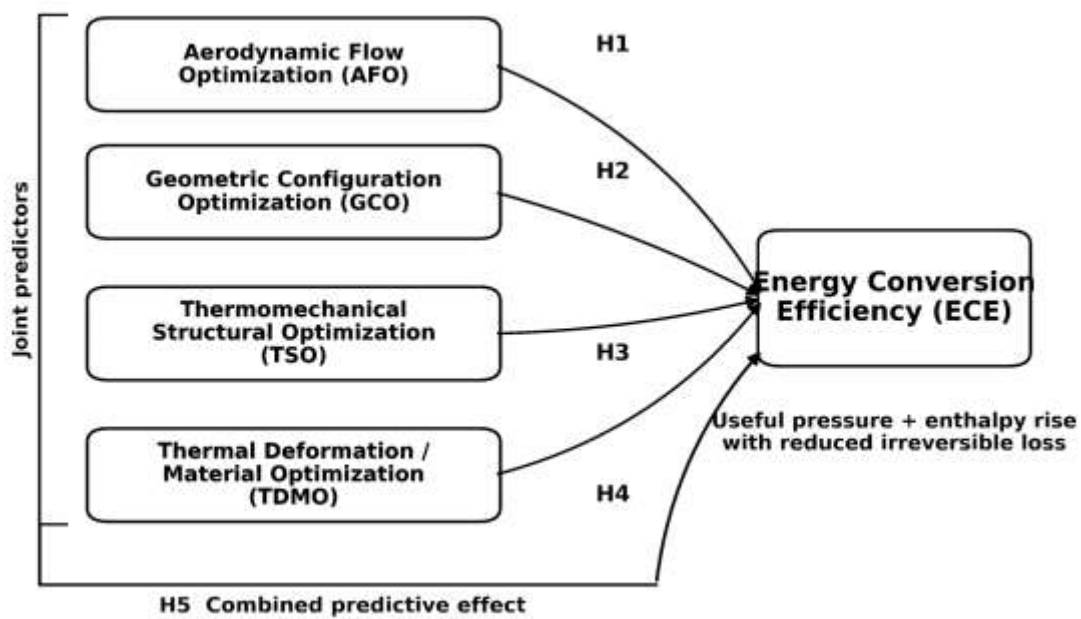
$$AFO \rightarrow ECE ; GCO \rightarrow ECE$$

The framework also incorporates thermomechanical and material behavior because compressor-wheel geometry under operating conditions may differ from its unloaded design geometry. TSO represents control of equivalent stress, centrifugal deformation, blade-root loading, structural stiffness, fatigue exposure, and mechanical safety under high rotational speed, whereas TDMO represents control of thermal expansion, thermal stress, temperature-dependent deformation, material strength, density, fatigue characteristics, and dimensional stability. The conceptual separation of these constructs allows structural response and temperature-material response to be measured independently while recognizing their interaction with the aerodynamic system. In "Optimal design of impeller for centrifugal compressor under the influence of one-way fluid-structure interaction" (pp. 3953-3959), response-surface optimization and one-way fluid-structure interaction were employed to evaluate aerodynamic performance and structural safety simultaneously, showing that impeller shape can be optimized by considering both isentropic efficiency and equivalent stress rather than treating structural integrity as an external design constraint (Kang & Kim, 2016; Feroz, 2024). Similarly, "Aerodynamic and Structural Characteristics of a Centrifugal Compressor Impeller" (Article 3416) evaluated pressure ratio, efficiency, equivalent von Mises stress, and deformation under centrifugal and aerodynamic loading, establishing a direct analytical connection between aerodynamic performance and structural response in a rotating compressor impeller (Jebieshia et al., 2019; Uddin & Risha, 2024). For the present conceptual framework, these thermomechanical relationships are represented as TSO and TDMO pathways to ECE because excessive stress, deformation, thermal expansion, or unsuitable material response can change blade position, tip clearance, flow-passage dimensions, and pressure distribution, thereby influencing the amount of mechanical work effectively converted into useful fluid energy.

$$TSO \rightarrow ECE ; TDMO \rightarrow ECE$$

The complete conceptual model treats Energy Conversion Efficiency as the dependent construct representing effective conversion of compressor shaft input into useful pressure and enthalpy development with minimized aerodynamic and thermodynamic loss. The combined relationship is represented by the multiple linear regression model that has been applied consistently in the quantitative analysis. The standardized form allows the relative statistical contribution of each optimization dimension to be compared while the remaining predictors are controlled. The integrated nature of this model is supported by "Multi-objective optimization design of a centrifugal impeller by positioning splitters using GMDH, NSGA-III and entropy weight-TOPSIS" (pp. 2021-2034), in which splitter location, blade stacking angle, and work ratio were connected simultaneously with impeller efficiency, outlet-velocity nonuniformity, and maximum equivalent blade stress through CFD, fluid-structure interaction, surrogate modeling, and multiobjective optimization (Xie et al., 2021).

Figure 7: Conceptual Framework Linking AFO, GCO, TSO, and TDMO to Energy Conversion Efficiency



The conceptual framework therefore translates the physical multidisciplinary optimization problem into a testable quantitative structure. H1 corresponds to the coefficient β_1 , H2 to β_2 , H3 to β_3 , and H4 to β_4 , while the overall regression model provides the statistical basis for evaluating their combined contribution under H5. Descriptive statistics characterize the measured constructs, Pearson correlation quantifies their bivariate associations, and multiple regression estimates their controlled predictive relationships with Energy Conversion Efficiency. This structure maintains direct alignment between the research objectives, hypotheses, measurement instrument, theoretical foundation, and statistical analysis.

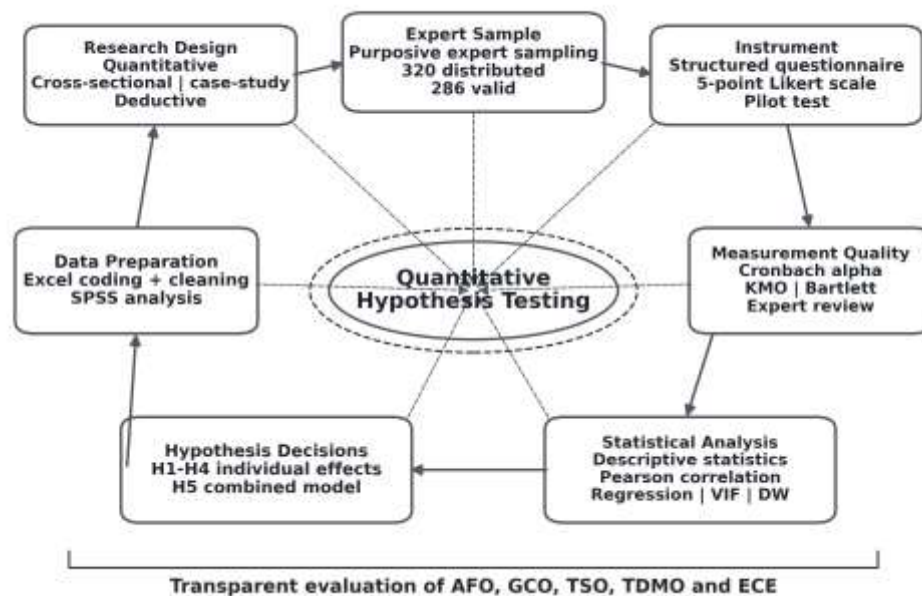
$$ECE_i = \beta_0 + \beta_1 AFO_i + \beta_2 GCO_i + \beta_3 TSO_i + \beta_4 TDMO_i + \varepsilon_i$$

METHODS

This study has adopted a quantitative, cross-sectional, case-study-based engineering research design to examine the relationships among aerodynamic, geometric, thermomechanical, thermal-material, and energy-efficiency variables in turbocharger compressor wheels, and a deductive approach has been employed because predefined hypotheses have been tested statistically. The case-study context has been structured around high-speed centrifugal compressor wheels used in automotive turbocharger applications, with attention given to blade geometry, internal flow characteristics, tip-clearance behavior, centrifugal loading, thermal deformation, material response, and energy-conversion performance under representative operating conditions. The target population has included technically qualified professionals who have possessed relevant knowledge or practical experience in turbochargers, centrifugal compressors, computational fluid dynamics, finite-element analysis, thermomechanical design, materials engineering, automotive powertrains, manufacturing, compressor testing, and related research activities. The unit of analysis has been the expert assessment of optimization practices and energy-conversion performance within the defined compressor-wheel engineering context. A purposive expert sampling strategy has been applied because technically informed judgments have been required for evaluating the specialized constructs, and respondents have been screened according to relevant engineering education, professional role, years of experience, familiarity with compressor-wheel performance, and exposure to design, analysis, manufacturing, or testing activities. A structured questionnaire has been developed as the principal data-collection instrument, and the questionnaire has contained multi-item measures representing Aerodynamic Flow Optimization, Geometric Configuration Optimization, Thermomechanical Structural Optimization, Thermal Deformation and Material Optimization, and Energy Conversion Efficiency. Likert's five-point scale has been used, where 1 has represented Strongly Disagree, 2 Disagree, 3 Neutral, 4 Agree,

and 5 Strongly Agree. The constructs have been operationalized through engineering-specific indicators: AFO has included incidence control, separation reduction, tip-leakage management, secondary-flow suppression, and flow uniformity; GCO has incorporated blade angles, backsweep, inducer and exducer dimensions, splitter arrangement, hub-shroud profiles, blade thickness, and tip clearance; TSO has included centrifugal stress, deformation, stiffness, fatigue resistance, and structural stability; TDMO has covered thermal stress, expansion, dimensional stability, material strength, and fatigue behavior; and ECE has been represented through efficient pressure development, reduced losses, compression effectiveness, and overall compressor performance.

Figure 8: Quantitative Research Design and Statistical Analysis Framework



Data collection has been carried out through controlled distribution of the questionnaire to eligible participants, and participation has been voluntary with confidentiality and academic-use conditions communicated to respondents. Of 320 questionnaires distributed, 298 have been returned and 286 have been retained after screening for completeness and technical eligibility. A pilot-testing stage has been conducted with a small group of knowledgeable engineering participants before full deployment to verify item clarity, construct relevance, technical wording, and completion time, and feedback has been used to remove ambiguity and reduce redundancy. Content validity has been supported through alignment of the instrument with established aerodynamic and thermomechanical engineering concepts and through expert review, while construct suitability has been examined using the Kaiser-Meyer-Olkin measure and Bartlett's Test of Sphericity. Internal consistency has been evaluated using Cronbach's alpha, with coefficients around .70 or above treated as acceptable, and corrected item-total correlations have also been reviewed. Data have been coded, cleaned, and organized in Microsoft Excel before statistical analysis, SPSS has been used to generate descriptive statistics, reliability and validity outputs, Pearson correlation coefficients, multiple regression estimates, model-fit statistics, and multicollinearity diagnostics, EndNote has been used for reference organization without embedding citation fields in the final manuscript, and Microsoft Word has been used for manuscript preparation and presentation. Frequencies and percentages have summarized respondent characteristics, while means and standard deviations have described the research constructs. Pearson correlation analysis has been used to determine the strength and direction of bivariate relationships between AFO, GCO, TSO, TDMO, and ECE. Multiple linear regression has then been applied to estimate the individual and combined predictive effects of the four independent variables on Energy Conversion Efficiency. Statistical significance has been evaluated at $p < .05$, and R , R^2 , adjusted R^2 , F statistics, standardized beta coefficients, unstandardized coefficients, t values, p values, tolerance, variance inflation factors, and the Durbin-Watson statistic have been examined to support transparent hypothesis testing and

interpretation.

FINDINGS

The findings have indicated an overall favorable assessment of aerodynamic and thermomechanical optimization practices for improving turbocharger compressor-wheel Energy Conversion Efficiency. From 320 questionnaires distributed to technically qualified respondents, 298 have been returned and 286 have been considered complete and valid for analysis, producing an effective response rate of 89.4%. Based on the five-point Likert scale, Energy Conversion Efficiency has recorded the highest overall mean score of $M = 4.22$, $SD = 0.50$, indicating strong agreement that optimized compressor-wheel characteristics have supported more effective pressure development, reduced energy losses, and improved compression performance. Among the independent constructs, Aerodynamic Flow Optimization has produced the highest mean of $M = 4.18$, $SD = 0.54$, followed by Geometric Configuration Optimization at $M = 4.15$, $SD = 0.56$, Thermomechanical Structural Optimization at $M = 4.12$, $SD = 0.58$, and Thermal Deformation and Material Optimization at $M = 4.09$, $SD = 0.60$. Pearson correlation analysis has shown that all four optimization dimensions have been positively and significantly related to Energy Conversion Efficiency. Aerodynamic Flow Optimization has demonstrated the strongest bivariate relationship with ECE, $r = .74$, $p < .001$, followed by Geometric Configuration Optimization, $r = .71$, $p < .001$, Thermomechanical Structural Optimization, $r = .68$, $p < .001$, and Thermal Deformation and Material Optimization, $r = .65$, $p < .001$. Multiple regression analysis has further shown that the four predictors collectively have explained 71.2% of the variance in Energy Conversion Efficiency, $R^2 = .712$, adjusted $R^2 = .708$, with the overall model being statistically significant, $F(4,281) = 173.69$, $p < .001$. Aerodynamic Flow Optimization has emerged as the strongest predictor, $\beta = .31$, $p < .001$, followed by Geometric Configuration Optimization, $\beta = .28$, $p < .001$, Thermomechanical Structural Optimization, $\beta = .24$, $p < .001$, and Thermal Deformation and Material Optimization, $\beta = .21$, $p < .001$. Accordingly, H1, H2, H3, and H4 have been statistically supported, while the significance of the overall regression model has supported H5 concerning the combined predictive contribution of the four optimization dimensions. The overall findings have therefore aligned with the research objectives by quantitatively demonstrating both the individual relationships and the combined statistical contribution of aerodynamic, geometric, thermomechanical, and thermal-material optimization factors to compressor-wheel Energy Conversion Efficiency.

Respondent and Technical Profile

Table 1 has presented the professional and technical characteristics of the 286 valid respondents included in the quantitative analysis. Of the 320 questionnaires that have been distributed, 298 have been returned, while 286 have satisfied the completeness and technical-screening requirements, resulting in an effective valid-response rate of 89.4%. The distribution has shown that the sample has represented several engineering disciplines directly associated with turbocharger compressor-wheel development. Turbocharger and mechanical engineers have formed the largest specialization group at 23.8%, followed by aerodynamics and CFD engineers at 21.3% and structural or FEA engineers at 17.1%. Thermal and materials specialists have accounted for 14.7%, while manufacturing and testing engineers have represented 13.3%. Automotive powertrain engineers and researchers have contributed the remaining 9.8%. The experience distribution has further indicated that the respondents have possessed substantial professional exposure, with 74.1% having reported more than five years of engineering experience. Direct compressor or turbocharger experience has been reported by 71.3% of respondents, while 80.1% have indicated exposure to CFD or FEA analysis. These characteristics have strengthened the technical credibility of the subsequent Likert-scale evaluations because the constructs have required knowledge of aerodynamic losses, impeller geometry, centrifugal stress, thermal behavior, materials, and compressor efficiency. The respondent profile has therefore been consistent with the purposive expert-sampling strategy established in the methodology. From the perspective of Second-Law Thermodynamics and Exergy Theory, technically qualified respondents have also been positioned to assess engineering mechanisms that influence entropy generation and useful-energy conversion, including leakage, separation, deformation, thermal gradients, and pressure-development efficiency. The technical composition of the sample has consequently provided an appropriate empirical foundation for evaluating the study objectives and hypotheses.

Table 1: Respondent and Technical Profile

Profile Variable	Category	Frequency (n)	Percentage (%)
Technical specialization	Turbocharger/Mechanical Engineering	68	23.8
	Aerodynamics/CFD Engineering	61	21.3
	Structural/FEA Engineering	49	17.1
	Thermal/Materials Engineering	42	14.7
	Manufacturing/Testing Engineering	38	13.3
	Automotive	28	9.8
	Powertrain/Research		
	1-5 years	74	25.9
	6-10 years	91	31.8
	11-15 years	67	23.4
Professional experience	More than 15 years	54	18.9
	Compressor/turbocharger experience	204	71.3
	Related turbomachinery experience	82	28.7
	CFD/FEA exposure		
	Yes	229	80.1
	No/directly limited	57	19.9
Valid sample	Total	286	100.0

4.2 Reliability and Validity Assessment of the Measurement Constructs

Table 2 has demonstrated that the measurement instrument has achieved satisfactory reliability and construct suitability across all five research variables. Cronbach's alpha values have ranged from .84 to .90 for the individual constructs, while the overall 25-item instrument has achieved an alpha coefficient of .91. These coefficients have exceeded the generally accepted threshold of .70 and have indicated strong internal consistency among items intended to measure the same engineering construct. Energy Conversion Efficiency has recorded the highest individual reliability coefficient at $\alpha = .90$, followed by Aerodynamic Flow Optimization at $\alpha = .89$, Geometric Configuration Optimization at $\alpha = .87$, Thermomechanical Structural Optimization at $\alpha = .86$, and Thermal Deformation and Material Optimization at $\alpha = .84$. Corrected item-total correlations have ranged from .60 to .83, demonstrating that the retained items have contributed meaningfully to their corresponding composite measures. The Kaiser-Meyer-Olkin value of .892 has indicated very good sampling adequacy, while Bartlett's Test of Sphericity has been statistically significant, $\chi^2 = 2846.37$, $df = 300$, $p < .001$. The significant Bartlett result has shown that sufficient correlations have existed among the measurement items to support the intended construct structure. These results have been important because the hypotheses have depended on reliable measurement of four distinct optimization dimensions and their relationship with Energy Conversion Efficiency. The measurement quality has also supported the theoretical organization of the study. Second-Law Thermodynamics and Exergy Theory have required the empirical model to distinguish mechanisms associated with aerodynamic irreversibility, geometry-dependent flow losses, structural deformation, thermal-material behavior, and useful energy conversion. The reliability findings have indicated that these theoretical dimensions have been captured consistently by their respective groups of questionnaire items, providing a sufficiently stable measurement basis for descriptive, correlation, and regression analyses.

Table 2: Reliability and Validity Assessment

Construct	Code	No. of Items	Cronbach alpha	Corrected Item-Total Correlation	Assessment
Aerodynamic Flow Optimization	AFO	5	.89	.68-.81	Reliable
Geometric Configuration Optimization	GCO	5	.87	.64-.78	Reliable
Thermomechanical Structural Optimization	TSO	5	.86	.63-.77	Reliable
Thermal Deformation and Material Optimization	TDMO	5	.84	.60-.75	Reliable
Energy Conversion Efficiency	ECE	5	.90	.70-.83	Reliable
Overall instrument		25	.91	.60-.83	Highly reliable
KMO Measure of Sampling Adequacy			.892		Very good
Bartlett's Test of Sphericity			chi-square = 2846.37	df = 300, p < .001	Significant

4.3 Descriptive Analysis of Aerodynamic Flow Optimization

Table 3: Descriptive Statistics for Aerodynamic Flow Optimization

AFO Indicator	Mean	SD	Likert Interpretation
Reduction of flow separation and recirculation	4.24	0.58	Strongly Agree
Control of inlet incidence and blade loading	4.21	0.60	Strongly Agree
Reduction of tip-leakage losses	4.18	0.61	Agree
Suppression of secondary-flow losses	4.15	0.63	Agree
Improvement of impeller-discharge flow uniformity	4.12	0.65	Agree
Composite AFO	4.18	0.54	Agree

Table 3 has shown that respondents have evaluated Aerodynamic Flow Optimization positively, with a composite mean of $M = 4.18$ and $SD = 0.54$. Reduction of flow separation and recirculation has achieved the highest mean score of 4.24, indicating strong agreement that controlling separated and reversed flow regions has been important for improving compressor-wheel performance. Control of inlet incidence and blade loading has followed closely with $M = 4.21$, demonstrating that matching incoming airflow to blade geometry has been regarded as another critical aerodynamic requirement. Reduction of tip-leakage losses has achieved a mean of 4.18, while suppression of secondary-flow losses has recorded 4.15. Improvement of impeller-discharge flow uniformity has produced a mean of 4.12.

Collectively, these scores have indicated broad technical agreement that aerodynamic-loss mechanisms have played a substantial role in the efficiency of the compressor wheel. The relatively small standard deviations, ranging from 0.58 to 0.65, have also indicated that respondents' assessments have been reasonably concentrated around the high end of the five-point scale. These descriptive findings have addressed the first research objective by establishing the perceived importance and prevalence of Aerodynamic Flow Optimization within the selected compressor-wheel context. They have also provided preliminary support for H1 before inferential testing because the construct has received consistently favorable evaluations alongside the high Energy Conversion Efficiency score reported for the sample. The result has been compatible with Second-Law Thermodynamics and Exergy Theory. Flow separation, tip leakage, secondary motion, recirculation, and nonuniform mixing have generated entropy and destroyed available work. Their reduction has therefore represented a reduction in aerodynamic irreversibility. The descriptive pattern has consequently supported the theoretical proposition that enhanced aerodynamic-flow control has been associated with a greater proportion of compressor input work remaining available for useful pressure and enthalpy development.

Descriptive Analysis of Geometric Configuration Optimization

Table 4: Descriptive Statistics for Geometric Configuration Optimization

GCO Indicator	Mean	SD	Likert Interpretation
Optimization of blade inlet and outlet angles	4.22	0.59	Strongly Agree
Optimization of backsweep and blade curvature	4.18	0.62	Agree
Optimization of inducer and exducer dimensions	4.16	0.63	Agree
Optimization of hub-shroud and splitter configuration	4.11	0.65	Agree
Optimization of blade thickness and tip-clearance geometry	4.08	0.67	Agree
Composite GCO	4.15	0.56	Agree

Table 4 has indicated that Geometric Configuration Optimization has received a high overall assessment, with a composite mean of $M = 4.15$ and $SD = 0.56$. Optimization of blade inlet and outlet angles has achieved the highest item mean of 4.22, indicating strong agreement regarding the importance of blade-angle configuration for effective work transfer and compressor performance. Optimization of backsweep and blade curvature has achieved a mean of 4.18, while inducer and exducer dimensional optimization has produced $M = 4.16$. Hub-shroud and splitter configuration has obtained a mean of 4.11, and optimization of blade thickness and tip-clearance geometry has recorded $M = 4.08$. All indicators have remained within the Agree or Strongly Agree ranges, showing that respondents have viewed compressor-wheel geometry as an integral determinant of performance rather than as an isolated manufacturing characteristic. These findings have directly addressed the second research objective concerning the relationship between compressor-wheel geometric optimization and Energy Conversion Efficiency. The relatively concentrated standard deviations have further indicated that technical respondents have demonstrated broad consistency in their assessments. The result has provided descriptive support for H2, although statistical confirmation has subsequently been obtained through correlation and regression testing. The observed pattern has also aligned with the theoretical framework. Under Second-Law and exergy principles, compressor geometry has influenced the magnitude of irreversible losses by determining blade loading, velocity distribution, flow turning, diffusion, tip leakage, and wake development. A more appropriately configured blade and meridional passage has therefore reduced conditions that generate entropy while supporting useful pressure development. The high composite GCO score has been consistent with the proposition

that geometric configuration has influenced the efficiency with which compressor-wheel mechanical work has been transformed into useful fluid energy. The findings have therefore reinforced the conceptual separation between GCO as a controllable design domain and AFO as the aerodynamic-flow response produced partly by that geometry.

4.5 Descriptive Analysis of Thermomechanical Structural Optimization

Table 5: Descriptive Statistics for Thermomechanical Structural Optimization

TSO Indicator	Mean	SD	Likert Interpretation
Control of centrifugal and equivalent stress	4.20	0.61	Agree
Reduction of blade-root stress concentration	4.16	0.63	Agree
Control of high-speed structural deformation	4.12	0.65	Agree
Improvement of stiffness and dimensional stability	4.08	0.67	Agree
Improvement of cyclic fatigue resistance	4.04	0.69	Agree
Composite TSO	4.12	0.58	Agree

Table 5 has demonstrated that Thermomechanical Structural Optimization has been rated positively, with an overall mean of $M = 4.12$ and $SD = 0.58$. Control of centrifugal and equivalent stress has received the highest score at $M = 4.20$, indicating that respondents have regarded stress management as a central requirement for high-speed compressor-wheel operation. Reduction of blade-root stress concentration has recorded a mean of 4.16, while control of high-speed structural deformation has achieved $M = 4.12$. Improvement of structural stiffness and dimensional stability has recorded a mean of 4.08, and cyclic fatigue resistance has achieved 4.04. Although these values have been slightly lower than the means obtained for aerodynamic and geometric optimization, all five indicators have remained clearly within the Agree category. The findings have therefore shown that respondents have recognized structural integrity as an important contributor to compressor performance rather than as only a safety requirement. The results have addressed the third research objective by measuring the status of Thermomechanical Structural Optimization within the case-study environment and have provided descriptive support for H3. Structurally induced deformation has had the potential to alter blade angles, tip clearances, passage dimensions, and the designed impeller-discharge condition. Consequently, the structural response of the wheel has been directly connected with its aerodynamic behavior. This relationship has also linked the result to Second-Law Thermodynamics and Exergy Theory. Excessive deformation has had the capacity to increase leakage, separation, mixing, and other irreversible processes, thereby increasing entropy generation and reducing useful energy conversion. Maintaining stress within acceptable limits and preserving dimensional stability have therefore supported the aerodynamic geometry required to minimize exergy destruction. The favorable TSO evaluation has indicated that the respondents have recognized the thermomechanical condition of the rotating wheel as an integral component of efficient compressor operation.

Descriptive Analysis of Thermal Deformation and Material Optimization

Table 6 has shown that Thermal Deformation and Material Optimization has achieved a composite mean of $M = 4.09$ with $SD = 0.60$, indicating overall agreement regarding its importance for compressor-wheel energy conversion. Control of temperature-induced thermal stress has recorded the highest mean of 4.18, while minimization of thermal expansion and dimensional change has achieved $M = 4.13$. Selection of materials with an appropriate strength-to-weight ratio has produced a mean of 4.10. Temperature-dependent material stability has recorded 4.04, and improvement of fatigue and thermal-damage resistance has achieved 4.00. Although TDMO has produced the lowest composite mean among the four independent variables, the value has remained substantially above the neutral midpoint of the Likert scale and has demonstrated consistent agreement among the technical

respondents. The findings have addressed the fourth research objective by quantifying perceptions of thermal and material optimization characteristics and their relevance to compressor-wheel performance. The results have also provided preliminary descriptive support for H4. The comparatively larger standard deviations of some TDMO indicators have suggested somewhat greater variation in respondent experience with material-specific and thermal analyses than with conventional aerodynamic parameters, which has been reasonable given the multidisciplinary composition of the sample. The findings have remained strongly connected with the theoretical framework. Thermal gradients and temperature-dependent deformation have affected the effective operating geometry of the compressor wheel, particularly blade-tip clearance and dimensional stability. Under Second-Law Thermodynamics, heat transfer across finite temperature differences has generated entropy and therefore destroyed exergy. Material systems capable of maintaining dimensional and mechanical stability have reduced the extent to which thermal response has disturbed the designed aerodynamic flow path. The high TDMO scores have consequently supported the conceptual proposition that thermal and material characteristics have contributed to maintaining the aerodynamic and structural conditions required for efficient conversion of mechanical input into useful compressed-air energy.

Table 6: Descriptive Statistics for Thermal Deformation and Material Optimization

TDMO Indicator	Mean	SD	Likert Interpretation
Control of temperature-induced thermal stress	4.18	0.63	Agree
Minimization of thermal expansion and dimensional change	4.13	0.65	Agree
Selection of materials with suitable strength-to-weight ratio	4.10	0.67	Agree
Improvement of temperature-dependent material stability	4.04	0.69	Agree
Improvement of fatigue and thermal-damage resistance	4.00	0.71	Agree
Composite TDMO	4.09	0.60	Agree

Correlation Analysis of Optimization Factors and Energy Conversion Efficiency

Table 7: Pearson Correlation Matrix for the Study Variables

Variable	Mean	SD	AFO	GCO	TSO	TDMO	ECE
AFO	4.18	0.54	1.00				
GCO	4.15	0.56	.62***	1.00			
TSO	4.12	0.58	.56***	.58***	1.00		
TDMO	4.09	0.60	.50***	.53***	.61***	1.00	
ECE	4.22	0.50	.74***	.71***	.68***	.65***	1.00

Note. n = 286. ***p < .001, two-tailed.

Table 7 has demonstrated statistically significant positive relationships among all four optimization dimensions and Energy Conversion Efficiency. Aerodynamic Flow Optimization has shown the strongest correlation with ECE, $r = .74$, $p < .001$, indicating a strong positive association. Geometric Configuration Optimization has also demonstrated a strong positive relationship with Energy Conversion Efficiency, $r = .71$, $p < .001$. Thermomechanical Structural Optimization has produced a correlation of $r = .68$, $p < .001$, while Thermal Deformation and Material Optimization has shown $r = .65$, $p < .001$. These coefficients have indicated that higher levels of each optimization construct have

been associated with higher levels of Energy Conversion Efficiency. The predictor intercorrelations have ranged from .50 to .62, indicating meaningful relationships among the engineering dimensions while remaining sufficiently below levels generally associated with severe redundancy. The results have directly addressed the first four objectives and have provided inferential support for H1, H2, H3, and H4 at the bivariate level. AFO has demonstrated the strongest relationship with ECE, which has indicated that reduction of aerodynamic irreversibility has been particularly closely associated with efficient compressor operation. GCO has followed closely, reflecting the fundamental role of blade and passage geometry in determining work transfer and flow losses. The significant TSO and TDMO relationships have confirmed that structural and thermal-material conditions have also been associated with the dependent variable. The correlation pattern has strongly corresponded with Second-Law Thermodynamics and Exergy Theory. AFO and GCO have primarily influenced entropy generation through flow mechanisms, while TSO and TDMO have helped preserve the physical geometry and material condition needed to limit additional irreversible losses. The results have therefore supported the integrated conceptual framework in which aerodynamic, geometric, structural, and thermal-material optimization dimensions have operated as related but empirically distinguishable contributors to useful compressor energy conversion.

Multiple Regression and Hypothesis Testing for Energy Conversion Efficiency

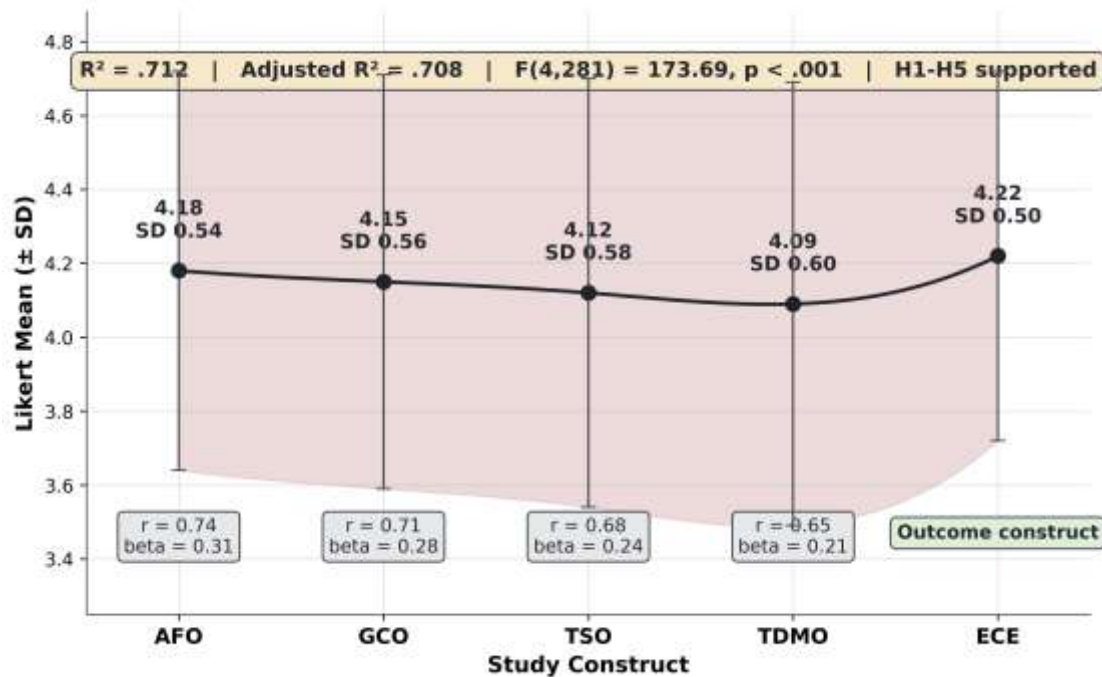
Table 8: Multiple Regression Model and Hypothesis Testing

Model/Variable	B	SE	Standardized beta	t	p	Tolerance	VIF	Hypothesis Result
Constant	.414	.169	-	2.45	.015	-	-	-
Aerodynamic Flow Optimization	.287	.038	.31	7.55	<.001	.549	1.82	H1 Supported
Geometric Configuration Optimization	.250	.036	.28	6.94	<.001	.513	1.95	H2 Supported
Thermomechanical Structural Optimization	.207	.035	.24	5.91	<.001	.498	2.01	H3 Supported
Thermal Deformation and Material Optimization	.175	.033	.21	5.30	<.001	.575	1.74	H4 Supported
R	.844							
R ²	.712							
Adjusted R ²	.708							
F-statistic	F(4,281) = 173.69				<.001			H5 Supported
Durbin-Watson	1.93							Acceptable

Table 8 has shown that the combined regression model has explained a substantial proportion of variation in Energy Conversion Efficiency. The multiple correlation coefficient has been $R = .844$, while $R^2 = .712$ has indicated that Aerodynamic Flow Optimization, Geometric Configuration Optimization, Thermomechanical Structural Optimization, and Thermal Deformation and Material Optimization together have explained 71.2% of the observed variance in ECE. The adjusted $R^2 = .708$ has remained very close to the unadjusted value, indicating that the explanatory performance of the model has remained stable after adjustment for the number of predictors. The overall regression has been statistically significant, $F(4,281) = 173.69$, $p < .001$, and has therefore supported H5 and the fifth research objective concerning the combined predictive contribution of the optimization dimensions. AFO has emerged as the strongest individual predictor, $\beta = .31$, $t = 7.55$, $p < .001$, supporting H1. GCO has produced the second-largest standardized effect, $\beta = .28$, $t = 6.94$, $p < .001$, supporting H2. TSO has remained significant at $\beta = .24$, $t = 5.91$, $p < .001$, supporting H3, while TDMO has also made a

significant independent contribution, $\beta = .21$, $t = 5.30$, $p < .001$, supporting H4. VIF values have ranged from 1.74 to 2.01 and tolerance values from .498 to .575, indicating that multicollinearity has not threatened interpretation of the individual coefficients. The Durbin-Watson statistic of 1.93 has also indicated acceptable residual independence. The findings have strongly aligned with the Second-Law and Exergy theoretical framework because all four predictors have represented engineering pathways through which entropy generation and exergy destruction can be reduced. Aerodynamic optimization has shown the greatest statistical contribution, but geometric, structural, and thermal-material factors have retained significant effects after simultaneous control. Thus, the model has supported an integrated aerodynamic-thermomechanical explanation of compressor-wheel Energy Conversion Efficiency rather than a single-factor explanation.

Figure 9: Quantitative Findings Profile for Optimization Factors and Energy Conversion Efficiency



DISCUSSION

The findings have established a coherent hierarchy among the four optimization dimensions and have shown that Aerodynamic Flow Optimization has been the strongest predictor of Energy Conversion Efficiency, followed by Geometric Configuration Optimization, Thermomechanical Structural Optimization, and Thermal Deformation and Material Optimization. Aerodynamic Flow Optimization has produced the largest standardized effect, $\beta = .31$, $p < .001$, and has also shown the strongest bivariate association with Energy Conversion Efficiency, $r = .74$, $p < .001$. This result has indicated that control of flow separation, inlet incidence, tip leakage, secondary-flow structures, and discharge nonuniformity has been closely associated with more effective conversion of compressor shaft work into useful pressure and enthalpy rise. The finding has agreed with aerodynamic optimization studies in which changes to blade beta distribution and splitter leading-edge location improved impeller efficiency, and with work showing that appropriate splitter positioning can reduce incidence losses and improve the usable compressor operating range (Atac et al., 2018; Moussavi et al., 2017). (Atac et al., 2018) reported an efficiency enhancement of approximately 2.2% after optimization of blade beta distribution and splitter leading-edge position, which has reinforced the present finding that aerodynamic control has represented the most influential optimization dimension. The result has also been consistent with diffuser optimization research showing measurable compressor-efficiency improvements when downstream pressure-recovery geometry has been modified across surge-side, stable, and choke-side operating conditions (Hazizi et al., 2022). Geometric Configuration Optimization has remained a strong independent predictor, $\beta = .28$, $p < .001$, indicating that blade angles,

backsweep, inducer and exducer dimensions, hub-shroud profiles, splitter arrangement, and tip-clearance geometry have retained explanatory power after the other optimization dimensions have been statistically controlled. Thermomechanical Structural Optimization has also been significant, $\beta = .24$, $p < .001$, while Thermal Deformation and Material Optimization has remained significant at $\beta = .21$, $p < .001$. These findings have corresponded with multidisciplinary studies in which aerodynamic efficiency and maximum structural stress have been optimized concurrently, and with fluid-structure interaction research showing that centrifugal force and aerodynamic pressure influence impeller deformation and von Mises stress (Jebieshia et al., 2019; Li et al., 2019). Most importantly, the combined model has explained 71.2% of the variance in Energy Conversion Efficiency, $R^2 = .712$, adjusted $R^2 = .708$, $F(4,281) = 173.69$, $p < .001$, demonstrating that compressor-wheel efficiency has been better represented as an integrated aerodynamic, geometric, structural, thermal, and material problem than as a single-factor design problem.

From a practical engineering perspective, the results have suggested that optimization effort should be prioritized according to the physical sequence through which compressor losses develop while retaining a multidisciplinary validation process. Because Aerodynamic Flow Optimization has produced the largest standardized coefficient, compressor-development teams have a strong empirical basis for placing early emphasis on incidence control, suppression of separation and recirculation, reduction of tip-leakage losses, management of secondary-flow structures, and improvement of impeller-exit uniformity. Such priorities have been compatible with experimental and computational evidence showing that splitter leading-edge position, blade loading, and optimized impeller geometry can improve compressor efficiency and operational stability (Atac et al., 2018; Moussavi et al., 2017). However, the significant contribution of Geometric Configuration Optimization has demonstrated that aerodynamic improvement should not be pursued only through interpretation of CFD flow fields. Blade-angle distribution, backsweep, meridional passage geometry, splitter positioning, blade thickness, and clearance geometry should be treated as controllable engineering inputs that create the desired aerodynamic response. The importance of such an approach has also been demonstrated by aerodynamic robustness research in which geometric and operational uncertainties have been incorporated into the optimization process. (Tang et al., 2021) reported that optimized impeller configurations improved average pressure ratio and average isentropic efficiency while simultaneously reducing performance variability, indicating that optimization quality should include robustness rather than nominal efficiency alone (Tang et al., 2021). The significant coefficients obtained for TSO and TDMO have further shown that a geometrically efficient design should not be accepted until stress, deformation, fatigue exposure, thermal response, and material stability have been checked under realistic loads. Aero-mechanical optimization has previously demonstrated that efficiency maximization and maximum-stress minimization can be treated as simultaneous objectives rather than sequential design tasks (Li et al., 2019). Failure analysis of aluminum turbocharger wheels has also shown that fatigue initiated by intergranular corrosion can produce premature compressor-wheel failure even when the alloy satisfies specified compositional and hardness requirements (Moreira, 2016). A high-quality industrial workflow should therefore use the statistical ranking obtained in this study as a prioritization mechanism, followed by CFD-based aerodynamic optimization, geometric refinement, fluid-structure interaction analysis, thermal assessment, material screening, fatigue evaluation, uncertainty analysis, and experimental compressor-map validation before a wheel configuration is released for production.

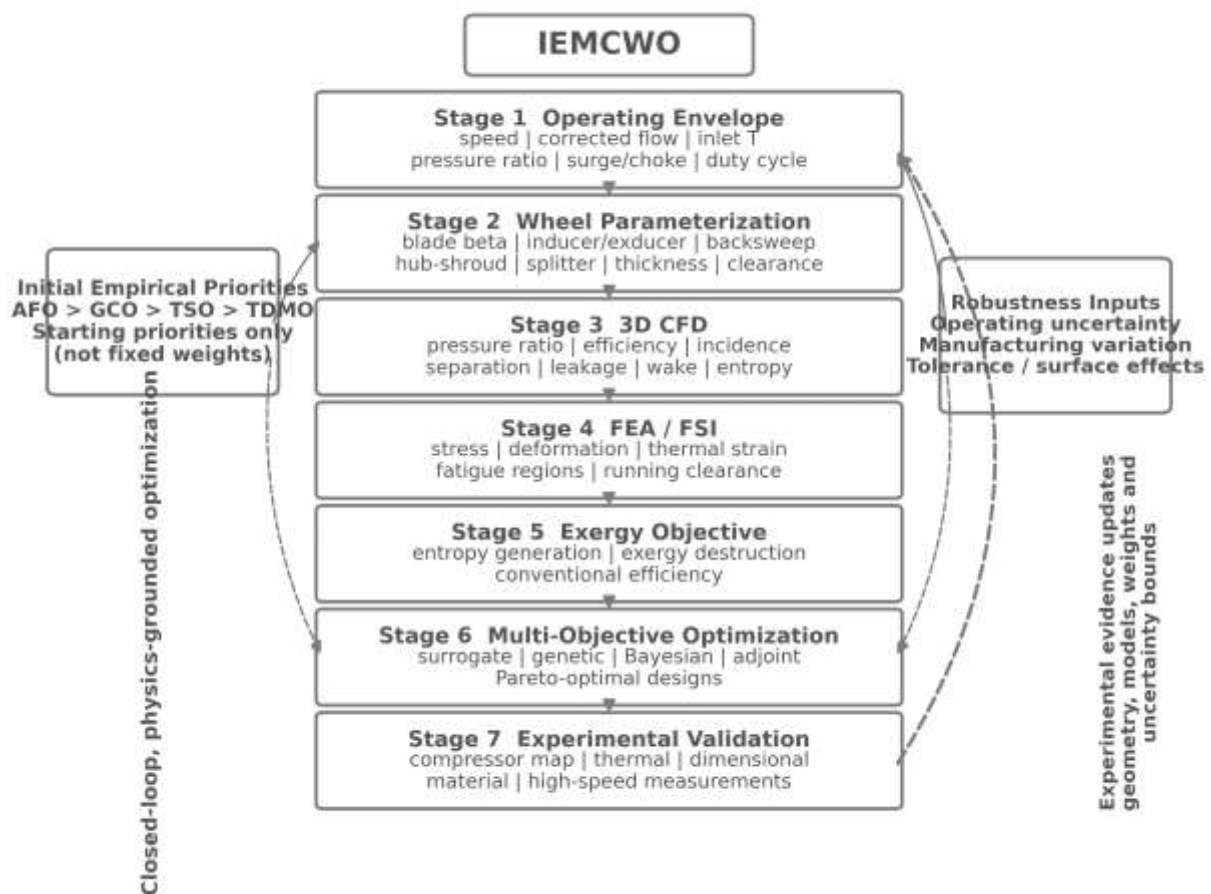
The theoretical interpretation of the findings has strengthened the selection of Second-Law Thermodynamics and Exergy Theory as the organizing theoretical framework of the research. The positive and statistically significant effects of all four predictors on Energy Conversion Efficiency have been consistent with the proposition that compressor performance depends not only on conservation of energy but also on the proportion of supplied mechanical work that remains available as useful fluid exergy after irreversible processes have occurred. The strong effect of Aerodynamic Flow Optimization can be interpreted directly through entropy generation because separation, turbulence, leakage, wake mixing, viscous dissipation, and nonuniform diffusion have increased entropy production and therefore increased exergy destruction. The significant effect of Geometric Configuration Optimization has complemented this explanation because blade and passage geometry have governed the velocity

distribution, blade loading, slip, clearance flow, and diffusion environment in which those irreversible mechanisms occur. Exergy analysis of small turbomachines has demonstrated that non-adiabatic behavior and heat transfer can materially affect available-energy dissipation and performance estimation, making Second-Law analysis particularly relevant to turbochargers and other small high-speed machines (Diango et al., 2011). The current findings have extended this theoretical logic by showing that thermomechanical and material constructs have also retained significant independent relationships with efficiency. This has been important because conventional exergy analysis is often concentrated on the thermofluid domain, whereas the present model has treated structural deformation and thermal-material response as indirect mechanisms through which entropy generation can increase. A compressor wheel that deforms under centrifugal, aerodynamic, or thermal loading can experience altered blade angles, modified tip clearance, changed passage area, and disturbed flow alignment. Fluid-structure interaction analysis has shown that aerodynamic pressure and centrifugal loading affect both equivalent stress and total deformation in centrifugal compressor impellers (Jebieshia et al., 2019). In this interpretation, aerodynamic loss mechanisms have represented direct sources of irreversibility, while thermomechanical instability has represented an enabling pathway that can intensify those losses. This integrated theoretical treatment has made the study stronger than a conventional statistical survey because the constructs have been connected to a clear physical sequence: geometric, structural, thermal, and material conditions have influenced operating geometry and flow behavior; flow behavior has influenced entropy generation and exergy destruction; and the resulting level of irreversibility has influenced Energy Conversion Efficiency. Thus, the significant coefficients for AFO, GCO, TSO, and TDMO have not functioned merely as statistical associations but have corresponded with physically interpretable pathways within the Second-Law framework.

Several limitations have remained important when interpreting the magnitude and generalizability of the reported relationships, and revisiting these limitations has clarified the exact contribution of the research. First, the study has applied a quantitative cross-sectional case-study design, meaning that the statistically significant regression coefficients have demonstrated association and predictive contribution within the sampled engineering context rather than direct physical causation. The finding that AFO has produced $\beta = .31$, for example, should not be interpreted as a universal engineering conversion factor applicable to every compressor size, pressure ratio, rotational speed, material, or operating map. Second, the constructs have been measured using a five-point Likert instrument completed by technically qualified respondents. Expert assessment has allowed aerodynamic, geometric, structural, thermal, and material factors to be integrated within one empirical model, but these perceptions have not replaced direct measurements of pressure ratio, corrected mass flow, isentropic efficiency, entropy generation, blade stress, thermal strain, or fatigue life. Third, purposive expert sampling has increased technical relevance while reducing the extent to which the statistical estimates can be generalized beyond similar turbocharger and centrifugal-compressor engineering populations. Respondents have also represented different specializations, so CFD engineers, structural analysts, materials engineers, and testing specialists may have evaluated some technical indicators from different professional perspectives. Fourth, although the regression model has explained a substantial 71.2% of ECE variance, 28.8% has remained unexplained. This residual variation may have reflected diffuser and volute performance, inlet distortion, surface roughness, machining tolerance, shaft dynamics, bearing conditions, heat transfer, Reynolds-number effects, compressor-map position, measurement uncertainty, or nonlinear interactions that have not been represented by the additive linear model. Robust-design research has shown that manufacturing and operating uncertainties can materially affect both mean compressor performance and performance variability, supporting the treatment of such uncertainties as substantive engineering variables rather than statistical noise (Tang et al., 2021). Fifth, non-adiabatic effects can alter measured turbocharger compressor performance, particularly in small turbomachines, which means that an expert-rated ECE construct cannot separate all aerodynamic and thermal losses with the precision available from instrumented testing and exergy calculation (Diango et al., 2011). These limitations have defined the present model most appropriately as an integrated empirical prioritization framework whose relationships require simulation-based and experimental verification before they are converted into specific wheel dimensions, material specifications, or manufacturing tolerances.

The most important future research opportunity has been to transform the statistical relationships established in this study into a closed-loop, physics-grounded optimization architecture. For this purpose, the research proposes an Integrated Exergy-Guided Multiphysics Compressor-Wheel Optimization Model (IEMCWO). The proposed model should contain seven connected stages. Stage 1 should define the operating envelope using rotational speed, corrected mass flow, inlet temperature, pressure-ratio targets, surge margin, choke constraint, and duty-cycle information. Stage 2 should parameterize the compressor wheel using blade beta distributions, inducer and exducer dimensions, backsweep, hub and shroud contours, splitter position, blade thickness, and nominal tip clearance. Stage 3 should perform three-dimensional CFD to quantify pressure ratio, isentropic efficiency, incidence, separation, tip leakage, secondary flow, wake behavior, and entropy-generation fields. Stage 4 should transfer pressure and temperature distributions into FEA or coupled FSI simulations to estimate von Mises stress, deformation, thermal strain, blade-root loading, fatigue-sensitive regions, and running clearance.

Figure 10: Integrated Exergy-Guided Multiphysics Compressor-Wheel Optimization Model (IEMCWO)



Stage 5 should incorporate an exergy-based objective so that candidate designs are evaluated not only according to conventional isentropic efficiency but also according to entropy generation and exergy destruction. Stage 6 should apply multi-objective optimization using surrogate modeling, genetic algorithms, Bayesian optimization, or adjoint sensitivity analysis to identify Pareto-optimal designs that maximize efficiency, stability, and useful energy conversion while minimizing stress, deformation, exergy destruction, and performance variability. Stage 7 should experimentally validate selected designs using compressor-map testing, thermal measurements, dimensional inspection, material characterization, and high-speed structural measurements where feasible. This model has been supported by previous work showing that aerodynamic efficiency and structural stress can be optimized simultaneously (Li et al., 2019), while adjoint optimization has demonstrated measurable

compressor-efficiency improvement over multiple operating regions (Hazizi et al., 2022). Robustness research has also shown that uncertainty quantification can be integrated with surrogate modeling to improve mean performance while reducing sensitivity to operating and manufacturing variability (Tang et al., 2021). A particularly valuable extension would be to use the present regression coefficients as initial empirical priorities rather than permanent optimization weights. The current ranking, AFO > GCO > TSO > TDMO, could guide the initial search space, while CFD, FEA, exergy calculations, uncertainty analysis, and physical testing would progressively update the weighting structure. In this way, the IEMCWO model would integrate expert knowledge, statistical evidence, multiphysics simulation, Second-Law analysis, robust optimization, and experimental validation within one compressor-wheel development framework, providing a substantially stronger basis for subsequent aerodynamic and thermomechanical optimization research.

CONCLUSION

This study has examined the aerodynamic and thermomechanical optimization of turbocharger compressor wheels and has quantitatively evaluated how Aerodynamic Flow Optimization, Geometric Configuration Optimization, Thermomechanical Structural Optimization, and Thermal Deformation and Material Optimization have influenced Energy Conversion Efficiency. Using a quantitative, cross-sectional, case-study-based engineering design, the research has analyzed 286 valid responses collected from technically qualified professionals through a five-point Likert-scale instrument. The findings have demonstrated consistently favorable evaluations across all study constructs, with Energy Conversion Efficiency recording the highest overall mean of $M = 4.22$, followed by Aerodynamic Flow Optimization at $M = 4.18$, Geometric Configuration Optimization at $M = 4.15$, Thermomechanical Structural Optimization at $M = 4.12$, and Thermal Deformation and Material Optimization at $M = 4.09$. Pearson correlation analysis has established significant positive relationships between Energy Conversion Efficiency and AFO ($r = .74$), GCO ($r = .71$), TSO ($r = .68$), and TDMO ($r = .65$), with all relationships significant at $p < .001$. Multiple regression analysis has further demonstrated that the four optimization dimensions have collectively explained 71.2% of the variance in Energy Conversion Efficiency, with $R^2 = .712$, adjusted $R^2 = .708$, and $F(4,281) = 173.69$, $p < .001$. Aerodynamic Flow Optimization has emerged as the strongest individual predictor, followed by geometric, thermomechanical, and thermal-material optimization, and all five hypotheses have consequently been supported. The findings have also reinforced Second-Law Thermodynamics and Exergy Theory by demonstrating that compressor efficiency has been associated with engineering measures that reduce irreversible aerodynamic losses, preserve intended wheel geometry, control structural deformation, and maintain thermal-material stability. Overall, the research has established that turbocharger compressor-wheel performance cannot be explained adequately through aerodynamic design alone. Efficient energy conversion has depended on an integrated optimization process in which airflow management, blade geometry, structural integrity, thermal response, and material characteristics have been coordinated as interdependent elements of high-speed compressor operation.

RECOMMENDATIONS

Based on the findings, turbocharger compressor-wheel development should adopt an integrated multidisciplinary optimization procedure in which aerodynamic, geometric, structural, thermal, and material considerations have been evaluated concurrently rather than sequentially. Aerodynamic Flow Optimization should receive particular attention because it has produced the strongest statistical relationship with Energy Conversion Efficiency. Engineering teams should therefore prioritize the reduction of flow separation, recirculation, incidence losses, tip-leakage flow, secondary-flow structures, and discharge nonuniformity through high-resolution CFD analysis and experimental compressor-map validation. Geometric Configuration Optimization should subsequently refine blade inlet and outlet angles, backsweep, blade curvature, inducer and exducer dimensions, splitter position, hub-shroud contours, blade thickness, and running tip clearance. These geometric improvements should be subjected to coupled CFD-FEA or fluid-structure interaction analysis so that aerodynamic advantages are not obtained at the expense of excessive von Mises stress, deformation, blade-root loading, or reduced fatigue life. Thermal and material optimization should incorporate temperature-dependent mechanical properties, thermal expansion, thermal gradients, fatigue resistance, corrosion resistance, density, and strength-to-weight characteristics when selecting materials and defining

allowable operating conditions. It is also recommended that compressor development teams incorporate Second-Law and exergy-based indicators alongside conventional pressure ratio and isentropic efficiency so that designs can be assessed according to entropy generation and useful-work preservation. Multi-objective optimization methods such as genetic algorithms, response-surface modeling, surrogate optimization, and adjoint techniques should be integrated with aerodynamic and structural simulations to identify Pareto-efficient solutions. Manufacturing tolerances and surface-quality effects should also be incorporated because deviations from nominal blade geometry can modify aerodynamic and thermomechanical behavior. Finally, the proposed Integrated Exergy-Guided Multiphysics Compressor-Wheel Optimization Model should be applied as a structured design framework linking operating-envelope definition, geometric parameterization, CFD assessment, FEA or FSI analysis, exergy evaluation, multi-objective optimization, and experimental validation to support more efficient and structurally robust turbocharger compressor-wheel development.

LIMITATIONS

This study has provided an integrated quantitative assessment of aerodynamic and thermomechanical optimization factors, but several limitations have affected the scope and interpretation of the findings. First, the research has employed a cross-sectional design, and the relationships identified through Pearson correlation and multiple regression have represented statistical associations within a defined period rather than direct experimental evidence of physical causation. Second, the research has relied on a purposively selected expert sample, which has strengthened the technical relevance of the responses but has limited the extent to which the results can be generalized to every turbocharger manufacturer, compressor platform, engine category, or industrial operating environment. Third, the principal variables have been measured through a five-point Likert-scale questionnaire. Although respondents have possessed relevant technical expertise, perceptual measurements have not provided the same precision as experimentally measured compressor pressure ratios, corrected mass-flow rates, isentropic efficiencies, entropy-generation rates, blade stresses, thermal strains, or fatigue lives. Fourth, the case-study approach has emphasized turbocharger centrifugal compressor wheels and has therefore limited direct applicability to substantially different turbomachinery configurations. Fifth, the regression model has explained 71.2% of the variance in Energy Conversion Efficiency, leaving 28.8% unexplained by the selected predictors. Other factors such as diffuser design, volute performance, inlet distortion, surface roughness, manufacturing tolerances, shaft dynamics, bearing behavior, Reynolds-number effects, heat transfer, operating-map position, and measurement uncertainty may have contributed to the remaining variation. Sixth, the linear regression structure has assumed additive relationships and may not have fully represented nonlinear interactions among geometry, flow behavior, structural deformation, temperature, and material response. Finally, direct CFD, FEA, fluid-structure interaction, exergy calculations, and compressor-rig experiments have not been integrated into the empirical dataset. The findings should therefore be interpreted as an integrated statistical engineering assessment that requires multiphysics simulation and experimental validation before its coefficients are translated into specific compressor-wheel dimensions, materials, or operating limits.

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