Design and Analysis of Centrifugal Turbocharger Turbine Postprint

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Abstract

Centrifugal turbocharger turbines exhibit a structure distinct from conventional turbines. This study investigates the one-dimensional aerodynamic design, three-dimensional flow field simulation and optimization, and off-design performance of a centrifugal turbine characterized by low flow rate, high rotational speed, and small wheel diameter. Initially, simplifications are applied to the fluid working medium and flow process to obtain one-dimensional aerodynamic design results. Subsequently, computational fluid dynamics software is utilized to conduct numerical simulations of the centrifugal turbine stage, and blade profile optimization is performed by adjusting parameters such as blade number, blade thickness, and camber line shape to achieve a more reasonable flow field. Finally, the off-design performance of the centrifugal turbine under varying rotational speeds and flow rates (back pressures) is analyzed.

Full Text

Design and Analysis of Centrifugal Turbocharger Turbine

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Abstract

The centrifugal turbocharger turbine features a structure distinct from conventional turbines. This paper investigates the one-dimensional aerodynamic design, three-dimensional flow field simulation and optimization, and off-design performance characteristics of a small-flow-rate, high-speed, small-wheel-diameter centrifugal turbine. First, the fluid medium and flow process are simplified to obtain one-dimensional aerodynamic design results. Next, computational fluid dynamics software is employed for numerical simulation of the centrifugal turbine stage, optimizing the blade profile by varying blade count, blade thickness, and mean camber line shape to achieve a more rational flow field. Finally, the off-design performance of the centrifugal turbine is analyzed under different rotational speeds and flow rates (back pressures).

Keywords: centrifugal turbine; turbocharger; numerical simulation; off-design performance

0 Introduction

Turbochargers deliver comprehensive benefits in improving automotive engine power-to-weight ratio, enhancing torque characteristics, increasing fuel economy, and reducing engine noise and exhaust emissions. With increasingly severe energy constraints and stringent emission regulations in China, turbocharger development has become an inevitable trend. As the prime mover of turbochargers, the turbine is critical to performance improvement.

Turbocharger development spans over a century. In 1905, Swiss engineer Alfred Büchi first proposed the concept of exhaust gas turbocharging, obtaining patents in Germany and the United States. The world' s first exhaust-driven supercharger emerged in 1912. During the 1920s, ships began equipping turbocharged diesel engines, and during World War II, the United States first applied turbocharging extensively to military aircraft, enabling mass production. Early turbocharger applications focused on marine vessels, aircraft, and high-power stationary engines before gradually expanding to smaller engines. However, due to difficulties in developing structurally reliable, high-performance, low-cost small radial turbochargers, automotive applications were significantly delayed until 1961 when General Motors tentatively installed turbochargers on certain vehicle models. China began turbocharger research and development from the late 1950s to early 1960s. Following national liberation, turbocharger research, design, and manufacturing developed alongside marine diesel engines. China' s first radial turbocharger was developed collaboratively by the Marine Product Design Office and Shanghai Qiuxin Shipyard, with design completed in 1954 and certification finished in 1958 [1].

Radial turbines are classified into centripetal and centrifugal types based on working fluid flow direction. In centripetal turbines, Coriolis force contributes to effective work, resulting in large enthalpy drops. Consequently, radial turbines almost exclusively adopt the centripetal configuration, with minimal research, design, and application of centrifugal turbines. Centrifugal turbine research traces back to Ljungström' s [2] cantilevered double-inlet counter-rotating centrifugal steam turbine, operating across power ranges from several hundred kW to 65 MW. Researchers from Politecnico di Milano, including G. Persico and M. Pini, published detailed studies on preliminary design and aerodynamics of organic Rankine cycle centrifugal turbines [3-5]. In China, Huang Diangui' s research group proposed a novel double-sided inlet centrifugal turbine [6].

During expansion in centrifugal turbines, specific volume increases, matching the turbine’ s flow passage cross-section diameter. Centrifugal turbine blades can be designed as constant-height straight blades, with velocity ratio designed near optimal values, resulting in essentially two-dimensional flow. This paper proposes applying centrifugal turbines to exhaust turbochargers, using ideal gas as the working fluid to investigate aerodynamic performance and off-design characteristics at high speeds [7], thereby exploring the application potential of centrifugal turbines.

1 One-Dimensional Design of Centrifugal Turbine

Referencing one-dimensional flow analysis of axial turbines, one-dimensional thermodynamic calculations are performed for the centrifugal turbine. During the initial design phase and thermodynamic calculations, engine exhaust gas is treated as ideal air, assuming axisymmetric, adiabatic, inviscid steady flow through blade passages [8].

Actual operating parameters of a turbocharger are used as design parameters, as shown in Table 1 . Among the various efficiencies of centrifugal turbines, wheel efficiency u can be expressed through design parameters, making it the primary criterion for selecting appropriate design parameters [9].

A C language program was developed, using rotor inlet flow angle α_1, reaction degree Ω, velocity ratio xa, and diameter ratio DT as iterative variables. Calculation results were screened to select parameter sets with high wheel efficiency and appropriate wheel diameter for subsequent numerical simulation, as presented in Table 2 . Nozzle velocity coefficient and rotor velocity coefficient were set as ϕ=0.97 and Ψ=0.93, respectively.

2 Three-Dimensional Simulation of Centrifugal Turbine

Based on one-dimensional design pressures before and after the stator and rotor, preliminary flow field analysis was conducted separately for stator and rotor passages, establishing stator maximum thickness of 2.5 mm with 10 blades, and rotor maximum thickness of 4 mm with 21 blades.

2.1 Blade Profile Parameterization

Blade sections consist of four curves: leading edge, trailing edge, pressure surface, and suction surface. Leading and trailing edges are circular arcs, with design parameters including blade height, leading/trailing edge radii, maximum blade thickness, blade count, and inlet/outlet geometric angles [10]. Pressure and suction surfaces are constructed using Bézier curves. Eight variable parameters control the two-dimensional blade profile for both stator and rotor: four parameters control the mean camber line shape, and four control blade thickness distribution along the radial chord length [11]. Two-dimensional blade design parameters are listed in Table 3 .

Blade count and inlet/outlet geometric angles are fixed control parameters during optimization. The figure below illustrates stator blade profile construction and the selection of four control points; rotor blade profile construction follows the same method.

[Figure 1: see original paper] Meridional channel
[Figure 2: see original paper] Stator blade profile
[Figure 3: see original paper] Stator blade thickness distribution and control point selection
[Figure 4: see original paper] Medial camber line tangential angular distribution and control point selection

Adjusting variable control point positions modifies the Bézier curve, generating a series of optimized airfoils. The mathematical model for this optimization problem is expressed as follows: design variables [1-4] represent thickness values at control points for stator and rotor blades, M[1-8] denote position coordinates along radial chord length, and A[1-4] represent mean camber line tangential angles ([1-4] indicates four variables $_1$, $_2$, $_3$, $_4$; same notation applies to M[1-8] and A[1-4]). A total of 16 variables participate in optimization, with wheel power as the constraint condition and wheel efficiency as the objective function [12].

Based on preliminary stator and rotor analysis, a screening method was employed for optimization. Sample parameters were integrated, sorted, and grouped, with sequential calculations yielding several compliant parameter sets, thereby improving initial optimization parameter quality and accuracy. Optimized primary blade profile parameters are presented in Table 4 .

Numerical simulation was used to compare aerodynamic parameters inside the impeller before and after optimization. Results show that optimized rotor outlet flow angle becomes more radial, reducing residual velocity loss, increasing wheel power by 2.95%, and improving wheel efficiency by 1.8 percentage points. Optimized airfoil velocity parameters approach one-dimensional design values. Due to small size, velocity coefficients are relatively small, resulting in numerically simulated wheel efficiency lower than thermodynamic design values.

2.2 Full-Stage Optimization Design

Among blade design parameters, blade height, leading/trailing edge radii, Table 5 compares impeller parameters before and after optimization, while Table 6 presents the optimized blade profile velocity triangle.

[Figure 5: see original paper]-[Figure 8: see original paper] illustrate eddy viscosity distribution, Mach number distribution, pressure, and velocity contours at 50% span.

[Figure 5: see original paper] Eddy viscosity distribution at 50% span
[Figure 6: see original paper] Mach number distribution at 50% span
[Figure 7: see original paper] Pressure distribution at 50% span
[Figure 8: see original paper] Velocity distribution at 50% span

3 Off-Design Performance Study

Turbochargers for vehicle, agricultural machinery, marine, and construction machinery engines operate under variable speed and load conditions, causing exhaust gas flow rate, pressure, and temperature to change accordingly and turbine operating conditions to deviate from design conditions. Therefore, off-design performance must be investigated in centrifugal turbocharger turbine design.

3.1 Off-Design Performance at Design Speed

At design speed, maintaining constant inlet total temperature and pressure, off-design simulation was conducted by varying outlet flow rate to obtain centrifugal turbine flow and efficiency characteristic curves, shown in Figures 9 [Figure 9: see original paper] and 10 [Figure 10: see original paper].

Results indicate that as pressure ratio p_2/p_0* decreases, flow rate gradually increases with slowing trend. When pressure ratio reduces to a certain value, turbine flow becomes constant, reaching choking condition. CFX simulation yields a critical pressure ratio of 0.519 at design condition, with maximum critical flow rate of 0.0262 kg/s. Wheel efficiency first increases slowly then decreases rapidly with pressure ratio, reaching maximum at pressure ratio of 0.921 (one-dimensional design pressure ratio is 0.932).

Figure 11 [Figure 11: see original paper] illustrates the relationship between wheel efficiency and inlet total temperature T_0* at design speed, based on results provided in Table 7 . Results demonstrate that inlet total temperature has minimal impact on wheel efficiency, indicating that centrifugal turbines can operate efficiently across a wide temperature range within material limits.

3.2 Off-Design Performance at Variable Speeds

Figure 12 [Figure 12: see original paper] shows the relationship between wheel efficiency and flow rate for the centrifugal turbine stage at different rotational speeds. Results show that maximum efficiency points correspond to different flow rates at different speeds—higher speeds require larger flow rates. Under variable speed conditions, centrifugal turbines offer a large operable flow range and strong adaptability. Higher speeds increase the minimum operable flow rate, while maximum critical flow rate changes minimally. During variable speed operation, the flow range where wheel efficiency exceeds 70% is relatively large, demonstrating good off-design performance.

Conclusions

This paper primarily focuses on optimization design and analysis of centrifugal turbocharger turbines and their off-design performance. Main conclusions are:

1. Using wheel efficiency as the objective function and blade thickness distribution and mean camber line tangential angles as parameters, airfoil optimization was performed, yielding a centrifugal turbine suitable for turbocharger applications with a stage efficiency of 80.1%.
2. Off-design performance analysis of the centrifugal turbine stage reveals that at design speed, as pressure ratio $p_2/p_0{}^*$ decreases, flow rate gradually increases with slowing trend. When pressure ratio reduces to a certain value, turbine flow becomes constant, reaching choking condition. Wheel efficiency first increases slowly then decreases rapidly with pressure ratio. Inlet total temperature has minimal impact on wheel efficiency, theoretically enabling efficient operation across a wide temperature range. During variable speed operation, maximum wheel efficiency corresponds to different flow rates at different speeds—higher speeds require larger flow rates for peak efficiency. With rotational speed varying between 40,000–70,000 rpm, the centrifugal turbine offers a wide operable flow range and strong adaptability, with a relatively large flow range where wheel efficiency exceeds 70%. Results demonstrate that off-design performance of this centrifugal turbine is comparable to conventional axial and centripetal turbines.

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Note: Figure translations are in progress. See original paper for figures.