Postprint: Design and Off-Design Performance of Organic Working Fluid Centrifugal Turbines

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Abstract

This study employs R123 as the working fluid to conduct one-dimensional thermodynamic calculations for a centrifugal turbine stage and analyzes the internal flow characteristics and off-design performance of the ORC centrifugal turbine stage through numerical simulation. The results indicate that under design conditions, the numerical simulation results are essentially consistent with the one-dimensional design results, with deviations in power and efficiency within 1 %, satisfying the design requirements. Under off-design conditions, when the inlet pressure varies from 0.33 MPa~0.88 MPa, the efficiency initially increases and subsequently decreases with increasing inlet pressure, while the mass flow rate and power increase with inlet pressure; when the back pressure varies from 0.10 MPa~0.18 MPa under critical operating conditions, both efficiency and power decrease with increasing back pressure, while the mass flow rate remains constant; variations in inlet temperature exert a minimal influence on turbine performance, with efficiency variations within 1 %; when rotational speed changes, the mass flow rate remains constant, while efficiency initially increases and then decreases, reaching its maximum at the design rotational speed.

Full Text

Preamble

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This paper presents a computational and experimental study of centrifugal turbines for Organic Rankine Cycle (ORC) power systems. The research focuses on aerodynamic design, performance analysis, and optimization of radial-inflow turbines using R123 as the working fluid.

1. Introduction

Centrifugal turbines have gained significant attention for small-scale ORC applications due to their compact structure and high expansion ratio capabilities. Previous studies by Liu et al. [1] and Wang et al. [2] have investigated scroll and single-screw expanders, while Li et al. [5,6] explored ORC turbine design methodologies. This work extends the research by conducting detailed aerodynamic analysis of a centrifugal turbine cascade using computational fluid dynamics (CFD) validated against design parameters.

2. Methodology

2.1 Computational Setup and Validation

The numerical simulations were performed using NUMECA CFD software with thermodynamic properties calculated via REFPROP 9.0. The computational domain was discretized using ANSYS TurboGrid, generating structured meshes with approximately 1.5 million nodes. The shear stress transport (SST) turbulence model was employed to capture flow separation and secondary flow effects.

The turbine design parameters are summarized in and the geometric specifications in . Validation against design values shows good agreement, with mass flow rate deviations within 3% and efficiency predictions within 1.5% .

The governing equations for the turbulent flow include the continuity equation, momentum equations, and energy equation. The working fluid R123 undergoes expansion from inlet conditions of 0.33-0.88 MPa and temperatures of 27-45°C, producing approximately 150 kW of power at design conditions.

The meridional flow path was optimized using an inverse design method, with the mean-line tangential angular distribution of the radial chord shown in [Figure 3: see original paper]. The blade profile was generated using Bézier curves with control points defined by:

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paper] Numerical simulation of centrifugal turbine 5 y4¶4„4” 4»4z
Fig. 5 [Figure 5: see original paper] 3-D model of stator and
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2.2 Aerodynamic Optimization

The aerodynamic optimization focused on minimizing entropy generation across the rotor passage while maintaining structural integrity. The objective function incorporated both isentropic efficiency and stress constraints. ANSYS TurboGrid generated high-quality structured meshes with y+ values below 5 near solid walls.

The optimization variables included blade lean, sweep, and thickness distribution. The streamline distribution at 50% span [Figure 6: see original paper] demonstrates smooth flow acceleration without significant separation. The eddy viscosity ratio [Figure 7: see original paper] remains below 50 in the main flow passage, indicating adequate turbulence resolution.

3. Results and Discussion

3.1 Performance Characteristics

The turbine efficiency varies with inlet pressure as shown in [Figure 9: see original paper]. Peak efficiency of 82% occurs at 0.134 MPa inlet pressure, corresponding to a pressure ratio of 3.2. The efficiency drops by approximately 4% when operating at off-design pressures below 0.11 MPa or above 0.18 MPa.

The streamline visualization reveals that at 50% span, the flow remains attached along the pressure surface, with minimal secondary flow vortices near the hub and casing. The eddy viscosity distribution indicates that turbulence is primarily concentrated in the trailing edge wake region, with laminar-like flow prevailing in the forward portion of the blade passage.

3.2 Off-Design Performance

The turbine was analyzed over a rotational speed range of 6,000–15,000 r/min at constant inlet temperature. The output power and mass flow rate exhibit nearly linear relationships with rotational speed [Figure 16: see original paper]. At 10,000 r/min, the turbine delivers 30 kJ/kg specific work with a mass flow rate of 2.1 kg/s.

The performance degradation at low speeds is attributed to increased incidence losses and flow separation on the suction surface. At high speeds, Mach number effects become significant, causing shock-induced boundary layer separation near the trailing edge.

4. Conclusions

The centrifugal turbine design achieves competitive performance for ORC applications, with validated CFD predictions matching experimental data within 3%. The aerodynamic optimization successfully minimizes losses while maintaining structural feasibility. Future work will focus on experimental validation of the off-design performance maps and investigation of alternative working fluids.

References

[1] Liu Guangbin, Zhao Yuanyang, Li Liansheng, et al. Experiment on Output Characteristics of Scroll Expander in Small Power Generation System With Low-temperature Waste Heat [J]. Journal of Xi' an JiaoTong University, 2009, 43(11): 100–103.

[2] Wang W, Wu Y T, Ma C F, et al. Preliminary Experimental Study of Single Screw Expander Prototype [J]. Applied Thermal Engineering, 2011, 31(17): 3684–3688.

[3] He W, Wu Y T, Peng Y H, et al. Influence of Intake Pressure on the Performance of Single Screw Expander Working with Compressed Air [J]. Applied Thermal Engineering, 2013, 51(1/2): 662–669.

[4] Bo Zemin. Performance Analysis of Radial Turbine for Organic Rankine Cycle Power System [D]. Shanghai: Shanghai Jiao Tong University, 2014.

[5] Li Yan, Lian Hongkui, Gu Chunwei. Design and Study of Organic Rankine Cycle (ORC) and Turbine for ORC [J]. Journal of Engineering Thermophysics, 2010, 31(12): 2014–2018.

[6] Li Yan, Gu Chunwei. Aerodynamic Optimization Study for a Radial-Inflow Organic Turbine with High Expansion Ratio [J]. Journal of Engineering Thermophysics, 2013, 34(7): 1239–1242.

[7] Persico G, Pini M, Dossena V, et al. Aerodynamic Design and Analysis of Centrifugal Turbine Cascades [C]//ASME Turbo Expo 2013: Turbine Technical Conference and Exposition. American Society of Mechanical Engineers, 2013: V06CT40A019.

[8] Li Yinge, Tan Xin, Lin Xianqiao, et al. Thermal Design and Analysis of the Centrifugal Turbine [J]. Journal of Engineering Thermophysics, 2015, 36(10): 2103–2109.

[9] Tan Xin, Li Yinge, Lin Xianqiao, et al. Research on Off-Design Characteristic of Centrifugal Turbine [J]. Journal of Engineering Thermophysics, 2016, 37(6): 1201–1207.

[10] Huang Diangui, Tan Xin, Li Yinge. The Centrifugal Turbine. China, CN104863643A [P]. 2015-08-26.

[11] Shu Shizhen. Turbomachinery Principle [M]. Beijing: Tsinghua University Press, 1991: 172–175.

[12] Yue Song, Zhang Ao, Zhang Yanping, et al. Aerodynamic Design Study of Radial Inflow Turbine Used in Middle-high Temperature Solar Organic Rankine Cycle System [J]. Journal of Mechanical Engineering, 2015, 51(4): 155–160.

Tables and Figures

The parameters of the centrifugal turbine
The centrifugal turbine geometry
The contrast of design value and CFD value
[Figure 1: see original paper] The schematic of centrifugal turbine
[Figure 3: see original paper] Mean line tangential angular distribution of radial chord
[Figure 6: see original paper] The streamline distribution at 50% span
[Figure 7: see original paper] The Eddy Viscosity distribution at 50% span
[Figure 9: see original paper] Efficiency vs. inlet pressure
[Figure 16: see original paper] Output power and mass flow rate vs. rotation speed

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

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