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Research Paper

Aerodynamic design and numerical analysis of a radial inflow turbine for the supercritical carbon dioxide Brayton cycle

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HIGHLIGHTS

- A design method for S-CO_2 radial inflow turbine was presented.
- The aerodynamic design of a 1.5-MW S-CO_2 radial inflow turbine was conducted.
- The analysis for off-design performance of the turbine was carried out.

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ABSTRACT

The supercritical carbon dioxide (S-CO_2) Brayton cycle is considered to be one of the most promising power cycles for the future. Its main advantages include compactness, high efficiency, high safety and good environmental friendliness. The system performance depends much on the turbine, which is one of the core components of the S-CO_2 Brayton cycle. Compared to the axial turbine, the radial inflow turbine has a lower cost and more compact structure, and can provide a high operating efficiency under small volume flows. In this study, a design method for an S-CO_2 radial inflow turbine is proposed and a 1.5-MW S-CO_2 radial inflow turbine is designed. The three-dimensional (3D) numerical simulation of the designed turbine is carried out by using ANSYS-CFX commercial software, and the results are in good agreement with the design values. The off-design performance of the turbine is predicted by using the one-dimensional (1D) model and the 3D numerical simulation. The results are consistent with each other. It means that the proposed design method for the S-CO_2 radial inflow turbine is reliable.

1. Introduction

Supercritical carbon dioxide (S-CO_2) is a type of carbon dioxide fluid whose temperature and pressure are higher than its critical values (30.98 °C, 7.38 MPa). It is stable, non-toxic, environment-friendly, readily available, and has a high density and thermal conductivity [1]. When used as a working fluid, S-CO_2 can improve cycle performance, allow equipment to be more compact and be believed to be a potential working medium in power conversion systems [2,3]. Owing to its outstanding advantages, the S-CO_2 Brayton cycle is considered to be one of the most promising power cycles, and studies on the S-CO_2 Brayton cycle for different energy sources, such as nuclear energy, solar energy, geothermal energy, and waste heat, are being carried out extensively [4–7].

The S-CO_2 Brayton cycle has been developed over several decades. In 1948, it was first patented by the Sulzer Brothers company [8]. After the 1950 s, under the continuing study of Angelino [9], Feher [10], and other researchers, the theoretical system of the S-CO_2 Brayton cycle was improved. Since 2010, laboratories such as SNL [11], Knolls & Bettis [12], KAERI [13], and TIT [14] have continued to build experimental platforms and study the S-CO_2 Brayton cycle in real operating conditions.

The turbine is one of the core components of the power cycle. For small volume flow conditions, the radial inflow turbine is generally adopted. Compared to an axial turbine [15], the radial inflow turbine has a simpler manufacturing process, lower cost, more compact structure and can yield a high operating efficiency under small volume flows [16]. At present, the radial inflow turbine has been used widely in turbochargers and small gas turbines. It is also adopted as the main engine in some small-sized ships. Moreover, the radial inflow turbine has been applied as an appropriate gas expander for low temperature heat sources such as waste heat, ocean thermal energy, and solar energy [17,18,19].

The S-CO_2 radial inflow turbine has drawn increasing attention recently. SNL has been implementing and improving an S-CO_2

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Nomenclature

c	absolute velocity, m/s
w	relative velocity, m/s
u	peripheral velocity, m/s
h	enthalpy, kJ/kg
T	temperature, K
p	pressure, MPa
W	output power, MW
G	mass flow rate, kg/s
s	entropy, J/(kg·K)
R	radius, mm
x_a	velocity ratio
$\overline{D}$	diameter ratio
Ma	Mach number
N	number of blades
n	rotational speed, rpm
H	blade height, mm
Greek symbols	
α	absolute flow angle, deg
β	relative flow angle, deg
η	efficiency
φ	stator blade velocity coefficient
ψ	rotor blade velocity coefficient
ρ	density, kg/m^3
Ω	degree of reaction
ζ	loss coefficient
Subscripts	
0	stator inlet
1	between stator outlet and rotor inlet
2	rotor outlet
3	inducer outlet
in	inlet
out	outlet
s	stator
r	rotor
S	static
$T-S$	total-to-static
opt	optimal
u	peripheral
ra	radial
ax	axial
f	friction
l	leakage
Acronyms	
S-CO_2	supercritical carbon dioxide
CFD	computational fluid dynamics

Brayton cycle test loop since 2005, and a 0.2-MW radial inflow turbine was developed [11]. Working with Knolls & Bettis, Bechtel Marine Propulsion Corporation designed and built an S-CO_2 Brayton cycle integrated experimental system including a 0.2-MW radial inflow turbine. Its aim was to evaluate the applicability of an S-CO_2 Brayton cycle system in a nuclear shipboard. The Institute of Applied Energy and TIT also built an S-CO_2 test loop with a 20-kW radial inflow turbine [14]. Qi et al. [20] researched the S-CO_2 radial inflow turbine size influence on the turbine performance in the range from 100 kW to 200 kW. Researchers from the Massachusetts Institute of Technology considered the S-CO_2 radial inflow turbine to be applicable in systems with a power generation of 50 MW [21]. Zhang et al. [22] accomplished the aerodynamic design and numerical analysis of a 15-MW S-CO_2 axial turbine and a 1.5-MW radial inflow turbine. Luo et al. [23] completed the design and analysis of a single-stage S-CO_2 centrifugal turbine recently.

To sum up, the S-CO_2 radial inflow turbine can be widely applied for 0.1 MW to 25 MW system. For smaller-scale energy production, turbomachines can have high power density because of the low flow rates of the high-density working fluids. For solar energy, radial inflow turbines with an output power of about 1 MW and S-CO_2 loops combined with thermal storage and small modular heliostat fields are highly suitable for solar base-load energy systems in rural settings [20,24]. In this study, a radial inflow turbine was applied in an S-CO_2 Brayton cycle. The design method for the S-CO_2 radial inflow turbine was proposed and a 1.5-MW S-CO_2 radial inflow turbine was designed. Numerical simulation and analysis of the turbine performance were accomplished. In addition, the 1D prediction and 3D numerical simulation of the off-design performance are compared.

2. S-CO_2 radial inflow turbine design method

The S-CO_2 radial inflow turbine is similar in structure to the conventional radial inflow turbine. The difference lies in the working fluid, which results in different working conditions of the turbine. For its design, a real gas model or database must be adopted due to a significant variation of the physical property of the working fluid [25]. In this paper, REFPROP 8.0 database [26] developed by NIST is adopted. The Span-Wagner equations of state are used for the calculation of S-CO_2 property in the REFPROP 8.0 database.

The S-CO_2 radial inflow turbine includes an inlet volute, a stator, a rotor, and an exhaust diffuser. A typical radial inflow turbine structure is shown in Fig. 1 [16]. The flow pressure can be transformed to the kinetic energy in the stator, so that the working fluid has a certain speed when flowing into the rotor. The rotor is the key part of the radial inflow turbine, and the performance of the radial inflow turbine is highly dependent on the rotor design. A good flow condition in the rotor is required to achieve a high performance. The *h-s* diagram for the radial inflow turbine is presented in Fig. 2. Line 0–1_s–2_{ss} is the related isentropic process and the actual process is represented by line 0–1–2 because of the energy loss during the expansion process. State 0 is the initial state point located at the stator inlet, where the total temperature of the working fluid is T_0^* and the total pressure is P_0^*. The fluid expands and accelerates in the stator. At state 1 between the stator outlet and rotor inlet, the velocity of the fluid increases to c_1, while the pressure and temperature decrease to P_1 and T_1, respectively. The working fluid expands in the rotor, and at the rotor outlet the pressure of the fluid is P_2 and the temperature is T_2. Then the working fluid flows through the exhaust diffuser and the outlet static pressure is P_3. The velocity triangles at the rotor inlet and outlet are presented in Fig. 3. At the inlet of the rotor, the absolute flow angle is α_1, while at the outlet, the relative flow angle is β_2. The flow chart of the S-CO_2 radial inflow turbine design method is presented in Fig. 4.

2.1. Thermodynamic cycle parameters

Based on the Brayton cycle calculation with the REFPROP 8.0 database for each cycle-state point, the turbine stator inlet total pressure $P_0{}^*$, total temperature $T_0{}^*$, the turbine exhaust diffuser