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Preliminary Design and Computational Fluid Dynamics Analysis of Supercritical Carbon Dioxide Turbine Blade

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1. Introduction

The supercritical gas turbine Brayton cycle has been adopted in the secondary loop of the Generation IV Nuclear Energy Systems, and planned to be installed in power conversion cycles of the nuclear fusion reactors as well. The supercritical carbon dioxide (SCO_2) is one of widely considered fluids for this concept. The potential beneficiaries include the Secure Transportable Autonomous Reactor- Liquid Metal (STAR-LM), the Korea Advanced Liquid Metal Reactor (KALIMER) and Battery Omnibus Reactor Integral System (BORIS) which is being developed at the Seoul National University. The reason for these welcomed applications is that the SCO_2 Brayton cycle can achieve higher overall energy conversion efficiency than the steam turbine Rankine cycle.

Seoul National University has recently been working on the SCO_2 based Modular Optimized Brayton Integral System (MOBIS). The MOBIS design power conversion efficiency is about 45% [1]. Gas turbine design is crucial part in achieving this high efficiency. In this paper, the preliminary analysis on first stage of gas turbine was performed using CFX® as a solver.

2. Blade Design and Computational Simulation

2.1 Boundary Conditions

The design goal of MOBIS was based on 10 MW_e of electric power generation from 22.2 MW_{th} of thermal power output. To achieve this amount of electric power, the boundary conditions of SCO_2 gas turbine were found. Table 1 shows the boundary conditions. From these boundary conditions, 95.8% of the turbine efficiency was obtained.

Table 1. Turbine boundary conditions.

Parameters	Value
Inlet Pressure [MPa]	20.0
Inlet Temperature [K]	823
Outlet Pressure [MPa]	7.4
Mass Flow Rate [kg/ s]	112.8
Revolution [rev/s]	60

2.2 Preliminary Design of Turbine Blade

The turbine blade design is very important in achieving high performance. The preliminary turbine blade design was conducted in prior to three-dimensional (3D) computational fluid dynamics analysis.

$$\tan\alpha_{in} = \frac{R_n \cdot u}{\phi \cdot u} \tag{1}$$

$$\tan\alpha_{out} = -\frac{(\psi - R_n)\cdot u}{\phi \cdot u} \tag{2}$$

where, α_{in} and α_{out} is inlet and outlet flow angle, and R_n is the stage reaction.

The stage reaction of general turbine is 0.5. ϕ and ψ is the flow coefficient and the work coefficient. These two factors should be decided to find out appropriate inlet and outlet flow angle. A one of popular methods to decide these factors is to use Smith diagram [2]. The Smith diagram presents the work coefficient and the flow coefficient from designed turbine efficiency.

From inlet and outlet flow angle, the ratio of pitch to the blade axial chord can be obtained.

$$\left(\frac{s}{b}\right) = \frac{2}{C_L}\cos^2\alpha_{out}\left[\left(\frac{W_{in}\sin\alpha_{in}}{W_{out}\cos\alpha_{out}}\right) - \tan\alpha_{out}\right] \tag{3}$$

where, C_L is tangential lift coefficient and W_{in} and W_{out} is simple mainstream velocity at inlet and outlet.

Kacker and Okapuu suggested a guide for obtaining setting angle from nominal blade inlet and outlet angle [3]. The nominal blade inlet angle is given by

$$\beta_{in} = \alpha_{in} + \Delta\theta_{ind} \tag{4}$$

$$\Delta\theta_{ind} = 14\left(1 - \frac{\alpha_{in}}{70^\circ}\right) + 9\left(1.8 - \frac{c}{s}\right) \tag{5}$$

$$c = \frac{b}{\cos\lambda} \tag{6}$$

where, $\Delta\theta_{ind}$ represents induced incidence, c is blade chord, and λ is setting angle.

Equation (5) was suggested by Dunavant and Erwin [4]. The blade chord is a function of setting angle, but it is also a variable in deciding setting angle. Table 2 contains obtained preliminary gas turbine design parameters. Blade axial chord and blade chord is related with pitch length, which is decided by number of blades and hub diameter.

Table 2. Preliminary design parameters for high performance gas turbine.

Parameters	Value
Inlet Flow Angle [°]	28.5
Outlet Flow Angle [°]	-58.5
Blade Axial Chord [m]	1.19·s
Chord [m]	1.45·s
Setting Angle [°]	35.0

2.3 Computational Fluid Dynamics Analysis

The first stage of the turbine was created using the commercial computational fluid dynamics (CFD) modeling software BladeGen^{TM} with preliminary design factors. SCO_2 gas flow was simulated with CFX$^{®}$ as a solver. Uniform pressure drop through each stage was assumed to estimate total pressure drop of the turbine. In the design phase of Gas Advanced Turbine Operation Study (GATOS), gas turbine with 4 stages was adopted. The analysis was conducted to find out appropriate number of blades, diameter of hub and height of blade based on mass flow rate of BORIS power conversion cycle. The diameter of hub, the height of blade and the number of blades were assumed based on STAR-LM gas turbine design as 0.04m, 0.025m, and 25, respectively [5].

2.4 Results

The SCO_2 flow around the designed turbine blade was simulated using CFX$^{®}$. Figure 1 shows velocity vector profiles in the first stage. The results are summarized in Table 3.

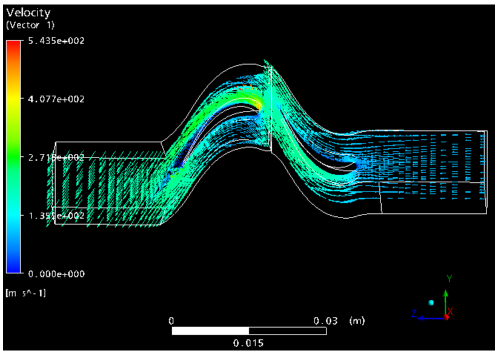

Figure 1. Velocity vector profiles in first stage of designed gas turbine.

Total mass flow rate of this model was 95.25 kg/s. It was lower than designed value. The obtained isentropic turbine efficiency was about 60%.

Table 3. Mass flow rate and total enthalpies at inlet and outlet.

	Inlet	Outlet
Mass Flow Rate [kg/s]	3.81	3.81
Enthalpy [kJ/kg]	1035	1020
Isentropic Enthalpy [kJ/kg]	-	1010

3. Conclusion

The SCO_2 gas turbine blade was designed based on theoretical and experimental correlations. The 3D model for the first stage of gas turbine blade was created with preliminary design parameters. The SCO_2 flow around turbine blade was simulated with CFX$^{®}$. The obtained mass flow rate and turbine efficiency were less than designed parameters. To find out an optimal design, the size of turbine and number of blades should be adjusted.

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