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Computational Analysis of Supercritical Carbon Dioxide Gas Turbine for Liquid Metal Cooled Reactor

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1. Introduction

Energy demands at a remote site are increased as the world energy requirement diversifies so that they should generate power on their own site. A Small Modular Reactor (SMR) becomes a viable option for these sites. Generally, the economic feasibility of a high power reactor is greater than that for SMR. As a result the supercritical fluid driven Brayton cycle is being considered for a power conversion system to increase economic competitiveness of SMR. The Brayton cycle efficiency is much higher than that for the Rankine cycle. Moreover, the components of the Brayton cycle are smaller than Rankine cycle's due to high heat capacity when a supercritical fluid is adopted. A lead (Pb) cooled SMR, BORIS, and a supercritical fluid driven Brayton cycle, MOBIS, are being developed at the Seoul National University (SNU) [1, 2]. Dostal et al. [3, 4] have compared some advanced power cycles and proposed the use of a supercritical carbon dioxide (SCO_2) driven Brayton cycle. According to their suggestion SCO_2 is adopted as a working fluid for MOBIS. The turbo machineries are most important components for the Brayton cycle. The turbo machineries of Brayton cycle consists of a turbine to convert kinetic energy of the fluid into mechanical energy of the shaft, and a compressor to recompress and recover the driving force of the working fluid. Therefore, turbine performance is one of the pivotal factors in increasing the cycle efficiency. In MOBIS a supercritical gas turbine is designed in the Gas Advanced Turbine Operation (GATO) and analyzed in the Turbine Integrated Numerical Analysis (TINA). A three-dimensional (3D) numerical analysis is employed for more detailed design to account for the partial flow which the one-dimensional (1D) analysis cannot consider.

2. One-dimensional Turbine Design

Turbine converts the energy of supercritical fluid to rotational energy of turbine hub. Moisseytsev el al. suggests a 1D turbine design methodology applying an enthalpy loss model [5]. The enthalpy change passing through each stage was calculated based on the real SCO_2 properties which supplied by NIST. A stator and a rotor consist of one stage of axial turbine. SCO_2 is expanded passing through the stator, whose meridian momentum is converted to rotational momentum of the rotor shaft. The methodology starts from three major assumptions to simplify the analysis. The axial velocity component is assumed to be constant and the velocity is perpendicular to the surface of inlet of each stator.

In the 1D design two assumptions are added to simplify the analysis. First, the hub radius is fixed to facilitate calculation of the flow area in each stage. Second, a constant pressure change through each stator and rotor is assumed.

Table 1 presents input parameters for the turbine design. The boundary conditions are supplied from the conceptual design of MOBIS. Case study is performed by changing the number of stages and hub radius with the conditions in Table 1.

Table 1 Boundary Conditions

Parameters	Value [Unit]
Inlet pressure	19.9 [MPa]
Inlet temperature	823 [K]
Outlet pressure	7.5 [MPa]
Mass flow rate	112.8 [kg/s]
Revolution speed	60 [rev/s]
Maximum centrifugal stress of blade material	3.0 [MPa]
Density of blade material	8300 [kg/m^3]

Fig. 1 presents the simulation results to optimize size and efficiency. Note that the efficiency increases with the hub radius, but the maximum tip radius increases as well. If the hub radius is fixed, higher stage achieves higher efficiency but the axial length is increased. Fig. 2 shows the turbine efficiency dependency with the number of stages for given boundary condition. These points indicate the optimal sizing of each stage turbine. The highest efficiency is observed for the four stage turbine of which the hub radius is 0.37 m, but the differences are minimal.

3. Three-dimensional CFD Analysis

The 3D turbine models are nodalized reflecting the mesh dependency test result. The inlet and outlet pressures are applied as the boundary condition. The shear stress transport model is adopted for turbulence, and the stage option is applied to the type of interface which exists between the stator and rotor or the rotor and stator.

Fig. 3 illustrates the result for the isentropic static to static efficiency. Generally the efficiency tends to be decreased as the number of stages is increased since the applied losses are increased. The secondary flow effect, however, is the most dominant of loss terms in this 3D numerical analysis. It is therefore considered that the five stage turbine achieves a highest efficiency.

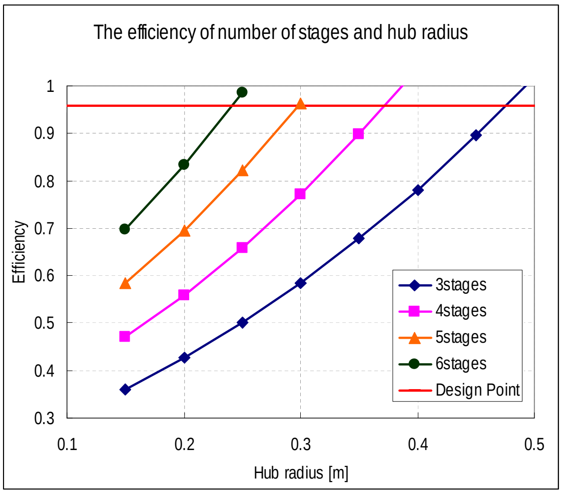

Fig. 1. Sizing Dependency

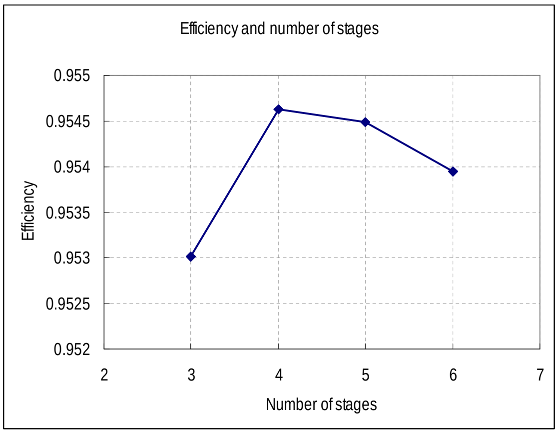

Fig. 2. Number of Stage Dependency for Efficiency

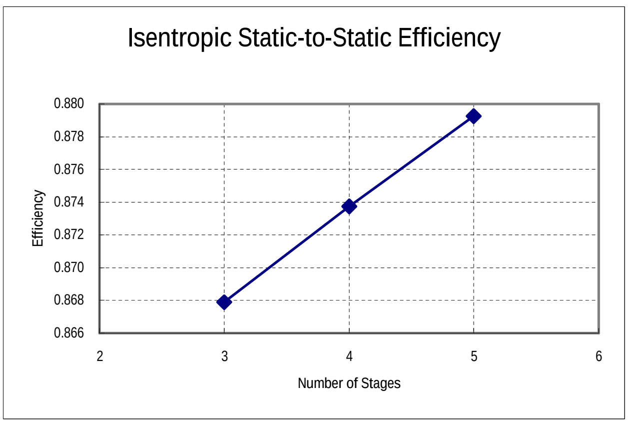

Fig. 3. Isentropic Static-to-static Efficiency

4. Conclusions

In this study, a 3D SCO_2 gas turbine model for MOBIS was created based on the 1D design analysis. The 3D numerical analysis was performed utilizing CFX® 11.0. The analysis gave two kinds of feedback to 1D design processes. The first is consideration of loss by flow area expansion. The effect of sudden expansion of flow area turned out to be the most dominant term affecting turbine efficiency in 3D computational fluid analysis. As a result, a turbine with more stages was observed to achieve higher efficiency. This rapid change in the turbine flow area in the small number of stages came from the convergence criteria. Because the flow area of the last stage was fixed as maximum allowable value based on the structural analysis, the flow area was rapidly expanded to correct itself during design processes. As a result, the flow area of the last stage was almost the same regardless of the number of stages. The second is the assumption about hub radius. The working fluid tended to cohere due to centrifugal force exerted by the rotor. In consequence the fluid became less dense near the hub then the neighboring area was not useful any more passing through the stages. This situation, however, was not considered in the 1D design process. The assumption of a constant hub radius should thus be modified.

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REFERENCES

[1] W.J. Kim, T.W. Kim, M.S. Sohn, K.Y. Suh, "Supercritical Carbon Dioxide Brayton Power Conversion Cycle Design for Optimized Battery-type Integral Reactor System," *Proceedings of International Congress on Advances in Nuclear Power Plants*, Reno, NV, USA, (2006).

[2] T.W. Kim, N.H. Kim, K.Y. Suh, "Power Conversion System for Lead-cooled Battery-type Integral Fast Reactor System BORIS," *Transactions of American Nuclear Society Annual Meeting*, Boston, MA, USA, (2007).

[3] V. Dostal, P. Hejzlar, M.J. Driscoll, "High-performance Supercritical Carbon Dioxide Cycle for Next-generation Nuclear Reactors," *Nuclear Technology*, 154, 265, (2006).

[4] V. Dostal, P. Hejzlar, M.J. Driscoll, "The Supercritical Carbon Dioxide Power Cycle: Comparison to Other Advanced Power Cycles," *Nuclear Technology*, 154, 283, (2006).

[5] A.V. Moisseytsev, J.J. Sienicki, D.C. Wade, "Turbine Design for a Supercritical Carbon Dioxide Gas Turbine Brayton Cycle," *Proceedings of International Congress on Advanced Nuclear Power Plants*, Cordoba, Spain, (2003).