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Computational Fluid Dynamics Analysis of Supercritical Carbon Dioxide Turbine

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1. Introduction

The supercritical carbon dioxide (SCO_2) gas turbine Brayton cycle has been not only adopted in the secondary loop of the Generation IV nuclear energy systems but also planned to be installed in the high efficiency power conversion cycles of the nuclear fusion reactors. The potential beneficiaries include the Korea Advanced Liquid Metal Reactor (KALIMER), the Korea Superconducting Tokamak Advanced Research (KSTAR) as well as the International Thermonuclear Experimental Reactor (ITER). The reason for these welcomed applications is that the cycle can achieve the overall energy conversion efficiency as high as 45%. The SCO_2 turbine efficiency is one of the major parameters affecting the overall Brayton cycle efficiency. Thus, optimal turbine design determines the economics of the Generation IV as well as the future nuclear fission and fusion energy industry.

Seoul National University has recently been working on the SCO_2 based Modular Optimized Brayton Integral System (MOBIS). MOBIS includes the Gas Advanced Turbine Operation Study (GATOS), the Loop Operating Brayton Optimization Study (LOBOS), the Nonsteady Operation Multidimensional Online Simulator (NOMOS), and the Turbine Advanced Compressor Operation Study (TACOS). This paper presents results from GATOS [1].

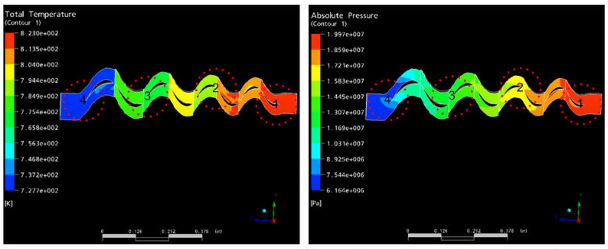
2. Computational Analysis

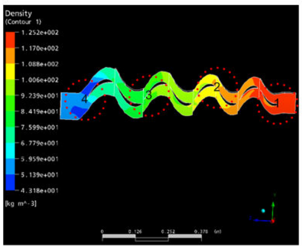
2.1 Input of SCO_2 properties to CFX®

CFX® needs first be supplied with accurate SCO_2 thermophysical properties. The SCO_2 properties may be input to CFX® via such method as a lookup table or a user defined mode. Since these methods are difficult to use, the Redlich-Kwong properties were adopted instead. The simulation of the SCO_2 turbine with CFX® was found to produce proper results when compared against the results calculated with the NIST code. Figure 1 differentiates the calculated properties in CFX® and NIST [2].

2.2 3D Modeling of Turbine Stator and Rotor

Computational analysis of the SCO_2 flow around a turbine blade utilizing CFX® was performed to study the possible efficiency of the SCO_2 turbine. This determines the basic design values like the blade and nozzle types, number of stages, blade height, and minimum and maximum radii of hub and tip. Basic design values of the turbine blade based on the Argonne National Laboratory design code was generated by ANSYS BladeGen™ [3,4,5]. Figure 2 shows three-dimensional shape of the generated turbine.





Location	Temp. [K]	Press. [MPa]	CFX Density [kg/m³]	NIST Density [kg/m³]	Error [%]
1	823	19,97	125,2	124,24	0,77
2	794	17,21	112,4	111,97	0,38
3	804	14,45	92,4	93,225	0,88
4	737	7,54	55,4	53,930	2,72

Figure 1. Comparison of calculated densities in CFX® and NIST.

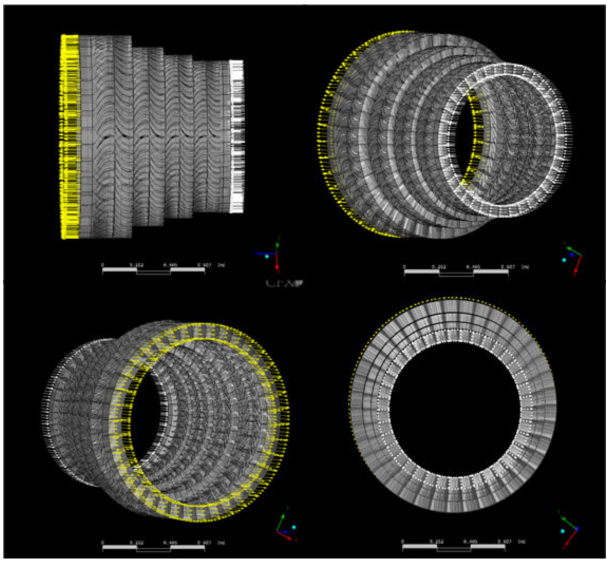


Figure 2. Three-dimensional SCO_2 turbine design with ANSYS BladeGen™.

2.3 Boundary Conditions

Boundary conditions were based on the secondary loop, i.e. the Brayton cycle of Ref. [6]. The inlet total pressure was 20 MPa at temperature of 823 K. The revolution of rotor was 60 per second. The average static pressure at the outlet was 7.4 MPa.

3. Results

While the absolute pressure was fixed at 20 MPa for inlet and 7.4 MPa for outlet, the temperature changed from 550 °C to 449 °C, the density decreased from 125.2 kg/m^3 to 44.2 kg/m^3 and the total mass flow rate was computed to be 1638 kg/s. The isentropic efficiency of the SCO_2 turbine was computed to be 50%. In general, however, the turbine isentropic efficiency was calculated as follows [7]:

$$\frac{\dot{m}\, c_p (T_1 - T_2)}{\dot{m}\, c_p (T_1 - T_{2s})} = \frac{h_1 - h_2}{h_1 - h_{2s}} \tag{1}$$

The SCO_2 turbine efficiency was calculated to be 90% using Eq. (1).

Figures 3 and 4 depict the characteristic curves of the SCO_2 turbine. Figure 3 shows variation of mass flow rates against the pressure ratio between inlet and outlet. Figure 4 illustrates variation of the isentropic efficiency in CFX® against the pressure ratio between inlet and outlet. The choking point of the SCO_2 turbine was determined from the characteristic curves.

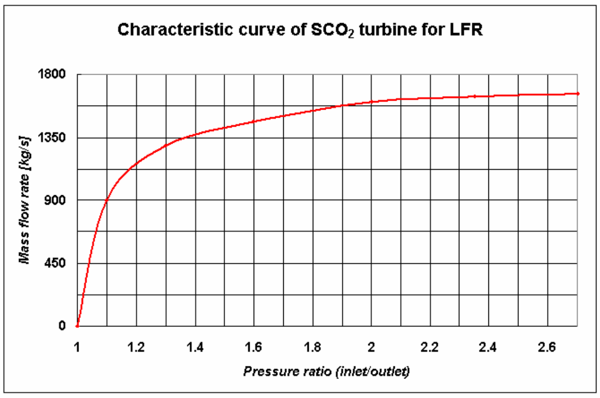


Figure 3. Mass flow rate variation with pressure ratio between inlet and outlet.

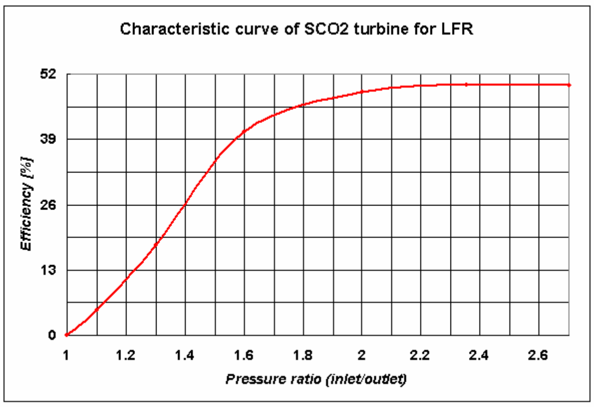


Figure 4. Efficiency variation with pressure ratio between inlet and outlet.

4. Conclusion

An optimal SCO_2 turbine blade was developed for a high efficiency of 90% by the computational analysis. The characteristic curves were analyzed to optimize the SCO_2 turbine.

ACKNOWLEDGMENTS

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