Design Analysis of Supercritical Carbon Dioxide Compressor for KALIMER-600

T.W. Kim [a], W.S. Jeong [a], K.Y. Suh [a*], J.E. Cha [b], S.O. Kim [b]
[a] *Department of Energy Systems Engineering, Seoul National University*
599 Gwanak-Ro, Gwanak-Gu, Seoul, 151-744, Korea
[b] *Korea Atomic Energy Research Institute*
1045 Daeduk-Ro, Yuseong-Gu, Daejeon, 305-353, Korea
[*] *Corresponding author: kysuh@snu.ac.kr*

1. Introduction

The supercritical carbon dioxide (SCO_2) driven Brayton cycle has been adopted for power conversion in some of the Generation IV Nuclear Energy Systems, and is as well planned to be implemented in fusion power reactors. The welcomed application is attributed mainly to the prospective thermal efficiency of the gas driven Brayton cycle exceeding that of the steam driven Rankine cycle in the range of 33~40%. The isentropic efficiency of the compressor happens to be a most vital parameter in determining the SCO_2 cycle efficiency. Thus, the optimal compressor design should contribute to the economics of future nuclear energy systems.

2. Design Goal

The power conversion system in a Brayton cycle, turbine and its compressors are connected with the same shaft. Fig. 1 is a schematic configuration of the ultimate design goal. Shown left is the four-stage turbine, center is compressor #1, and right is compressor #2.

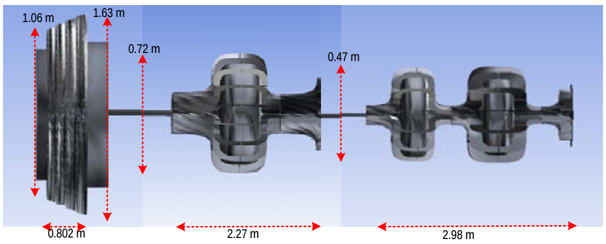

Figure 1. Schematic configuration of turbine and compressors on the same shaft in the SCO_2 Brayton cycle.

3. One-Dimensional Design

Since there is no practical experience or design data for the SCO_2 compressor, it is necessary to establish the methodologies for the design and performance analysis before the detailed design and manufacturing stage. Hence, a one-dimensional (1D) code for the compressor is developed to design and analyze its performance.

3.1 Design Code

A performance analysis code for a SCO_2 driving radial compressor is developed resorting to the mean-streamline analysis method. This 1D method analyzes the flow and energy along a mean-streamline path. Since a delicate loss model is required to include the effect of the impeller configuration and the flow path parameter, the loss model suggested by Oh [1] was considered in developing the 1D code.

The loss in the compressor is divided into internal and external ones. The internal loss can in turn be split into those of the impeller and diffuser. It, however, turned out that the recirculation loss suggested by Oh [1] yielded an impractical value in the application range. Hence the loss model suggested by Jansen [2] is taken instead to conduct the performance analysis in the code. Fig. 2 shows the flow diagram of the 1D code, which includes a change of the operation condition and stage order to obtain the exit condition for the next stage.

The 1D code is applied to analysis of the power conversion system for KALIMER-600, a 600 MWe sodium cooled fast reactor being developed at the Korea Atomic Energy Research Institute.

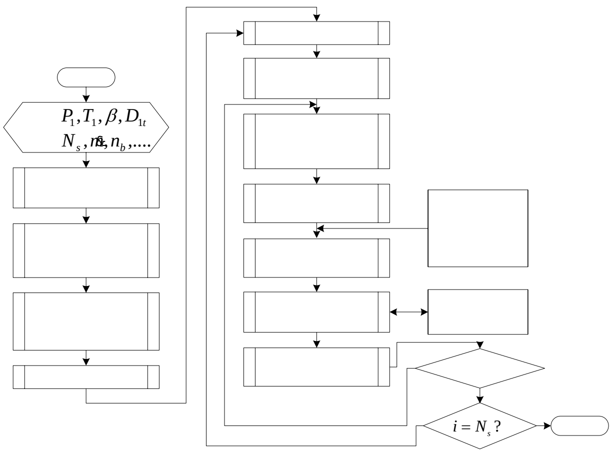

Figure 2. Flow diagram of the compressor 1D analysis code.

3.2 Sensitivity Analysis

As a result of the iterative calculation, the stages of compressors #1 and #2 are respectively determined as two and three based on the design parameters. The isentropic efficiency of the compressor is estimated to be more than 80% for the SCO_2 Brayton cycle coupled to KALIMER-600 during the process of the conceptual design. A sensitivity analysis was carried out for a total of eleven parameters using the 1D code. Fig. 3 presents the result of the sensitivity analysis.

The sensitivity analysis indicates that, whereas the tip diameter and the exit diameter considerably affect the efficiency as well as the exit blade angle, the others are not as significant. The exit diameter and the exit width, and the diffuser exit diameter and the exit blade angle affected the pressure ratio most [3].

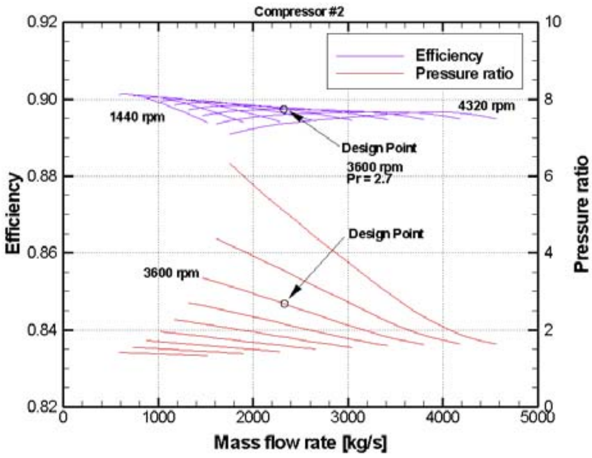

Figure 3. Performance characteristics of compressor #2 for the off-design-points.

3.3 Code Modification

In order to refine the optimal compressor design, 1D shape and boundary conditions are estimated with the Casey-Robinson, Rodgers, and Casey-Marty correlation models [4-6]. From the estimation, the 1D design results are located in the dramatic variation of efficiency. It signifies that the 1D design results might be deviated from the design point of view. In this regard the 1D design results are modified with design equations in VISTA [4-6].

4. Three-Dimensional Analysis

A three-dimensional (3D) analysis is conducted with the commercial computational fluid dynamics (CFD) code CFX® [7] to corroborate the 1D code results.

Performance of a reversed compressor is prevented from choking and surging points. The static-to-static isentropic efficiency is calculated to be about 78 %. The mass flow rate is computed to be about 1,930 kg/s at the operating point. These results do not satisfy the required values. These results indicate that the compressor is far from an optimal condition. From the off-set design performance curve as depicted in Fig 4, an optimal condition given the same blade shape should be located with an efficiency of 87 % at a mass flow rate of 1,000 kg/s.

5. Conclusion

A 1D supercritical centrifugal compressor design was evaluated with CFX® from the viewpoint of viability, optimization and its prospect for future application. It was found that there is a need to modify and reanalyze the 1D compressor for KALIMER-600 Brayton cycle. The 3D analysis results were supplemented for an optimal centrifugal multistage compressor. The results for the performance of the compressor operation were not satisfactory, however. In particular, the calculated thermal power which was about 112 MW was lower than the required 165 MW. The SCO_2 Brayton cycle nonetheless appears to be deployable when a multistage SCO_2 gas centrifugal compressor is modified slightly and the performance is checked from the safety point of view.

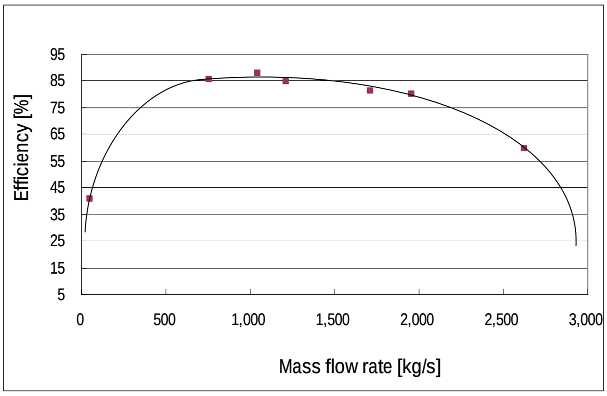

Figure 4. Performance curve for the first stage impeller in compressor #2.

ACKNOWLEDGEMENTS

This work was performed under the auspices of the Brain Korea 21 Energy System Engineering as part of the U.S.-R.O.K. International Nuclear Energy Research Initiative (INERI) program funded by the Korean Ministry of Education, Science & Technology.

REFERENCES

[1] H.W. Oh, "Investigation on the Design and Performance Analysis of Centrifugal Turbomachinery," PhD Dissertation, Korea Advanced Institute of Science & Technology, 1998.
[2] C.H. Song, et al., Multi-dimensional Thermal Hydraulic Phenomena in Advanced Nuclear Reactor Systems: Current Status and Perspectives of the R&D Program at KAERI, 10th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-10), Seoul, Korea, 2003.
[3] S.O. Kim, J.J. Sienicki, Supercritical Carbon Dioxide Brayton Cycle Energy Conversion, U.S.-R.O.K. International Nuclear Energy Research Initiative (INERI), Annual Report, 2007.
[4] M.V. Casey, C.J. Robinson, A Guide to Turbocharger Compressor Characteristics, Dieselmotorentechnik, 10th Symposium, Ostfildern, Ed. M. Bargende, TAE Esslingen, ISBN 3-924813-65-5, 30-31, March 2006.
[5] P. Dalbert, B Ribi, M.V. Casey, Radial Compressor Design for Industrial Compressors, Journal of Mechanical Engineering Sciences, 213 (C1), 71-83, 1999.
[6] C. Rodgers, Centrifugal Compressor Design, Cranfield University Short Course on Centrifugal Compressors, 1992.
[7] CFX® Release 11.0 User Manual, ANSYS, Inc., 2007.