Preliminary Design of Supercritical CO_2 Radial Turbine for Micro Modular Reactor

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1. Introduction

The high capital cost of the existing large nuclear power plants and the increasing demand for small grid size are becoming the motivation of the Small Modular Reactor (SMR) development. A SMR generates electricity less than 300MWe and it is designed to be constructed in module. According to a report, the global market for SMRs was evaluated to be approximately 65-85GW by 2035 [1].

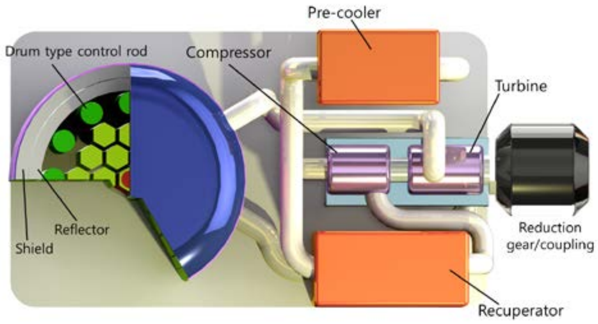

Fig. 1. Concept of KAIST MMR

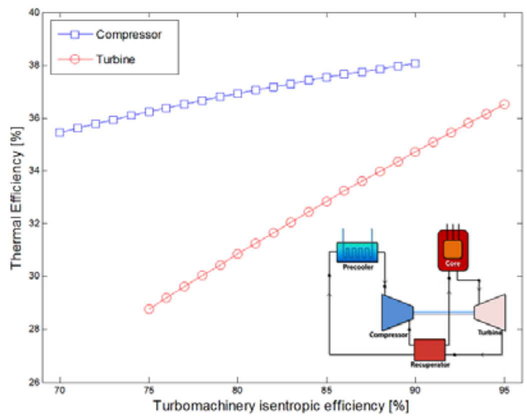

Fig. 2. Parameters sensitivity analysis with $S\text{-}CO_2$ recuperated cycle layout

Initially, the KAIST research team suggested an innovative concept of SMR called KAIST Micro Modular Reactor (MMR). It is aimed for achieving complete modularization of a nuclear power plant including the Power Conversion Unit (PCU) for simple transportation and installation. To accomplish a complete modularization of the system, a supercritical CO_2 ($S\text{-}CO_2$) Brayton cycle was adopted as the power cycle. As depicted in Fig. 1, the $S\text{-}CO_2$ Brayton cycle has small cycle components thanks to small specific volume of $S\text{-}CO_2$ and development of the compact heat exchanger technology. In consideration of the maintenance, $S\text{-}CO_2$ has superior characteristic to the light water because it is less corrosive. Table I represents summary of the main design results of KAIST MMR [2].

Table I: Summary of main design results

Thermal power	36.2MWth	Mass flow rates	175.34kg/s
Net electric power	12.0MWe	Thermal efficiency	33.12%
Generator efficiency	98%	Mechanical efficiency	98%
Compressor inlet pressure	7.50MPa	Pressure ratio	2.67
Rotating speed	20,200rpm	Compressor efficiency	85%
Turbine efficiency	92%	Recuperator effectiveness	95%
Design point of recuperator	Hot side inlet : 432.7℃, 7.58MPa Cold side inlet : 149.9℃, 20.0MPa Temperature difference : 22-58℃		

Despite these advantages, it should overcome technical challenges to accomplish the theoretical performances. As such efforts the study on $S\text{-}CO_2$ turbomachinery has been actively conducted because the $S\text{-}CO_2$ Brayton cycle operates under extreme conditions such as high rotational speed, high pressure, and dramatic change of thermodynamic properties near the critical point (30.98°C, 7377kPa). To achieve higher thermal efficiency, the operation near the critical point is prerequisite in the $S\text{-}CO_2$ Brayton cycle. For these reasons, research works on the $S\text{-}CO_2$ turbomachinery naturally have been focused on the compressor which operates near the critical point. However, as shown in Fig. 2, the efficiency of the turbine affects thermal efficiency of a PCU more than that of the compressor. Thus, in this paper the preliminary design of a $S\text{-}CO_2$

radial turbine is conducted by using 1D mean-line method.

2. Methodology

Compared to the computational fluid dynamics (CFD) analysis, the advantage of using 1D mean-line method is to estimate design and off design performance easily by introducing empirical correlations, i.e. loss models. Since a nuclear power plant has to achieve high level of safety, the system transient performance prediction is an important issue. Various loss models were collected from open literature. Finally the following models are selected in this paper. These loss models are integrated to a turbomachinery design in-house code, KAIST-TMD [3].

2.1 Loss Models

2.1.1 Loss Models for Volute

The function of the volute is to provide a uniform velocity and uniform static pressure for the fluid entering nozzle and impeller. The installation of the volute is helpful to let the fluid to flow in a rotor passage with proper capacity, and also the system is not subject to sudden radial loading. Eqs. (1) and (2) represent circumferential distribution loss and friction losses, respectively.

$$P_{loss-V-cd} = \left(\frac{\frac{V_{1-in} r_{1-in}}{r_2} - V_{1-w}}{V_1} \right)^2 (P_{o1-avg} - P_{avg}) \quad (1)$$

$$P_{loss-V-fr} = f_{vol} \frac{L_{vol}}{D_{h-vol}} \left(P_{o-avg} - P_{avg} \right) \quad (2)$$

2.1.2 Loss Models for Nozzle

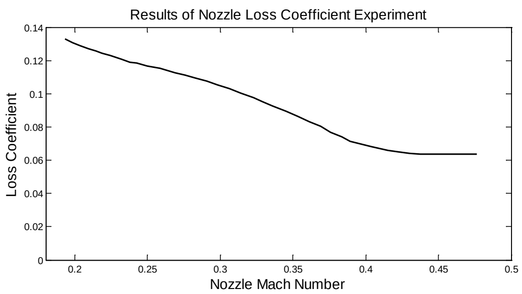

Fig. 3. Results of nozzle coefficient experiment [4]

After passing through a volute, fluid enters into a nozzle. Eq. (3) represents the loss coefficient of the nozzle. It is expressed regarding a static enthalpy loss. The value of loss coefficient is determined using Fig. 3. When Mach number exceeds the range, the loss coefficient is decided by using an extrapolation method.

$$\xi = \frac{h_3 - h_{3s}}{h_{03} - h_3} = \frac{h_3 - h_{3s}}{\frac{1}{2} C_3^{\,2}} \quad (3)$$

2.1.3 Loss Models for Impeller

Since complicated phenomena occur within an impeller, it is difficult to estimate its loss accurately. However, the mean-line method and these loss models are sufficient to predict the turbomachinery performance and generate rotor and stator geometries in the preliminary design step. Following four loss models; incidence loss, rotor passage loss, clearance loss, and disk friction loss, are considered in this work for losses in the impeller. Eqs (4)-(8) predict each loss in the order named.

$$h_{inc} = \frac{1}{2} W_4^{\,2} (1 - \cos^2 \beta_4) \quad (4)$$

$$h_{inc} = \frac{1}{2} W_4^{\,2} \sin^2 (\beta_4 - \beta_{4,opt}) \quad (5)$$

$$h_{passage} = \frac{\phi^{1.75} (1 + K_I)^2}{8} \zeta_I U_4^{\,2} \quad (6)$$

$$\textit{where, } K_I = \frac{C_{m4}}{C_{m5}}, \ \phi = \frac{C_{m4}}{U_4}, \textit{ and } \zeta_I = 0.88 - 0.5\phi$$

$$\Delta h_{clearance} = 0.6 \frac{CL}{Vd} C_{w4} \times \sqrt{2 \frac{\pi}{Vdn_{vane}} C_{w4} C_{m5} \frac{D_{5,tip}^{\,2} - D_{5,hub}^{\,2}}{(D_4 - D_{5,tip})(1 + \frac{\rho_4}{\rho_5})}} \quad (7)$$

$$h_{disk} = f_{disk} \frac{\bar{\rho} r_4^{\,2} U_4^{\,3}}{4 \dot{m}} \quad (8)$$

$$f_{disk} = \frac{2.67}{\mathrm{Re}_{disk}^{\,0.5}}, \ (\mathrm{Re}_{disk} < 3 \times 10^5)$$

$$f_{disk} = \frac{0.0622}{\mathrm{Re}_{disk}^{\,0.2}}, \ (\mathrm{Re}_{disk} \geq 3 \times 10^5)$$

2.2 KAIST-TMD

KAIST-TMD is a turbomachinery design in-house code implemented in MATLAB environment. It can estimate a radial turbine geometry and performance at design conditions and off design performance from the generated geometry. When a radial turbine is designed, design code considers volute, nozzle, and rotor as main components. The main code structure is shown in FIGURE 4. To minimize the kinetic energy loss at the impeller exit, no swirl condition is applied at the design condition.

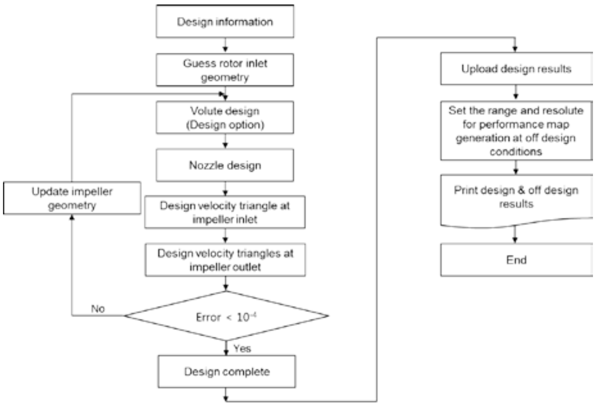

Fig. 4. Main algorithm of KAIST-TMD

2.3 Code Validation

Due to the absence of the test data for $S\text{-}CO_2$ turbine, an indirect validation carried out by utilizing the experimental data for air driven turbine. Figs 5 and 6 represent validation results of comparing experimental data with the design code results for 100% and 80% design speed. The predicted pressure ratio map shows a good agreement with the experimental data and the maximum error is 3.2%. The predicted efficiency map has theoretically a single curve for all speeds. The predicted curves overlap on a single curve.

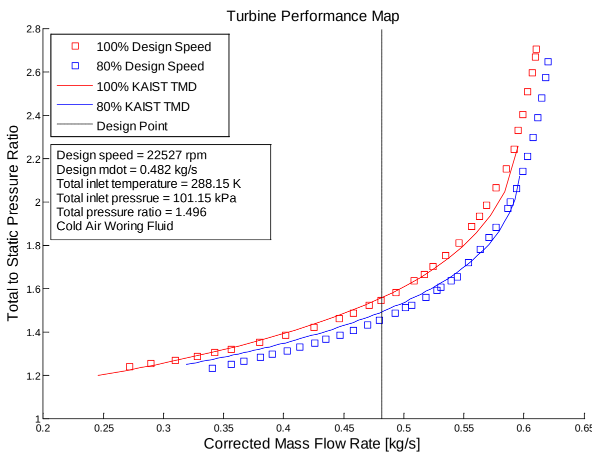

Fig. 5. Comparison of pressure ratio map [5]

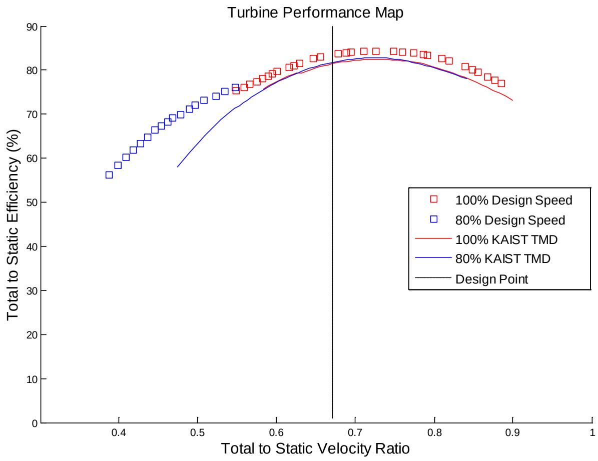

Fig. 6. Comparison of efficiency map [5]

4. Results

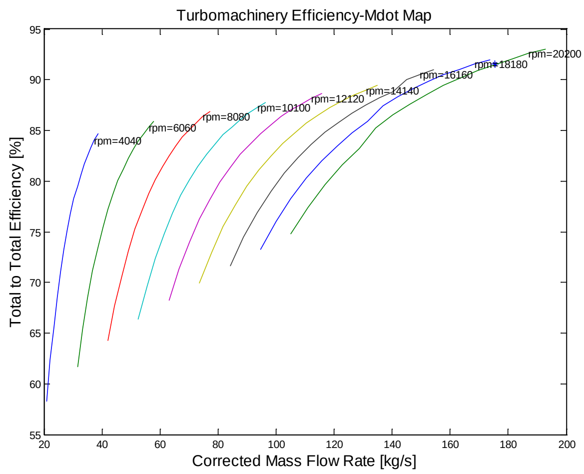

Fig. 7. Efficiency map for MMR turbine

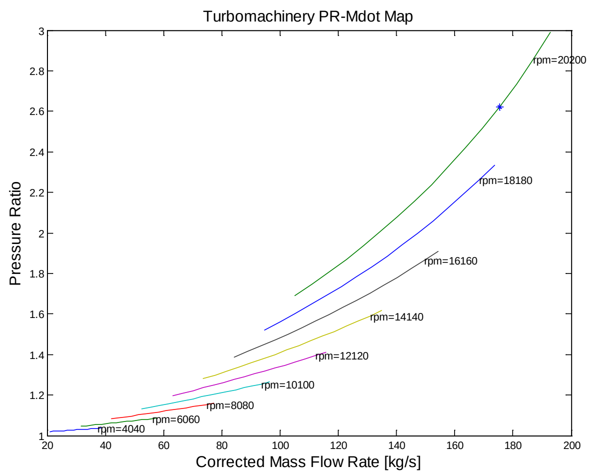

Fig. 8. Pressure ratio map for MMR turbine

Performance maps of a radial turbine satisfying given conditions, such as turbine inlet condition, pressure ratio, rotational speed, stage number, and target efficiency, were generated by using the developed design code. Since these maps are utilized for system analysis under abnormal operations, it provides efficiency and pressure ratio in terms of total state at the inlet. Performance maps are generated depending on the change of mass flow rate and rotational speed. Figs. 7 and 8 depict corrected mass flow rate vs. total to total efficiency map and corrected mass flow rate vs. total pressure ratio map, respectively.

4. Summaries and further works

A turbomachinery design code, namely KAIST-TMD for a S-CO_2 radial turbine design was developed on the basis of 1D mean-line method. Due to the absence of loss models in S-CO_2 field, loss models with air turbine were first utilized to design and predict the off design performance of a S-CO_2 turbine. To check propriety of the code logic the code results compared with experimental data measured in air condition. The predicted values showed good agreement with the experiment data. Lastly, performance maps for S-CO_2 turbine for the MMR were generated with change of mass flow rate and rotational speed.

Even though KAIST-TMD showed a good agreement with the air turbine data, it should be compared with the S-CO_2 turbine data in various operating conditions in the future. Furthermore, the selected loss models will be revised properly in accordance with the validation results to improve the accuracy of the code in the future.

ACKNOWLEDGEMENT

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