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Design and Evaluation of Supercritical CO_2 Axial Turbine for Micro Modular Reactor

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1. Introduction

Recently, small-sized modular nuclear power plants are attracting attention worldwide. This is because small reactors have great potential in developing countries with low power grid capacity and in areas requiring distributed power. In addition, supercritical CO_2 cycle, a technology that can potentially replace the existing steam cycle in the process of developing the Gen-IV nuclear power generation system, is attracting much attention. Supercritical CO_2 cycles are also suitable for small modular nuclear power plants because the sizes of the turbines and compressors, which are components of the cycle, are very compact compared to other cycles.

Another advantage is that the supercritical CO_2 cycle has higher thermal efficiency at moderate turbine inlet temperatures compared to the steam Rankine cycle and the Helium Brayton cycle. For the small modular nuclear power plant, heat exchangers have to be small size. Therefore the PCHE(Printed circuit Heat Exchanger) was used for small modular nuclear power plant to solve this problem. The PCHE is a plate-type heat exchanger with high surface to volume ratio, allowing supercritical fluids to effectively exchange heat. By combining these technologies, KAIST researchers developed a concept of MMR (Micro module reactor) [1].

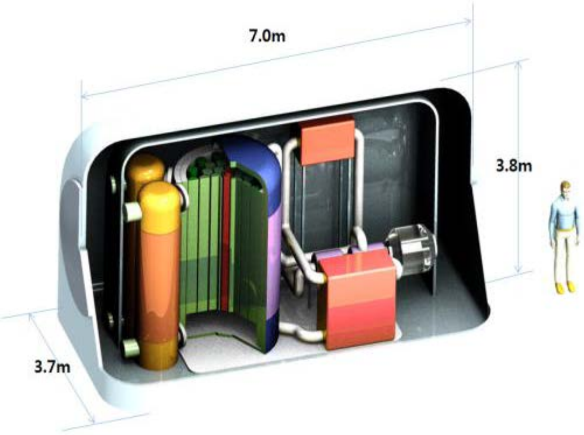

Fig1. Conceptual view of MMR

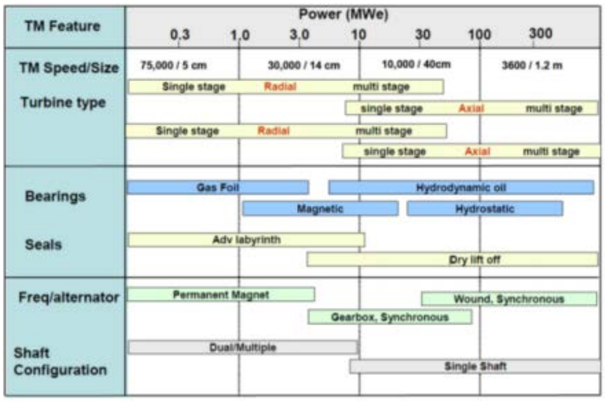

Fig2. Component and technology options for s-co2 cycles

Since the MMR is a small-sized modular power plant with a capacity of 12 MWe, it is designed as a radial turbine in the MMR cycle with reference to Fig 2 [2]. However, it is becoming increasingly important to increase efficiency due to the accelerating global warming and the rapid growth of power demand due to population growth.

Therefore, in this study, to improve the efficiency of MMR cycle, axial turbine was designed instead of radial turbine to compare the behavior at design point and off - design point.

2. Methods

2.1 Design conditions of MMR

The design conditions of the MMR already developed are as follows.

Table1. Summary of main design results

Thermal power	36.2MWth	Net electric power	12MWe
Thermal efficiency	32.6%	Mechanical efficiency	98%
Mass flow rate	180.0kg/s	Pressure ratio	2.49
Turbine efficiency	92%	Compressor efficiency	85%
Generator efficiency	98%	Rotating speed	19,300rpm
Recuperator effectiveness	95%	Compressor inlet pressure	8.0MPa
Design point of recuperator	Hot side inlet : 440.7℃, 8.2MPa Cold side inlet : 142.1℃, 20.0MPa Temperature difference : 22-58℃		

2.2 KAIST_TMD

KAIST-TMD is a turbomachinery design in-house MATLAB code.

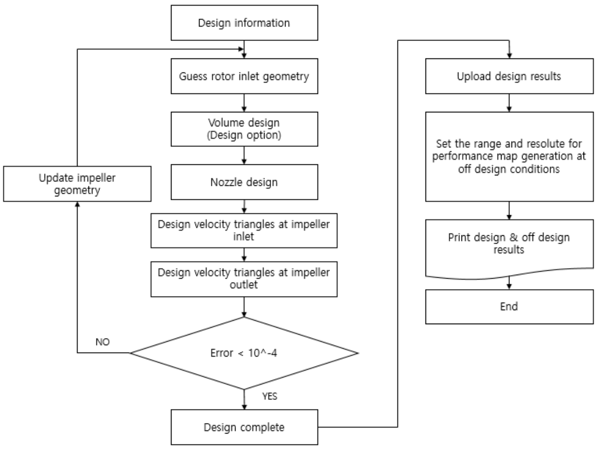

Fig 3. Main algorithm of KAIST-TMD

The main design parameters defined the designer when designing a turbine by KAIST-TMD are volute, nozzle, and rotor. It can estimate the performance and geometry of several turbines at the design point. The performance at the off-design point can also be estimated. The main code structure is shown in Fig 3.

3. Results

The radial turbine was designed by KAIST_TMD _radial code using the design points in Table 1.
Also, the axial turbine was designed by revised KAIST_TMD_axial code using same design point for comparison of radial turbine.

The range of performance evaluation for off-design is as follows :
The ratio of the minimum mass flow rate = 0.5
The ratio of the maximum mass flow rate = 0.99
The ratio of the minimum rpm = 0.5
The ratio of the maximum rpm = 0.99

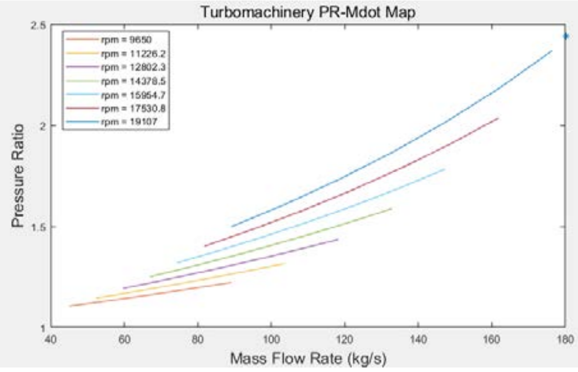

Fig 4. Pressure ratio map for MMR radial turbine

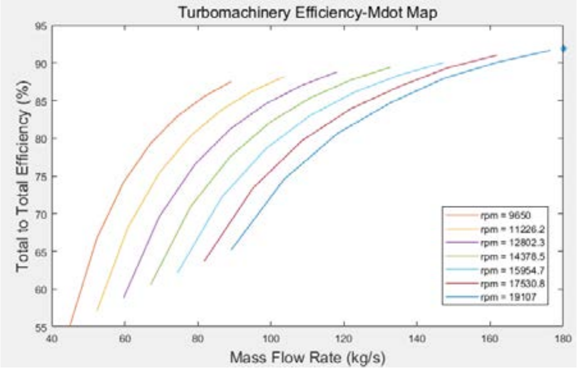

Fig 5. Efficiency map for MMR radial turbine

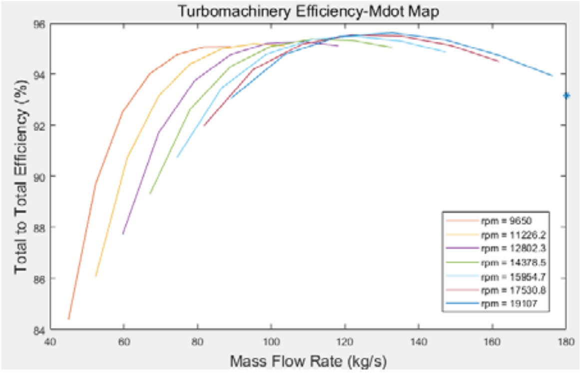

Fig 6. Efficiency map for MMR axial turbine

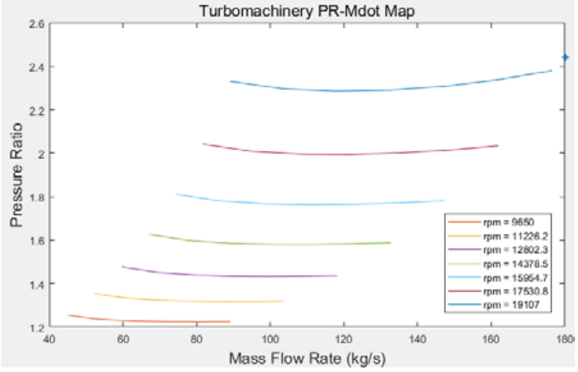

Fig 7. Pressure ratio map for MMR axial turbine

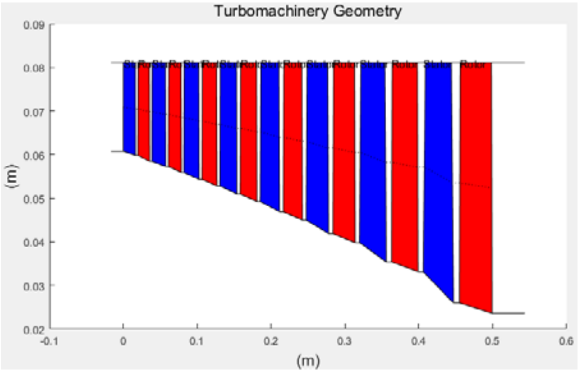

Fig 8. Turbomachinery geometry for MMR axial turbine

Table2. Comparison of each TMD results

	Radial turbine cycle	Axial turbine cycle
Number of stages	1	8
Turbomachinery work	21.6079MW	21.9063MW
Pressure Ratio	2.4421	2.4396
Turbomachinery total efficiency	91.9085%	93.1779%
Thermal efficiency	32.6%	33.05%

When comparing at the design point, it can be seen that the adiabatic efficiency of the axial turbine was measured to be about 1.27% larger than that of the radial turbine. Also, the thermal efficiency of axial turbine cycle was 0.45% higher than that of radial turbine cycle.

First, the turbine efficiency map shows that the axial turbine has more gradual slope than the radial turbine. This is advantageous not only for the axial turbine on design performance, but also for higher efficiency on average at off-design points due to the gradual change in turbine efficiency for different mass flowrate.

Secondly, because the axial turbine has a relatively more gradual slope of the mass flow-pressure ratio graph, the pressure ratio at the off-design point can also be predicted to be higher than that of the radial turbine.

4. Summary

Axial turbines in MMR show superior performance over radial turbines in terms of efficiency at design and off-design points. However, there are several drawbacks to using an axial turbine.

First, the axial turbine requires 9 stages in order to achieve high efficiency under equal conditions of radial turbine. This may result in an increase in capital cost.

Secondly, in KAIST-TMD, the range of off-design performance evaluation is limited compared to radial turbine, so it may be difficult to compare off-design points. It is estimated that the evaluation range of the off-design point is limited because the axial turbine has many stages relative to the radial turbine and the iteration error tends to increase when the number of stage is large.

Therefore, if the axial turbine is designed in MMR, the efficiency of the cycle can be improved, but it is necessary to set up the operation strategy in terms of off - design performance.

Acknowledgement

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[1] S. G. Kim, et al., Conceptual System Design of a Supercritical CO_2 cooled Micro Modular Reactor, Proceedings of ICAPP, 2015.

[2] Darryn Fleming, et al., Scaling Considerations for a Multi-Megawatt Class Supercritical CO2 Brayton Cycle and Path Forward for Commercialization, Sandia National Laboratories, 2012.