Conceptual Design of Supercritical CO_2 Brayton Cycle Radial Turbomachinery for SMART Application

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1. Introduction

System-integrated Modular Advanced Reactor (SMART) is one of Korean type nuclear reactors developed by Korea Atomic Energy Research Institute (KAERI). Main target of SMART development is 40,000 tons/day of desalination with 90MWe of electricity generation from 330 MWth of reactor thermal power. Since the main concept of SMART is small modular, compactness of whole system is important. The Supercritical CO_2 Brayton cycle technology can have good synergy effect when it is coupled with small modular reactor due to its compactness while achieving high efficiency.

In this paper, turbomachinery sizing of S-CO2 Brayton cycle for SMART designed by Ref.[1] will be briefly introduced.

2. S-CO2 Brayton cycle design for SMART

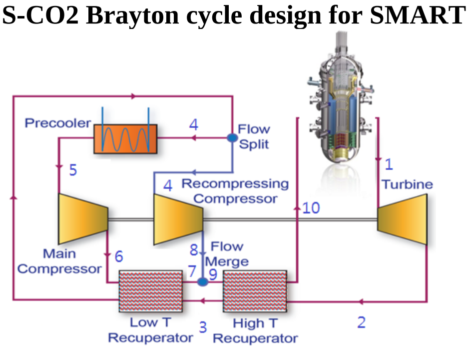

Fig. 1. S-CO_2 Recompressing Cycle layout and operating points

Preliminary analysis of S-CO2 Brayton cycle coupled to SMART is discussed in Ref. [1]. Authors suggested 15 MPa of cycle maximum pressure recompressing layout and that of 22 MPa as most effective layout. However, our discussion in this paper will be limited to 15 MPa recompressing layout. Preliminary operating conditions in Ref.[1] is summarized in Table.1

Table. 1. Design specifications of the S-CO2 Brayton cycle in SMART condition for 15 MPa of cycle maximum pressure layout. (Ref.[1])

Net efficiency, %	29.03
Total mass flow rate of working fluid, kg/s	2839.19
Turbine Inlet Temperature, K	583.15
Turbine Pressure Ratio	1.89
Main Compressor Inlet Temperature, MPa	305.15
Main Compressor Outlet Pressure, MPa	15
Mass flow rate split ratio, %	46

3. Balje's ns-ds diagram

One of the most useful methods for compressor sizing is utilizing Balje's ns-ds diagram[2].

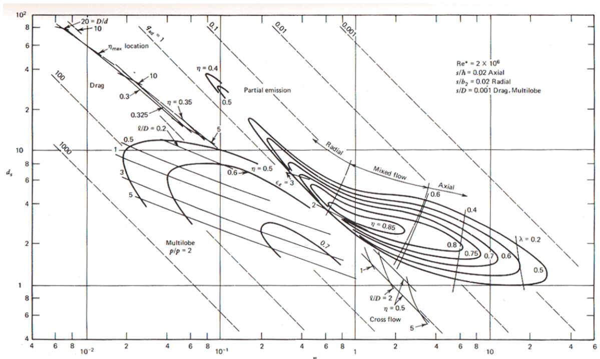

Figure.2. ns-ds diagram for single stage compressor

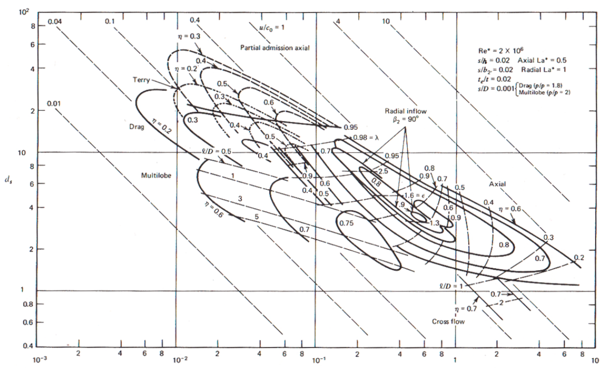

Figure.3. ns-ds diagram for single stage turbine

The contour line in Fig.2 and Fig.3, the ns-ds diagrams, means the same efficiency for given compressor type. specific speed, ns which is x axis value, and specific diameter, ds which is y axis value, can be calculated by Eq.1

$$n_s = \frac{\omega\sqrt{V_1}}{(gH_{ad})^{\frac{3}{4}}}, d_s = \frac{D(gH_{ad})^{\frac{1}{4}}}{\sqrt{V_1}} \qquad (1)$$

where angular velocity, ω , gravitational acceleration, g, impeller diameter, D, inlet volumetric flow rate, V_1 and adiabatic head, H_{ad} .

The most center contour line is the highest efficiency area and efficiency decreases at outer contour line in nsds diagrams. After design target efficiency selection, expected specific speed and specific diameter are decided by nsds diagrams. Compressor rotation speed and impeller diameter can be calculated with expected specific speed and specific diameter since volumetric flow rate, adiabatic head and gravitational acceleration are given values.

During ns and ds calculation, thermodynamic properties should be involved due to non-linear property variation of S-CO2. REFPROP was used for thermodynamic property.

Volumetric flow rate and adiabatic head are prescribed values from cycle operating conditions. Thus, target specific speed can determine angular velocity. The impeller diameter can be directly calculated with best specific diameter pair of target specific speed.

4. Results & Conclusion

The most efficient radial compressor can be designed at 0.65 of specific speed, ns, and 3.8 of specific diameter, ds in Fig.2 while the most efficient radial compressor can be designed at 0.55 of specific speed and 3.5 of specific diameter in Fig.3. To secure high compressor efficiency, various case of stage design was carried out under given temperature and pressure cycle step points. The best results and detail conditions are shown in Table.3-5.

Table. 3. Design specification of the S-CO2 Brayton cycle recompressing layout main compressor

Main Compressor	
Inlet Pressure, MPa	7.704
Inlet Temperature, K	305.150
Outlet Pressure, MPa	15
Outlet Temperature, K	324.627
Stages	5
RPM	3600
Impeller diameters, mm	619, 585, 575, 567, 561

Table. 4. Design specification of the S-CO2 Brayton cycle recompressing layout recompressing compressor

Recompressing Compressor	
Inlet Pressure, MPa	7.706
Inlet Temperature, K	330.508
Outlet Pressure, MPa	14.997
Outlet Temperature, K	388.459
Stages	3
RPM	3600
Impeller diameters, mm	995, 813, 701

Table. 5. Design specification of the S-CO2 Brayton cycle recompressing layout turbine

Turbine	
Inlet Pressure, MPa	14.822
Inlet Temperature, K	583.150
Outlet Pressure, MPa	7.838
Outlet Temperature, K	519.692
Stages	1
RPM	3600
Impeller diameters, mm	1134

The numbers used for specific speed and specific diameter are 0.64 and 3.8 for main compressor, 0.57, 4.5 for of recompressing compressor and 0.42, 4.0 for turbine. Reason why those ns, ds values were not the same with the values mentioned beginning of this chapter is limitation of adjustable parameters such as RPM, stage number. While our team performed this work, we set the RPM of one main shaft as 3600 for direct electricity grid connection. Thus, there was only one adjustable parameter which is the number of stages. Adiabatic head is highly related with stage pressure ratio and stage pressure ratio can be adjusted by stage number which is integer. Thus, to gain exact same ns and ds with target values cannot be achieved.

Authors tried to design radial turbomachineries for SMART application. However, designed impeller diameters and number of stages have much higher values than authors expected. Because, reference layout has high enough mass flow rate to use axial turbomachineries. Since SMART is Pressurized Water cooled Reactor, turbine inlet temperature is limited by steam generator outlet temperature of secondary side. Low turbine inlet temperature causes high mass flow rate of BOP system. Thus, designed impeller diameters and number of stages have higher values than expected.

According to Ref. [1], 10 stage main compressor with 483.6 mm of the first stage diameter, 7 stage recompressing compressor with 774.2 mm of the first stage diameter axial turbomachineries can be designed and it is more feasible than the results of abovementioned radial turbomachineries.

Since S-CO2 Brayton cycle for SMART application has high mass flow rate of BOP system, use of axial turbomachineries is more feasible.

REFERENCES

[1] H. J. Yoon, Y. Ahn, J. I. Lee, Y. Addad, “Potential advantages of coupling supercritical CO2 Brayton cycle to water cooled small and medium size reactor,” Nuclear Engineering and Design, Vol. 245, 223-232, (2012)

[2] O. E. Balje, TURBOMACHINES : A Guide to Design, Selection, and Theory, A Wiley-Interscience Publication, (1981)