Off-design performance prediction of Radial Compressor of S-CO_2 Brayton Cycle for KAIST Micro Modular Reactor

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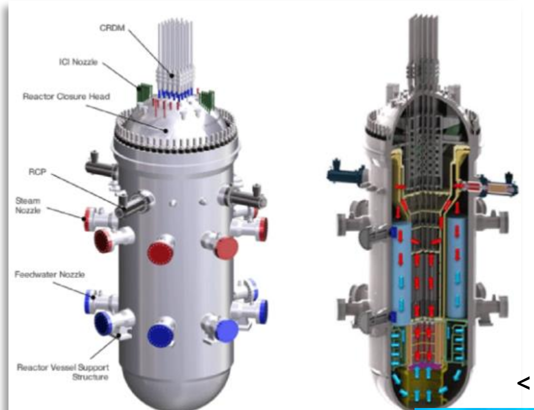
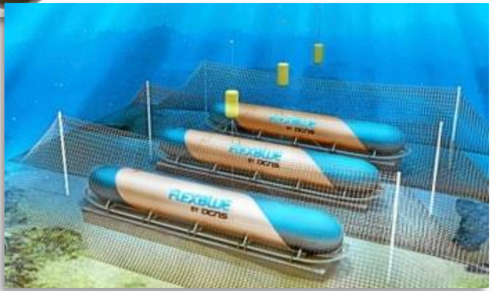
CONTENTS

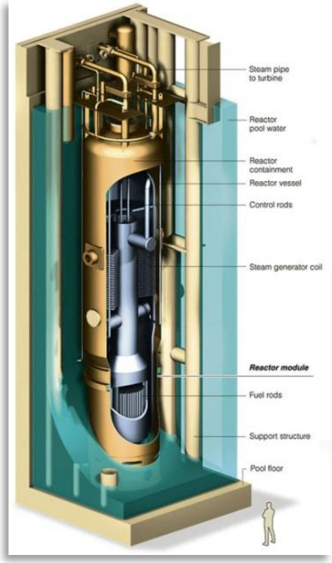
Background



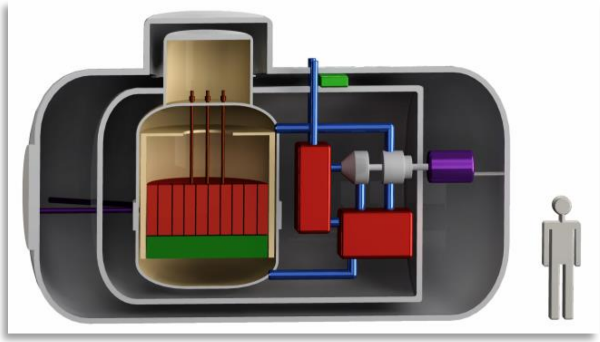
<SMART reactor (100MWe), KAERI>



<Flexblue (160MWe), DCNS>



<NuScale (50MWe), NuScale Power>



<MMR(12MWe), KAIST>

Small Modular Reactor (SMR)

- SMR concepts in the world
  - Achieve small size
  - Long life of reactor core

- Advantages of SMR
  - Low initial capital cost
  - Site flexibility

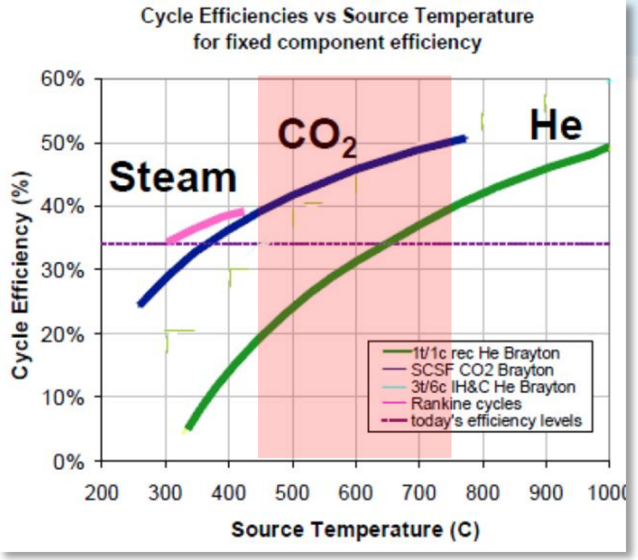
KAIST Micro Modular Reactor (MMR)

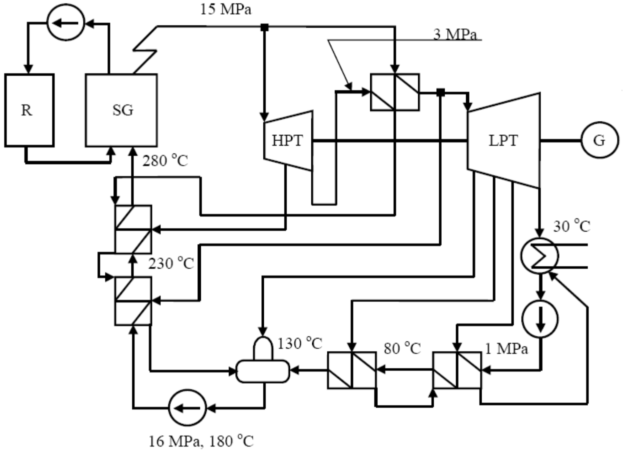
- Transportable modular reactor
- Economic benefit by series production
- **Supercritical CO_2-cooled** fast reactor
- Long life core without fuel reloading

Background

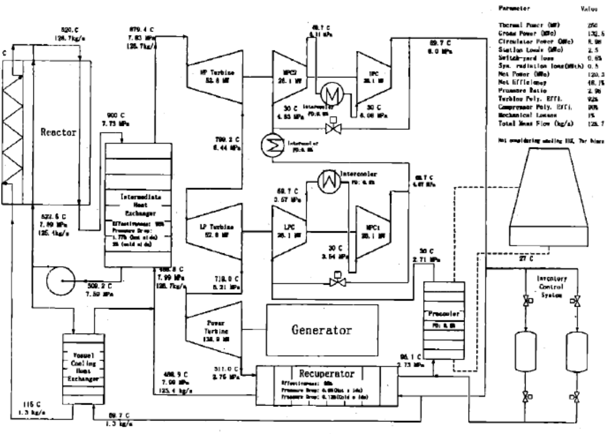
Supercritical CO_2 Brayton cycle for Micro Modular Reactor

- **S-CO_2 Brayton cycle** is used for power conversion system
- Advantages of S-CO2 cycle for SMR
  - **High cycle efficiency** in moderate temperature ranges (450~750 ℃)
  - **Compact component size with simple layout**

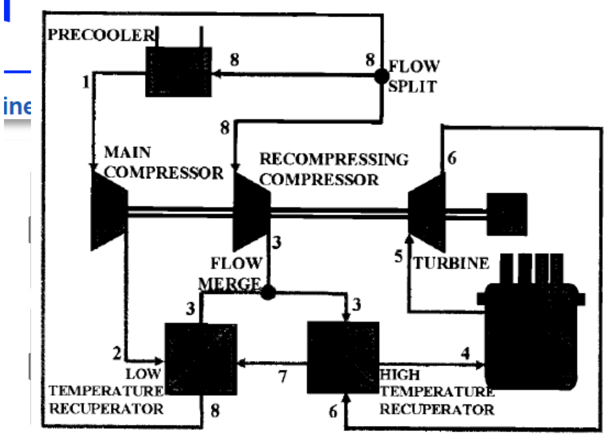




Steam cycle



Helium cycle



Precooler volume ≈ 24m³
(total volume for 8
precooler modules)

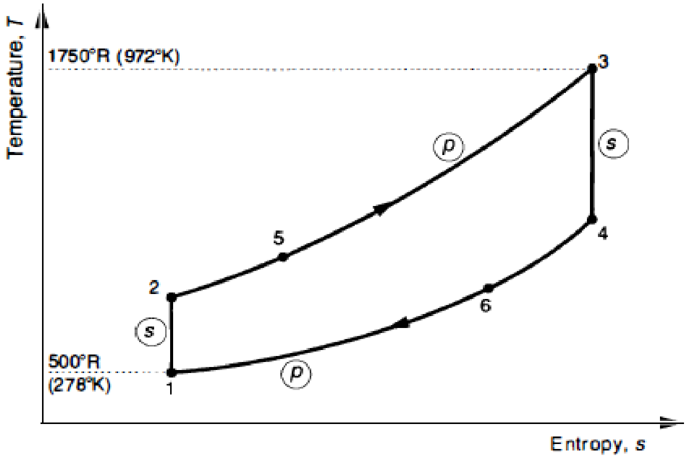
Main condenser volume ≈ 910m³
(includes half of turbine exhaust path)

S-CO_2 cycle

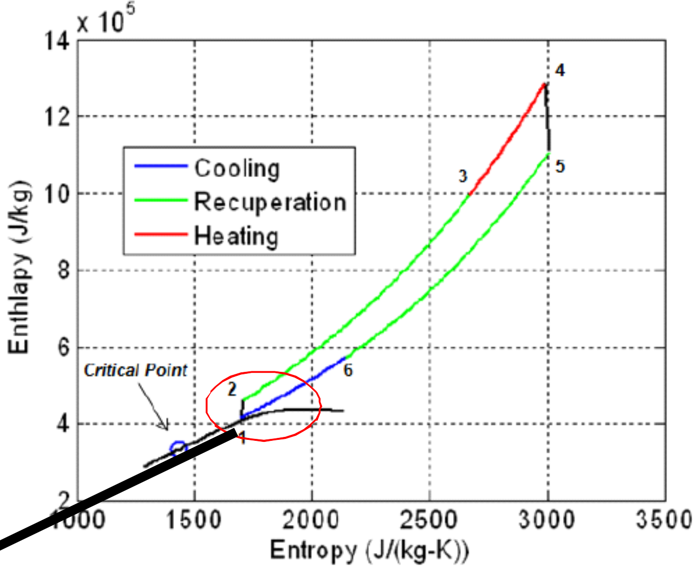
<Steven A. Wright, Supercritical technologies SCO2 overview>

Background

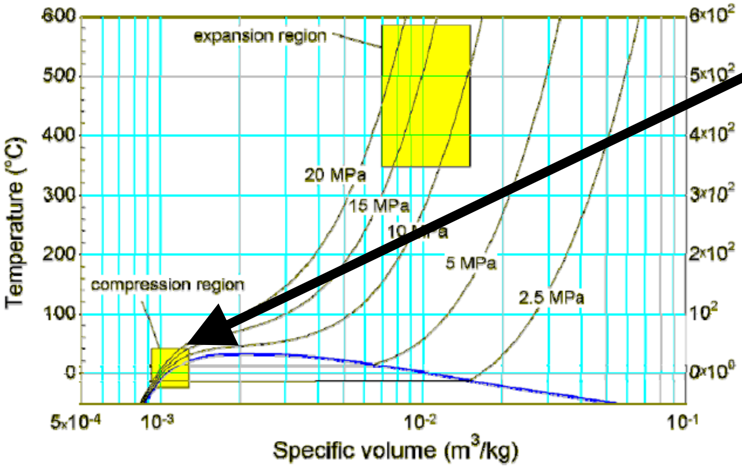
Ideal Gas Brayton Cycle



S-CO2 Brayton Cycle

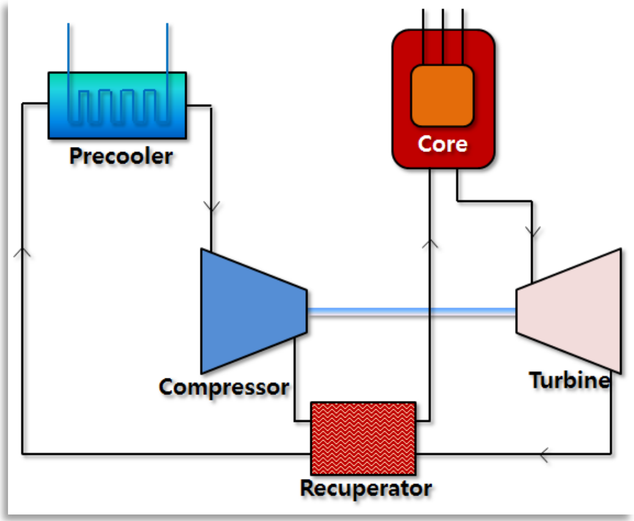


Specific Volume

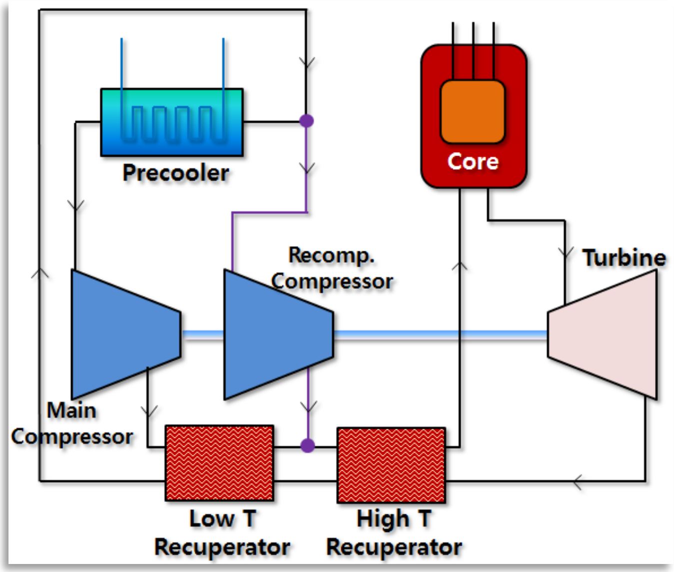


S-CO$_2$ Brayton Cycle is a hybrid of Rankine and Brayton cycles to maximize advantages from both cycles

Previous studies



<Simple recuperated S-CO_2 Brayton cycle>



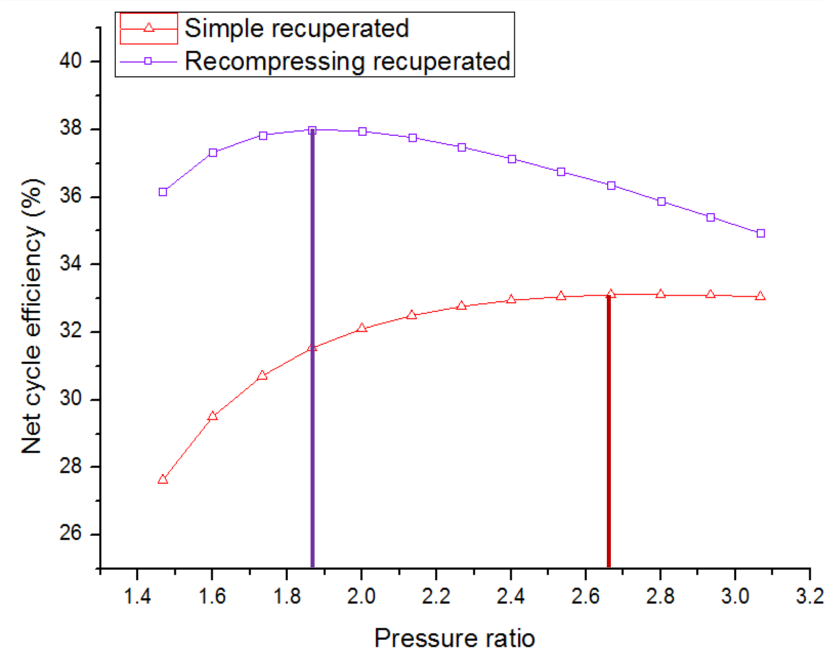
<Recompressing recuperated S-CO_2 Brayton cycle>

Design of S-CO_2 cycle

- An in-house code KAIST-CCD was used for cycle design.
- Direct cycle for MMR power conversion system
  - Simple recuperated S-CO_2 Brayton cycle
  - Recompressing recuperated S-CO_2 Brayton cycle
- Bottom temperature of cycle **(60℃)**
  → Considering **air-cooling capability** at pre-cooler cold side

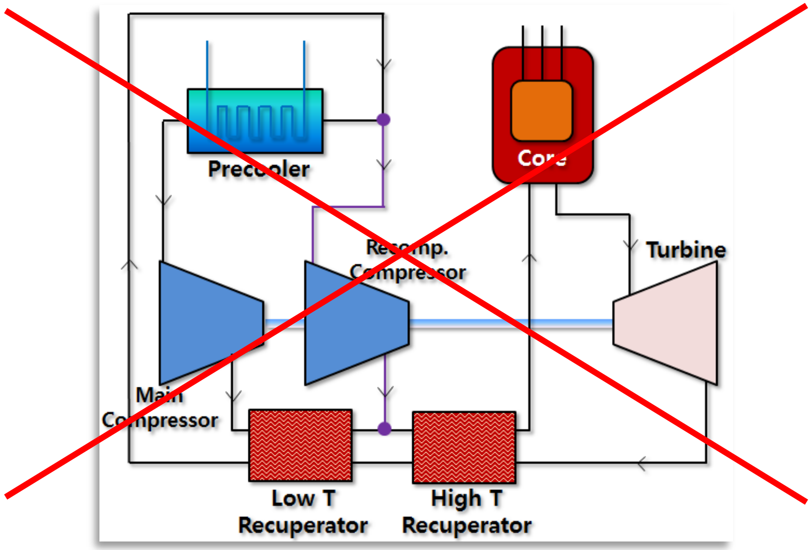
Target	
Electric power output	10-12 MWe
Turbine inlet temperature	550.0℃
Compressor inlet temperature	60.0℃
Total Weight	<100ton
Total Width	<8m
Cylindrical diameter	3-4m
Pre-cooler coldside coolant	Air

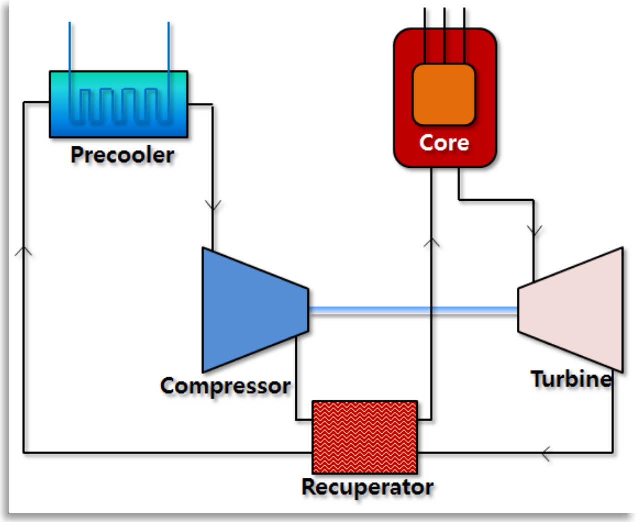
Previous studies



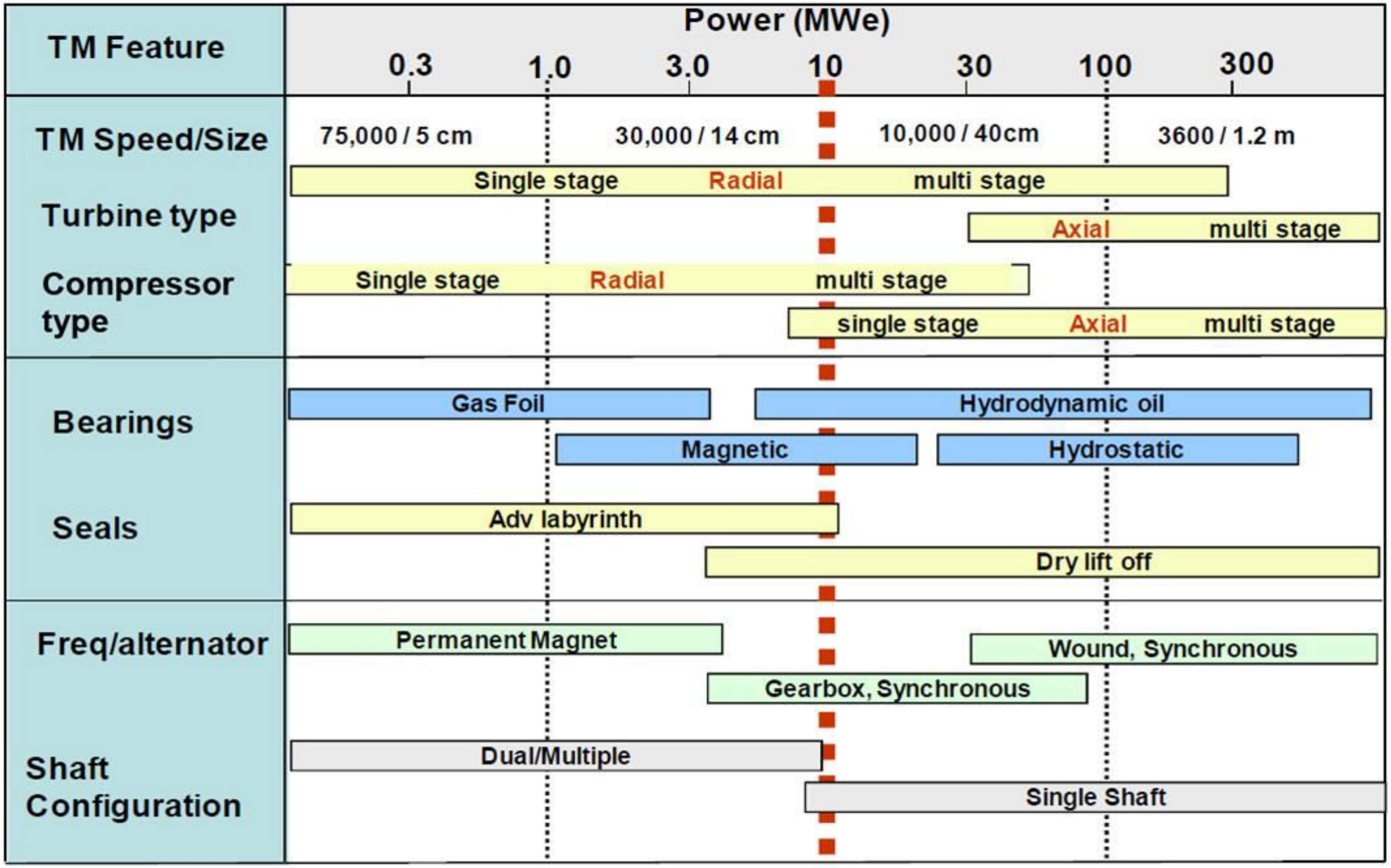
Determine top pressure

- **Cycle optimization study** was performed
- Find optimum cycle efficiency vs. pressure ratio
- Assumed efficiency of turbomachineries
  - Compressor : 85%
  - Turbine : 92%
  - Obtained from balje's non-dimensional number analysis
- Simple recuperated cycle : **33%** at 2.62 P ratio
- Recompressing cycle : **38%** at 1.87 P ratio





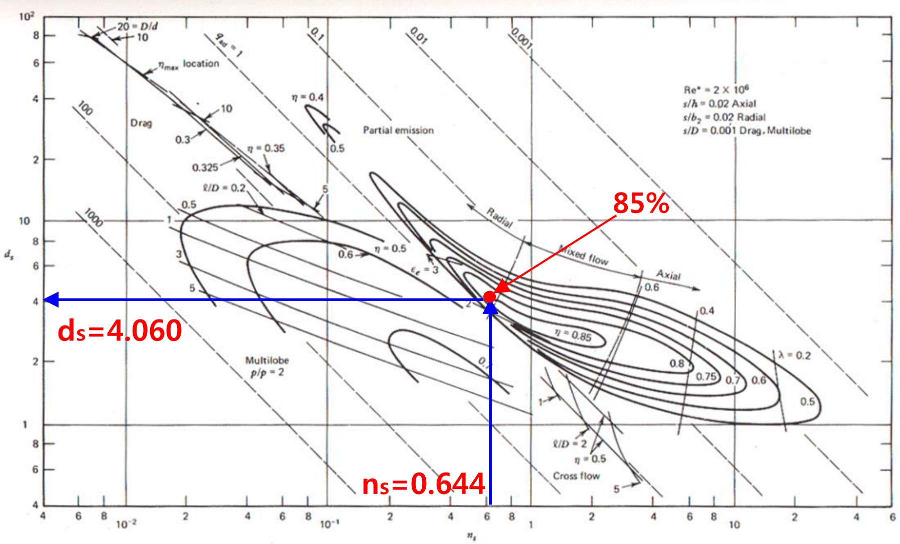
Previous studies



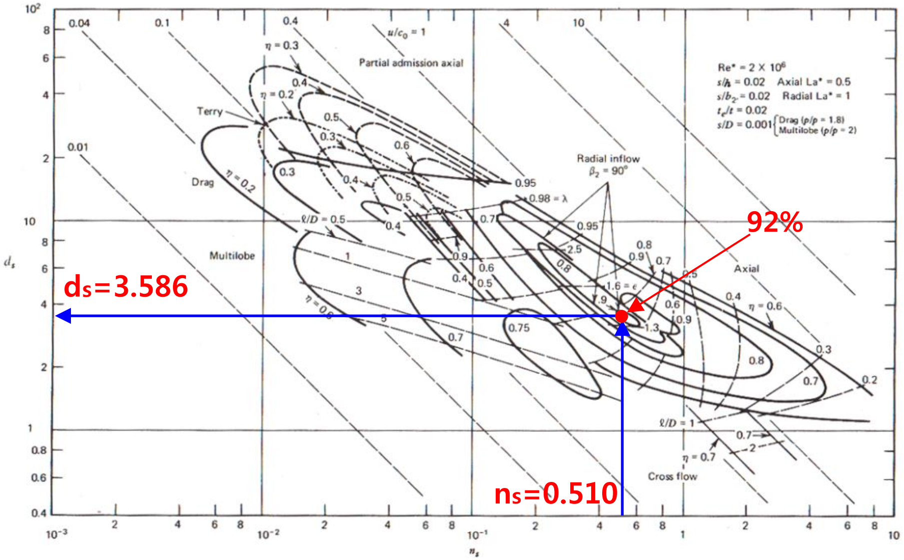
Sienicki, et al., Scale Dependencies of Supercritical Carbon Dioxide Brayton Cycle Technologies and the Optimal Size for a Next-Step Supercritical CO2 Cycle Demonstration, SCO2 Power Cycle Symposium, 2011

Previous studies

nsds diagram for single stage compressor



nsds diagram for single stage turbine



ns and ds, are used for estimating efficiency and compressor sizing

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

ns : specific speed, ds : specific diameter

ω : Angular velocity [radian/sec]
g : Gravitational acceleration [ft/s^2]
D : Impeller diameter [ft]
V_1 : Inlet volumetric flow rate [ft^3/s]
H_{ad} : Adiabatic head [ft]

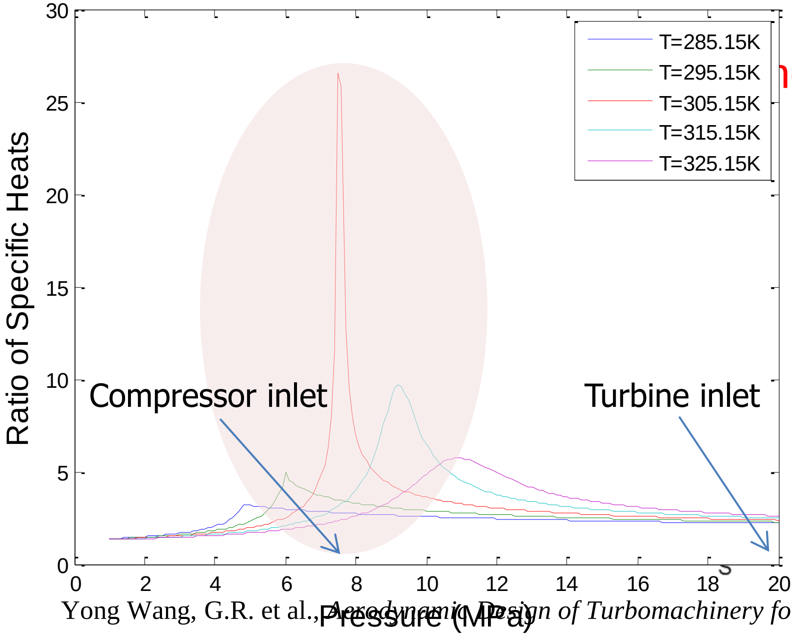
O. E. Balje, 1980, Turbomachines : A Guide to Design, Selection, and Theory, A WILEY.

Turbomachinery performance analysis

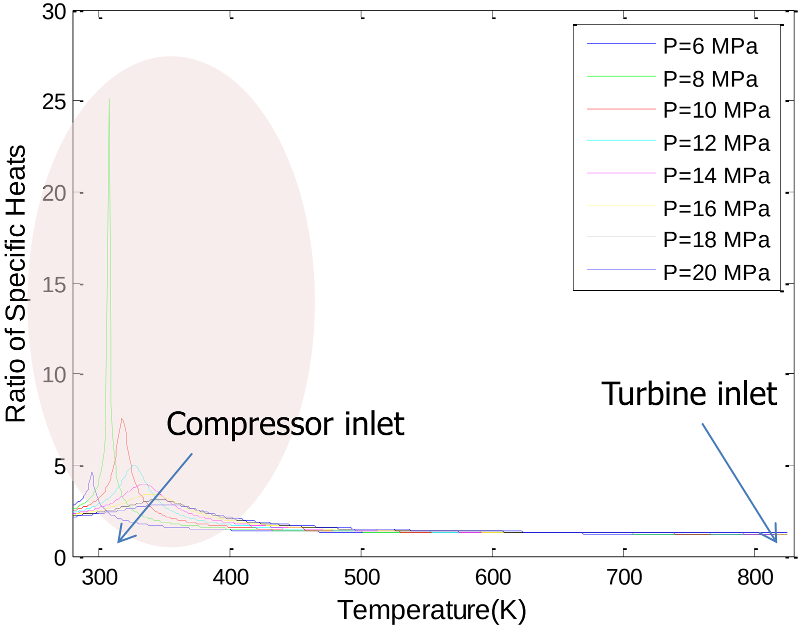
(1) Design methodology

- Ideal gas based correlations cannot be used for S-CO2
  - Thus, the static condition should be calculated from the stagnation condition based on the original definition.

$$\xcancel{\frac{T_o}{T_s} = 1 + \frac{V^2}{2C_p T_s} = 1 + \frac{\gamma - 1}{2} M^2 \qquad \frac{P_o}{P_s} = \left(\frac{T_o}{T_s}\right)^{\frac{\gamma}{\gamma-1}} = \left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}}}$$



Yong Wang, G.R. et al., *Aerodynamic Design of Turbomachinery for 3*



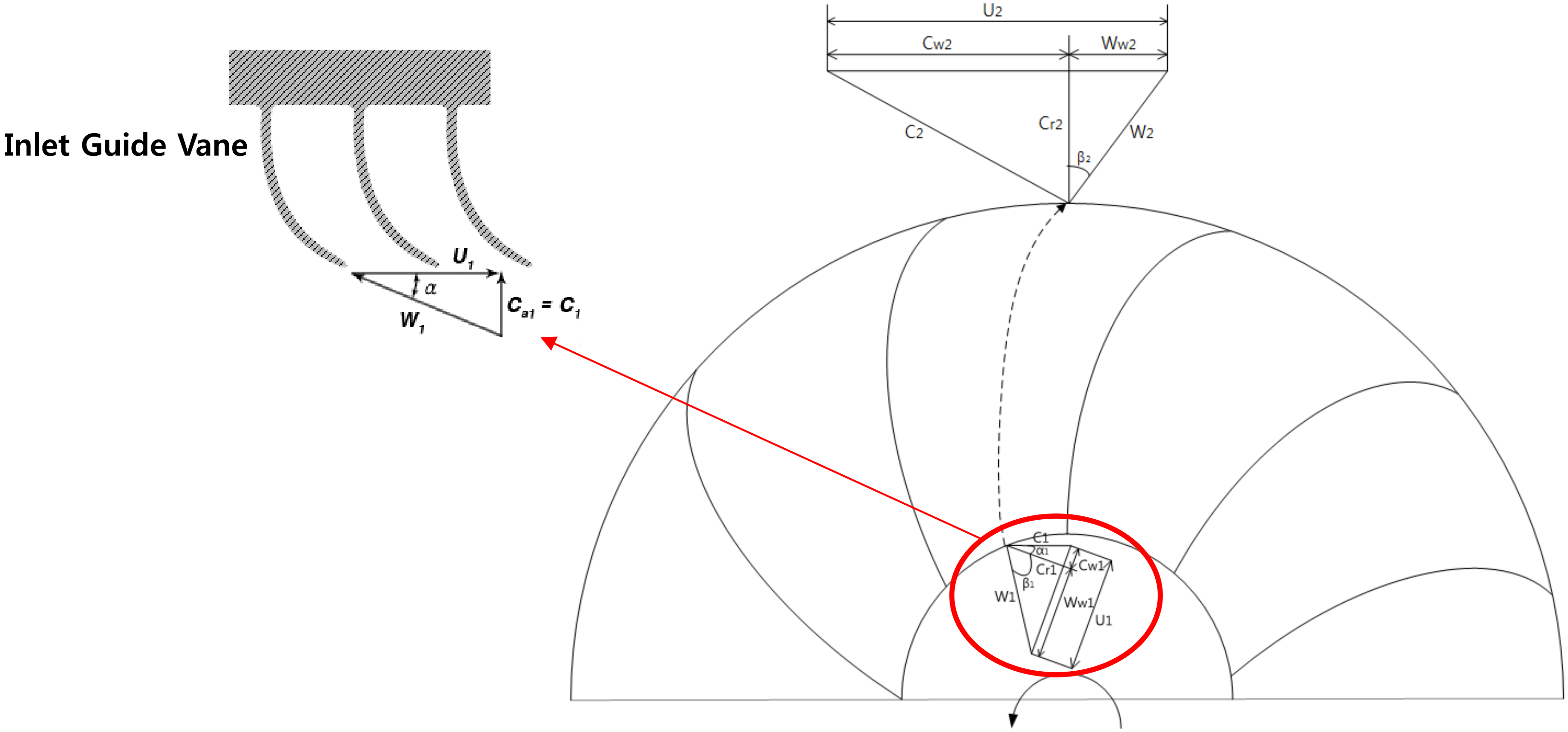
Turbomachinery performance analysis

(1) Design methodology

- Mass conservation + Euler equation

$$\dot{m} = \rho(h_s, P_s)AV \qquad h_{02} - h_{01} = U_2W_{w2} - U_1W_{w1}$$

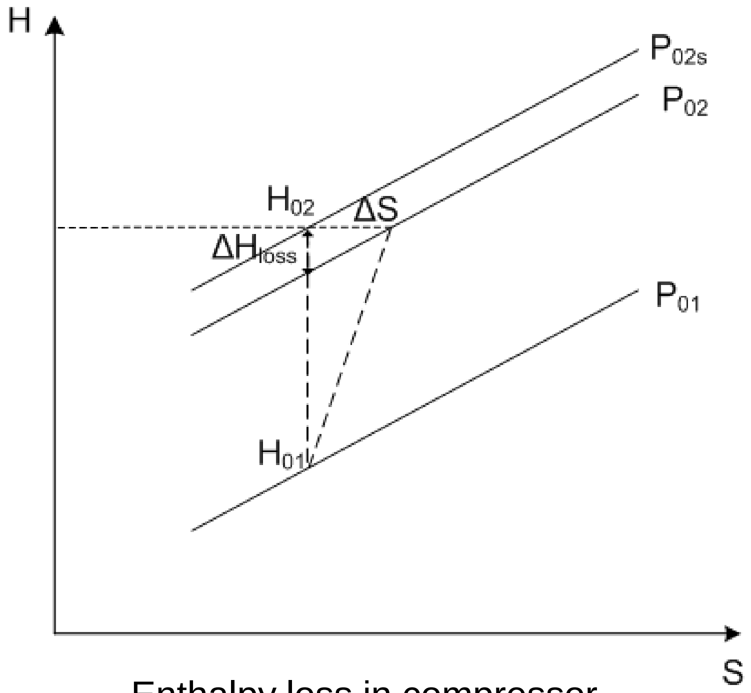
- Velocity profile (Mean stream line analysis)



Turbomachinery performance analysis

(1) Design methodology

- Loss models included in KAIST_TMD for Radial compressor
  - Enthalpy loss models

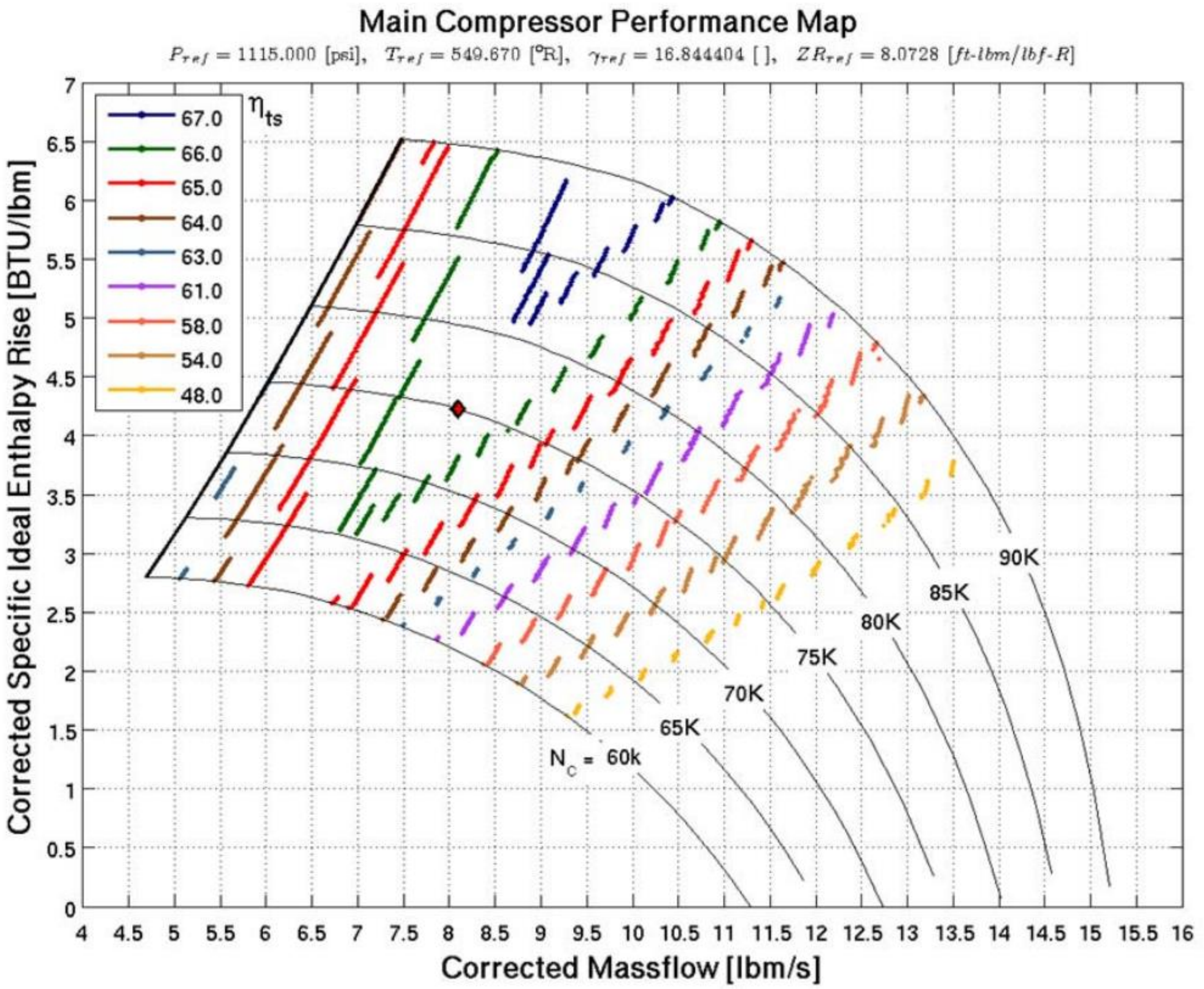


Enthalpy loss in compressor

Radial compressor	
Loss model	**Proposer**
Incidence loss	Conrad et al.
Blade loading loss	Coppage eet al.
Skin friction loss	Jansen
Clearance loss	Jansen
Disk friction loss	Daily and Nece
Mixing loss	Johnston and Dean
Recirculation loss	Oh et al.
Leakage loss	Aungier

Turbomachinery performance analysis

(2) On design vs. Off design

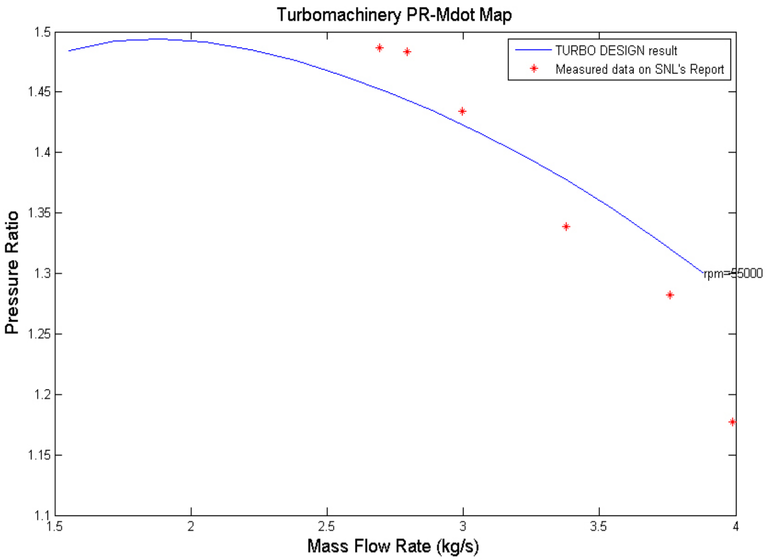


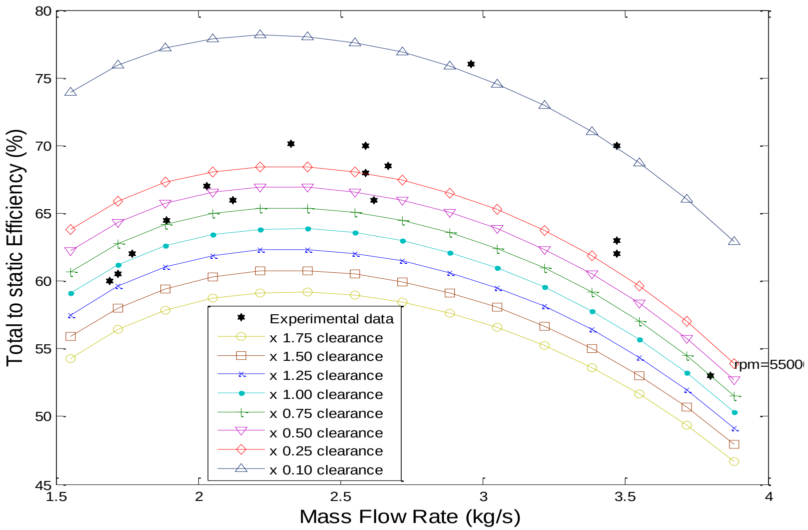
Jim Pasch, et al., Supercritical CO2 Recompression Brayton Cycle: Completed Assembly Description, SANDIA REPORT

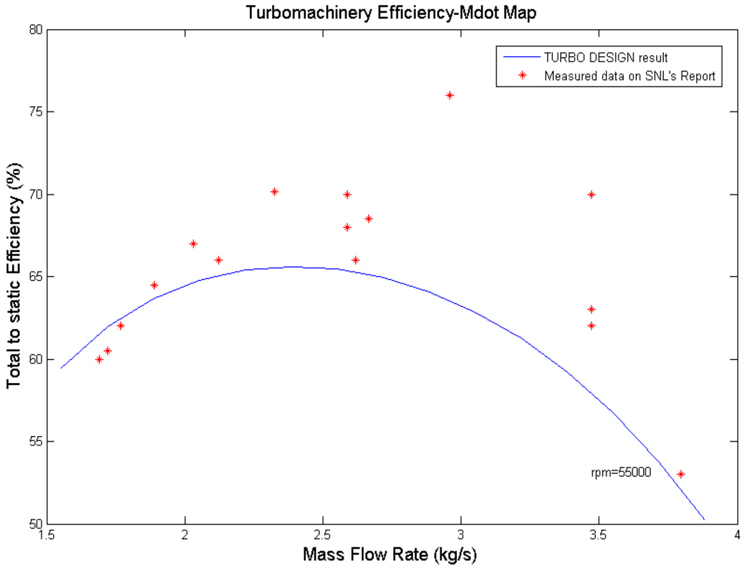
Turbomachinery performance analysis

(3) Code Validation with experiment data

- Off design performance comparison
  - Off design performance provided by KAIST_TMD compares with experiment data from SNL research team.
  - The trend is different but in reasonable agreement
  - ~ 0.05 of difference in pressure ratio prediction
  - Overall efficiency is under estimate



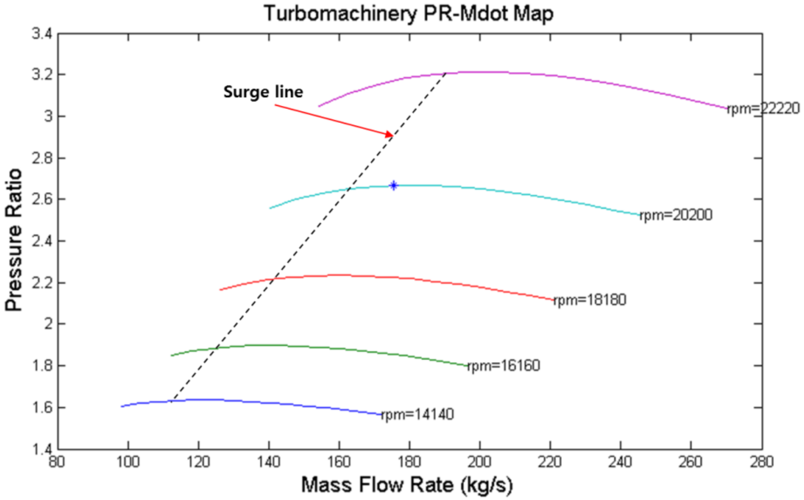


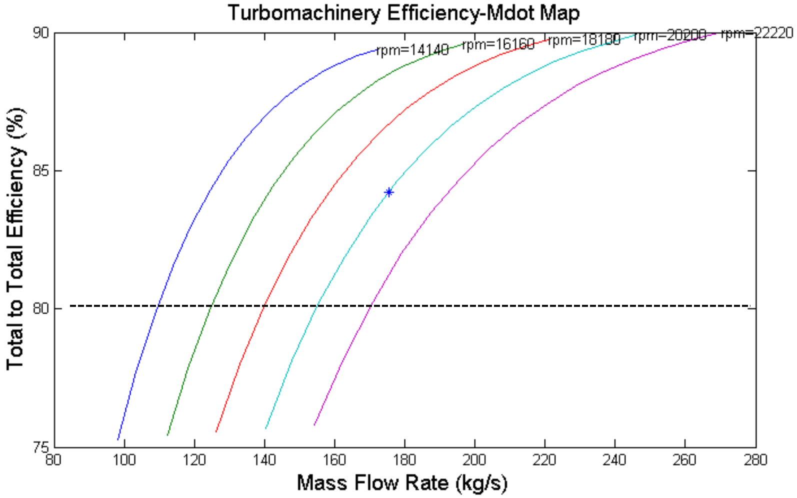


Turbomachinery performance analysis

(4) Results

- Off-design performance employs efficiency and pressure ratio curves.
- Compressor on-design performance achieved 84.2%.
- This is similar to non dimensional number analysis.





Summary & Further works

- **In previous studies, the feasibility of passive air cooling system in pre-cooler and cycle layout selection were performed.**

- **Compressor performance analysis in on design and off design conditions was conducted by KAIST_TMD.**
  - It is mean stream line analysis code
  - TMD adopts real gas approach and includes the loss models selected from open literatures..
  - Preliminary validation of TMD was carried out and the results are in reasonable agreement.

- **Compressor performance analysis in on design and off design conditions was conducted by KAIST_TMD.**
  - It is mean stream line analysis code.
  - Preliminary validation results are in reasonable agreement

- **KAIST_TMD doesn't include the diffuser loss. The proper loss model will be applied near the future.**

- **Additionally, radial turbine code and axial turbomachinery codes will be verified and modified in the future.**