TECHNICAL AND ECONOMIC FEASIBILITY OF DRY AIR COOLING FOR THE SUPERCRITICAL CO_2 BRAYTON CYCLE USING EXISTING TECHNOLOGY

Sandeep R Pidaparti, Patrick J. Hruska, Anton Moisseytsev, James J. Sienicki, Devesh Ranjan

The 5th International Symposium – Supercritical CO_2 power cycles
San Antonio, Texas
March 28-31, 2016

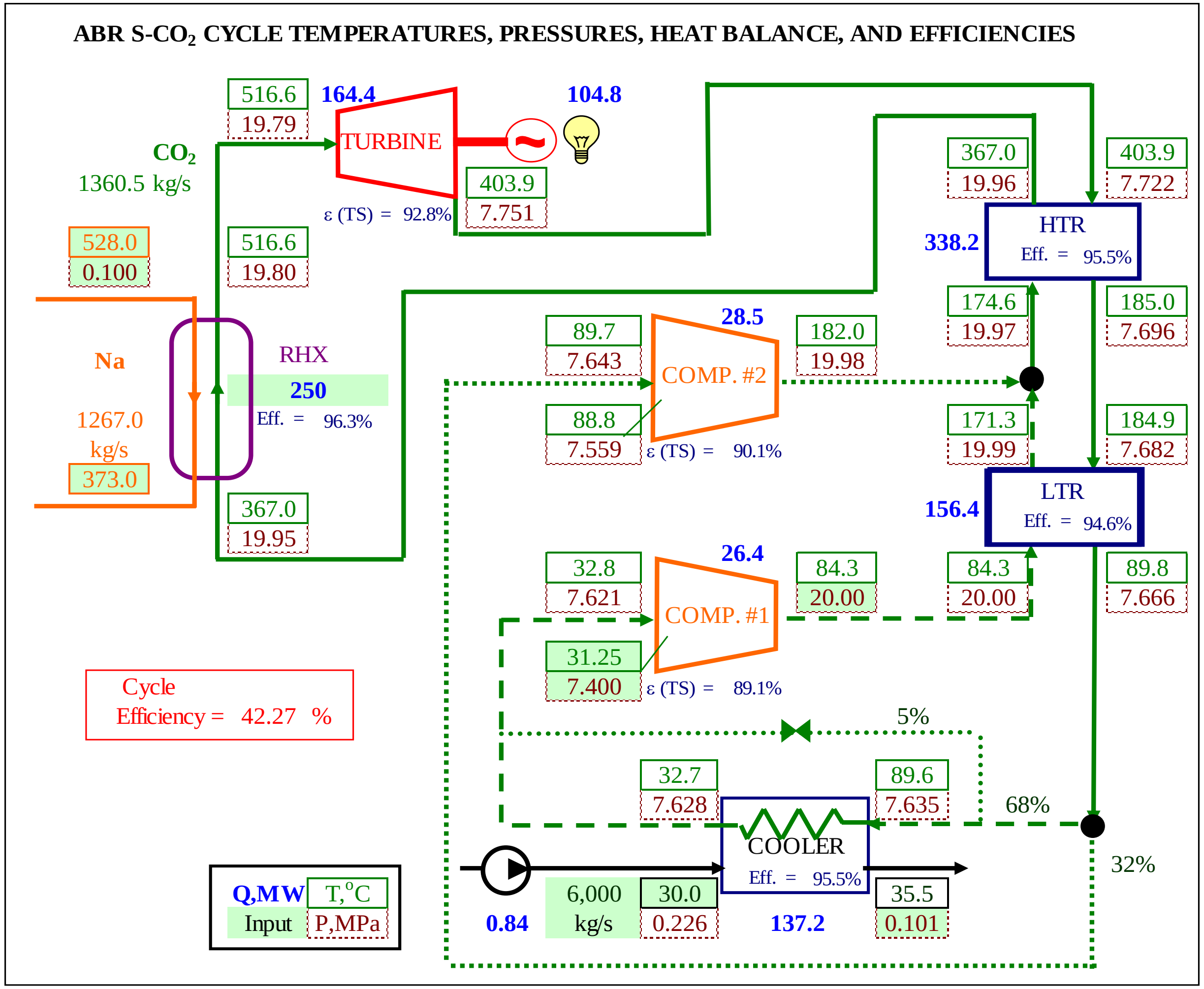
Background

- **Dry air cooling is an attractive option for the S-CO_2 Brayton cycle**
  - **Technically feasible but is it economical?**
  - **If feasible completely eliminates the need for water, increasing the range of applicability**
- **Previous investigation of Dry air cooling option[1]**
  - **Used Heatric Hybrid HX technology for Air-to-CO_2 cooler – Significant increase in plant capital cost per unit electrical output ($/kWe)**
- **Goal of the current investigation**
  - **Identify more economical Air-to-CO_2 cooler to reduce the plant capital cost**
  - **Perform cycle optimization to identify optimal cycle operating conditions using the modified Air-to-CO_2 cooler**

1) "Investigation of a Dry Air Cooling Option for an S-CO2 Cycle" by A. Moisseytsev, 4th S-CO2 Symposium, Pittsburgh, PA, September 9-10, 2014

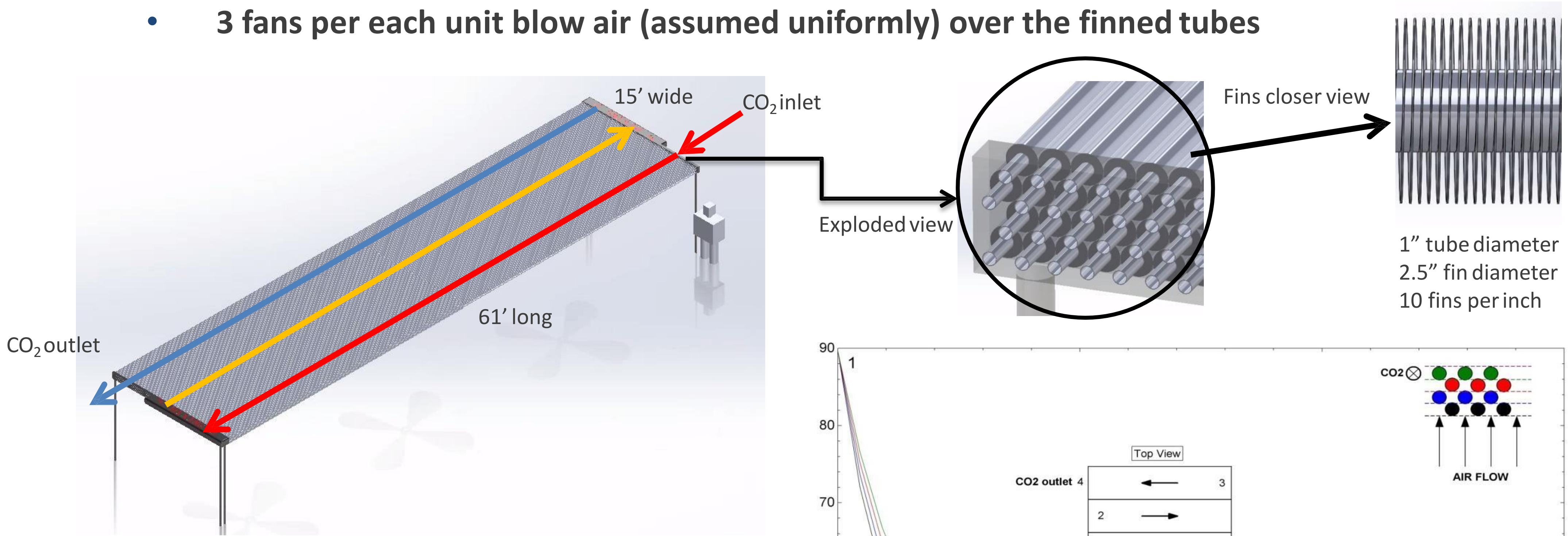
Reference conditions and Assumptions

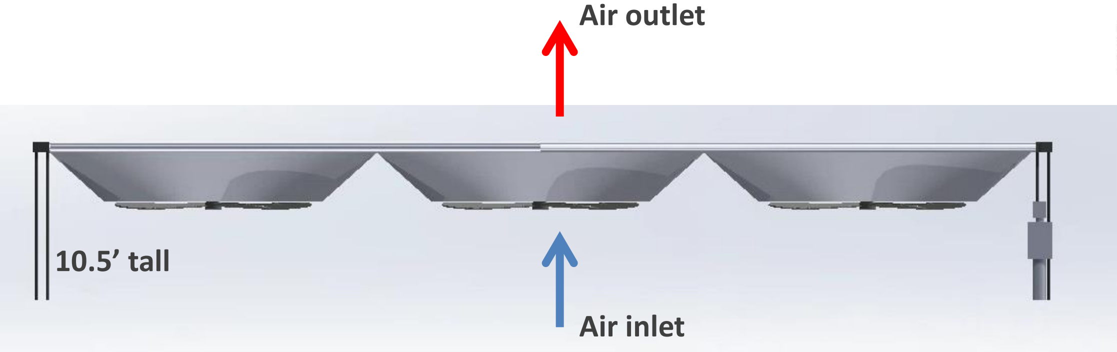
- 250 MWt (~105 MWe) S-CO_2 cycle for a Advanced Fast Reactor (AFR)
  - 42.27% cycle efficiency
- 31.25°C minimum cycle temperature
- 7.4 MPa minimum and 20 MPa maximum cycle pressures
- 30°C inlet water temperature
  - Assumed same for air
  - Atmospheric pressure

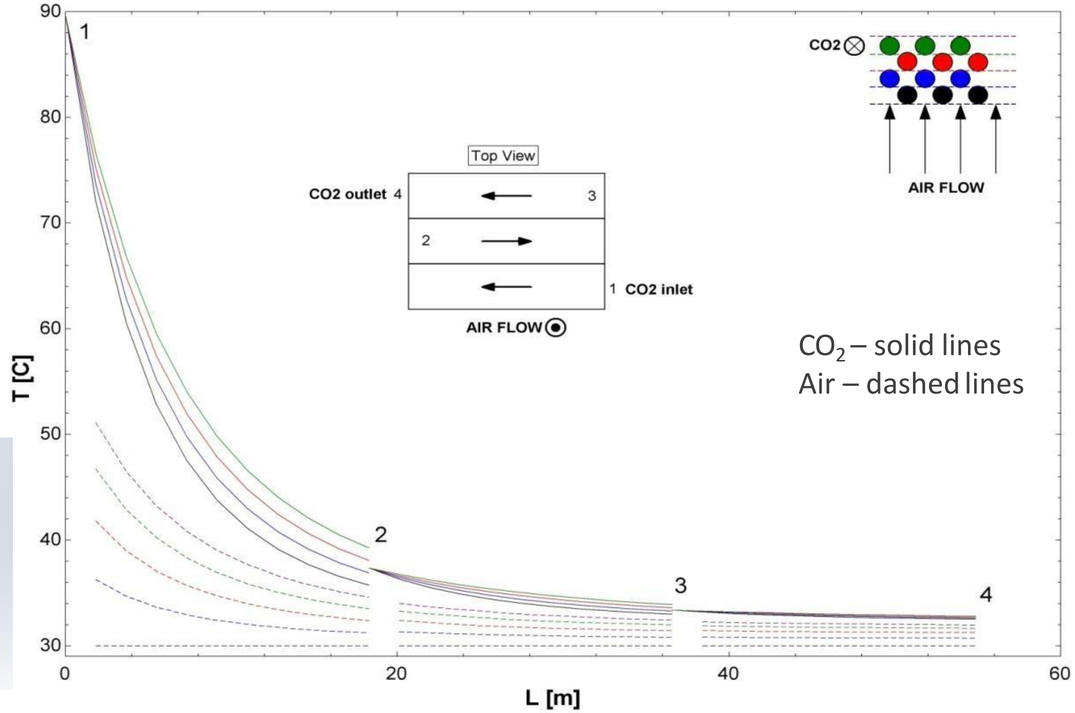


Air-to-CO_2 cooler design

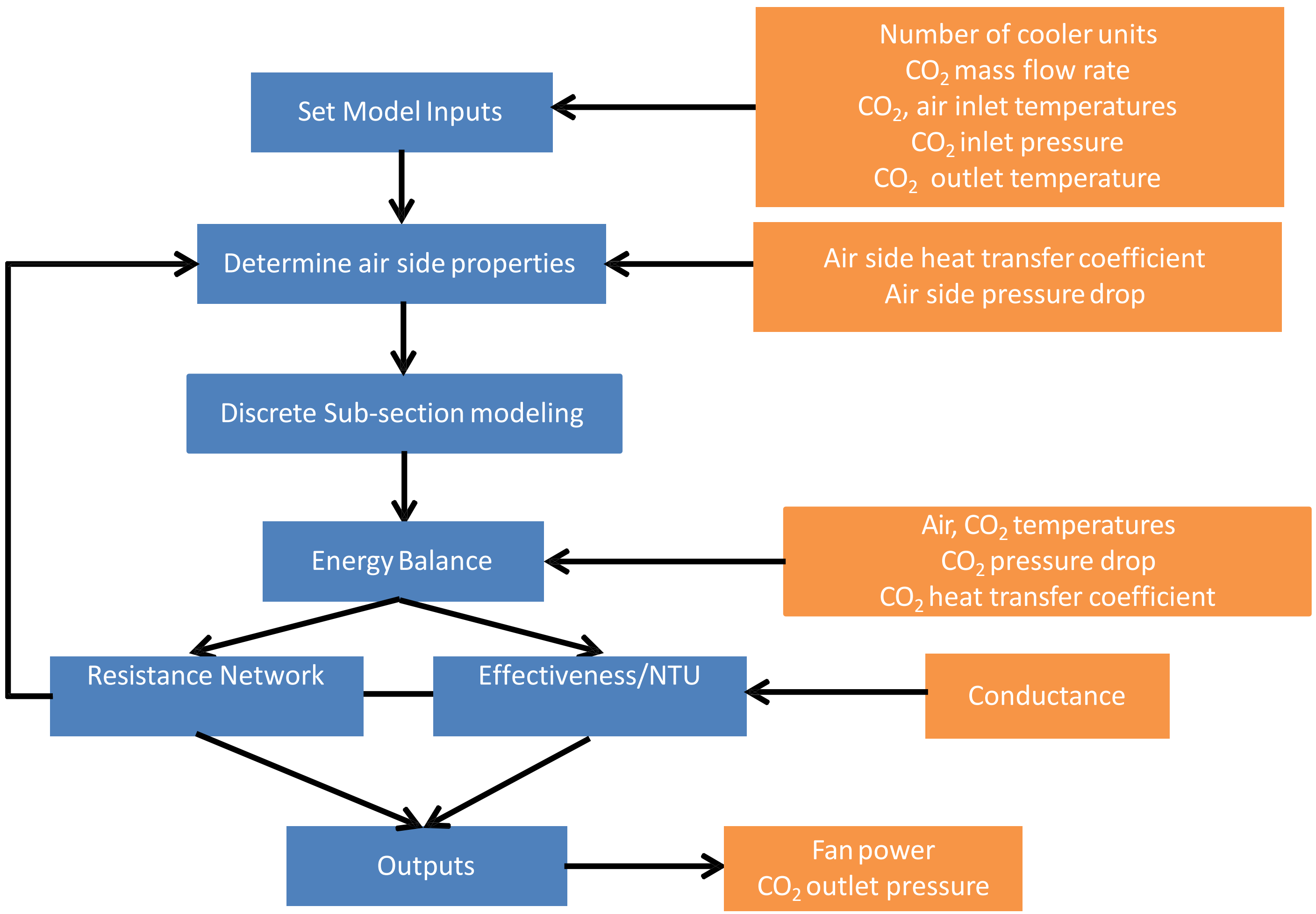
- Cross flow between CO_2 and air
  - CO_2 flowing through the SS316 tubes with external aluminum fins (3 passes)
  - 3 fans per each unit blow air (assumed uniformly) over the finned tubes







Cooler modeling



Cooler model verification

	Variable	Harsco Industrial Air-X-Changers	Calculated (EES model)	Calculated (EES model)
Inputs	Number of HEX units	86	86	86
	CO_2 flow rate per unit [Kg/s]	10.22	10.22	10.22
	CO_2 inlet temperature [°C]	89.61	89.61	89.61
	CO_2 inlet pressure (MPa)	7.736*	7.736*	7.635
	Air flow rate per unit [kg/s]	317.2	317.2	317.2
	Air inlet temperature [°C]	30	30	30
Outputs	Heat transfer capacity [MW_{th}]	1.691	1.696	1.61
	CO_2 outlet temperature [°C]	32.7	33.12	32.64
	CO_2 pressure drop [KPa]	6.895	6.645	6.802
	Air outlet temperature [°C]	52	51.2	51.11
	Air pressure drop [KPa]	Not provided	-	0.1112

*The CO_2 inlet pressure provided in the Harsco quotation didn't match the proposed design parameter.

Fans efficiency is calculated by using the estimated pressure drop from EES (built in finned tube geometry)

$$\eta_{fans}\dot{W}_{fan} = \frac{\dot{m}_{air}\Delta P_{air}}{\rho_{air}}$$

Using, $\dot{W}_{fan}$=32.95hp per fan → η_{fans}=41%

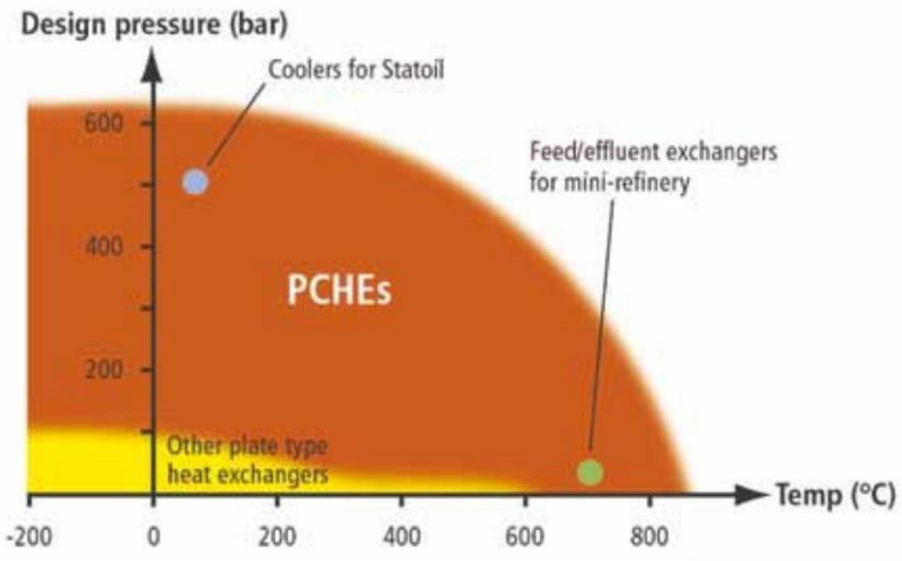
$S\text{-}CO_2$ air cooled cycle optimization

- **Parameters for optimization**
  - Cycle minimum pressure
  - Cycle minimum temperature
  - Cycle maximum pressure **(Limited by pressure containment capability of heat exchangers)**

Restricted to along the pseudo-critical line to take benefit of high fluid density (applies to cycle minimum pressure and cycle minimum temperature)

Selected conditions for optimization study

Minimum pressure (MPa)	Minimum Temperature (°C)	Maximum pressure (MPa)
7.4	31.25	18-30
7.628	32.5	18-30
8	35	18-30
8.864	40	19-30
9.688	45	20-30

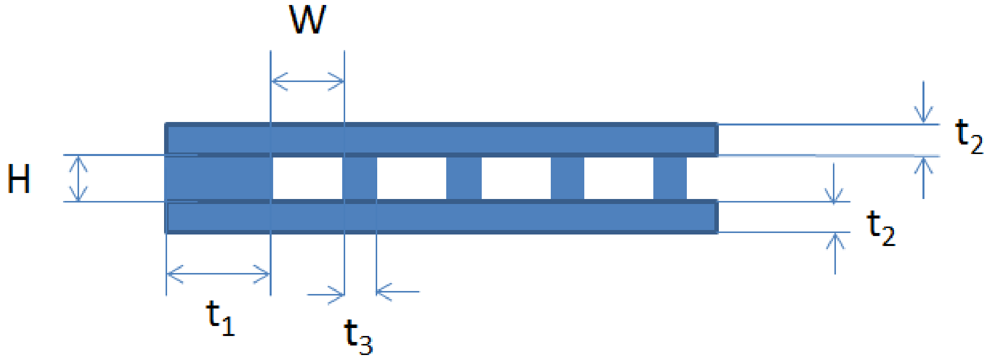


Pressure containment capabilities of Heatric PCHEs (From their website)

- **Cycle conditions demand mechanical design changes**
  - Reactor heat exchanger (RHX)
  - High temperature recuperator (HTR)
  - Low temperature recuperator (LTR)
  - Piping
  - Turbomachinery components (Not implemented in this study)

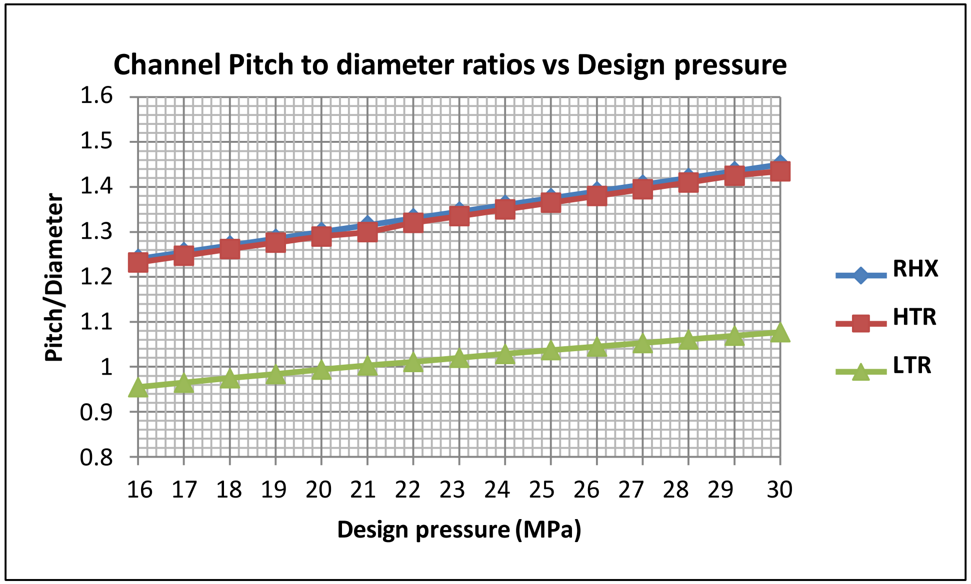
PCHE design methodology

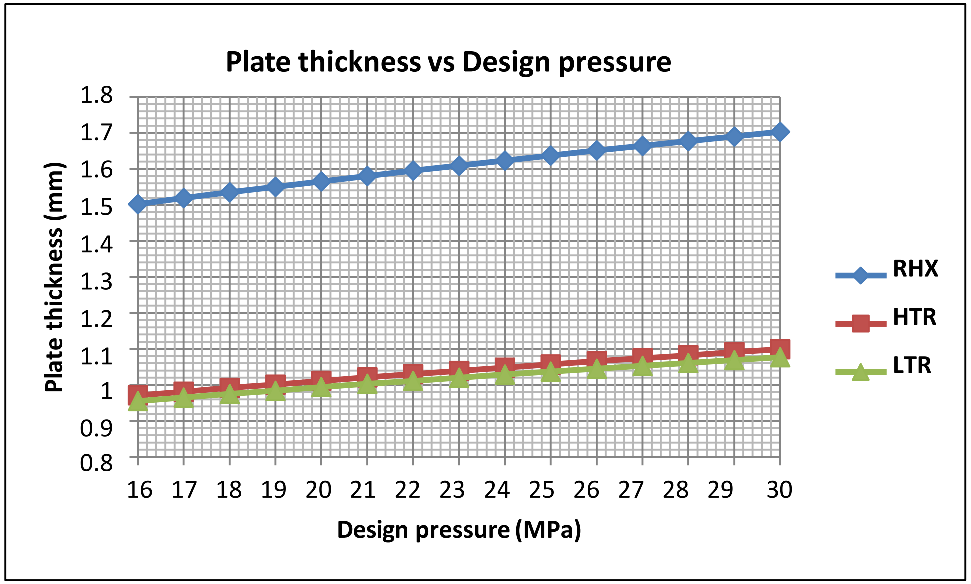
- Heatric design methodology was used to estimate the plate thickness (t_2), ridge thickness (t_3) as maximum pressure changes
- Semicircular channels are approximated as rectangular channels for design purposes
  - ASME 13-9



Parameters	RHX		HTR		LTR	
HEX type	Z/I PCHE		Platelet PCHE		Platelet PCHE	
Unit length (m)	1.5		0.6		0.6	
Unit width (m)	0.6		1.5		1.5	
Unit height (m)	0.6		0.6		0.6	
Design temperature (°C)	550		450		300	
Design pressure (MPa)	16-30		16-30		16-30	
	Hot side (Na)	Cold side (CO_2)	Hot side (CO_2)	Cold side (CO_2)	Hot side (CO_2)	Cold side (CO_2)
Channel diameter (mm)	6.0	2.0	1.3	1.3	1.3	1.3
Channel depth (mm)	4.0	1.0	0.65	0.65	0.65	0.65
Pitch to diameter ratio	1.083	Variable	Variable	Variable	Variable	Variable
Plate thickness (mm)	Variable	Variable	Variable	Variable	Variable	Variable

PCHE design methodology





- **Estimation of heat exchangers cost**

$$Unit\ cost = Unit\ volume.\rho_{ss316}.Material\ cost + Fabrication\ cost$$

$$HEX\ cost = Unit\ cost.Number\ of\ units$$

Material cost – 7.64 \$/kg
ρ_{ss316} – 8,000 kg/m^3
Unit volume – 0.54 m^3

Piping design methodology

- **Minimum wall thickness is estimated using ASME B31.1 design procedure**

$$Min\ thickness = \frac{0.5P_{design}.ID}{(P_{design}.Y+S_{allowable}.W).(1-UTP-CA)-P_{design}}$$

$$Nominal\ thickness = Min\ thickness.(1-UTP-CA)$$

$S_{allowable}$ - Allowable stress for SS316 (Table 1A of ASME B&PV code section II, Part D)

Y – Coefficient from ASME B31.1 Table 104.1.2(A)

W – 0.975 (Weld joint strength reduction factor)

UTP – Under tolerance allowance (12.5%)

CA – Corrosion allowance (12.5%)

- **As per the recent 3-D plant layout, there are 25 pipe sections connecting different components**
  - Lengths
  - Inner diameters
  - Design pressure
  - Design temperature

- **Estimation of piping cost**

$$OD = ID + 2.Min\ thickness$$
$$Material\ volume = \frac{\pi}{4}.(OD^2 - ID^2).L$$
$$Material\ cost = Unit\ volume.\rho_{ss316}.Material\ volume$$

Fabrication cost is neglected assuming that it is small compared to the material cost

Cost based optimization

- Plant capital cost based optimization technique is employed
- Plant capital cost per unit net electrical output is calculated as,

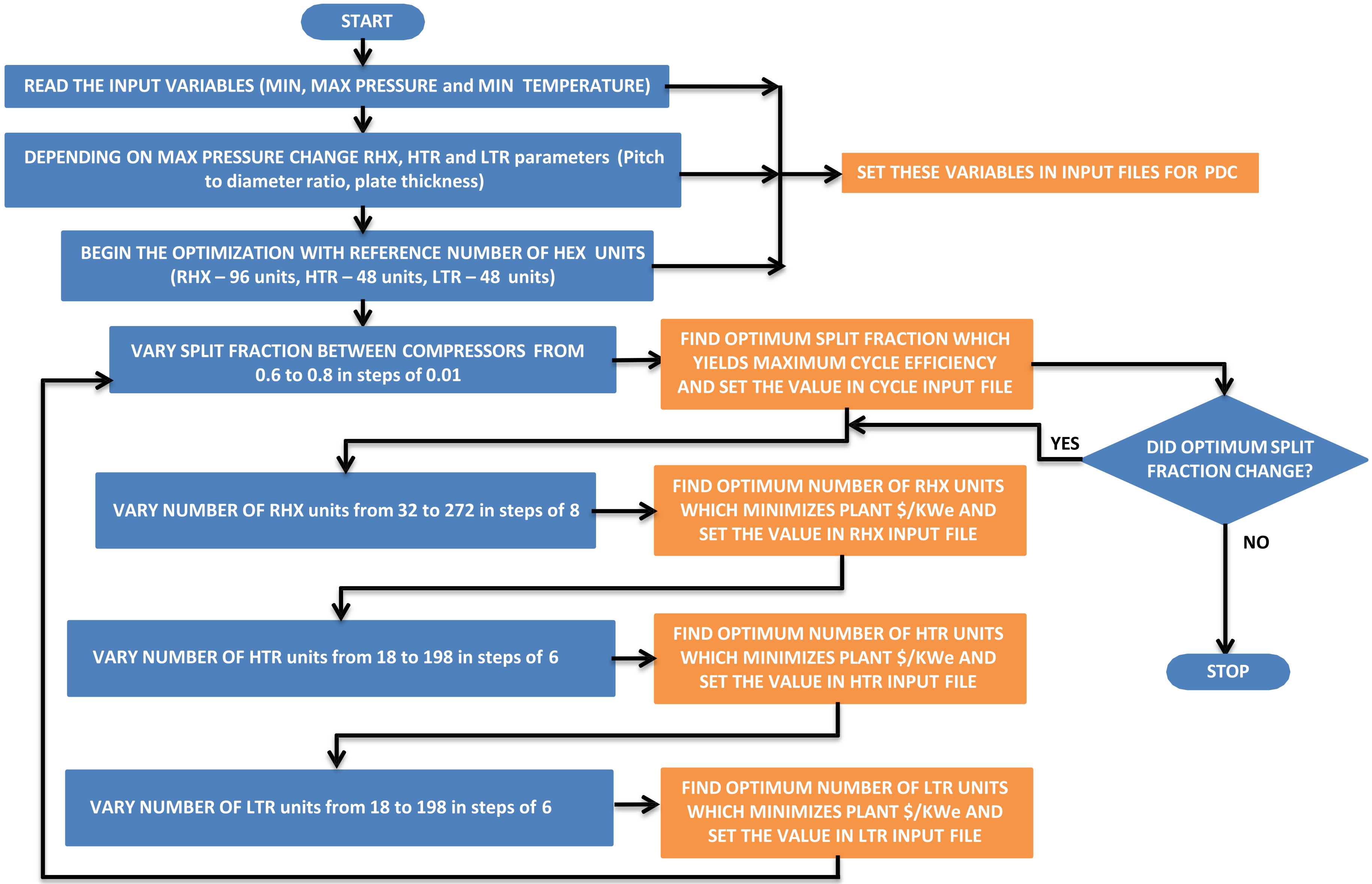
$$\frac{\$}{KW_e} = \frac{Rest of plant capital cost + RHX\ cost + HTR\ cost + LTR\ cost + Cooler\ cost + Piping\ cost}{P_{elec} - P_{fan}}$$

- Rest of plant capital cost is calculated for the reference conditions
  - Minimum pressure – 7.4MPa
  - Minimum temperature – 31.25^{o}C
  - Maximum pressure – 20MPa
  - Water cooling
  - 4480.432 $/KWe is the reference value calculated
  - 104.6 MWe is the reference grid power calculated

  } Rest of plant capital cost

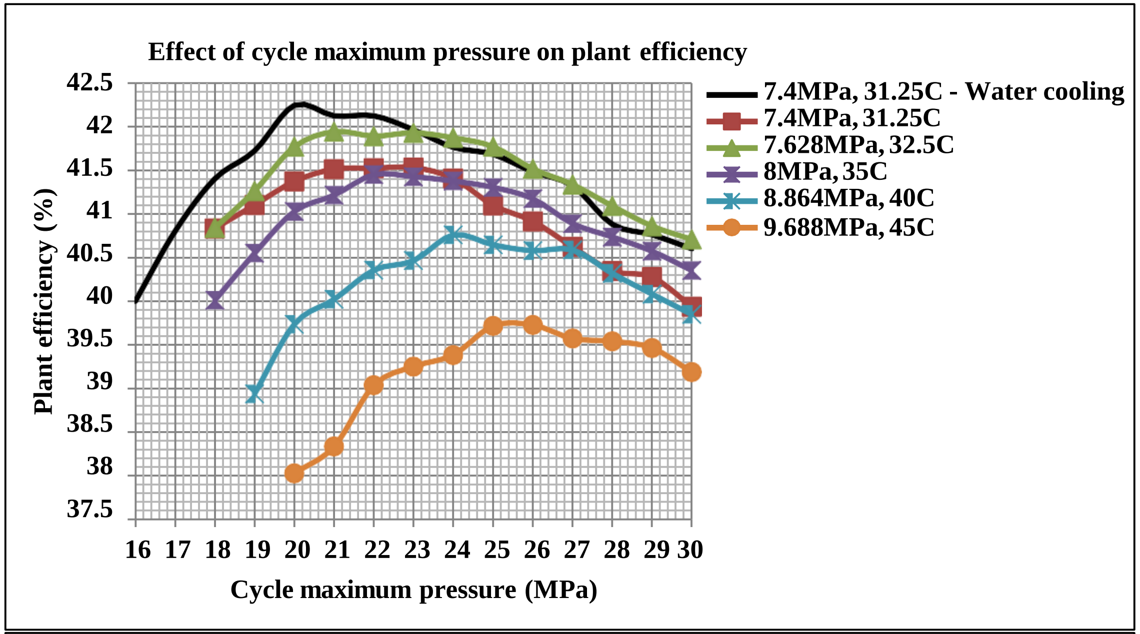
- A code was developed in Matlab to perform the optimization

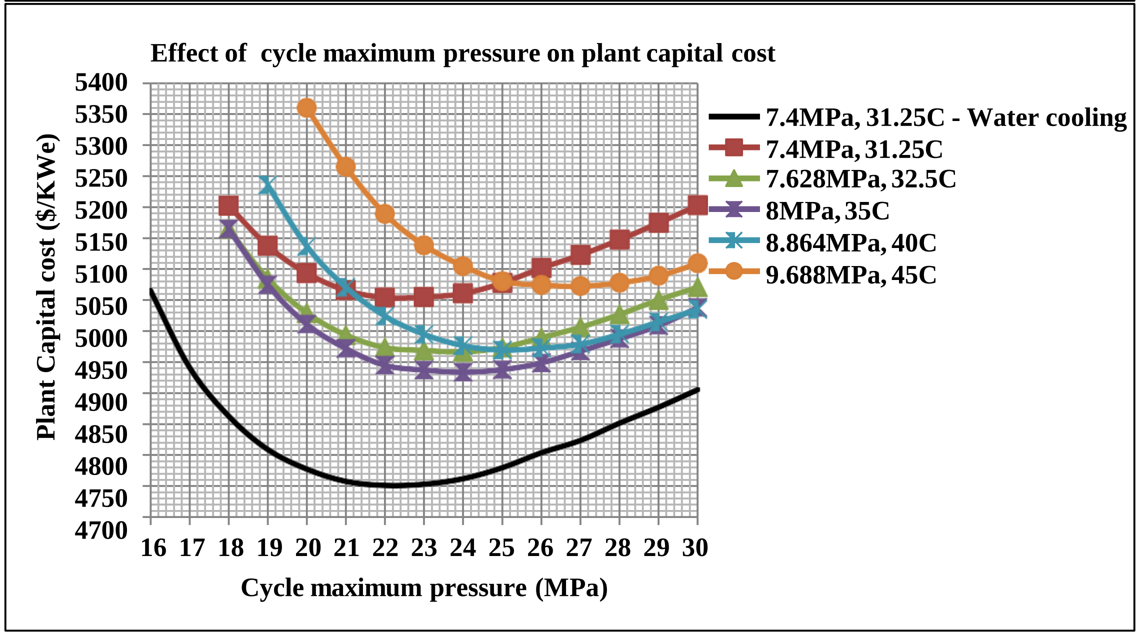
Optimization code flow chart



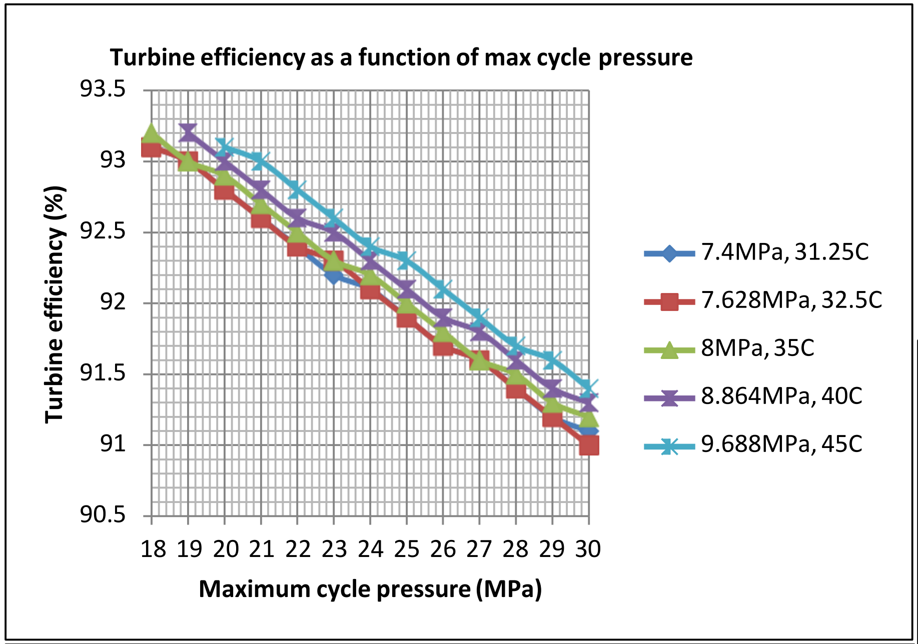
Results - Fixed turbomachinery design

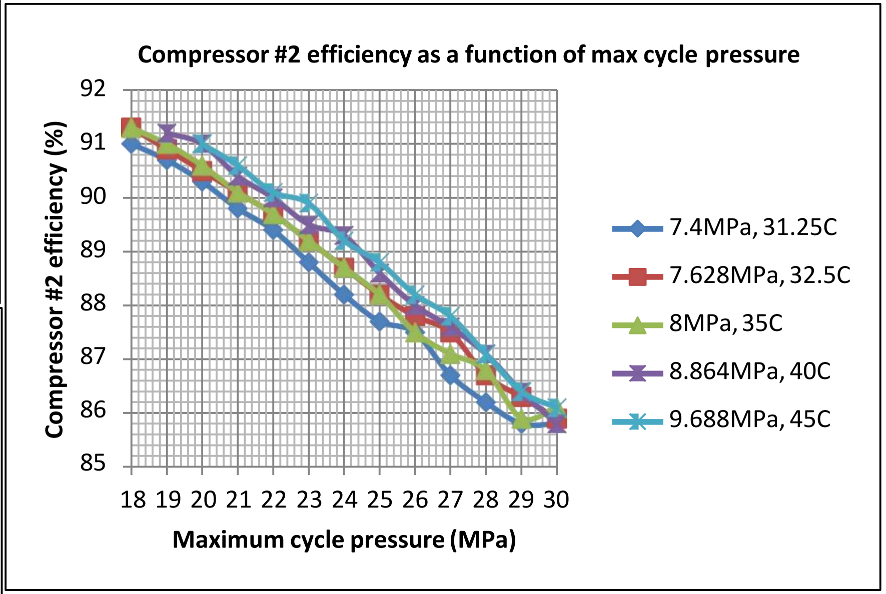
- Optimum conditions are
  - Minimum pressure – 8MPa
  - Minimum temperature – 35°C
  - Maximum pressure – 24 MPa
- The cycle efficiency decreases after a certain maximum pressure due to drop in turbine and compressors efficiency
- It is required to change design of turbomachinery equipment to maintain constant efficiencies
- These values might change if the efficiencies of compressors and turbine are maintained constant

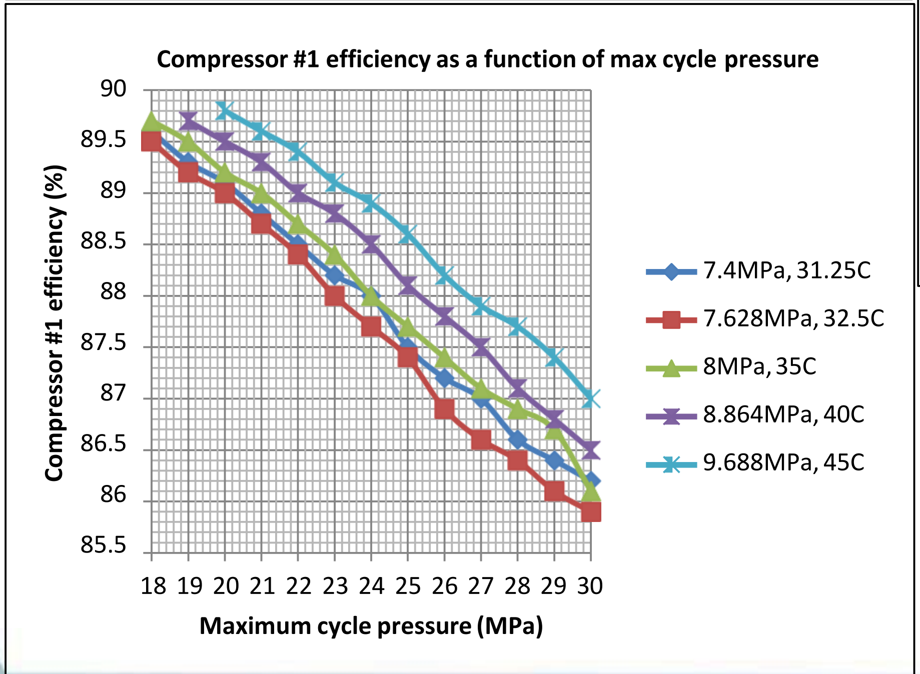




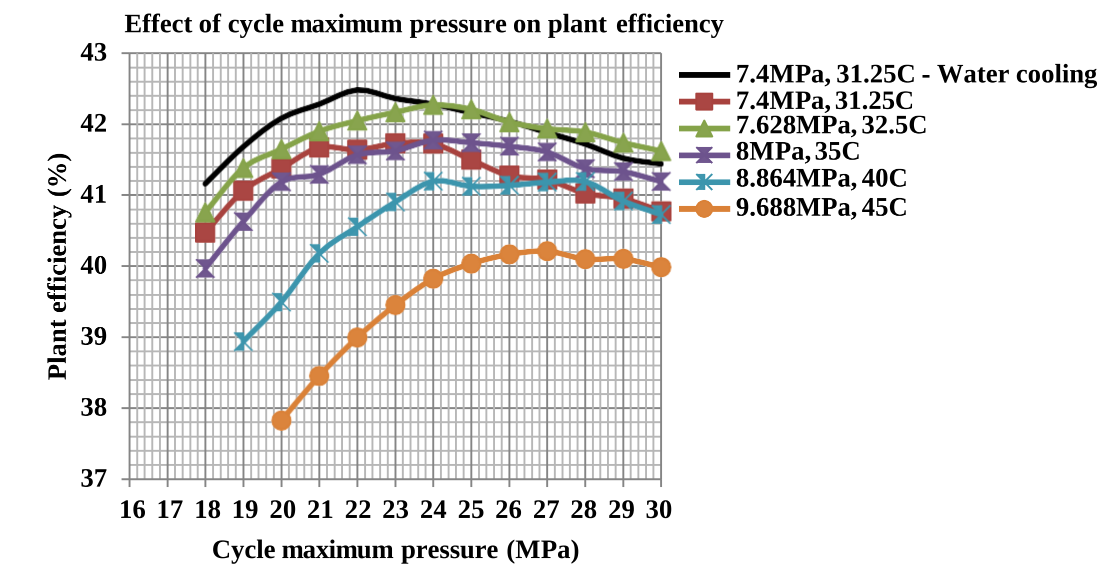
Results - Fixed turbomachinery design

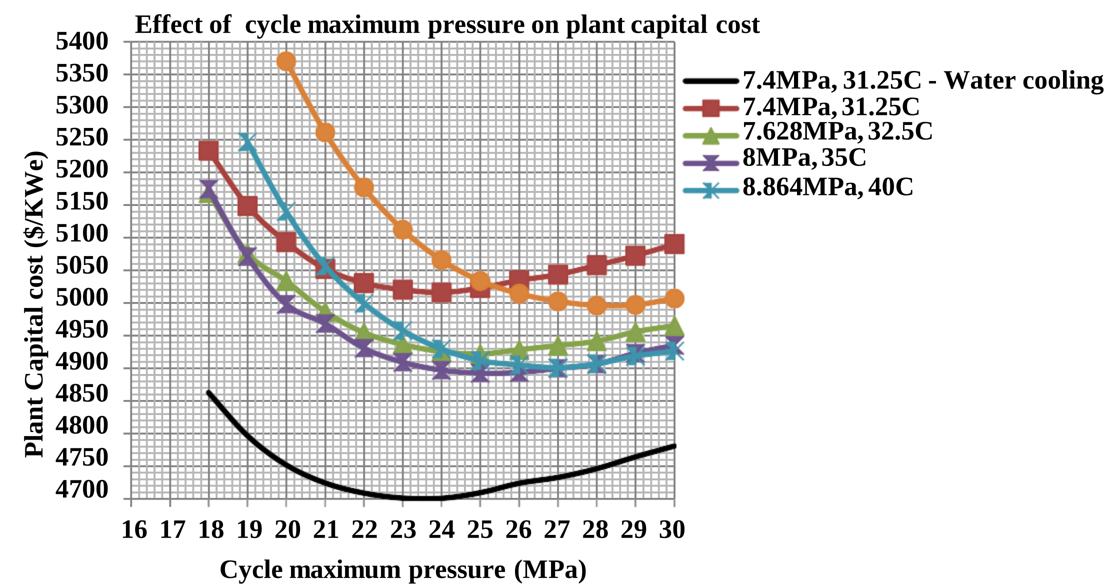






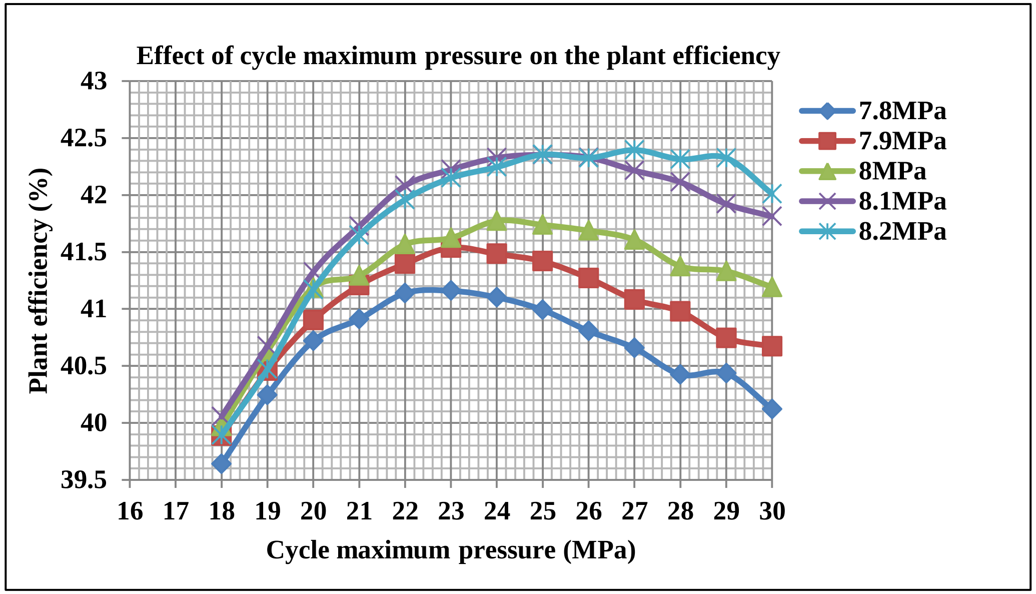
Results - Fixed turbine efficiency

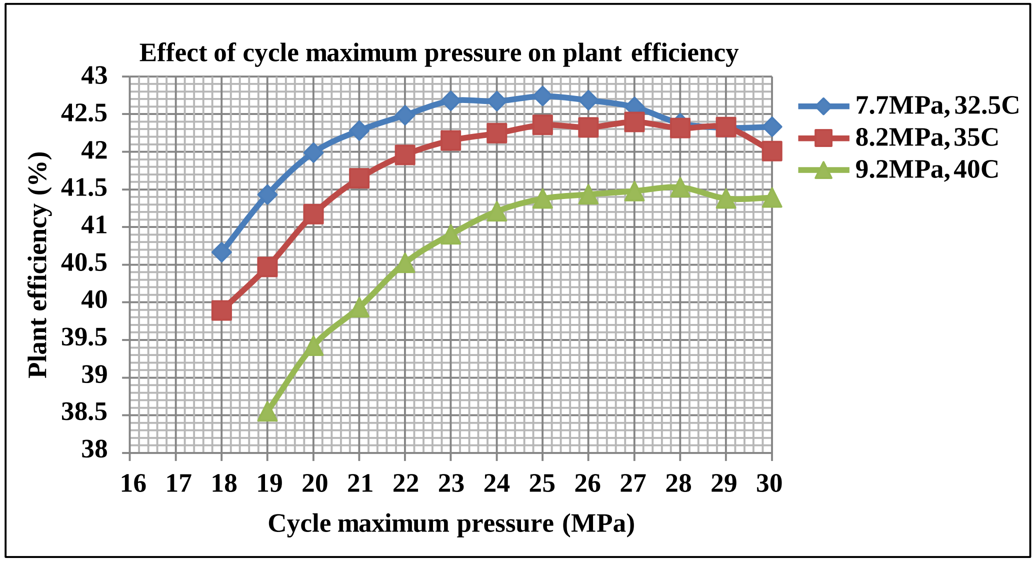


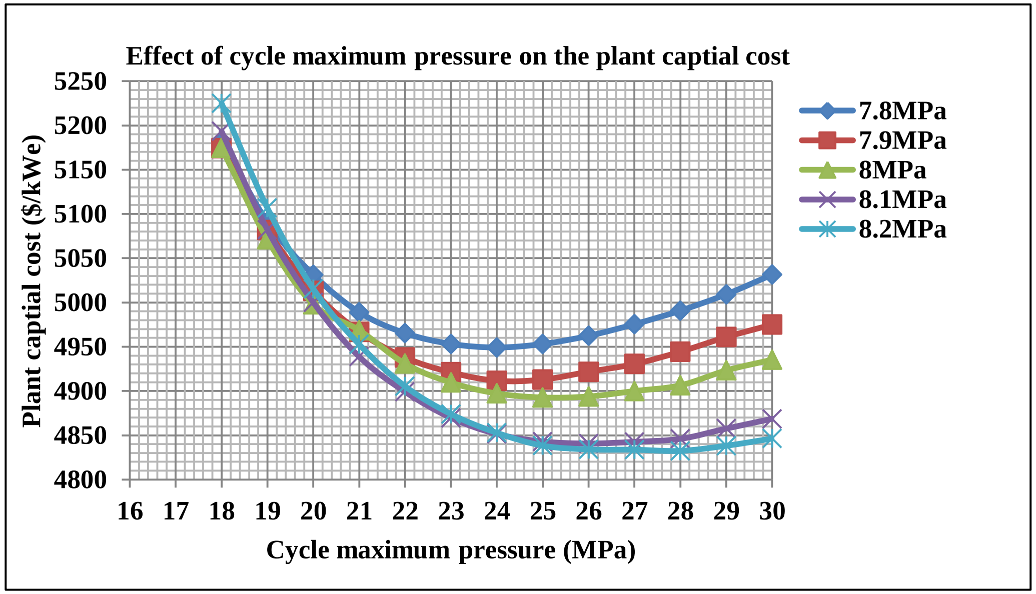


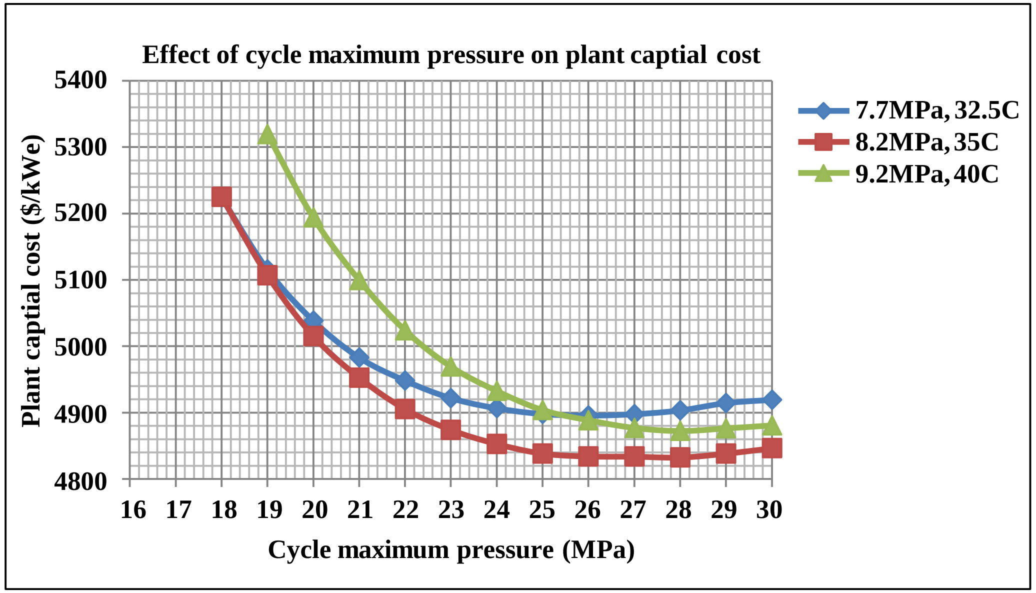
- Optimum conditions didn't significantly change compared to previous case
  - Minimum pressure – 8MPa
  - Minimum temperature – 35°C
  - Maximum pressure – 25 MPa
- $/kWe of air cooled plant is still about 5% higher compared to water cooled plant

Effect of cycle minimum pressure

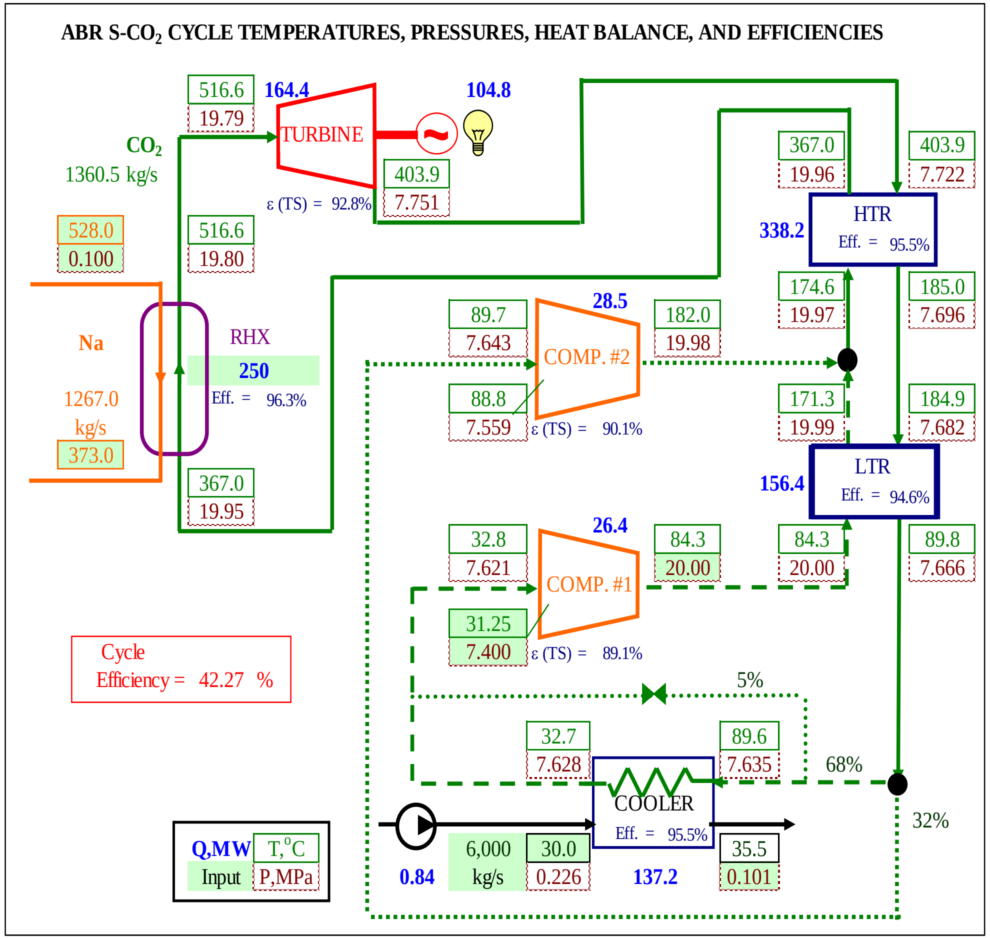


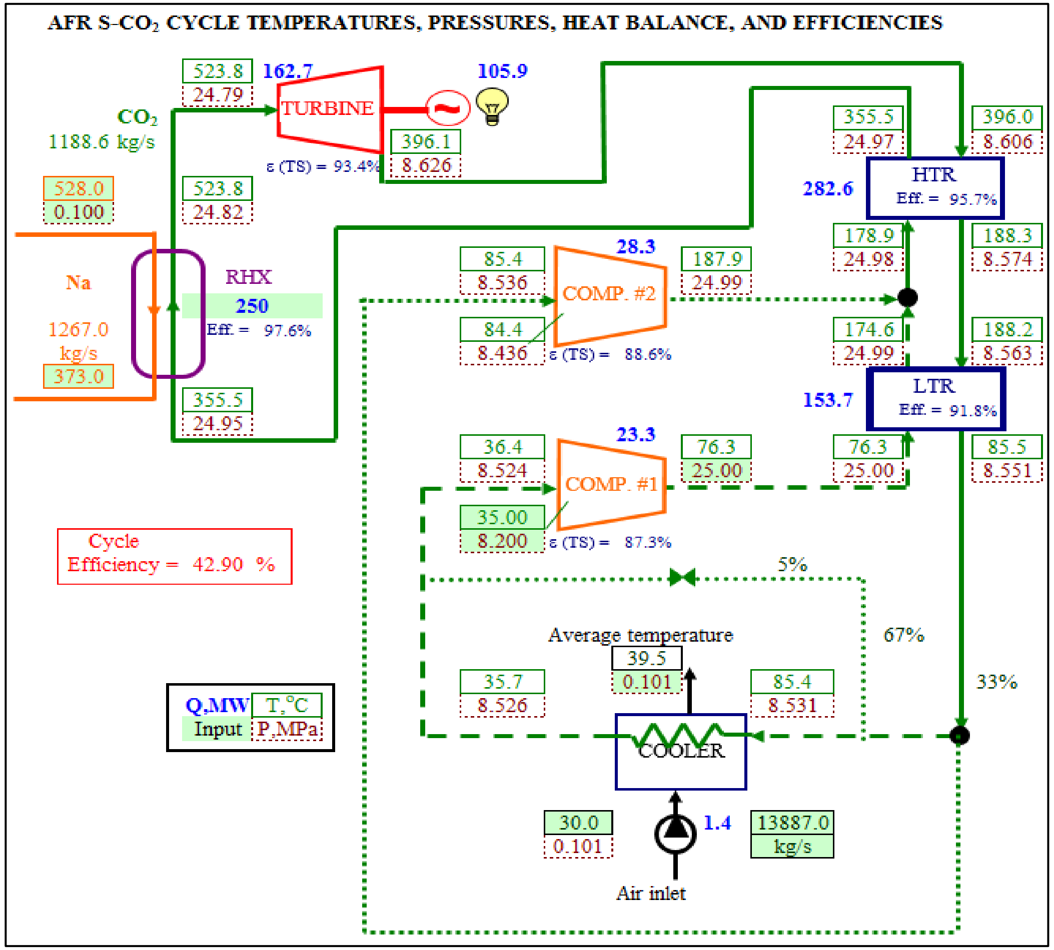






Water vs Air cooled optimal conditions





About 1-2% increase in the plant $/kWe compared to the water cooled cycle

Summary and Conclusions

- More economical Air-to-CO_2 cooler was identified and commercially available
- The cooler was modeled and the calculations were verified with the vendor specifications
- Using this cooler design, air cooled cycle optimization was performed in reference to the water cooled cycle
- New optimal conditions were calculated which results in only about 1-2% increase in the plant $/kWe compared to water cooled cycle
- Shows that dry air cooling is both technically and economically feasible

Thank you for your time!

Questions?

Piping design methodology

Section	Pipe ID (m)	Pipe length (m)
1	0.68302	29
2	0.68302	2
3	0.68302	12
4	0.68302	30
5	0.5	9.25
6	0.5	5.5
7	0.5	13
8	0.5	9.25
9	0.5	5
10	0.5	55
11	0.5	21
12	0.5	5
13	0.5	10
14	0.5	10
15	0.68302	10
16	0.68302	15
17	0.68302	2
18	0.5	12
19	0.45	38
20	0.25	17
21	0.25	21
22	0.25	11
23	0.25	11
24	0.25	12
25	0.25	25