MAE 570 APPLIED THERMODYNAMICS

PROJECT-3

A Combined Power & Cooling Cycle Driven by a Diesel engine's exhaust – Waste Heat Recovery cycle

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Motivation:

Energy is an important entity for the basic functioning and economic development of any country in the world. The rapid growth of the industrial sector has presented us with a situation wherein one needs to reduce the degradation of the environment and increase the production rate at the same time. Recycling is one of such practices which utilizes the components obtained from one process to make useful work of them when put in use in another process. However, building a practical bridge between these processes poses us an uneasy question. A major pollutant released into the earth's atmosphere is Carbon di Oxide, and in the model adopted, a study is made to recycle the CO2 emissions from diesel engines and use them to power a combined cycle to generate power and provide cooling to industrial buildings.

Abstract:

A Diesel Engine consumes over more than half of the overall fuel consumption currently, in the world. Also, it is difficult for the maximum efficiency of the diesel engine in generators to be higher than 41%; and as a result, a large amount of fuel energy gets rejected from the engine to the surroundings as waste heat in several forms, with a significant fraction through the exhaust. In this model, the exhaust CO2 is used to drive a system of an Organic Rankine Cycle combined with a Compression Refrigeration Cycle to generate cooling as a result. In this combined cycle, the Original Rankine Cycle translates the exhaust heat into power and drive the compressor of the Compression Refrigeration Cycle. One major advantage of the combined cycle is that both the ORC and CRC use the same working fluid i.e., Carbon dioxide CO2. Driving the combined cycle with the expense of using carbon dioxide from an engine's exhaust brings about a net reduction in the presence of CO2 in the atmosphere, reduce the effect of greenhouse gases in the air, all the while making the process natural, cost effective and environment friendly. Also, CO2 is nontoxic and has good heat transfer properties. The cycle parameters, including the coefficient of performance (COP) of the combined cycle and the cooling capacity (Qro) are calculated and found to yield positive cooling results, with appreciable coefficient of performance.

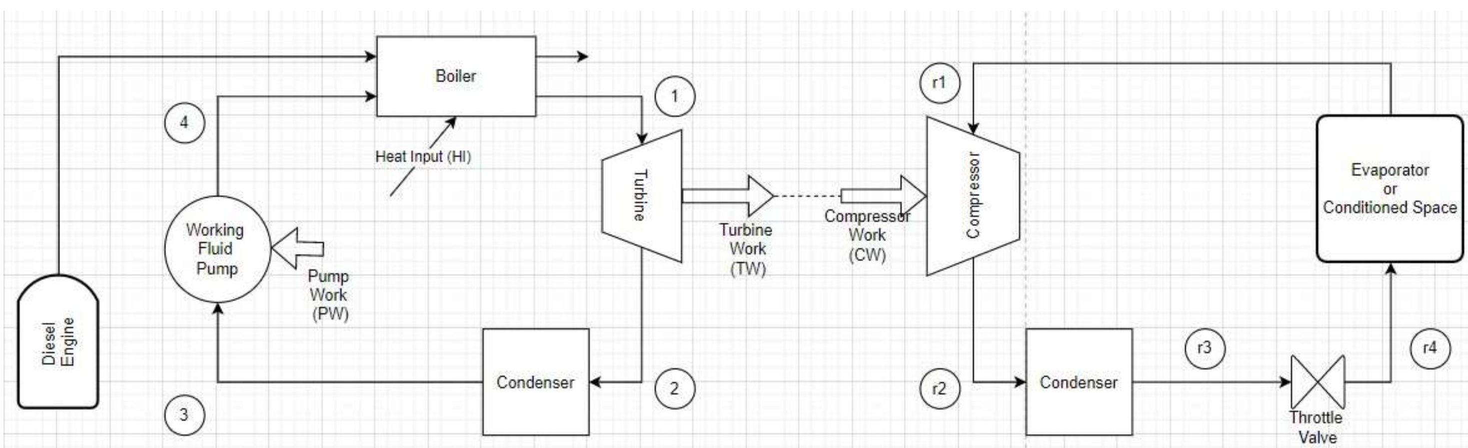
Theory:

The following are considered as a basic diesel engine generator's system description:

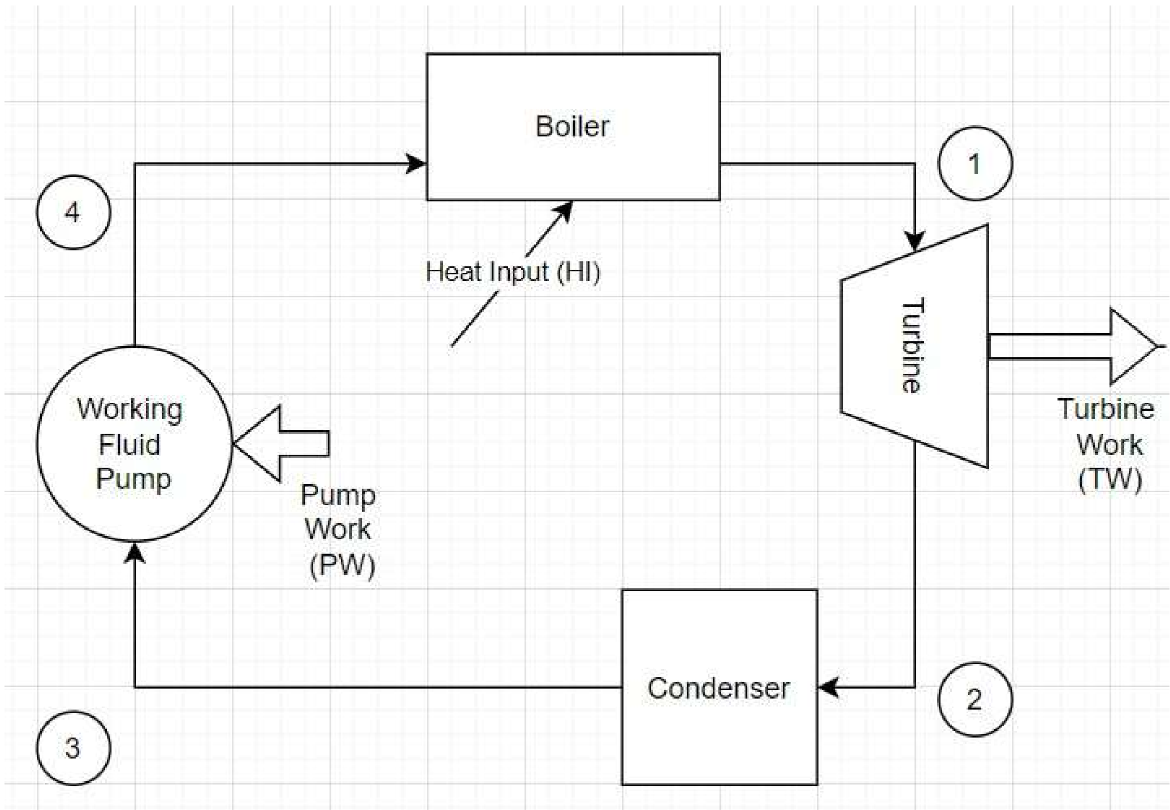
Parameter	Value
Exhaust Temperature	519 degree celsius
Exhaust Mass flow rate	990.8 kg/hour

The considered engine is an inline 6-cylinder 4 stroke supercharged diesel oil fired engine; a general diesel engine used for a generator. As the aim of this study analysis is to obtain the parameters optimization for the combined cycles use in exhaust heat recovery of diesel engine, we assume the engine to operate at rated conditions. The composition of the exhaust gases on the basis of mass has been calculated as: CO_2=15.10%, H_2O=5.37%, N_2=73.04%, O_2=6.49%. This composition is used to evaluate the gas properties.

Schematic Diagram:

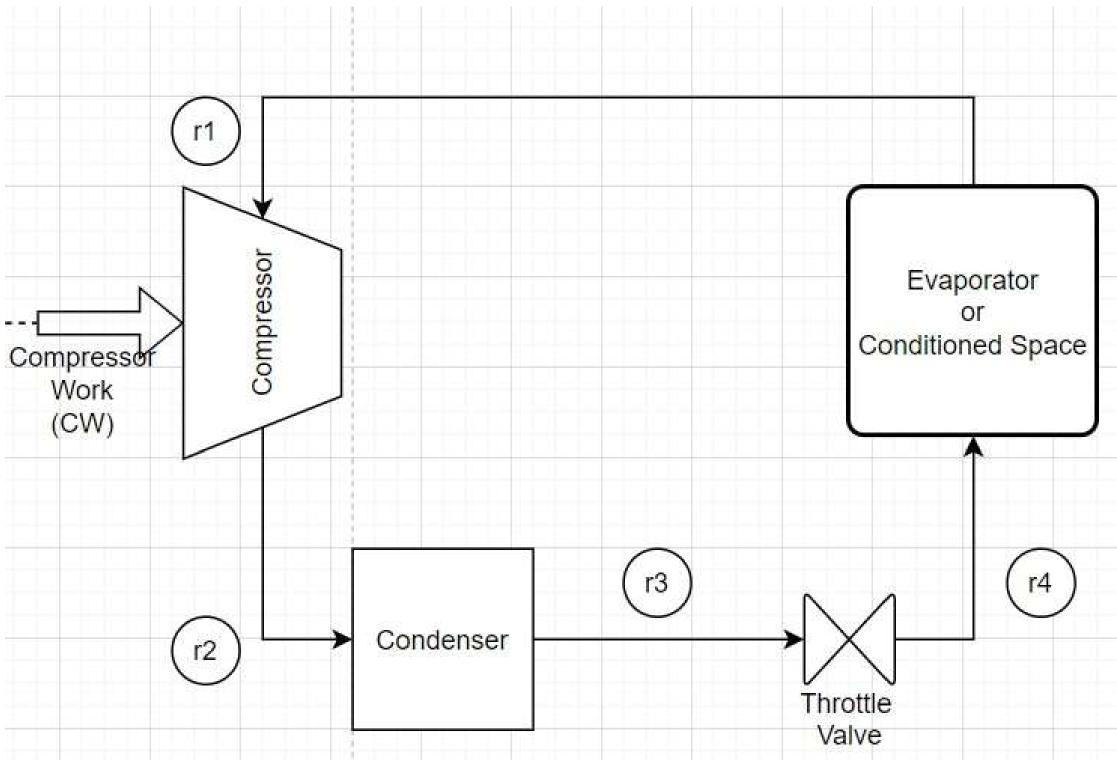


Working of the Combined Cycle:



The Organic Rankine Cycle is a supercritical expansion ORC using carbon dioxide as working fluid, consists of a turbine, a condenser, a working fluid pump, and a gas heater or a boiler. Hot exhaust from Diesel Engine rejects heat in the gas heater, and then discharges to the atmosphere. The working process of ORC can be described as follows. The generated high pressure supercritical carbon dioxide fluid in the gas heater flows into the turbine and its enthalpy is converted into work (process 1-2), which then drives the compressor of CRC. The low-pressure vapor exited from the turbine flows into the condenser where it is liquefied and condensed into saturated liquid (process 2-3). The saturated liquid available at the condenser outlet is pumped into high pressure liquid by working fluid pump (3-4), and then flows into the gas heater where it is heated into supercritical fluid by the exhaust (4-1).

Working of a Compression Refrigeration Cycle:



The Compression Refrigeration Cycle is a trans-critical compression refrigeration system using carbon dioxide as working fluid, consists of a compressor, a gas cooler or condenser, a throttle valve, and an evaporator. The working process of CRC can be described as follows: The compressor driven by the ORC, compresses the saturated carbon dioxide vapor into a supercritical fluid (process r1-r2). The supercritical fluid flows into gas cooler to rejects heat to cooling water from ambient sink (r2-r3), and then flows into the throttle valve (process r3-r4 with dotted line). The fluid output from throttle valve is a two-phase fluid and flows into the evaporator to absorb the heat from the air-conditioned space (r4-rl). Finally, the fluid from evaporator becomes the saturated carbon dioxide vapor and flows into compressor.

Calculations:

Turbine Work:

TW = M_ORC*(H_1 – H_2)

Turbine Efficiency:

$$\eta_t = (h_1 - h_2)/(h_1 - h_{2s})$$

Working Fluid Pump Work:

PW = M_ORC*(H_4 – H_3)

Pump Efficiency:

$$\eta_p = (h_{4s} - h_3)/(h_4 - h_3)$$

Heat Input to Boiler:

HI = M_ORC * (H_1 - H_4)

Energy at Condenser:

Q_c = M_ORC*(H_2 – H_3)

Compressor Work:

CW = (0.9) * TW transmission efficiency of 0.9

Compressor Efficiency:

$$\eta_{com} = (h_{r2s} - h_{r1})/(h_{r2} - h_{r1})$$

At Throttle valve:

H_R3 = H_R4

At CRC condenser:

Q_{rc} = M_REF*(H_R2 – H_R3)

At the evaporator or cooling space:

NetRef = M_REF*(H_R1- H_R4)

where, TW means the output power of the turbine (J/s); PW means the input power of working fluid pump (J/s); M_ORC means the mass flow rate of working fluid in ORC (kg/s); M_REF means the mass flow rate of working fluid in CRC (kg/s); H means the specific enthalpy (J/kg); η_t means the isentropic efficiency of turbine; η_p means the isentropic efficiency of refrigerant pump; η_{com} means the isentropic efficiency of compressor; Q means the heat capacity in heat exchanger (kW).

Therefore, the coefficient of performance of the combined cycle is obtained by:

COP_{cycle} = (NetRef)/(Heat Input to Boiler)

Organic Fluid Selection:

Carbon dioxide is chosen for the compression refrigeration cycle for its following unique properties, which are advantageous as a refrigerant:

(1) It is cheap and easily available.

In the environment, there is a large quantity of CO2, about 0.03% of the atmosphere and lots of by-products of several industries.

(2) Environmentally friendly.

CO2 has zero ODP, which means no effect on ozone destruction. CO2 is a greenhouse gas with GWP equal to 1. However, it can be obtained by recycling the waste gas of industrial emission, from the life cycle of GWP, using CO2 as a refrigerant is favourable to greenhouse effect.

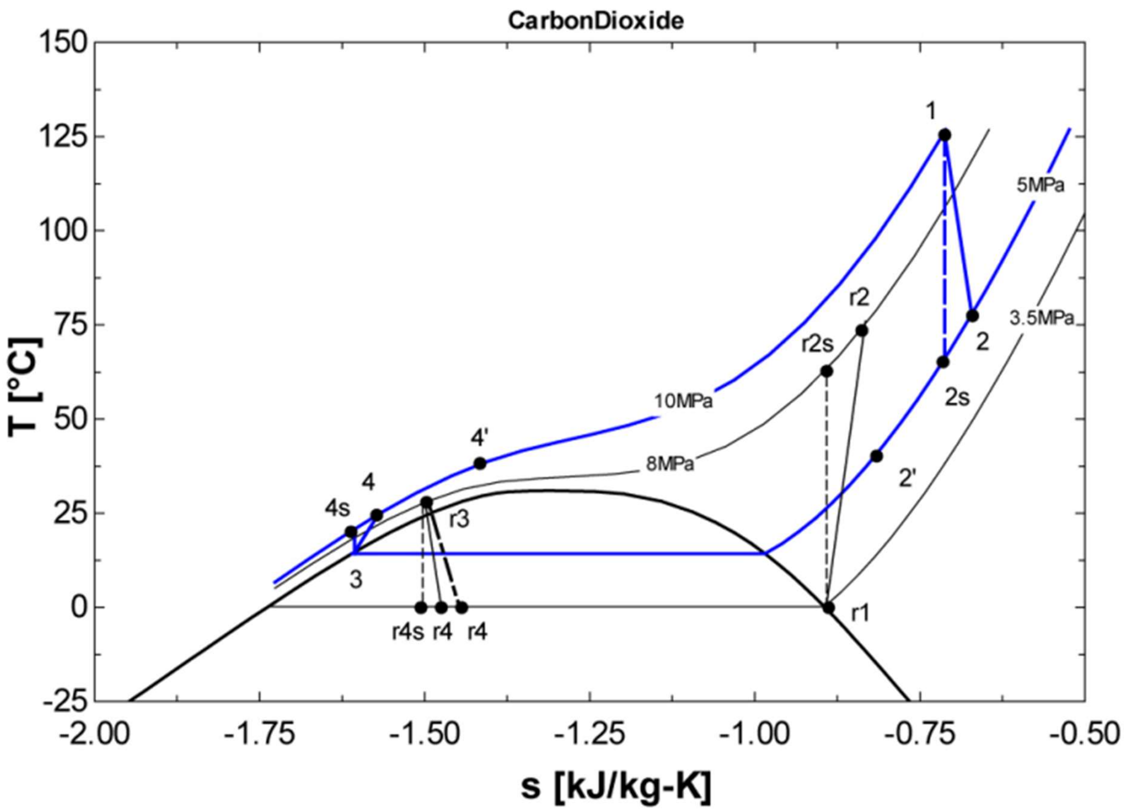
(3) Safe and inertial.

CO2 is non-toxic, non-flammable, non- explosive and non-excitant. Meanwhile, it has fairly good compatibility with common materials, such as metal, plastic and rubber.

(4) Good thermodynamic properties.

Because of its biggish refrigeration capacity, smaller compressor and fewer refrigerants can meet the needs (at 0°C, refrigeration capacity is 1.58 times of NH3, 5.12 times of R22, 8.25 times of R12). To the CO2 compressor, adiabatic index is higher (K=1.30) and compression ratio is (2.5-3.0) lower than other refrigeration system. Volume efficiency is relatively large and close to the best level.

T-s diagram of Carbon dioxide used for calculations:

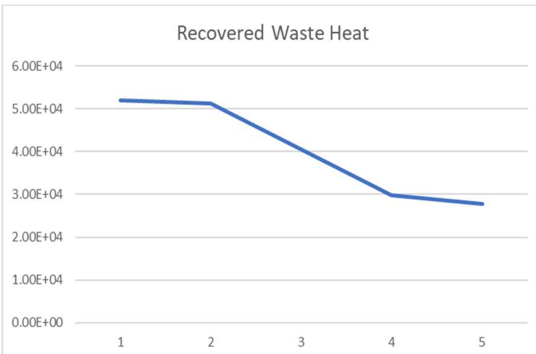


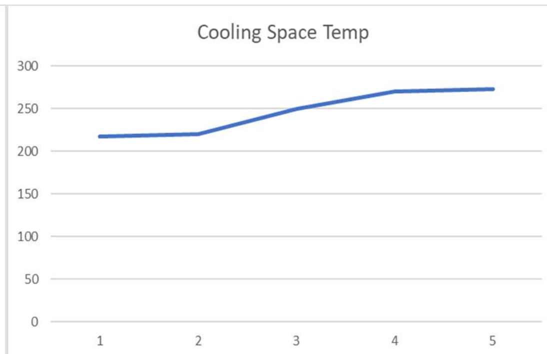
The analysis is done in a MATLAB Live Script (attached as Appendix-1). Thermodynamic properties are obtained from CoolProp tool (linked as reference tool in Appendix-2) available in Python code format, which includes as a data set for thermodynamic and thermophysical properties of different fluids used in thermodynamic calculations.

Results and Conclusions:

A novel combined power and cooling cycle based on the Organic Rankine Cycle (ORC) and the Compression Refrigeration Cycle (CRC) is used. The cycle can be driven by the exhaust heat form a diesel engine. Both the ORC and CRC are trans-critical cycles and using CO2 as working fluid. The variation of high pressure of the organic rankine cycle and the cooling space temperature conditions have resulted in the following observational data:

Cooling Space Temperature in K	Net Refrigeration Output or Recovered Waste Heat in J/s
217	NetRef = 5.2060e+04
220	NetRef = 5.1202e+04
250	NetRef = 4.0513e+04
270	NetRef = 2.9754e+04
273	NetRef = 2.7689e+04
300	NetRef = 7.5848e+03





From the mathematical calculations in MATLAB, we get that the final combined cycle coefficient of performance is around 0.225 for a desired cooling temperature condition of about 20℃; while, for the same conditions, the organic cycle efficiency was observed to be about 40.47%.

Thus, we can infer that the waste heat of the diesel engine exhaust can be utilized to power a combined cycle of an organic rankine cycle and a compression refrigeration cycle to generate cooling to a desired space. Moreover, addition of heat exchanging devices such as an expander or a heat accumulator can further increase the cycle's efficiency.

References:

1) Liu BT, Chien KH, Wang CC. Effect of working fluids on organic Rankine cycle for waste heat recovery. Energy 2004;29:1207-17.
2) Tian, Hua; Yang, Zhao; Li, Minxia; Ma, Yitai, Research and application of CO2 refrigeration and heat pump cycle, Science in China, Series E: Technological Sciences. 2009.6(52):1563-1567
3) Teng, H., Regner, G., and Cowland, C., "Waste Heat Recovery of Heavy-Duty Diesel Engines by Organic Rankine Cycle Part II: Working Fluids for WHR-ORC," SAE Technical Paper 2007-01-0543, 2007, doi: 10.4271/2007-01-0543.
4) Tian, H., Shu, G., Wei, H., Liang, X. et al., "Thermodynamic Analysis of a Novel Combined Power and Cooling Cycle Driven by the Exhaust Heat Form a Diesel Engine," SAE Int. J. Engines 6(2):2013, doi: 10.4271/2013-01-0858.

Appendix-1:

MATLAB Live Script

Appendix-2:

CoolProp Tool for Thermodynamic and thermophysical Properties

http://www.coolprop.org/

```
%Turbine Inlet Conditions
T_1 = 792 %Boiler exit Temperature in K
```

```
T_1 = 792
```

```
P_1 = 10000000 %in Pa
```

```
P_1 = 10000000
```

```
M_ORC = 0.28 %in kg/s
```

```
M_ORC = 0.2800
```

```
Turb_eff = 0.7 %Turbine Efficiency
```

```
Turb_eff = 0.7000
```

```
%%Thermodynamic Properties at 1
H_1 = py.CoolProp.CoolProp.PropsSI('H', 'T', T_1, 'P|supercritical_gas', P_1, 'CO2') %in J/kg
```

```
H_1 = 1.0053e+06
```

```
H_1test = py.CoolProp.CoolProp.PropsSI('H', 'T', T_1, 'P|not_imposed', P_1, 'CO2') %in J/kg
```

```
H_1test = 1.0053e+06
```

```
S_1 = py.CoolProp.CoolProp.PropsSI('S', 'T', T_1, 'P|supercritical_gas', P_1, 'CO2') %in J/kg/K
```

```
S_1 = 2.8379e+03
```

```
D_1 = py.CoolProp.CoolProp.PropsSI('D', 'T', T_1, 'P|supercritical_gas', P_1, 'CO2') %in kg/m^3
```

```
D_1 = 66.0505
```

```
%%Thermodynamic Properties at 2
T_2 = 348 %in K
```

```
T_2 = 348
```

```
%S_2 = S_1 %in J/kg/K
P_2 = 5000000 %in Pa
```

```
P_2 = 5000000
```

```
Q_2 = py.CoolProp.CoolProp.PropsSI('Q', 'T', T_2, 'P|supercritical_gas', P_2, 'CO2')
```

```
Q_2 = -1
```

```
H_2 = py.CoolProp.CoolProp.PropsSI('H', 'T', T_2, 'P|supercritical_gas', P_2, 'CO2') %in J/kg
```

```
H_2 = 5.1243e+05
```

```
%%Thermodynamic Properties at 3
Pump_eff = 0.8 %Pump Efficiency
```

```
Pump_eff = 0.8000
```

```
T_3 = 286 %in K
```

```
T_3 = 286
```

```
P_3 = py.CoolProp.CoolProp.PropsSI('P', 'T', T_3, 'Q', 0, 'CO2') %in Pa
```

```
P_3 = 4.8289e+06
```

```
%S_3 = py.CoolProp.CoolProp.PropsSI('S', 'T', T_2, 'Q', 0, 'R11') %in J/kg/K
D_3 = py.CoolProp.CoolProp.PropsSI('D', 'T', T_3, 'Q', 0, 'CO2') %in kg/m^3
```

```
D_3 = 839.1212
```

```
SV_3 = 1/D_3 %in m^3/kg
```

```
SV_3 = 0.0012
```

```
H_3 = py.CoolProp.CoolProp.PropsSI('H', 'T', T_3, 'Q', 0, 'CO2') %in J/kg
```

```
H_3 = 2.3370e+05
```

```
%%Thermodynamic Properties at 4
P_4 = P_1 %in Pa
```

```
P_4 = 10000000
```

```
PW = (SV_3 * (P_4 - P_3))/Pump_eff % in J/kg
```

```
PW = 7.7031e+03
```

```
H_4 = H_3 + PW %in J/kg
```

```
H_4 = 2.4141e+05
```

```
%%Performance
HI = M_ORC * (H_1 - H_4) % in J/kg
```

```
HI = 2.1390e+05
```

```
TW = (M_ORC * (H_1 - H_2))*Turb_eff % in J/kg
```

```
TW = 9.6612e+04
```

```
SOP = TW - PW % in J/kg
```

```
SOP = 8.8909e+04
```

```
Cycle_eff = SOP/HI
```

```
Cycle_eff = 0.4156
```

```
%%Compression refrigeration cycle properties

% Ref Properties at r1
T_R1 = 217 % in K
```

```
T_R1 = 217
```

```
P_R1 = 3500000 %in Pa
```

```
P_R1 = 3500000
```

```
H_R1 = py.CoolProp.CoolProp.PropsSI('H', 'T', T_R1, 'Q', 0, 'CO2') %in J/kg
```

```
H_R1 = 8.0835e+04
```

```
S_R1 = py.CoolProp.CoolProp.PropsSI('S', 'T', T_R1, 'Q', 0, 'CO2') %in J/kg/K
```

```
S_R1 = 524.9723
```

```
%%Ref properties at r2
T_R2 = 343 %in K
```

```
T_R2 = 343
```

```
P_R2 = 8000000 %in Pa
```

```
P_R2 = 8000000
```

```
Comp_eff = 0.8 %Compressor Efficiency
```

```
Comp_eff = 0.8000
```

```
H_R2s = py.CoolProp.CoolProp.PropsSI('H', 'T', T_R2, 'P|supercritical_gas', P_R2, 'CO2') %in J/kg
```

```
H_R2s = 4.7568e+05
```

```
H_R2 = ((H_R2s - H_R1) * Comp_eff) + H_R1
```

```
H_R2 = 3.9671e+05
```

```
%%Ref properties at r3
T_R3 = 300 %in K
```

```
T_R3 = 300
```

```
P_R3 = 8000000 %in Pa
```

```
P_R3 = 8000000
```

```
H_R3 = py.CoolProp.CoolProp.PropsSI('H', 'T', T_R3, 'P|supercritical_liquid', P_R3, 'CO2') %in J/kg
```

```
H_R3 = 2.6996e+05
```

```
%%Ref properties at r4
T_R4 = T_R1 %in K
```

```
T_R4 = 217
```

```
P_R4 = P_R1
```

```
P_R4 = 3500000
```

```
H_R4 = H_R3
```

```
H_R4 = 2.6996e+05
```

```
%% CRC Performance
CW = (0.9) * TW %transmission of turbine work to compressor work in J/kg
```

```
CW = 8.6950e+04
```

```
M_REF = (CW)/(H_R2 - H_R1) %in kg/s
```

```
M_REF = 0.2753
```

```
NetRef = M_REF * abs(H_R1 - H_R4) %in J/s
```

```
NetRef = 5.2060e+04
```

```
COP_cycle = NetRef/HI
```

```
COP_cycle = 0.2434
```