Homework 3-1

Imports

[1]:
```
from thermostate import Q_, State, units
```

Definitions

[2]:
```
substance = 'ammonia'

p_1 = Q_(3.25, 'MPa')
T_1 = Q_(147.0, 'degC')

p_2 = Q_(410.0, 'kPa')
T_2 = Q_(14.21, 'degC')

x_3 = Q_(0.0, 'dimensionless')

mdot = Q_(305.6, 'kg/s')

eta_p = Q_(0.9, 'dimensionless')
```

Problem Statement

A binary geothermal power plant uses geothermal water as a heat source. The cycle operates on a superheat Rankine cycle with ammonia as the working fluid. Ammonia enters the turbine at 3.25 MPa and 147.0 °C at a rate of 305.6 kg/s, and leaves the turbine at 410.0 kPa and 14.21 °C.

The ammonia is then condensed in an air-cooled condenser to a saturated liquid before being pumped to the heat exchanger pressure in, well, a pump. The pump has an isentropic efficiency of 90%.

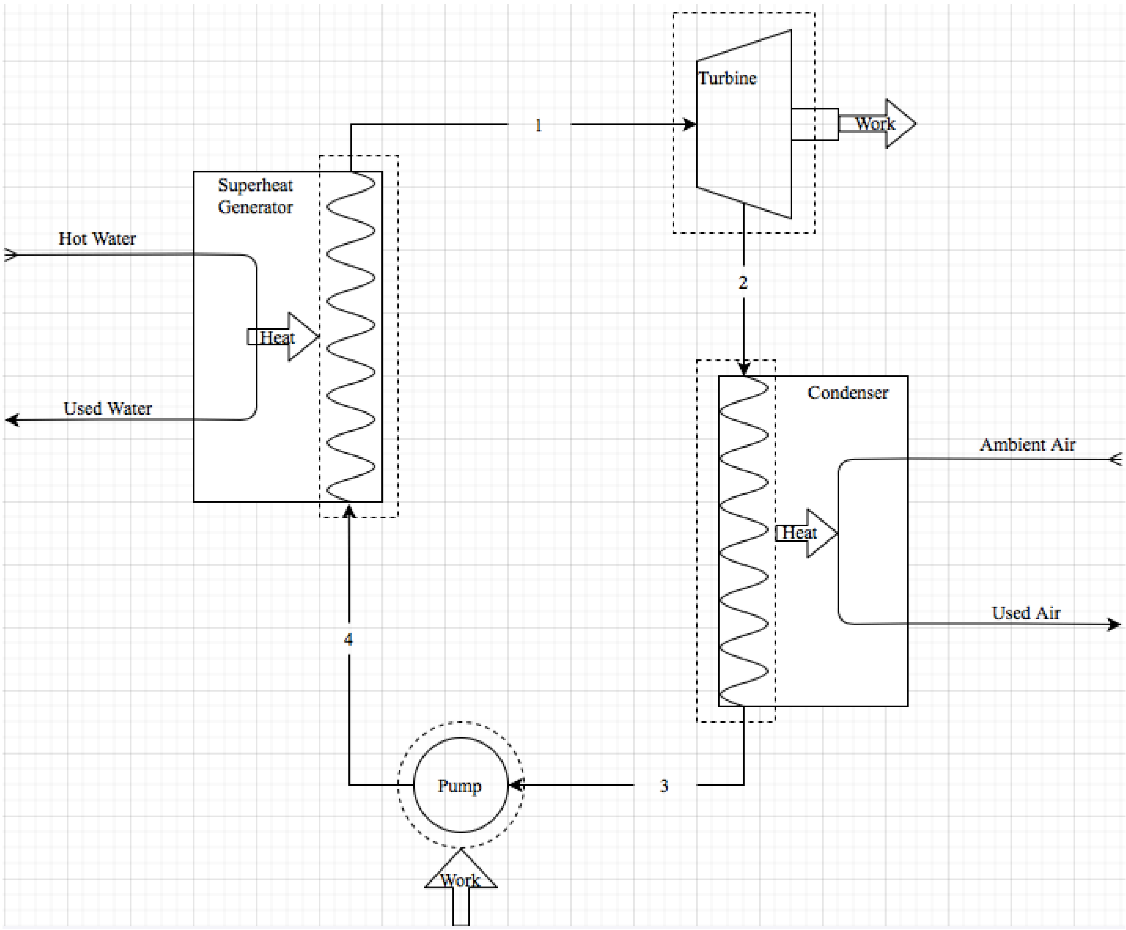
1. Draw a system diagram and label the states.

Determine the following:

2. the isentropic efficiency of the turbine,
3. the net power output of the plant, in MW,
4. the thermal efficiency of the cycle.

Solution

Part 1: System Diagram



Part 2: Isentropic Efficiency of Turbine

Important Equations: 1. $\eta_t = \frac{h_1 - h_2}{h_1 - h_2 s}$

[3]:
```
# Write your code here to solve the problem
# Make sure to write your final answer in the cell below.
st_1 = State(substance,p=p_1,T=T_1)
st_2s = State(substance,p=p_2,s=st_1.s)
st_2 = State(substance,p=p_2,T=T_2)
eta_t = (st_1.h-st_2.h)/(st_1.h-st_2s.h)
print(eta_t)
```

```
0.7909381254963901 dimensionless
```

Answer: 79.09% efficency

Part 3: Net Power Output of Plant

Important Equations:

1. $\frac{\dot{W}_t}{\dot{m}} = h_1 - h_2$
2. $\frac{\dot{W}_p}{\dot{m}} = h_3 - h_4$
3. $\dot{W}_{net} = \dot{W}_t + \dot{W}_p$

[4]:
```
# Write your code here to solve the problem
# Make sure to write your final answer in the cell below.
st_3 = State(substance, p=p_2,x=x_3)
st_4 = State(substance, p=p_1,s=st_3.s)
W_t = (st_1.h-st_2.h) * mdot
W_p = (st_3.h-st_4.h) * mdot
W_net = W_t + W_p
print(W_net.to("MW"))
```

```
73.65666532860274 megawatt
```

Answer: 73.6567 MW

Part 4: Thermal Efficiency of Cycle

Important Equations:

1. $\frac{\dot{W}_t}{\dot{m}} = h_1 - h_2$
2. $\frac{\dot{W}_p}{\dot{m}} = h_3 - h_4$
3. $\frac{\dot{Q}_{in}}{\dot{m}} = h_1 - h_4$
4. $\eta = \frac{\dot{W}_{cycle}/\dot{m}}{\dot{Q}_{in}/\dot{m}}$

[5]:
```
# Write your code here to solve the problem
# Make sure to write your final answer in the cell below.
eta = ((st_1.h-st_2.h)+(st_3.h-st_4.h))/(st_1.h-st_4.h)
print(eta)
```

```
0.1558027034951207 dimensionless
```

Answer: 15.58% efficency

Homework 3-2

Imports

[1]:
```
from thermostate import Q_, State
```

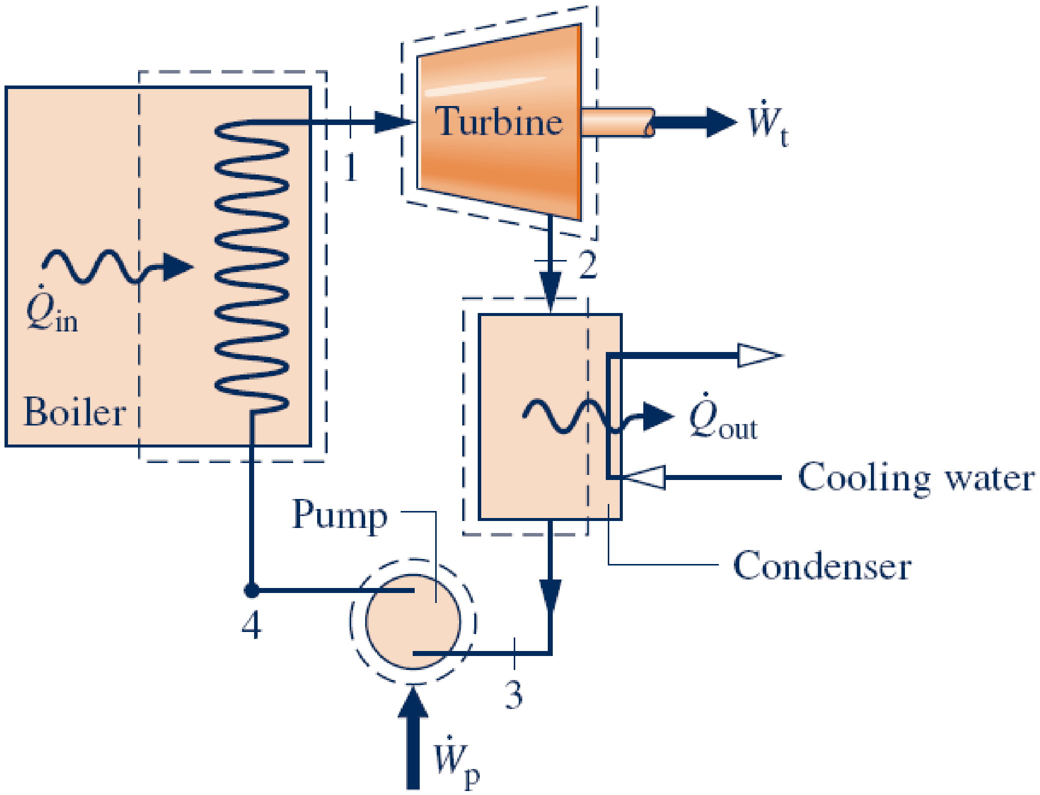
Definitions

[2]:
```
substance = 'water'

T_1 = Q_(520.0, 'degC')
p_1 = Q_(10.0, 'MPa')

p_2 = Q_(10.0, 'kPa')

x_3 = Q_(0.0, 'dimensionless')

eta_t = eta_p = Q_(0.85, 'dimensionless')

Wdot_net = Q_(210.0, 'MW')
```

Problem Statement

Consider a 210.0 MW steam power plant that operates on an ideal superheated Rankine cycle. Steam enters the turbine at 10.0 MPa and 520 °C, and is then cooled in the condenser at a pressure of 10.0 kPa until the quality is 0.0. The turbine and pump can be treated as ideal, with isentropic efficiencies of 100%. Determine:

1. the quality of the steam at the exit of the turbine,
2. the thermal efficiency of the cycle,
3. the mass flow rate of the steam, in kg/s,
4. 1-3 again, if the isentropic efficiency of the pump and turbine are both 85%.



Solution

Part 1: Quality at Turbine Exit

Important Equations:

1. $s_1 = s_2$

[3]:
```
# Write your code here to solve the problem
# Make sure to write your final answer in the cell below.
st_1 = State(substance,p=p_1,T=T_1)
st_2 = State(substance,p=p_2,s=st_1.s)
print(st_2.x)
```

```
0.8021347556280831 dimensionless
```

Answer: 0.8021

Part 2: Thermal Efficiency of Cycle

Important Equations:

1. $\frac{\dot{W}_t}{\dot{m}} = h_1 - h_2$

2. $\frac{\dot{W}_p}{\dot{m}} = h_3 - h_4$
3. $\frac{\dot{Q}_{in}}{\dot{m}} = h_1 - h_4$
4. $\eta = \frac{\dot{W}_{cycle}/\dot{m}}{\dot{Q}_{in}/\dot{m}}$

[4]:
```
# Write your code here to solve the problem
# Make sure to write your final answer in the cell below.
st_3 = State(substance, p=p_2, x=x_3)
st_4 = State(substance, p=p_1, s=st_3.s)
eta = (st_1.h-st_2.h+(st_3.h-st_4.h))/(st_1.h-st_4.h)
print(eta)
```

```
0.4049452667896198 dimensionless
```

Answer: 40.49% efficency

Part 3: Mass Flow Rate

Important Equations:

1. $\frac{W_{net}}{\dot{m}} = \frac{\dot{W}_t}{\dot{m}} + \frac{\dot{W}_p}{\dot{m}}$
2. $\frac{\dot{W}_t}{\dot{m}} = h_1 - h_2$
3. $\frac{\dot{W}_p}{\dot{m}} = h_3 - h_4$
4. $\dot{m} = \frac{\dot{W}_{net}}{(h_1-h_2)+(h_3-h_4)}$ is obtained from combinding the above equations

[5]:
```
# Write your code here to solve the problem
# Make sure to write your final answer in the cell below.
mdot = (Wdot_net)/((st_1.h-st_2.h)+(st_3.h-st_4.h))
print(mdot.to("kg/s"))
```

```
160.82805101320366 kilogram / second
```

Answer: 160.828 $\frac{kg}{s}$

Part 4: Repeat 1-3 With New Isentropic Efficiencies

Part 1-4: Quality at Turbine Exit

Important Equations:

1. $\eta_t = \frac{h_1-h_2}{h_1-h_{2s}} \Rightarrow h_2 = (h_{2s} - h_1) \cdot \eta_t + h_1$

[6]:
```
# Write your code here to solve the problem
# Make sure to write your final answer in the cell below.
```

```
st_1 = State(substance,p=p_1,T=T_1)
st_2s = State(substance,p=p_2,s=st_1.s)
h_2 = (st_2s.h-st_1.h)*0.85 + st_1.h
st_2 = State(substance, p=p_2, h=h_2)
print(st_2.x)
```

```
0.8846463349095887 dimensionless
```

Answer: 0.8846

Part 2-4: Thermal Efficiency of Cycle

Important Equations:

1. $\eta_p = \frac{h_{4s}-h_3}{h_4-h_3} \Rightarrow h_4 = \frac{h_{4s}-h_3}{\eta_c} + h_3$
2. $\frac{\dot{W}_t}{\dot{m}} = h_1 - h_2$
3. $\frac{\dot{W}_p}{\dot{m}} = h_3 - h_4$
4. $\frac{\dot{Q}_{in}}{\dot{m}} = h_1 - h_4$
5. $\eta = \frac{\dot{W}_{cycle}/\dot{m}}{\dot{Q}_{in}/\dot{m}}$

[7]:
```
# Write your code here to solve the problem
# Make sure to write your final answer in the cell below.
st_3 = State(substance, p=p_2, x=x_3)
st_4s = State(substance,p=p_1,s=st_3.s)
h_4 = (st_4s.h-st_3.h)*0.85 + st_3.h
st_4 = State(substance, p=p_1, h=h_4)
eta = (st_1.h-st_2.h+(st_3.h-st_4.h))/(st_1.h-st_4.h)
print(eta)
```

```
0.3440422909118857 dimensionless
```

Answer: 34.404% efficency

Part 3-4: Mass Flow Rate

Important Equations:

1. $\frac{W_{net}}{\dot{m}} = \frac{\dot{W}_t}{\dot{m}} + \frac{\dot{W}_p}{\dot{m}}$
2. $\frac{\dot{W}_t}{\dot{m}} = h_1 - h_2$
3. $\frac{\dot{W}_p}{\dot{m}} = h_3 - h_4$
4. $\dot{m} = \frac{\dot{W}_{net}}{(h_1-h_2)+(h_3-h_4)}$ is obtained from combinding the above equations

[8]:
```python
# Write your code here to solve the problem
# Make sure to write your final answer in the cell below.
mdot = (Wdot_net)/((st_1.h-st_2.h)+(st_3.h-st_4.h))
print(mdot.to("kg/s"))
```

```
189.2094717802366 kilogram / second
```

Answer: 189.2095 $\frac{kg}{s}$

Answer:

Homework 3-3

Imports

[1]:
```
from thermostate import Q_, State, units
```

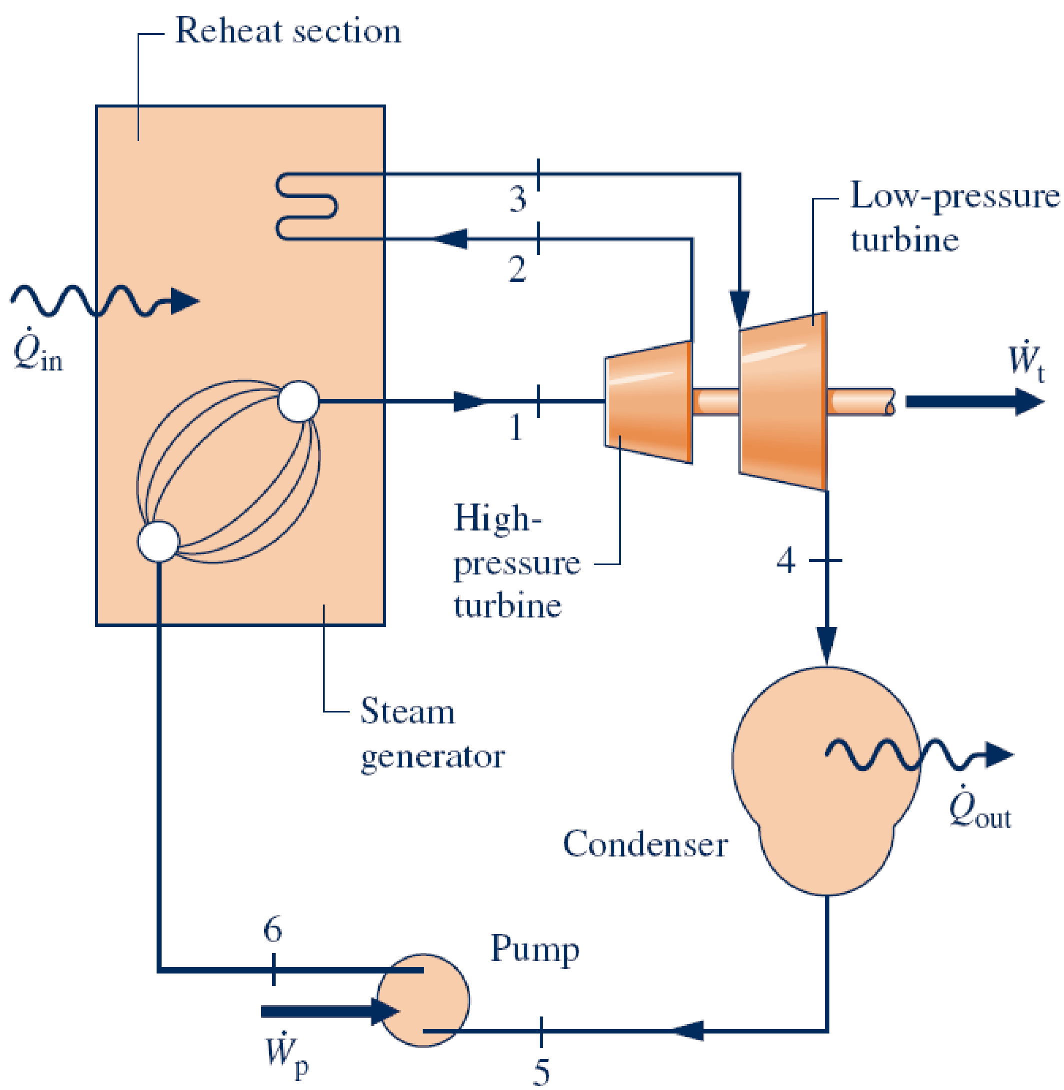
Definitions

[2]:
```
substance = 'water'

p_2 = Q_(1500.0, 'kPa')
x_2 = Q_(0.96, 'dimensionless')

p_4 = Q_(20.0, 'kPa')
x_4 = x_2

x_5 = Q_(0.0, 'dimensionless')

p_6 = Q_(6000.0, 'kPa')
```

Problem Statement

Consider a steam power plant that operates on the ideal reheat Rankine cycle at steady state. The plant maintains the boiler at 6000.0 kPa, the reheat section at 1500.0 kPa, and the condenser at 20.0 kPa. The mixture quality at the exit of both turbines is 96%. At the exit of the condenser, the water is a saturated liquid. The effects of stray heat transfer, kinetic energy, and potential energy can be neglected. Determine:

1. the temperature at the inlet of each turbine, in °C,
2. the cycle's thermal efficiency.



Solution

Part 1: Temperature at Turbine Inlets

Reheat Rankine Cycle Properties:

1-2: Isentropic expansion from superheated vapor to p_2

2-3: Isobaric heating using extra energy from an excess combustion

3-4: Isentropic expansion to p_c

4-5: Isobaric condensation to a saturated liquid

5-6: Isentropic compression to subcooled liquid

6-1: Isobaric evaporation to superheated vapor

[3]:
```
# Write your code here to solve the problem
# Make sure to write your final answer in the cell below.
```

```python
st_2 = State(substance, p=p_2, x=x_2)
st_4 = State(substance, p=p_4, x=x_4)

st_3 = State(substance, p=p_2, s=st_4.s)
st_5 = State(substance, p=st_4.p, x=x_5)
st_6 = State(substance, p=p_6, s=st_5.s)
st_1 = State(substance, p=p_6, s=st_2.s)

print("High Pressure Turbine Inlet Temperature: {}".format(st_1.T))
print("Low Pressure Turbine Inlet Temperature: {}".format(st_3.T))
```

```
High Pressure Turbine Inlet Temperature: 610.8788428476176 kelvin
Low Pressure Turbine Inlet Temperature: 791.880319569662 kelvin
```

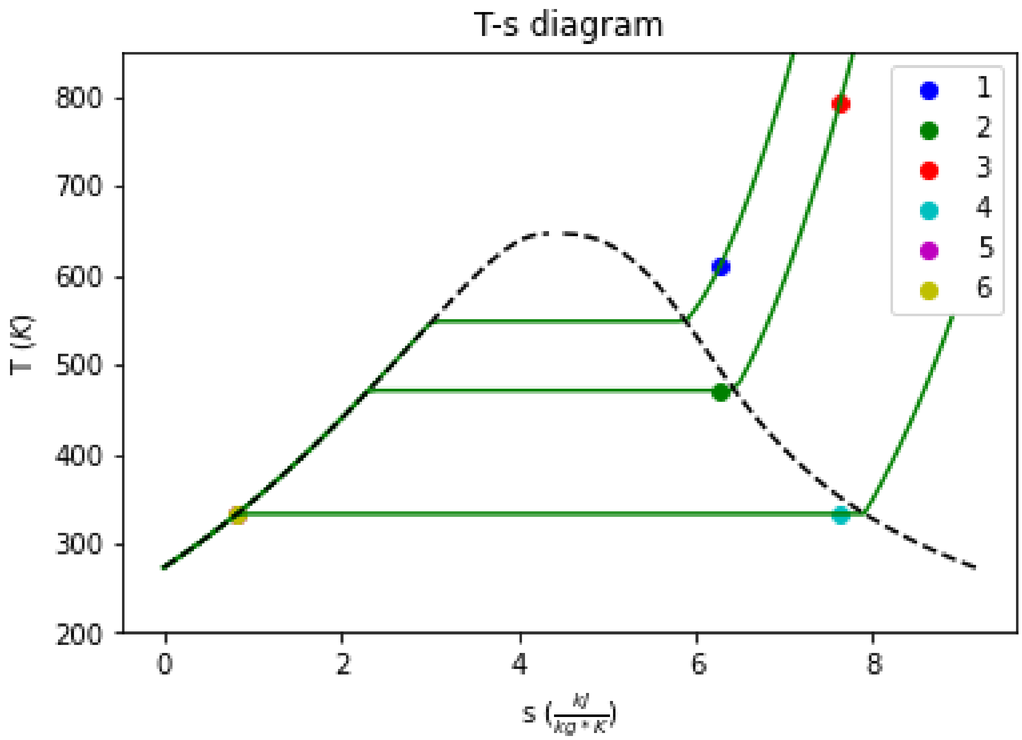
Answer: High Pressure Turbine Inlet Temperature: 610.8788 K
Low Pressure Turbine Inlet Temperature: 791.8803 K

I got curious in class and did this

[4]:
```python
import matplotlib.pyplot as plt
import numpy as np

s_range = np.arange(0,9,0.1)*(units.kJ/units.kg/units.K)
T_range = np.arange(273.06,647.096,1)*units.K

def plot_isobar(p):
    result = []
    for i in s_range:
        st_i = State(substance,p=p,s=i)
        result.append(st_i.T.magnitude)
    return result

def plot_satliquid():
    result = []
    for i in T_range:
        st_i = State(substance,T=i,x=Q_(0.0, 'dimensionless'))
        result.append(st_i.s.to("kJ/kg/K").magnitude)
    return result

def plot_satvapor():
    result = []
    for i in T_range:
        st_i = State(substance,T=i,x=Q_(1.0, 'dimensionless'))
        result.append(st_i.s.to("kJ/kg/K").magnitude)
    return result
```

```
state = ["1","2","3","4","5","6"]
s_points = [st_1.s.to("kJ/kg/K").magnitude,st_2.s.to("kJ/kg/K").magnitude,st_3.
↪s.to("kJ/kg/K").magnitude,st_4.s.to("kJ/kg/K").magnitude,st_5.s.to("kJ/kg/
↪K").magnitude,st_6.s.to("kJ/kg/K").magnitude]
T_points = [st_1.T.magnitude,st_2.T.magnitude,st_3.T.magnitude,st_4.T.
↪magnitude,st_5.T.magnitude,st_6.T.magnitude]

colors_list = "bgrcmy"
for i in range(len(colors_list)):
    plt.plot(s_points[i],T_points[i],colors_list[i]+"o",label = state[i])

plt.plot(s_range.magnitude,plot_isobar(st_6.p),"g-")
plt.plot(s_range.magnitude,plot_isobar(st_2.p),"g-")
plt.plot(s_range.magnitude,plot_isobar(st_4.p),"g-")
plt.plot(plot_satliquid(),T_range,"k--")
plt.plot(plot_satvapor(),T_range,"k--")

print(st_5.T,st_6.T)


plt.ylim(200,850)
plt.xlabel("s ($\\frac{kJ}{kg*K}$)")
plt.ylabel("T ($K$)")
plt.title("T-s diagram")
plt.legend()
plt.show()
```

```
333.2079603743207 kelvin 333.4613909484461 kelvin
```



Part 2: Cycle Thermal Efficiency

Important Equations:

1. $\frac{\dot{W}_{th}}{\dot{m}} = h_1 - h_2$
2. $\frac{\dot{W}_{tl}}{\dot{m}} = h_3 - h_4$
3. $\frac{\dot{W}_p}{\dot{m}} = h_5 - h_6$
4. $\frac{\dot{Q}_{in}}{\dot{m}} = h_1 - h_6$
5. $\frac{\dot{Q}_{in}}{\dot{m}} = h_3 - h_2$
6. $\eta = \frac{\dot{W}_{cycle}/\dot{m}}{\dot{Q}_{in}/\dot{m}}$

[6]:
```
# Write your code here to solve the problem
# Make sure to write your final answer in the cell below.
eta = ((st_1.h-st_2.h)+(st_3.h-st_4.h)+(st_5.h-st_6.h))/((st_1.h-st_6.h)+(st_3.
 ↪h-st_2.h))
print(eta)
```

```
0.36289703624874525 dimensionless
```

Answer: 36.29% efficency

Homework 3-4

Imports

[1]:
```
from thermostate import Q_, State, units
import numpy as np
import matplotlib.pyplot as plt

# this just suppresses a warning due to the plotting code
import warnings
warnings.filterwarnings('ignore')
```

Definitions

[2]:
```
substance = 'water'

T_1 = Q_(520.0, 'degC')

p_2 = Q_(10, 'kPa')

x_3 = Q_(0.0, 'dimensionless')
p_3 = Q_(10.0, 'kPa')
```

Problem Statement

Part of engineering is observing trends as certain parameters change in a design.

Consider an ideal Rankine cycle operating on a power plant consisting of a boiler, a turbine, a condenser, and a pump. The state parameters are given in the Definitions section above (they're very similar to HW 3-1). Note that some states are incomplete, since the properties at those states are dependent on the value of the boiler pressure.

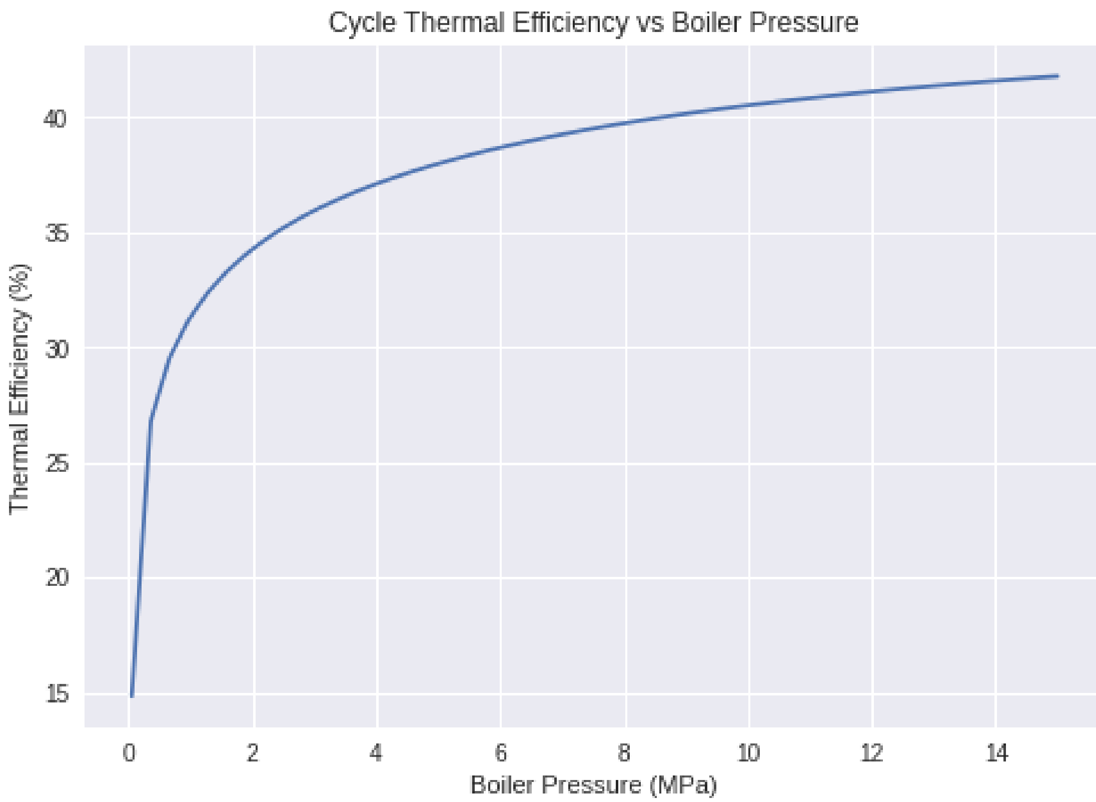
The function given below takes in the boiler pressure ($p_1 = p_2$), and computes the thermal efficiency of the cycle. The rest of the cell below the function plots the thermal efficiency against the changing boiler pressure.

What trends do you see? If you were the design engineer, would you want the boiler pressure to be higher or lower? Are there any practical considerations that might bound the possible boiler pressure?

Solution

You don't need to write any code for this problem, just read through the code below, understand what it's doing, and write your analysis in the Markdown cell below. You might want to save this code for future reference, since plotting trends is going to come up throughout the semester.

[8]:
```
def calc_thermal_efficiency(boiler_pressure):
    ''' Calculate the thermal efficiency (%) of an ideal Rankine
    cycle power plant given the boiler pressure (MPa).'''
    p_1 = p_4 = boiler_pressure

    st_1 = State(substance, p=p_1, T=T_1)
    h_1 = st_1.h
    s_1 = st_1.s

    s_2 = s_1
    st_2 = State(substance, p=p_2, s=s_2)
    h_2 = st_2.h

    st_3 = State(substance, p=p_3, x=x_3)
    h_3 = st_3.h
    s_3 = st_3.s

    s_4 = s_3
    st_4 = State(substance, s=s_4, p=p_4)
    h_4 = st_4.h

    w_t = h_1 - h_2
    w_p = h_3 - h_4
    q_in = h_1 - h_4

    eta = (w_t + w_p)/q_in
    eta = eta.to('dimensionless')*100

    return eta

# create a list of pressures between 0.05 MPa and 15.0 MPa
boiler_pressures = np.linspace(0.05, 15.0)*units.MPa

# calculate the cycle thermal efficiency for each pressure
eta = np.zeros_like(boiler_pressures)
for i, boiler_pressure in enumerate(boiler_pressures):
    eta[i] = calc_thermal_efficiency(boiler_pressure)

# plot the thermal efficiency against the boiler pressure
plt.style.use('seaborn')  # this just makes the plot look nicer
plt.title('Cycle Thermal Efficiency vs Boiler Pressure')
plt.xlabel('Boiler Pressure (MPa)')
plt.ylabel('Thermal Efficiency (%)')
plt.plot(boiler_pressures, eta);  # this draws the curve
# the semicolon at the end suppresses some matplotlib output
```



Write your engineering model, equations, and/or explanation of your process here.

[4]:
```
# Write your code here to solve the problem
# Make sure to write your final answer in the cell below.
```

Answer: Looking at the trend, it seems that an increase boiler pressure is logrithmically followed by an increase in thermal efficency. It does seem like thermal efficency tops off at around 43%. This being said, our practical upper limit in boiler pressure would be yielding strength of the containment system. We can not infinitly increase pressure because at some point the containment system will burts.