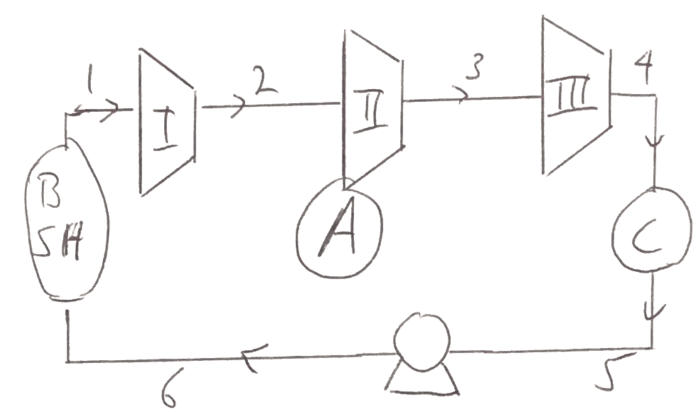
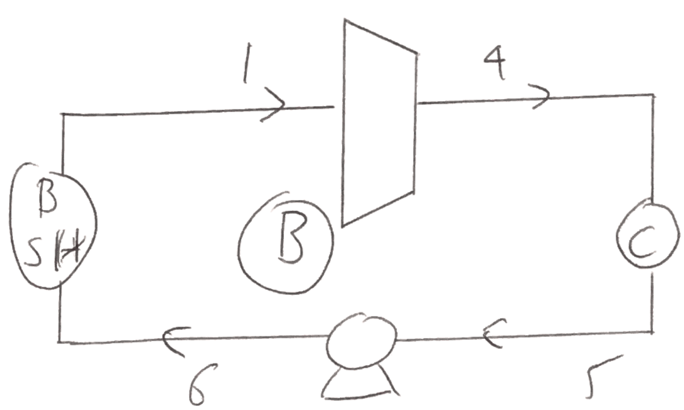
Quiz 5 ChE Thermodynamics
February 13, 2020
TAKE HOME Due Friday at midnight

A three stage Rankine cycle has been proposed as a means to improve efficiency (cycle A below) as an alternative to a single stage Rankine cycle (cycle B below). You need to do a back of the envelope calculation to determine if this is reasonable given roughly twice the cost for the three-stage versus a single stage system.

- Use the answer to homework problem, 4.18, $P_2 = \sqrt{(P_1 P_3)}$, to solve for pressures P_2 and P_3.
-The efficiency of the turbines are all $\eta_{\text{eff}} = 0.80$ and the efficiency of the pump is $\eta_{\text{eff}} = 0.85$.
-Calculate the efficiencies for the two cycles as well as for the Carnot cycle.
-Give a percentage of the ideal for A and B by dividing your efficiency by the Carnot efficiency for both cycles.
-Comment on the final temperature leaving the last turbine in both cases.
-Use the steam tables at the back of the book for the values and do interpolation. **<u>Round the pressures to a tabulated value.</u>**
-Plot on the *P-H* and on the *T-S* graphs the 6 and 4 points of cycles A and B. (Check to make sure all of the table values, *H*, *S*, *T*, *P* match for each point for each graph).
-Fill in all of the values in the two tables.
-Turn in Pages 2, 3, 4, and all of your work, use the phone app **Scannable** (part of Evernote) to make a pdf of your answers and email to the homework email address. Work alone!!!





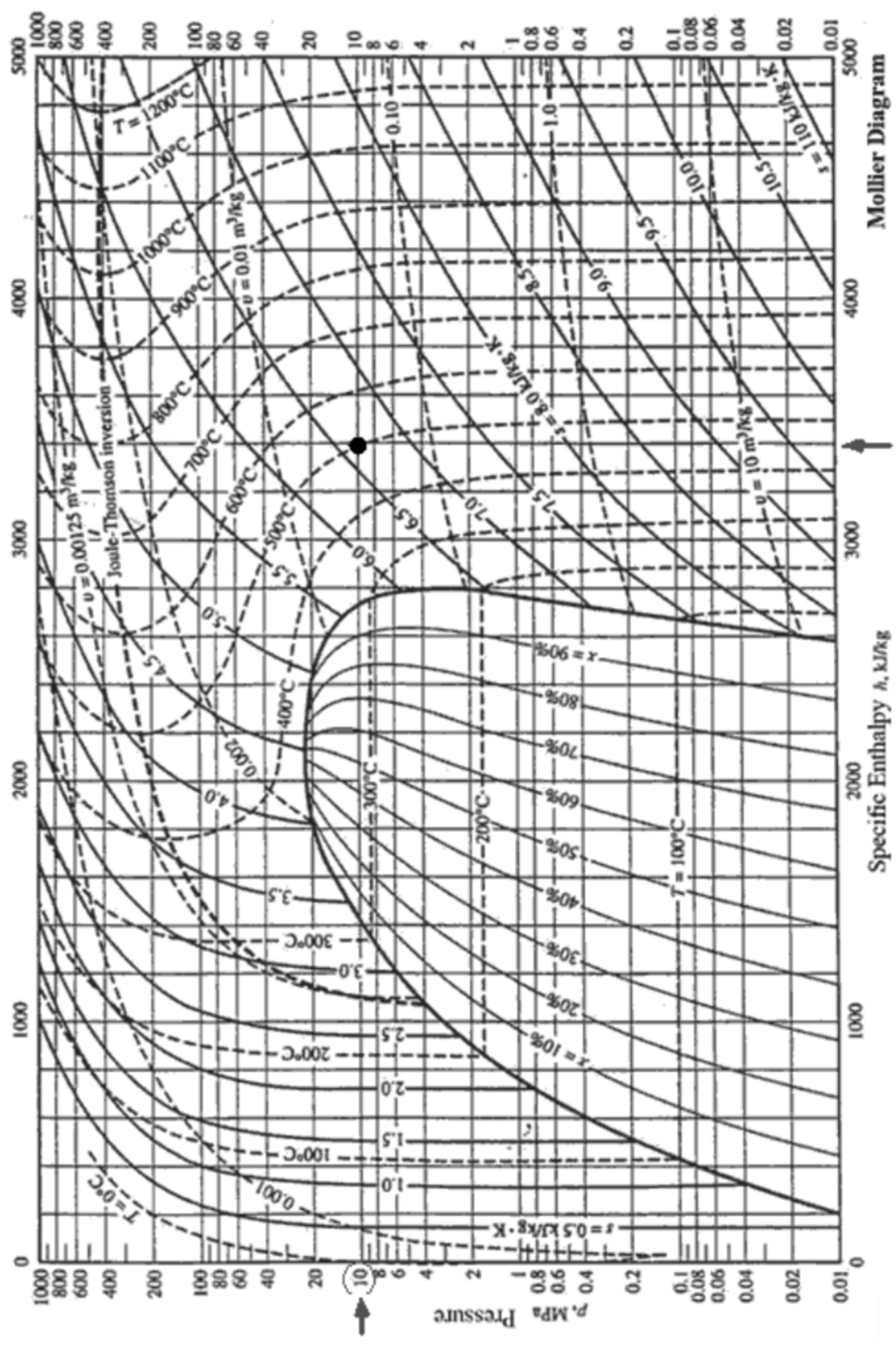
Cycle A

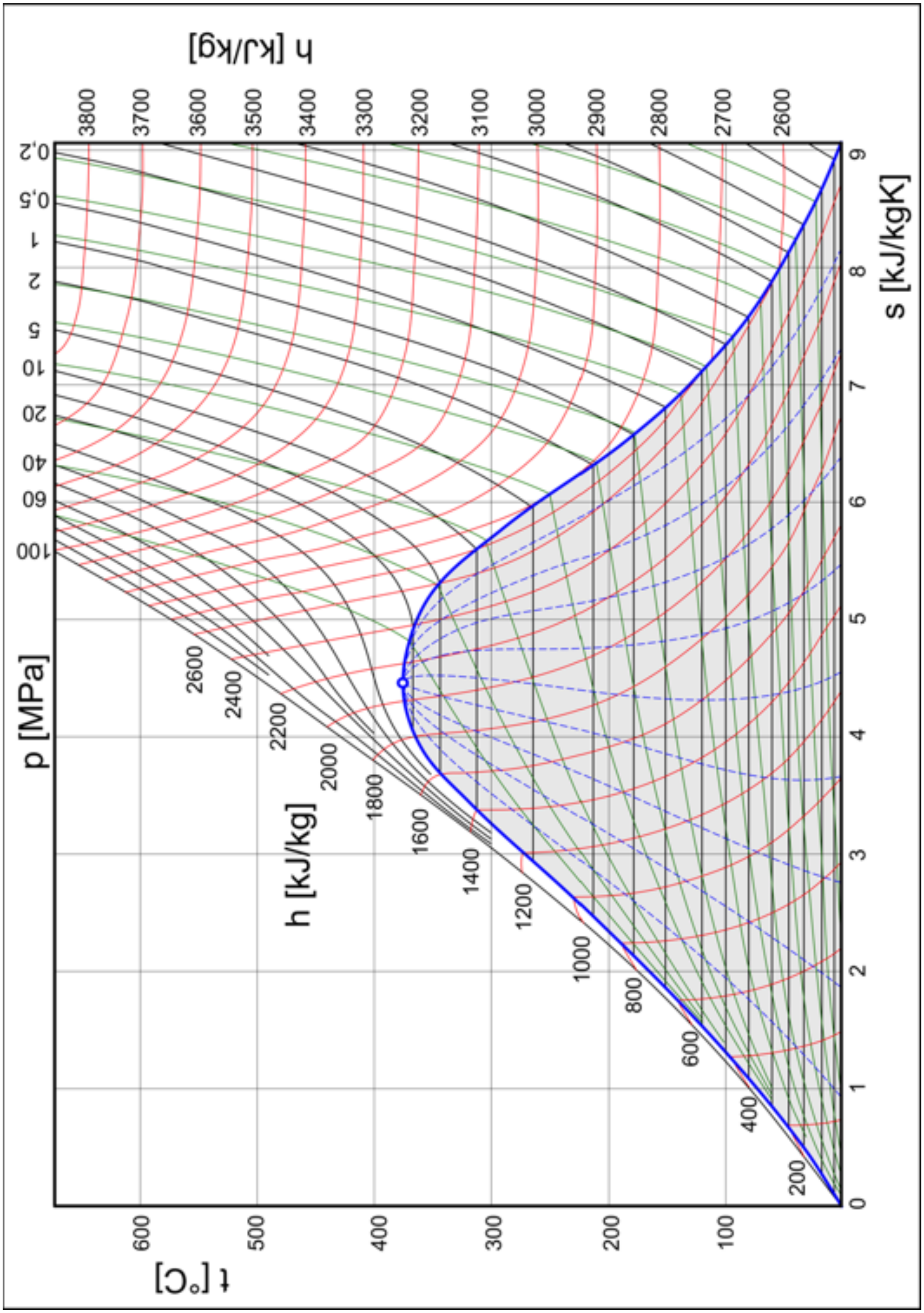
Stream	P, Mpa	T, °C	H, kJ/kg	S, kJ/(kg K)	W/Q, kJ/kg	State	q
1	5	500			-		
2'							
2							
3'							
3							
4'							
4	0.1						
5						SL	
6'							
6							

Cycle B

Stream	P, Mpa	T, °C	H, kJ/kg	S, kJ/(kg K)	W'	State	q
1	5	500			-		
4'							
4	0.1						
5						SL	
6'							
6							

	Efficiency	ηeff/ηCarnot
Cycle A		
Cycle B		
Carnot Cycle		1


Mollier Diagram
Specific Enthalpy h, kJ/kg
p, MPa Pressure
T = 1200°C
1100°C
1000°C
900°C
800°C
700°C
600°C
500°C
400°C
300°C
200°C
T = 100°C
T = 0°C
Joule-Thomson inversion
v = 0.001125 m³/kg
v = 0.01 m³/kg
v = 10 m³/kg
s = 0.5 kJ/kg · K
s = 8.0 kJ/kg · K
s = 11.0 kJ/kg · K
x = 90%
x = 10%


t [°C]
h [kJ/kg]
p [MPa]
s [kJ/kgK]
h [kJ/kg]
0,2
0,5
1
2
5
10
20
40
60
100
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
600
500
400
300
200
100
3800
3700
3600
3500
3400
3300
3200
3100
3000
2900
2800
2700
2600
0
1
2
3
4
5
6
7
8
9

Summary of Process and General Rules

Nozzle $\Delta S = 0$
$\Delta H = 1/2\ mv^2$

Throttle $\Delta S = -R\ln(P_2/P_1)$ (i.g.)
$\Delta H = 1/2\ mv^2$

Pump $\Delta S = 0$ for adiabatic reversible
$\Delta H = W_S = \Delta H' / \eta_{eff}$
$W_{S,Pump} = V\ \Delta P$

Turbine $\Delta S = 0$ for adiabatic reversible
$\Delta H = W_S = \Delta H'\ \eta_{eff}$

Carnot (Use °K)

Engine $\eta_{eff} = (T_H - T_C)/T_H$
Refrigerator $COP = T_C/(T_H - T_C)$
Heat Pump $COP = T_H/(T_H - T_C)$

Isothermal $(\Delta S)_T = R\ \ln[V_2/V_1]$ i.g.
$= -R\ \ln[P_2/P_1]$
$(\Delta H)_T = 0$

Ideal Mixing $\Delta S_{mix} = -R\ \Sigma x_i\ \ln x_i$

Adiabatic, Reversible
$\Delta S = 0$

Isobaric $(dS)_P = C_p\ (dT)_P/T$
$(dS/dT)_P = C_p/T$

Constant Volume
$(dS)_V = C_V\ (dT)_V/T$
$(dS/dT)_V = C_V/T$

Phase Change $\Delta S_{trans} = \Delta H_{trans}/T_{trans}$

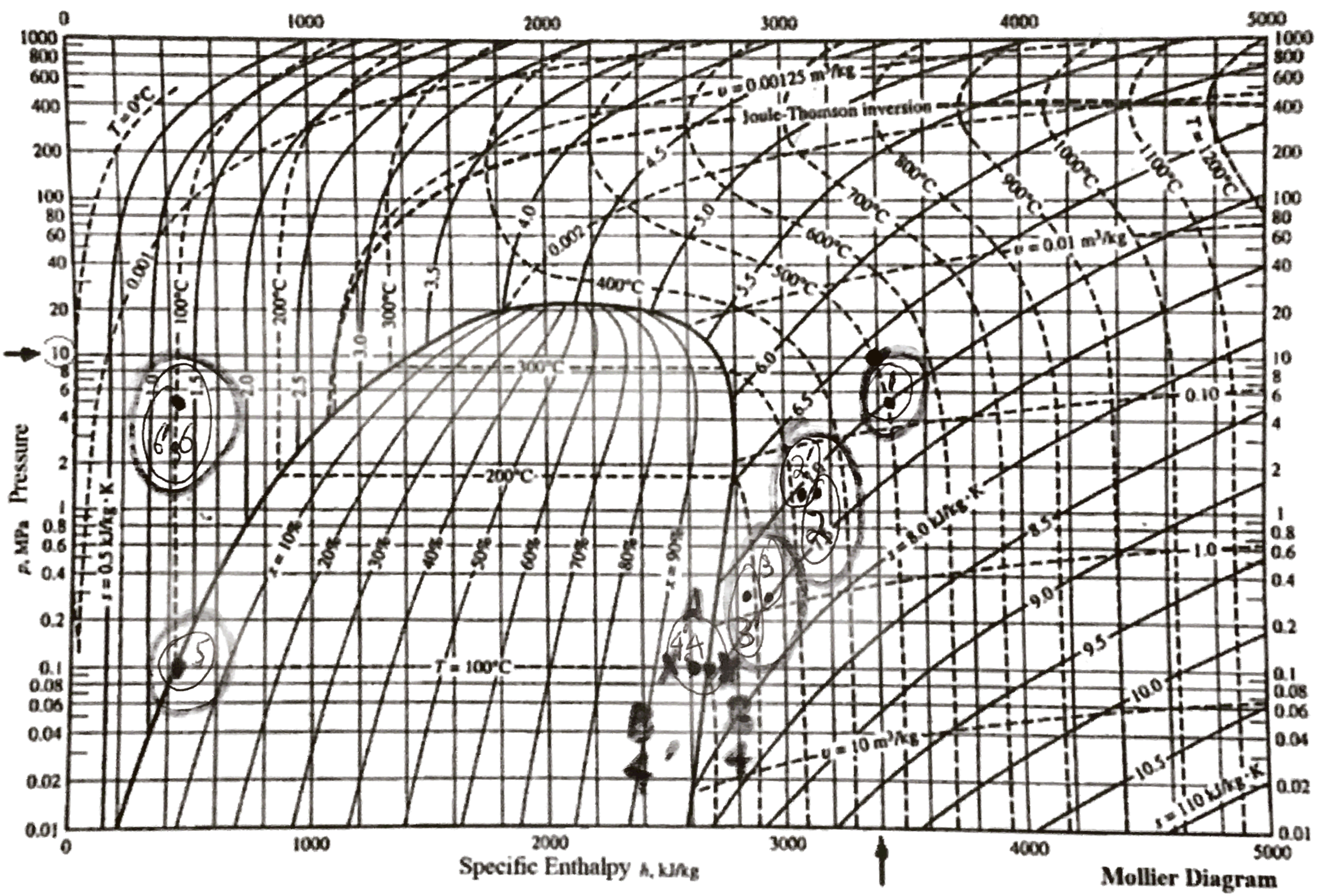
Cycle A

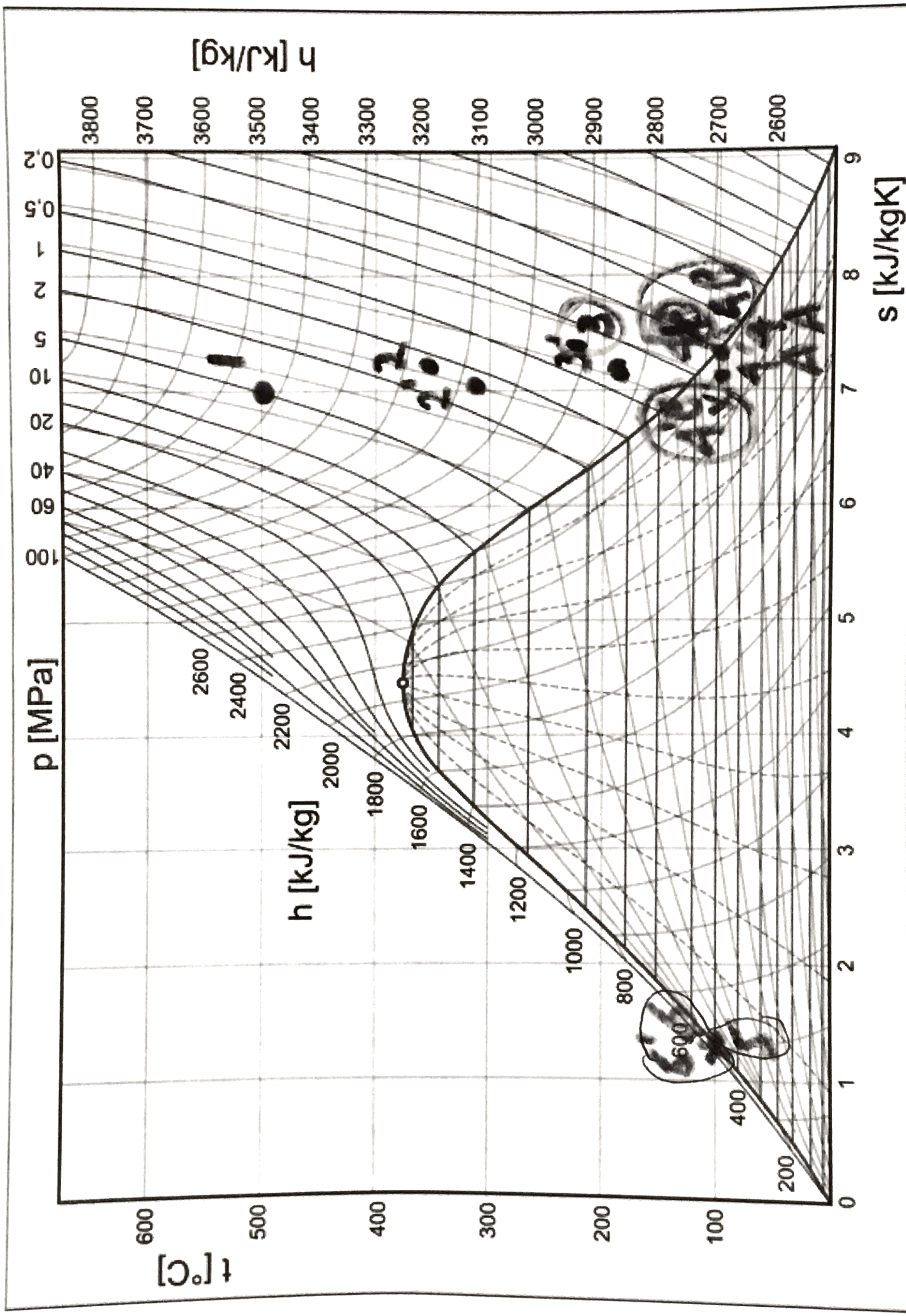
Stream	P, Mpa	T, °C	H, kJ/kg	S, kJ/(kg K)	W/Q, kJ/kg	State	q
1	5	500	3430	6.98	-	V	1
2'	1.36	306	3050	6.98	-380	V	1
2	1.36	341	3130	7.11	-300	V	1
3'	0.368	188	2830	7.11	-300	V	1
3	0.368	215	2890	7.23	-240	V	1
4'	0.1	99.6	2630	7.23	-260	V/L	0.979
4	0.1	99.6	2680	7.36	-208	SV	1
5	0.1	99.6	418 kJ/kg	1.30	-2260	SL	0
6'	5	100	423	1.30	5.10	L	0
6	5	100	424	1.31	6.00	L	0

Cycle B

Stream	P, Mpa	T, °C	H, kJ/kg	S, kJ/(kg K)	W'	State	q
1	5	500	3430	6.98	-	V	1
4'	0.1	99.6	2540	6.98	-890	V/L	0.937
4	0.1	120	2720	7.46	-712	V	1
5	0.1	99.6	418	1.30	-2300	SL	0
6'	5	100	423	1.30	5	L	0
6	5	100	424	1.30	5.88	L	0

	Efficiency	ηeff/ηCarnot
Cycle A	0.247	0.477
Cycle B	0.235	0.454
Carnot Cycle	0.518	1


Mollier Diagram
Specific Enthalpy h, kJ/kg
p, MPa Pressure
T = 0°C
T = 100°C
T = 200°C
300°C
400°C
500°C
600°C
700°C
800°C
900°C
1000°C
1100°C
T = 1200°C
v = 0.00125 m³/kg
Joule-Thomson inversion
v = 0.01 m³/kg
v = 10 m³/kg
s = 0.5 kJ/kg · K
s = 8.0 kJ/kg · K
s = 11.0 kJ/kg · K
x = 10%
x = 90%


h [kJ/kg]
s [kJ/kgK]
p [MPa]
t [°C]

① Calculate P_2 & P_3 for Ⓐ

$P_2 = \sqrt{P_1 P_3} \quad P_3 = \sqrt{P_2 P_4}$

$P_2 = \sqrt{P_1 \sqrt{P_2 P_4}}$

$P_2^{\,3} = P_1^{\,2} P_4 \quad P_2 = \sqrt[3]{P_1^{\,2} P_4} = \sqrt[3]{(5\,\text{MPa})^2\, 0.1\,\text{MPa}}$

$= 1.36\,\text{MPa} \sim 1.4\,\text{MPa}$

$P_3 = \sqrt{P_2 P_4} = \sqrt{(1.36\,\text{MPa})(0.1\,\text{MPa})} = 0.369\,\text{MPa} \sim 0.4\,\text{MPa}$

② Stage 2' $P_2 = 1.4\,\text{MPa} \quad S_2 = 6.98\,\text{kJ/kgK}$

T °C	H kJ/kg	S kJ/kg K
300	3040	6.95
350	3150	7.14

$W_{2'} = H_{2'} - H_{in}$
$= -380\,\text{kJ/kg}$

$H_{2'} = 3040\,\frac{\text{kJ}}{\text{kg}} + (3150-3040)\,\frac{\text{kJ}}{\text{kg}}\,\frac{(6.98-6.95)\,\text{kJ/kgK}}{(7.14-6.95)\,\text{kJ/kgK}}$

$= 3050\,\frac{\text{kJ}}{\text{kg}}$

$T_{2'} = 300\,°\text{C} + 50\,\text{K}\left(\frac{0.03\,\text{kJ/kgK}}{0.19\,\text{kJ/kgK}}\right) = 308\,°\text{C}$

Stage 2 $H_2 = 3430\,\text{kJ/kg} - 0.80(3430-3050)\,\frac{\text{kJ}}{\text{kg}} = 3130\,\frac{\text{kJ}}{\text{kg}}$

$T_2 = 300\,°\text{C} + 50\,°\text{C}\left(\frac{3130-3040}{3150-3040}\right)\frac{\text{kJ/kg}}{\text{kJ/kg}} = 341\,°\text{C}$

$W_2 = -300\,\text{kJ/kg}$

$S_2 = 6.95\,\frac{\text{kJ}}{\text{kgK}} + 0.818\,(7.14-6.95)\,\frac{\text{kJ}}{\text{kgK}}$

$= 7.11\,\frac{\text{kJ}}{\text{kgK}}$

(3) Step 3'

$P_{3'} = 0.4\,MPa \quad S_{3'} = 7.11 \frac{kJ}{kg\,K}$

$$H_{3'} = 2710\frac{kJ}{kg} + \frac{(7.11-6.93)\frac{kJ}{kg\,K}}{(7.17-6.93)\frac{kJ}{kg\,K}}(2860-2710)\frac{kJ}{kg}.$$

0.75

T °C	H kJ/kg	S kJ/kg K
150	2710	6.93
200	2860	7.17

$= 2830\ kJ/kg$

$T_{3'} = 150°C + 50°C(0.75) = 188°C$

T °C	H kJ/kg	S kJ/kg K
200	2860	7.17
250	2960	7.38

$H_3 = 2890\ kJ/kg$

$$S_3 = 7.17\frac{kJ}{kg\,K} + (7.38-7.17)\frac{kJ}{kg\,K}\frac{(2890-2860)\ kJ/kg}{(2960-2860)\ kJ/kg}$$

0.3

$= 7.23\ kJ/kg\,K$

$T_3 = 200°C + 0.3(50°C)$

$= 215°C$

(4) Step 4' $P = 0.1\,MPa$ $S_{4'} = 7.23$

$T_{4'} = 99.6\ °C$

$W_{4'} = 260\frac{kJ}{kg}$

$H^L = 418\ kJ/kg$

$H^V = 2675\ kJ/kg$

$S^L = 1.30\ kJ/kg\,K$

$S^V = 7.36\ kJ/kg\,K$

$$H_{4'} = 418\frac{kJ}{kg} + (2675-418)\frac{kJ}{kg}\ \frac{7.23-1.3}{7.36-1.3}\frac{kJ/kg\,K}{kJ/kg\,K}$$

0.979

$= 2630\ kJ/kg$

$T_{4'} = 99.6°C$

Step 4 $P = 0.1\,MPa$ $H_4 = 2680\ kJ/kg$

$W_4 = 208\frac{kJ}{kg}$

SV

$S_4\ 7.36\ kJ/kg\,K$

(5) Step 5 SL $P = 0.1\,MPa$ $H^L = 418\ kJ/kg$ $S^L = 1.30\ kJ/kg$

$T_5 = 99.6°C$

Cyc 6 B

Stage 4' $P = 0.1\ MPa \quad S = 6.98$

$T = 99.6°C$

H^L	418	kJ/kg
H^V	2680	kJ/kg
S^L	1.30	kJ/kg K
S^V	7.36	kJ/kg K

$$H_{4'} = 418\frac{kJ}{kg} + (2680-418)\frac{kJ}{kg}\left(\frac{(7.36-1.30)\frac{kJ}{kg\,K}}{(6.98-1.30)\frac{kJ}{kg\,K}}\right)^{-1}$$

0.937

$$= 2540\frac{kJ}{kg}$$

$T_{4'} = 99.6°C$

Stage 4

$H_4 = 2720\frac{kJ}{kg}$

T °C	H kJ/kg	S kJ/kg K
100	2680	7.36
150	2780	7.61

$$S_4 = 7.36\frac{kJ}{kg\,K} + (7.61-7.36)\frac{kJ}{kg\,K}\frac{2720-2680\ \frac{kJ}{kg}}{\left(100\frac{kJ}{kg}\right)}$$

(0.4)

$$= 7.46\frac{kJ}{kg\,K}$$

$$T_4 = 100°C + 50°C(0.4) = 120°C$$

Stage 6'

$S_{6'} = 1.30\frac{kJ}{kg\,K}$

$T = 100°C$

$H = 423\frac{kJ}{kg}$

$$\eta_A = \frac{(300+240+208-6.00)\frac{kJ}{kg}}{(3430-424)\frac{kJ}{kg}} = 0.247$$ 47.7% of Carnot

$$\eta_B^{eff} = \frac{(712-6)\ kJ/kg}{(3430-424)\ kJ/kg} = 0.235$$ 45.4% of Carnot

$$\eta_{Carnot}^{eff} = \frac{500°C - 99.6°C}{(500+273)K} = 0.518$$

$\Delta = 2\%$

net worth it