Practical Rankine cycle

define some units $kJ := 10^3 \cdot J$

$kN := 10^3 \cdot N$ $kPa := 10^3 \cdot Pa$

$MPa := 10^6 Pa$ $bar := 0.1MPa$

this file calculates ***irreversible*** Rankine cycle with following parameters:
condenser 40 deg C
steam pressure 30 bars (3 MPa)
superheat 460 deg_C
file derived from Rankine class example.mcd

differences/assumptions:

1-2 adiabatic irreversible compression
2-3 heat transfer - small pressure loss - ignore
3-4 adiabatic irreversible expansion
4-1 heat transfer to saturated liquid - small subcooling - ignored

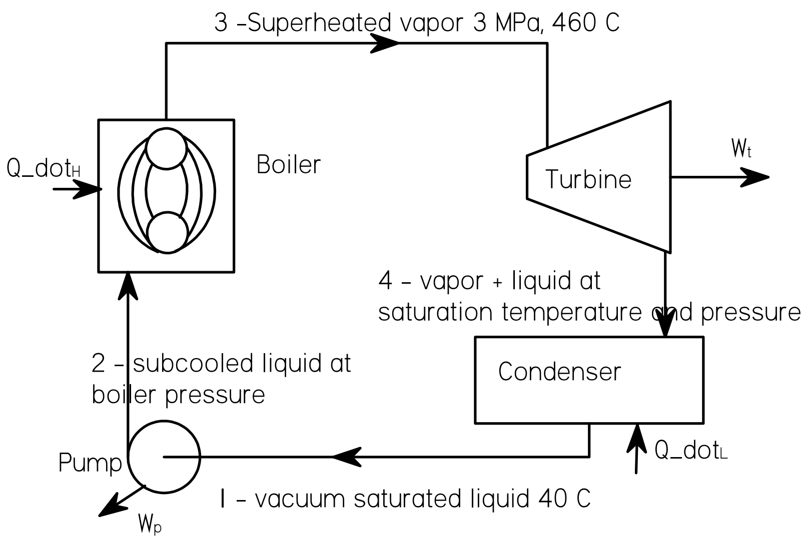
states are the same

1 - vacuum; saturated liquid

2 - sub cooled liquid at boiler pressure

3 - superheated vapor

4 - vapor + liquid @ saturation temperature and pressure



xx_s designates reversible (isentropic) process where different

refer to T-s and H-s diagrams at end of file

state 1: condenser outlet

same as reversible

Table 1 or Table A.1.1

$T_1 := 40$ $p_1 := 7.384kPa$ $v_{f\_1} := 0.0010078 \frac{m^3}{kg}$ $v_1 := v_{f\_1}$

$s_{f\_1} := 0.5725 \frac{kJ}{kg \cdot K}$ $s_{fg\_1} := 7.6845 \frac{kJ}{kg \cdot K}$ $h_{f\_1} := 167.57 \frac{kJ}{kg}$ $h_{fg\_1} := 2406.7 \frac{kJ}{kg}$

$s_1 := s_{f\_1}$ $h_1 := h_{f\_1}$

▸ properties p =3 Mpa

state 2: pump outlet - reversible

assume $v_f = v_1$constant, isentropic, ds = 0 =>T*ds= 0 => h2 = h1+v1*dp from relationships Tds = dh + v*dp integrated with constant v and Tds = 0

$s_{2s} := s_1$

$p_2 := 30bar$ $h_{2s} := h_1 + v_1 \cdot (p_2 - p_1)$ $h_{2s} = 170.586 \frac{kJ}{kg}$

$w_{ps} := h_1 - h_{2s}$ $w_{ps} = -3.016 \frac{kJ}{kg}$

calc of T in earlier version incorrect see VW&S 5.18 with C = 4.184 kJ/(kg*K) Table A.7

using C_p $Cp := 4.184 \frac{kJ}{kg}$ $\frac{kJ}{kg \cdot K}$ actual units

and ... eqn 5.18 $h_2 - h_1 = Cp \cdot (T_2 - T_1)$

@ T = 40 C
p = 3 MPa

and ... eqn 5.18 $h_2 - h_1 = Cp \cdot (T_2 - T_1)$

$p_2 = 3 MPa$

$h_{22s} := 170.21 \cdot \frac{kJ}{kg}$ $h_{2s} = 170.586 \frac{kJ}{kg}$ $T_{22} := 40$ $T_{2s} := T_{22} + \frac{h_{2s} - h_{22s}}{Cp}$ $T_{2s} = 40.09$

state 2: pump outlet - **irreversible**

pressure same as above ...

pump efficiency ... $\eta_p = \frac{reversible\_\Delta h}{actual\_\Delta h} = \frac{h_1 - h_{2s}}{h_1 - h_2}$ $h_{2s} = h_1 + v_1 \cdot (p_2 - p_1)$ $\eta_p := 0.9$

$h_2 := h_1 + \frac{v_1 \cdot (p_2 - p_1)}{\eta_p}$ $h_2 = 170.921 \frac{kJ}{kg}$ $w_p := h_1 - h_2$ $w_p = -3.351 \frac{kJ}{kg}$

$T_2 := T_1 + \frac{h_2 - h_1}{Cp}$ $T_2 = 40.801$

@ T = 40 C
p = 3 MPa

and ... eqn 5.18 $h_2 - h_1 = Cp \cdot (T_2 - T_1)$

$p_2 = 3 MPa$

$h_{22} := 170.21 \cdot \frac{kJ}{kg}$ $h_2 = 170.921 \frac{kJ}{kg}$ $T_{22} := 40$ $T_2 := T_{22} + \frac{h_2 - h_{22}}{Cp}$ $T_2 = 40.17$

find s from p = p_2, h = h_2: interpolate from tbl_2_3MPa row 2 (index 1)

▶ interpolation details

T	s	h
40	0.571	170.21
80	1.073	337.26

data = (above) input = h_2 w/o units input = 170.921

interpolate for s_2 and T_2 $s_2 = 0.573 \frac{1}{K} \frac{kJ}{kg}$ T_int = 40.17

N.B. different from T_2 above ?? granularity; investigating

summary ..

reversible ... $h_{2s} = 170.586 \frac{kJ}{kg}$ $T_{2s} = 40.09$ $s_{2s} = 0.572 \frac{1}{K} \frac{kJ}{kg}$ $w_{ps} = -3.016 \frac{kJ}{kg}$

irreversible ... $h_2 = 170.921 \frac{kJ}{kg}$ $T_2 = 40.17$ $s_2 = 0.573 \frac{1}{K} \frac{kJ}{kg}$ $w_p = -3.351 \frac{kJ}{kg}$

state 3: boiler outlet

same as reversible

$p_3 := p_2$ $T_3 := 460$ $p_3 = 3 MPa$ $h_3 := 3366.5 \frac{kJ}{kg}$ $s_3 := 7.113 \frac{kJ}{kg \cdot K}$

from interpolation Table A.1.3 P=3MPa page 622 interpolation_class_example.mcd

state 4: turbine outlet -reversible

isentropic expansion to 40 deg C
determine h_4 from x

$s_{4s} := s_3$

$s_4 = s_{f\_1} + x \cdot s_{fg\_1}$ => $xs := \frac{s_{4s} - s_{f\_1}}{s_{fg\_1}}$ $xs = 0.851$

$h_{4s} := h_{f\_1} + h_{fg\_1} \cdot xs$ $h_{4s} = 2216 \frac{kJ}{kg}$ $w_{ts} := h_3 - h_{4s}$ $w_{ts} = 1151 \frac{kJ}{kg}$ $T_{4s} := 40$

state 4: turbine outlet - **irreversible**

same temperature $T_4 := 40$

$\eta_t = \frac{actual\_enthalpy\_change}{reversible\_enthalpy\_change} = \frac{h_3 - h_4}{h_3 - h_{4s}}$ $h_4 = h_3 - \eta_t \cdot (h_3 - h_{4s})$ $\eta_t := 0.9$

$h_4 := h_3 - \eta_t \cdot (h_3 - h_{4s})$ $h_4 = 2331.034 \frac{kJ}{kg}$

work of turbine $w_t := w_{ts} \cdot \eta_p$ $w_t = 1035.466 \frac{kJ}{kg}$ or ... $w_t := h_3 - h_4$ $w_t = 1035.466 \frac{kJ}{kg}$

now calculate x should be > xs
see plot below

$h_4 = h_{f\_1} + h_{fg\_1} \cdot x$ $x := \frac{h_4 - h_{f\_1}}{h_{fg\_1}}$ $x = 0.899$

$s_4 := s_{f\_1} + x \cdot s_{fg\_1}$ $s_4 = 7.48 \frac{1}{K} \frac{kJ}{kg}$

summary ..

reversible ... $h_{4s} = 2215.982 \frac{kJ}{kg}$ $T_{4s} = 40$ $s_{4s} = 7.113 \frac{1}{K} \frac{kJ}{kg}$ $w_{ts} = 1150.518 \frac{kJ}{kg}$

irreversible ... $h_4 = 2331.034 \frac{kJ}{kg}$ $T_4 = 40$ $s_4 = 7.48 \frac{1}{K} \frac{kJ}{kg}$ $w_t = 1035.466 \frac{kJ}{kg}$

thermal efficiency - reversible

$\eta_{th} = \frac{work\_net}{Q_H} = \frac{Q_H + Q_L}{Q_H} = \frac{w_t + w_p}{Q_H} = \frac{(h_3 - h_4) + (h_1 - h_2)}{h_3 - h_2}$

$\eta_{ths} := \frac{(h_3 - h_{4s}) + (h_1 - h_{2s})}{h_3 - h_{2s}}$ $\eta_{ths} = 0.359$ $\eta_{ths} := \frac{w_{ts} + w_{ps}}{h_3 - h_{2s}}$ $\eta_{ths} = 0.359$

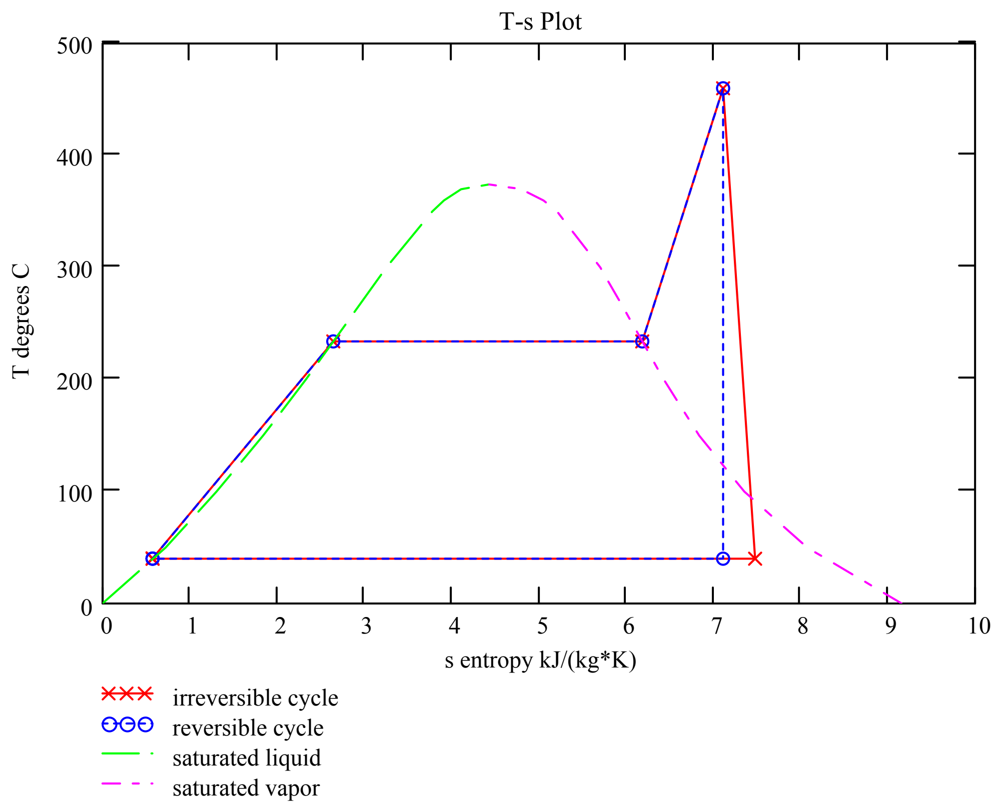
$Q_{Hs} := h_3 - h_{2s}$ $Q_{Ls} := h_1 - h_{4s}$ $\eta_{th\_1s} := \frac{Q_{Hs} + Q_{Ls}}{Q_{Hs}}$ $\eta_{th\_1s} = 0.359$

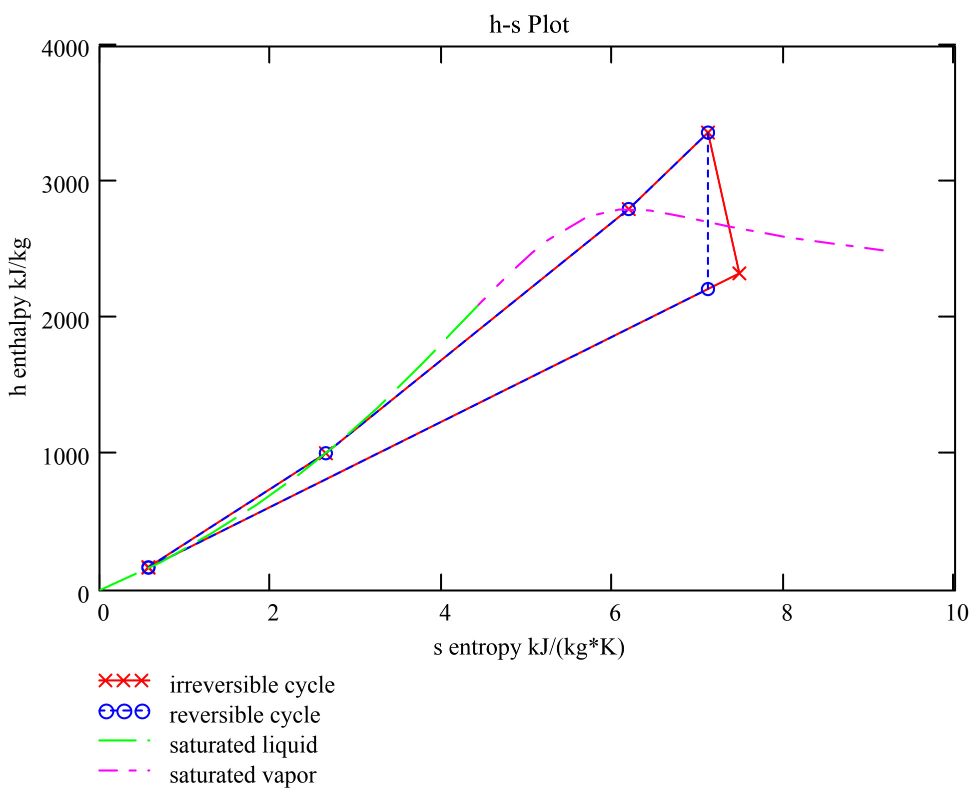
thermal efficiency - **irreversible**

$\eta_{th} := \frac{(h_3 - h_4) + (h_1 - h_2)}{h_3 - h_2}$ $\eta_{th} = 0.323$ $\eta_{th} := \frac{w_t + w_p}{h_3 - h_2}$ $\eta_{th} = 0.323$

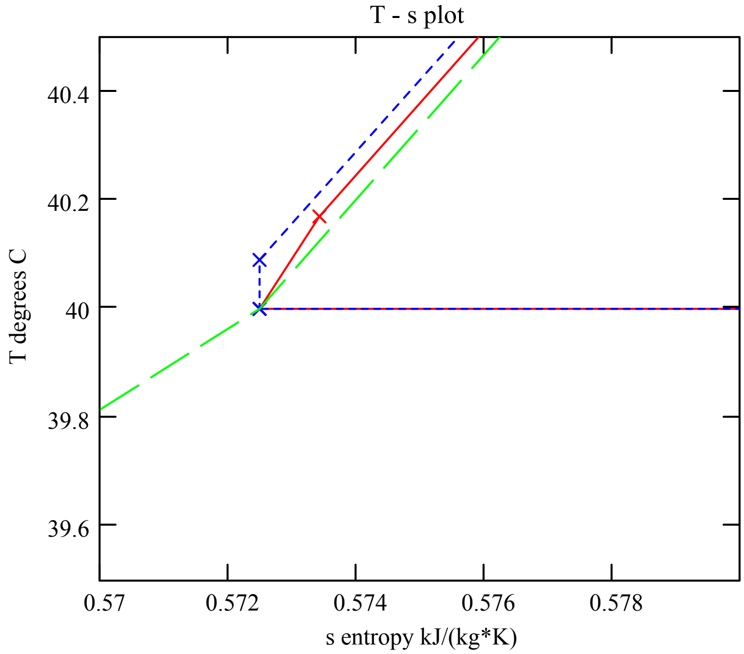
$Q_H := h_3 - h_2$ $Q_L := h_1 - h_4$ $\eta_{th\_1} := \frac{Q_H + Q_L}{Q_H}$ $\eta_{th\_1} = 0.323$

▸ data for saturation curve
▸ data for T s and H s plots

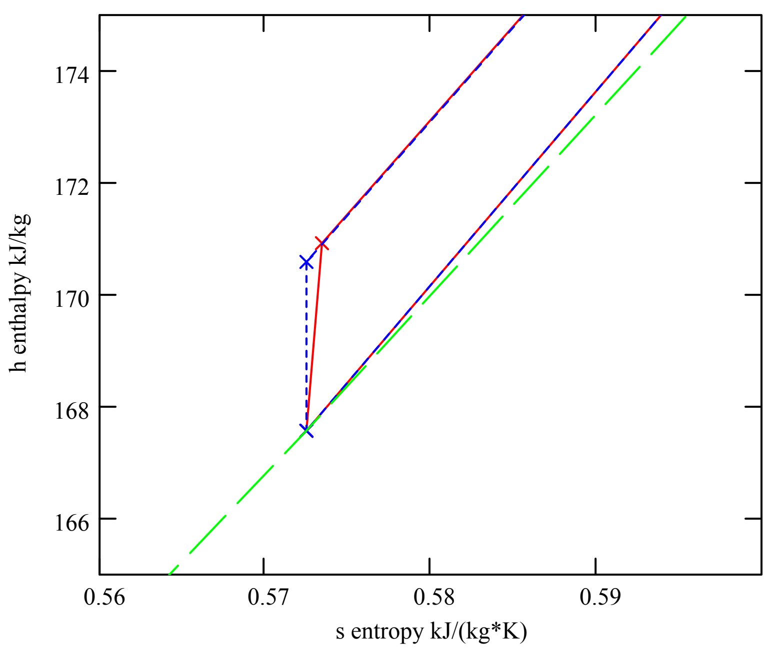

T-s Plot
500
400
300
200
100
0
T degrees C
0
1
2
3
4
5
6
7
8
9
10
s entropy kJ/(kg*K)
irreversible cycle
reversible cycle
saturated liquid
saturated vapor


h-s Plot
4000
3000
2000
1000
0
h enthalpy kJ/kg
0
2
4
6
8
10
s entropy kJ/(kg*K)
irreversible cycle
reversible cycle
saturated liquid
saturated vapor

close up of points 1 and 2



much expanded ref: class example scale
39.5 < T < 40.5
0.57 < s < 0.58



much expanded ref: class example scale
165 < h < 175
0.56 < s < 0.6