ON THE OPTIMIZATION OF ORC SYSTEMS

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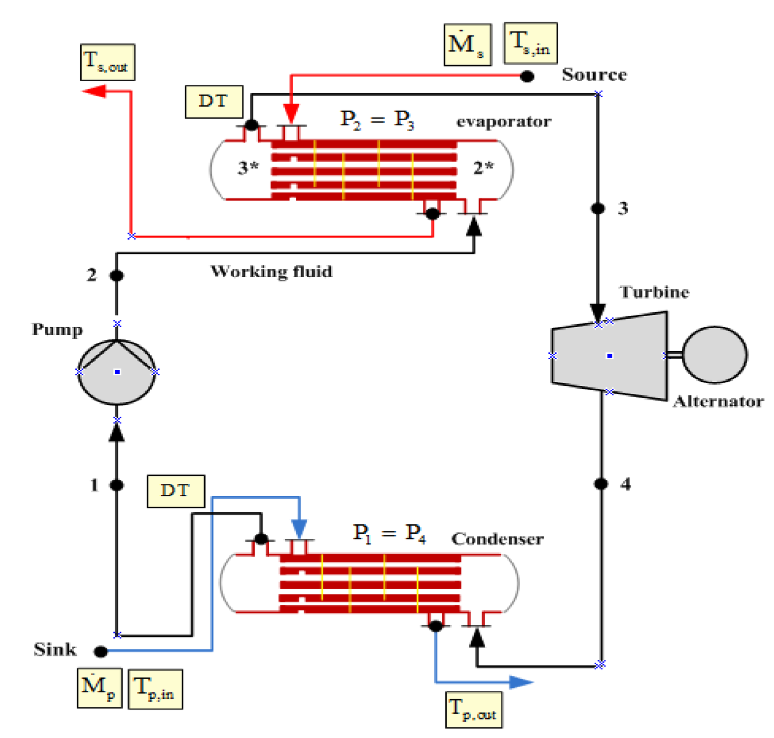
1. Introduction

Subcritical and transcritical Rankine cycles operating between a low temperature heat source ($T_{s,in}$ = 100, 165 and 230 °C) of fixed volume flowrate (1.2 10^6 m^3/h, idealized as atmospheric air at P_s = 101 kPa) and a fixed temperature heat sink (water at $T_{p,in}$ = 10 °C) have been analyzed using the principles of classical and finite-size thermodynamics. The model of the system and its validation have been presented elsewhere.

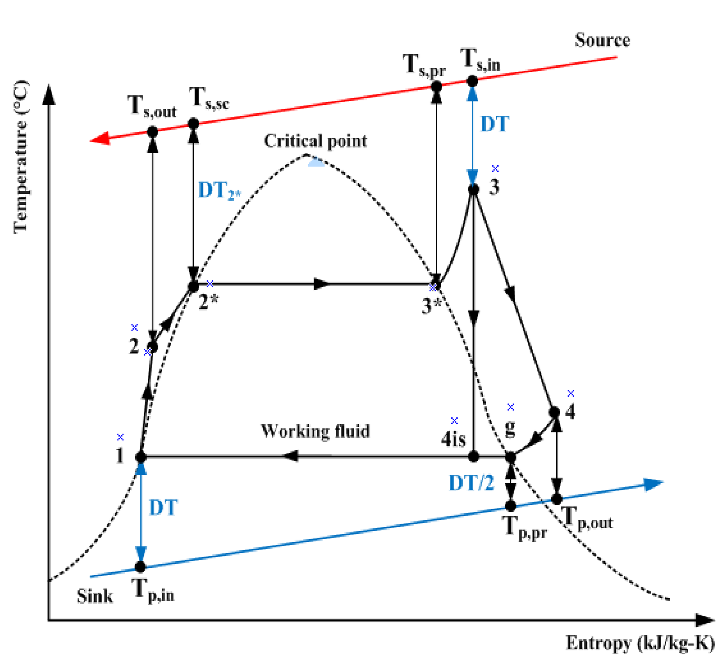
Optimum operating conditions (pressure of the working fluid during heat addition, P_{ev}, and temperature difference DT between the working fluid and the two external fluids) and the corresponding values of several system characteristics have been determined for different net power outputs using the variable metric method for each of the following objectives: maximum thermal efficiency, minimum total exergy destruction, minimum total thermal conductance of the two heat exchangers UA_t and minimum turbine size SP.

Typical results with R134a as the working fluid are presented.

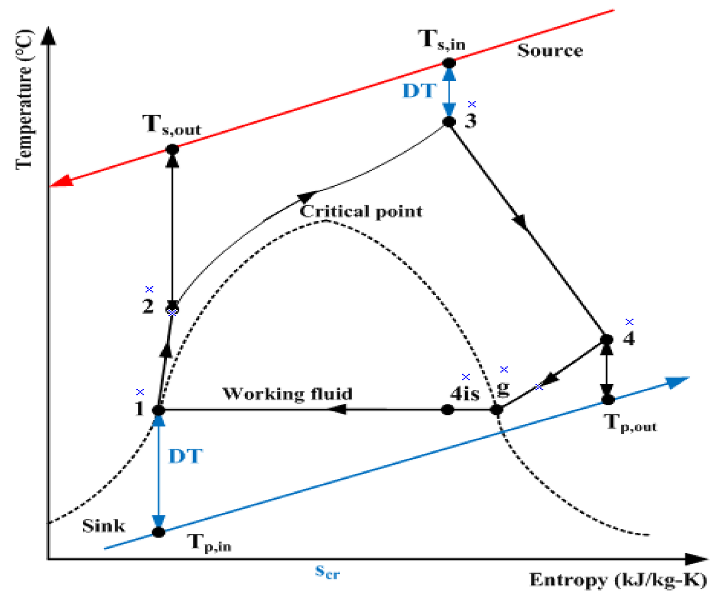
2. Assumptions and Model



Schematic representation of the system



T-s Diagram of subcritical cycle



T-s Diagram of transcritical cycle

2.1 Assumptions:

- Each component is an open system in steady-state operation
- Kinetic and potential energy are neglected
- At exit from condenser the working fluid is saturated liquid
- Pressure and heat losses are neglected
- Fixed temperature heat sink (water at $T_{p,in}$ = 10 °C)

2.2 Equations:

- Conservation of mass and energy for each component
- Relations between thermodynamic properties
- Definition of turbine and pump efficiencies

2.3 Performance indicators:

- Thermal efficiency : (η_{th})
- Non dimensional total exergy losses : (β)
  $\beta = Ed_t / M_s\, e_{s,in}$
- Non dimensional net output : (α)
  $\alpha = W_{net}/W_{ref}$
  where $W_{ref} = M_s Cp_s (T_{s,in} - T_{p,in}) [1 - (T_{p,in}/T_{s,in})]$
- Total UA_t
- Evaporator pinch
- Turbine size (SP)

3. Results for R134a

$T_{s,in}$ = 100 °C
(Subcritical Cycle)
DT (5 -25) °C
W_{ref} = 6897 kW

α	$\eta_{th,max}$ %	$P_{ev,opt}$ (kPa)	DT_{opt} (°C)	β %	UA_t (kW/K)	SP (m)	$\dot{m}$ (kg/s)	x_4	$Pinch_{ev}$ (°C)
0.04	11.26	2365.0	5.00	7.64	662.3	0.0502	10.376	1.122	5.00
0.08	11.26	2365.0	5.00	14.19	1351.5	0.0710	20.753	1.122	5.00
0.12	11.26	2365.0	5.00	19.61	2087.3	0.0870	31.129	1.122	5.00

α	β_{min} %	$P_{ev,opt}$ (kPa)	DT_{opt} (°C)	η_{th} %	UA_t (kW/K)	SP (m)	$\dot{m}$ (kg/s)	x_4	$Pinch_{ev}$ (°C)
0.04	7.64	2365.0	5.00	11.26	662.3	0.0502	10.376	1.122	5.00
0.08	14.19	2365.0	5.00	11.26	1351.5	0.0710	20.753	1.122	5.00
0.12	19.61	2365.0	5.00	11.26	2087.3	0.0870	31.129	1.122	5.00

α	$UA_{t,min}$ (kW/K)	$P_{ev,opt}$ (kPa)	DT_{opt} (°C)	β %	η_{th} %	SP (m)	$\dot{m}$ (kg/s)	x_4	$Pinch_{ev}$ (°C)
0.04	341.0	2365.0	21.69	12.09	8.07	0.0559	18.101	1.012	18.09
0.08	749.0	2320.9	18.80	20.54	8.55	0.0773	32.504	1.042	12.71
0.12	1268.3	2205.5	15.91	26.93	8.84	0.0945	44.678	1.079	8.57

α	SP_{min} (m)	$P_{ev,opt}$ (kPa)	DT_{opt} (°C)	β %	η_{th} %	UA_t (kW/K)	$\dot{m}$ (kg/s)	x_4	$Pinch_{ev}$ (°C)
0.04	0.0502	2365.0	5.00	7.64	11.26	662.3	10.376	1.122	5.00
0.08	0.0710	2365.0	5.00	14.19	11.26	1351.5	20.753	1.122	5.00
0.12	0.0870	2365.0	5.00	19.61	11.26	2087.3	31.129	1.122	5.00

$T_{s,in}$ = 165 °C
(Trancritical Cycle)
DT (5 -25) °C
W_{ref} = 17565 kW

α	$\eta_{th,max}$ %	$P_{ev,opt}$ (kPa)	DT_{opt} (°C)	β %	UA_t (kW/K)	SP (m)	$\dot{m}$ (kg/s)	x_4	$Pinch_{ev}$ (°C)
0.04	15.94	7120.9	5.00	7.96	1044.7	0.0568	16.882	1.176	5.00
0.08	15.94	7120.9	5.00	14.93	2115.3	0.0803	33.764	1.176	5.00
0.12	15.94	7120.9	5.00	20.87	3222.2	0.0984	50.646	1.176	5.00

α	β_{min} %	$P_{ev,opt}$ (kPa)	DT_{opt} (°C)	η_{th} %	UA_t (kW/K)	SP (m)	$\dot{m}$ (kg/s)	x_4	$Pinch_{ev}$ (°C)
0.04	7.96	7081.6	5.00	15.94	1042.9	0.0568	16.849	1.178	5.00
0.08	14.93	7078.6	5.00	15.94	2111.3	0.0803	33.694	1.178	5.00
0.12	20.87	7075.0	5.00	15.94	3215.5	0.0984	50.531	1.178	5.00

α	$UA_{t,min}$ (kW/K)	$P_{ev,opt}$ (kPa)	DT_{opt} (°C)	β %	η_{th} %	SP (m)	$\dot{m}$ (kg/s)	x_4	$Pinch_{ev}$ (°C)
0.04	390.6	4968.1	25.00	11.84	11.84	0.0589	25.936	1.199	25.00
0.08	814.5	4968.1	25.00	21.86	11.84	0.0833	51.871	1.199	25.00
0.12	1295.0	4968.1	25.00	29.87	11.84	0.1019	77.863	1.197	25.00
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α	SP_{min} (m)	$P_{ev,opt}$ (kPa)	DT_{opt} (°C)	β %	η_{th} %	UA_t (kW/K)	$\dot{m}$ (kg/s)	x_4	$Pinch_{ev}$ (°C)
0.04	0.0565	6428.5	10.47	8.76	14.88	600.5	18.678	1.183	10.47
0.08	0.0800	6428.7	10.47	16.39	14.88	1225.4	37.358	1.183	10.47
0.12	0.0979	6429.1	10.47	22.81	14.88	1886.1	56.033	1.183	10.47

$T_{s,in}$ = 230 °C
(Trancritical Cycle)
DT (5 -25) °C
W_{ref} = 31158 kW

α	$\eta_{th,max}$ %	$P_{ev,opt}$ (kPa)	DT_{opt} (°C)	β %	UA_t (kW/K)	SP (m)	$\dot{m}$ (kg/s)	x_4	$Pinch_{ev}$ (°C)
0.04	18.63	15468.0	5.00	8.54	1316.2	0.0613	21.370	1.365	5.00
0.08	18.63	15468.0	5.00	16.12	2660.2	0.0866	42.740	1.365	5.00
0.12	18.63	15468.0	5.00	22.66	4042.6	0.1061	64.111	1.365	5.00

α	β_{min} %	$P_{ev,opt}$ (kPa)	DT_{opt} (°C)	η_{th} %	UA_t (kW/K)	SP (m)	$\dot{m}$ (kg/s)	x_4	$Pinch_{ev}$ (°C)
0.04	8.54	15323.4	5.00	18.63	1314.0	0.0613	21.329	1.367	5.00
0.08	16.12	15313.1	5.00	18.63	2655.04	0.0867	42.652	1.367	5.00
0.12	22.66	15299.8	5.00	18.63	4034.7	0.1061	63.966	1.368	5.00

α	$UA_{t,min}$ (kW/K)	$P_{ev,opt}$ (kPa)	DT_{opt} (°C)	β %	η_{th} %	SP (m)	$\dot{m}$ (kg/s)	x_4	$Pinch_{ev}$ (°C)
0.04	450.0	9038.7	25.00	11.39	14.78	0.0599	29.182	1.464	25.00
0.08	928.9	9085.7	25.00	21.20	14.79	0.0847	58.386	1.462	25.00
0.12	1452.4	9180.0	25.00	29.25	14.82	0.1036	87.654	1.458	25.00

α	SP_{min} (m)	$P_{ev,opt}$ (kPa)	DT_{opt} (°C)	β %	η_{th} %	UA_t (kW/K)	$\dot{m}$ (kg/s)	x_4	$Pinch_{ev}$ (°C)
0.04	0.0589	12813.2	24.54	10.98	15.25	466.5	30.813	1.333	24.54
0.08	0.0832	12813.2	24.54	20.50	15.25	961.6	61.626	1.333	24.54
0.12	0.1019	12813.2	24.54	28.42	15.25	1500.4	92.439	1.333	24.54

4. Conclusions

- At the turbine outlet the fluid is always superheated vapor.
- The lowest exergy losses as well as the smallest total conductance and turbine are obtained with $T_{s,in}$ = 100 °C while the highest thermal efficiencies are obtained with $T_{s,in}$ = 230 °C.
- The combinations of $\mathbf{P_{ev}}$ and **DT** which maximize $\boldsymbol{\eta_{th}}$ and minimize **β** are essentially identical. For these conditions **α** has no effect on $\boldsymbol{\eta_{th}}$. On the other hand **β** as well as **SP** and $\mathbf{UA_t}$ increase with **α**, albeit at different rates. In all these cases the pinch in the high temperature heat exchanger occurs at the heat source inlet.
- The combinations of $\mathbf{P_{ev}}$ and **DT** which minimize $\mathbf{UA_t}$ and **SP** are different from each other and from those which maximize $\boldsymbol{\eta_{th}}$. The conditions which minimize $\mathbf{UA_t}$ give turbine sizes not much bigger than the corresponding minimum size; on the other hand, the conditions which minimize **SP** give a $\mathbf{UA_t}$ significantly bigger than the corresponding minimum values.