Exergy Analysis of Engineering Applications

Dr. Md. Zahurul Haq, *Ph.D., CEA, FBSME, FIEB*

Professor
Department of Mechanical Engineering
Bangladesh University of Engineering & Technology (BUET)
Dhaka-1000, Bangladesh

zahurul@me.buet.ac.bd
http://zahurul.buet.ac.bd/

ME 407: Advanced Thermodynamics
http://zahurul.buet.ac.bd/ME407/

Second Law Efficiency (η_{II}) or Effectiveness (ϵ)

- A performance parameter based on the exergy concept is know as Second Law Efficiency (η_{II}) or as Second Law Effectiveness (ϵ).
- A first-law efficiency gauges how well the energy is used when compared against an ideal process, whereas an effectiveness indicates how well exergy is utilized.
- Second Law efficiency can approach unity for a thermodynamically perfect device and it therefore provides a true indication of the efficiency of the system.

$$\eta_{II} \equiv \epsilon \equiv \frac{\text{exergy of desired output}}{\text{exergy supplied}} = 1 - \frac{\text{exergy destruction}}{\text{exergy supplied}}$$

Equations: CM & CV Systems

CM System:

- $Q - W = \Delta U$
- $W_u = W - P_0\Delta V = W - W_0$
- $\phi = (u - u_0) + P_0(v - v_0) - T_0(s - s_0)$
- $\Phi_Q = \sum_{j=1}^{n} Q_j \left(1 - \frac{T_0}{T_j}\right)$
- $\Delta\Phi = \Phi_Q - W_u - I_{cm}$

SSSF CV System:

- $Q - W_{sf} = m(\Delta h + \Delta pe + \Delta he) = m\Delta h$
- $W_u = W_{sf} - P_0\Delta V^{\nearrow 0} = W_{sf}$
- $\psi = (h - h_0) - T_0(s - s_0) + \frac{\mathbb{V}^2}{2} + gz$
- $\Phi_Q = \sum_{j=1}^{n} Q_j \left(1 - \frac{T_0}{T_j}\right)$
- $\Delta(m\psi) = \sum_e \dot{m}_e\psi_e - \sum_i \dot{m}_i\psi_i = \dot{\Phi}_Q - \dot{W}_u - \dot{I}_{cv}$

Adiabatic Compression & Pumping

CM process:

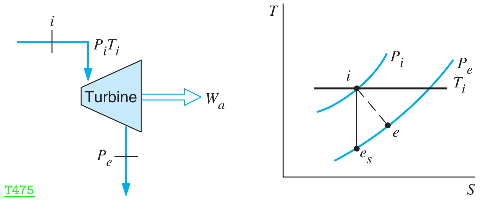
- $\Delta\Phi = \Phi_Q - W_u - I_{cm}$
- $W_u = W_{act} + P_0\Delta V$
- $\boxed{\epsilon \equiv \frac{\Delta\Phi}{W_{act}}}$

CV process:

- $\Delta\Psi = \Phi_Q - W_u - I_{cv}$
- $W_u = W_{act}$
- $\boxed{\epsilon \equiv \frac{\Delta\Psi}{W_{act}}}$

- Effectiveness (ϵ) is defined as the increase in the specific availability of the fluid per unit of actual work input.
- First law efficiency, $\eta \equiv \frac{W_s}{W_{act}}$.

Steam/Gas Turbine, Throttling & Nozzle



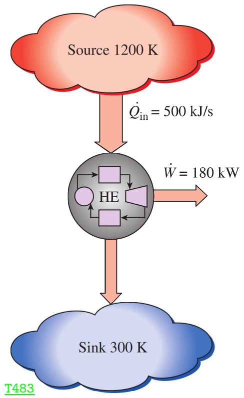
Turbines:

- $\eta = \frac{w_a}{\Delta h}$
- $\Delta\psi = \phi_Q - w_u - i_{cv}$
- $\boxed{\epsilon = \frac{w_a}{\Delta\psi}}$

- Throttling:
- $0 = \cancelto{0}{q} - \cancelto{0}{w} + h_i - h_e - \cancelto{0}{\Delta ke}$
- $\Delta\psi = \cancelto{0}{\phi_Q} - \cancelto{0}{w_u} - I_{cv}$
- $\boxed{\epsilon = \frac{\psi_e}{\psi_i}}$

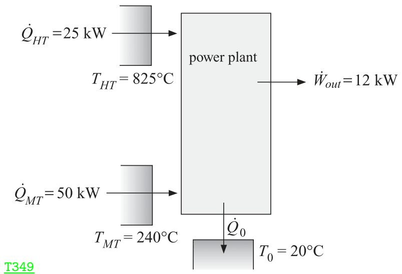
- Nozzle:
- $\cancelto{0}{q} + \cancelto{0}{w} = h_e - h_i + \Delta ke$
- $\eta = \frac{\Delta ke_a}{\Delta ke_s}$
- $\Delta\psi = \cancelto{0}{\Phi_Q} + \cancelto{0}{w_u} - I_{cv}$
- $\boxed{\epsilon = \frac{\Psi_e}{\Psi_i}}$

Cyclic Heat Engine



- $\eta_{th} = \frac{W_{out}}{Q_H} = \frac{180}{500} = 0.36$
- $\eta_{Carnot} = 1 - \frac{T_L}{T_H} = 1 - \frac{300}{1200} = 0.75$
- $\Phi_Q = Q_H \eta_{Carnot} = (500)(0.75) = 375$ kW
- $\epsilon = \frac{W_{out}}{\Phi_Q} = \frac{180}{375} = 0.48$
- $\epsilon = \frac{W_{out}}{\Phi_Q} = \frac{\eta_{th} Q_H}{\eta_{Carnot} Q_H} = \frac{\eta_{th}}{\eta_{Carnot}} = \frac{0.36}{0.75} = 0.48$

Power Plant Using Different Heat Sources



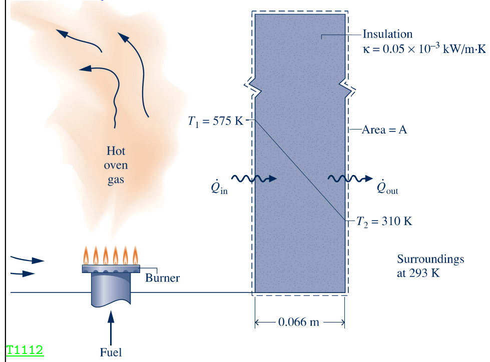
- $\eta_I = \frac{W_{out}}{Q_{HT}+Q_{MT}} = \frac{12}{25+50} = 16\%$
- $\Phi_{Q,HT} = 25\left(1 - \frac{293}{1098}\right) = 18.33$
- $\phi_{Q,MT} = 50\left(1 - \frac{293}{513}\right) = 21.44$
- $\eta_{II} = \frac{W_{out}}{\Phi_{Q,HT}+\Phi_{Q,MT}} = 30.2\%$

Energy balance: $\dot{Q}_{HT} + \dot{Q}_{MT} - \dot{Q}_{0,rev} - \dot{W}_{out,rev} = 0$

Entropy balance: $\frac{\dot{Q}_{HT}}{T_{HT}} + \frac{\dot{Q}_{MT}}{T_{MT}} - \frac{\dot{Q}_{0,rev}}{T_0} = 0$

Heat Conduction Through Wall

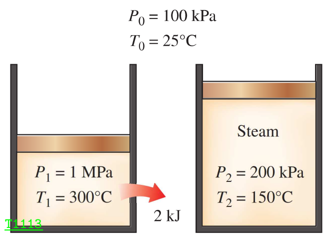
Moran, Ex. 7-3 ▷



- $\dot{q} = -k\left[\frac{T_2 - T_1}{L}\right] = 0.2\ \frac{kW}{m^2}$
- $\dot{\phi}_{Q,in} = q\left[1 - \frac{T_0}{{}_1T}\right] = 0.1\ \frac{kW}{m^2}$
- $\dot{\phi}_{Q,out} = q\left[1 - \frac{T_0}{{}_2T}\right] = 0.01\ \frac{kW}{m^2}$
- $I_Q = \dot{\phi}_{Q,in} - \dot{\phi}_{Q,out} = 0.09\ \frac{kW}{m^2}$

CM System: Expansion of Steam inside Cylinder

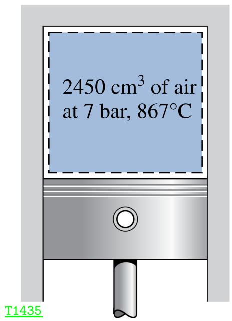
Cengel, Ex. 8-11 ▷ Piston-cylinder assembly contains 0.05 kg steam.



- $Q - W = m(\Delta u + \Delta KE + \Delta PE) \simeq m\Delta u$
- $\phi \equiv (u - u_0) + P_0(v - v_0) - T_0(s - s_0)$
- $W_u = W - W_0 = 8.826 - 3.509 = 5.317$ kJ
- $\phi_Q = 0$: Heat loss to T_0
- $\Delta\phi = -9.648$ kJ
- $I_{CM} = \phi_Q - W_u - \Delta\phi = 4.331$ kJ
- $\epsilon = \frac{W_u}{-\Delta\phi} = 0.551$

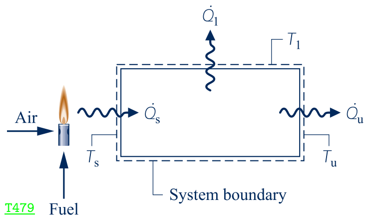
Evaluating the Exergy of Exhaust Gas

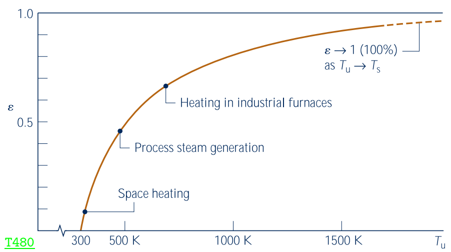
Moran Ex. 7.1 ▷ A cylinder of an internal combustion engine contains 2450 cm^3 of gaseous combustion products at a pressure of 7 bar and a temperature of 867°C just before the exhaust valve opens. Determine the specific exergy of the gas, in kJ/kg. Assume, the combustion products as air as ideal gas.



- $T_0 = 300$ K, $P_0 = 1.0$ bar
- $\phi \equiv (u - u_0) + P_0(v - v_0) - T_0(s - s_0)$
- $u - u_0 = c_v(T - T_0) = 600$ kJ/kg
- $P_0(v - v_0) = R(\frac{P_0 T}{P} - T_0) = 39.36$ kJ/kg
- $s - s_0 = c_p \ln(T/T_0) - R\ln(P/P_0) = 0.7870$ kJ/kg
- $\phi = 324.54$ kJ/kg
- If accurate thermodynamic properties are used, $\phi = 369.45$ kJ/kg

Efficient Use of Heat Source





- First Law: $\cancelto{0}{\frac{dE}{dt}} = (\dot{Q}_s - \dot{Q}_u - \dot{Q}_i) - \cancelto{0}{\dot{W}}$
- $\eta = \frac{\dot{Q}_u}{\dot{Q}_s}$: $Q_s \equiv$ heat transfer from source, $Q_u \equiv$ useful heat transfer
- SSSF: $\cancelto{0}{\Delta\Psi} = \Delta\Phi_Q - \cancelto{0}{W_{act}} - I_{cm} = \Phi_{Q,s} - \Phi_{Q,u} - \Phi_{Q,l} - I_{cm}$

$$\Rightarrow \boxed{\epsilon \equiv \frac{\Phi_{Q,u}}{\Phi_{Q,s}} = \frac{\dot{Q}_u(1 - T_0/T_u)}{\dot{Q}_s(1 - T_0/T_s)} = \eta\left[\frac{1 - T_0/T_u}{1 - T_0/T_s}\right]}$$

Wark (1995), Ex. 3.2: ▷ A heat transfer of 100 kJ occurs between reservoirs of 1000 K and 300 K. Estimate the effectiveness of the case and also for reservoir temperature of 40°C, 200°C & 420°C. $T_0 = 300$ K.

$$\epsilon \equiv \frac{\Phi_{Q,u}}{\Phi_{Q,s}} = \frac{\dot{Q}_u(1 - T_0/T_u)}{\dot{Q}_s(1 - T_0/T_s)} = \eta\left[\frac{1 - T_0/T_u}{1 - T_0/T_s}\right]$$

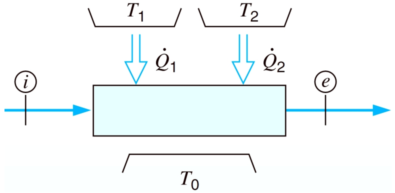
- For all cases, $\Phi_{Q,s} = \dot{Q}_s(1 - T_0/T_s) = 100(1 - 300/1000) = 70$ kJ
- For sink temperature of 420°C (e.g. furnace operation), $\Phi_{Q,u} = \dot{Q}_s(1 - T_0/T_u) = 100(1 - 300/673) = 56.7$ kJ.
- $I_{cm} = \Phi_{Q,s} - \Phi_{Q,u} = 13.3$ kJ
- $\epsilon = \frac{\Phi_{Q,u}}{\Phi_{Q,s}} = 0.81$

use	T_u [K]	Φ_U [kJ]	I_Q [kJ]	ϵ
Atmospheric sink	300	0	70	0.00
Space heating	313	4.2	65.8	0.06
Process steam generation	473	36.6	33.4	0.52
Furnace operation	693	56.7	13.3	0.81

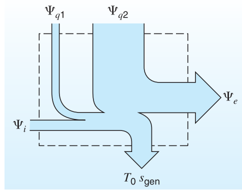
Feed Water Heater

Borgnakke, Ex. 8.1 + 8.9: ▷ A feedwater heater has 5 kg/s water at 5 MPa and 40°C flowing through it, being heated from two sources. One source adds 900 kW from a 100°C reservoir, and the other source transfers heat from a 200°C reservoir such that the water exit condition is 5 MPa, 180°C. Find the reversible work, irreversibility and effectiveness. [62 kJ/kg, 62 kJ/kg, 0.667]

T478



T477



- $\Psi \equiv (h - h_0) - T_0(s - s_0) + \frac{\mathbb{V}^2}{2} + gz \cong (h - h_0) - T_0(s - s_0)$
- $\Phi_{Q1} = q_1(1.0 - T_0/T_1) = 35.3$ kJ/kg, $\Phi_{Q2} = 151.2$ kJ/kg
- $\Psi_i = 6.08$ kJ/kg, $\Psi_e = 130.2$ kJ/kg
- $\epsilon = \frac{\Psi_e - \Psi_i}{\Phi_{Q1} + \Phi_{Q2}} = \frac{124.13}{186.5} = 0.667$ ◀

SSSF Compressor

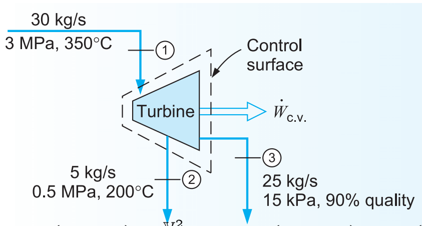
Holman, Ex. 5.10: ▷ A steady-flow compressor is used to compress air from 1 bar, 25°C to 8 bar in an adiabatic process. The first-law efficiency, η_I, of the process is 87%. Calculate the irreversibility and η_{II} of the process if $T_0 = 293$ K.

- $\Psi \equiv (h - h_0) - T_0(s - s_0) + \frac{\mathbb{V}^2}{2} + gz \cong (h - h_0) - T_0(s - s_0)$
- $w_a = h_1 - h_2 = -c_P(T_2 - T_1) \; : \; w_s = h_1 - h_{2s} = -c_P(T_{2s} - T_1)$
- $\eta_I = \frac{w_s}{w_a} = 0.87$
- $T_{2s} = T_1 \left(\frac{P_2}{P_1}\right)^{(k-1)/k} = 540 \text{ K} \rightarrow T_{2a} = \frac{W_a}{C_p} + T_1 = 571$ K
- $w_a = -279.0$ kJ/kg
- $w_{min} = -\Delta\Psi = -[(h_{2a} - h_1) - T_0(s_{2a} - s_1)] = -259.8$ kJ/kg
- $i_{sf} = T_0(s_{2a} - s_1) = 19.2$ kJ/kg
- $\eta_{II} = \frac{\Delta\Psi}{w_a} = 0.931$ ◀

SSSF Turbine

Borgnakke, Ex. 8.5: ▷

T351

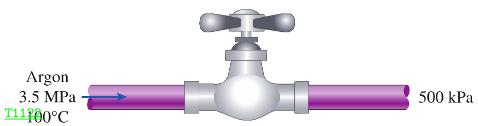


- $\Psi \equiv (h - h_0) - T_0(s - s_0) + \frac{\mathbb{V}^2}{2} + gz \cong (h - h_0) - T_0(s - s_0)$
- $\dot{w}_s = \dot{m}_1 h_1 - \dot{m}_2 h_{2s} - \dot{m}_3 h_{3s} = 25.27$ MW
- $\dot{w}_a = \dot{m}_1 h_1 - \dot{m}_2 h_2 - \dot{m}_3 h_3 = 20.18$ MW
- $\eta_I = \frac{\dot{w}_a}{\dot{w}_s} = 0.799$ ◀
- $\Delta(\dot{m}\Psi) = \dot{m}_1\Psi_1 - \dot{m}_2\Psi_2 - \dot{m}_3\Psi_3 = 24.65$ MW
- $\eta_{II} = \frac{\dot{w}_a}{\Delta(\dot{m}\Psi)} = 0.819$ ◀

Throttling Process

Cengel, P. 8-130 ▷ Argon gas expands from 3.5 MPa and 100°C to 500 kPa in an adiabatic expansion valve. For environment conditions of 100 kPa and 25°C, determine (a) the exergy of argon at the inlet, (b) the exergy destruction during the process, and (c) the second-law efficiency.

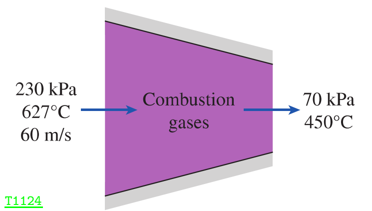
T1130



- $\psi_1 = 223.8$ kJ
- $\psi_2 = 103.3$ kJ
- $I_{cv} = -\Delta\psi = 120.5$ kJ
- $\epsilon = \frac{\psi_2}{\psi_1} = 0.461$

Nozzle

Cengel, P. 8-71 ▷ Hot combustion gases enter the nozzle of a turbojet engine. Assuming the nozzle to be adiabatic and the surroundings to be at 20°C, determine (a) the exit velocity and (b) the decrease in the exergy of the gases. Take air properties for the combustion gases.

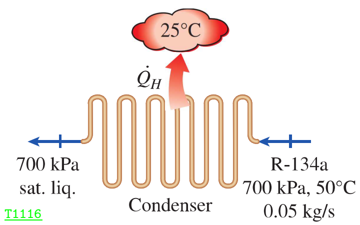


T1124

- $V_2 = \sqrt{V_1^2 - \Delta KE} = 627$ m/s
- $\psi_1 = 368.9$ kJ
- $\psi_2 = 339.4$ kJ
- $I_{cv} - \Delta\psi = 29.5$ kJ
- $\epsilon = \frac{\psi_2}{\psi_1} = 0.92$

Air Cooled Condenser

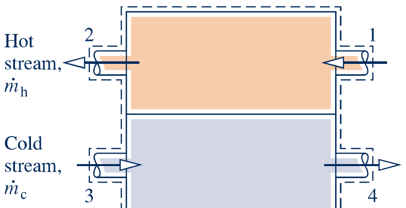
Cengel, P. 8-63 ▷ Determine (a) the rate of heat rejected in the condenser, (b) the COP of this refrigeration cycle if the cooling load at these conditions is 6 kW, and (c) the rate of exergy destruction in the condenser.



T1116

- $Q_L = 6$ kW
- $Q_H = \dot{m}(h_2 - h_1) = 9.98$ kW
- $COP = \frac{Q_L}{W_{in}} = \frac{Q_L}{Q_H - Q_L} = 1.5$
- $I_{cv} = -\Delta\psi = 0.0998$ kW
- $\epsilon = \frac{\psi_e}{\psi_i} = 0.955$

Heat Exchange without Mixing



T476

- $w = 0,\ q = 0,\ \Delta ke = 0,\ \Delta pe = 0$
- SSSF Energy: $0 = 0 - 0 + \sum_i (mh)_i - \sum_e (mh)_e$

$\Rightarrow m_1 h_1 + m_3 h_3 = m_1 h_2 + m_4 h_4 \rightarrow \boxed{m_c(h_4 - h_3) = -m_h(h_2 - h_1)}$

- Exergy balance:

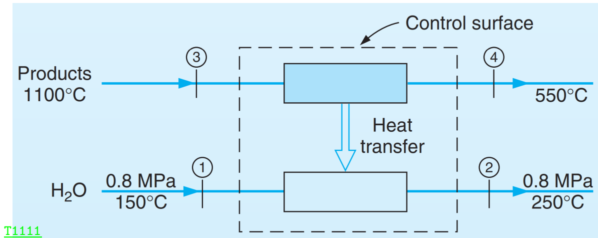
$\Delta(m\Psi) = \Phi_Q^{\nearrow 0} - W^{\nearrow 0} - I\,cv \rightarrow m_c(\psi_4 - \psi_3) + m_h(\psi_2 - \psi_1) = -I_{cv}$

$\Rightarrow \boxed{\epsilon \equiv \frac{m_c(\psi_4 - \psi_3)}{-m_h(\psi_2 - \psi_1)} \quad \text{or} \quad \epsilon \equiv \frac{m_c\psi_4 + m_h\psi_2}{m_c\psi_3 + m_h\psi_1}}$

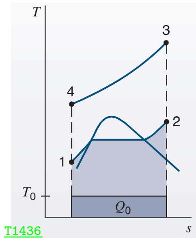
- The first form of ϵ for heat exchanger is usually preferred.

Boiler

Borgnakke, Ex. 8.6: ▷ Determine the second-law efficiency for this process and the irreversibility per kilogram of water evaporated. Assume, c_p of the products of combustion is 1.155 kJ/kg K.



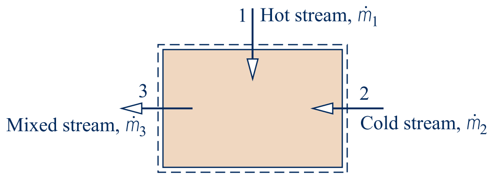
T1111



T1436

- $\frac{m_{gas}}{m_{water}} = \left[\frac{h_2 - h_1}{h_3 - h_4}\right] = 3.685$ kg/kg
- $\epsilon = \frac{m_{gas}(\psi_2 - \psi_1)}{m_{water}(\psi_3 - \psi_4)} = 0.458$
- $I_{cv} = -\Delta\psi = 9.09$ kW

Heat Exchange with Mixing



T481

- $w = 0,\ q = 0,\ \Delta ke = 0,\ \Delta pe = 0$
- SSSF Energy: $0 = 0 - 0 + \sum_i (mh)_i - \sum_e (mh)_e$

$\Rightarrow$ $m_1 h_1 + m_2 h_2 = m_3 h_3 \rightarrow$ $\boxed{m_c(h_3 - h_2) = -m_h(h_3 - h_1)}$

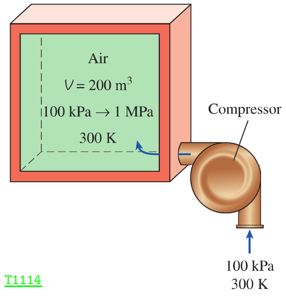
- Exergy balance:

$\Delta(m\Psi) = \cancel{\Phi_Q}^{0} - \cancel{W}^{0} - I\,cv \rightarrow m_c(\psi_3 - \psi_2) + m_h(\psi_3 - \psi_1) = -I_{cv}$

$\Rightarrow$ $\boxed{\epsilon \equiv \frac{m_c(\psi_3-\psi_2)}{-m_h(\psi_3-\psi_1)} \quad \text{or} \quad \epsilon \equiv \frac{(m_c+m_h)\psi_3}{m_c\psi_2+m_h\psi_1}}$

Charging a Compressed Air System

Cengel Ex. 8-17 ▷ A 200-m^3 rigid tank initially contains atmospheric air at 100 kPa and 300 K and is to be used as a storage vessel for compressed air at 1 MPa and 300 K. Determine the minimum work requirement for this process.

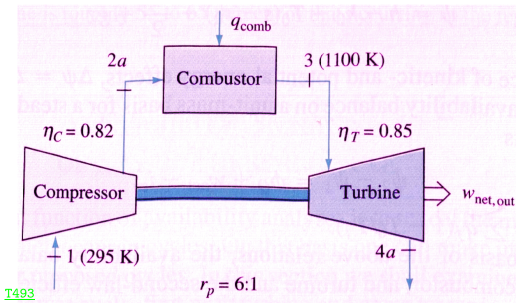


T1114

- $\phi = \psi = 0$, air within tank and supplied are at ambient condition.
- $m_2 = \frac{P_2 V}{R T_2} = 2323$ kg
- $\phi = (u - u_0) + P_0(v - v_0) - T_0(s - s_0)$
- $u - u_0 = 0$, as $T_2 = T_0$
- $s - s_0 = c_p \ln(T_2/T_0) - R\ln(P_2/P_0) = -R\ln(P_2/P_0)$
- $P_0(v - v_0) = RT_0(P_0/P_2 - 1)$
- $\phi_2 = 120.78$ kJ/kg
- Minimum work required $= m_2\phi_2) = 281$ MJ

Gas Turbine Cycle Analysis

Wark (1999), Ex.15.12: ▷



T493

- Energy: $q - w = \Delta h + \cancel{\Delta ke}^{0} + \cancel{\Delta pe}^{0}$
- Exergy: $\Delta\psi = \Phi_Q - w_u - I\,cv$
- $\eta_c = \frac{w_{c,s}}{w_{c,a}} = \frac{h_{2s}-h_1}{h_{2a}-h_1}$
- $\eta_t = \frac{w_{t,a}}{w_{t,s}} = \frac{h_{4a}-h_3}{h_{4s}-h_3}$

- Combustor: $w = 0,\ I_{c,comb} = 0$ (generally assumed).

$\Rightarrow$ $q_{comb} = h_3 - h_{2a} = 630$ kJ/kg, $\Phi_Q = \psi_3 - \psi_{2a} = 391$ kJ/kg

- Compressor:

$q = 0,\ w_{c,s} = (h_1 - h_{2,s}),\ w_{c,a} = w_{c,s}/\eta_c = (h_1 - h_{2,a})$

$\Rightarrow$ $w_{c,a} = -242$ kJ/kg, $I_{c,comp} = -w_{c,a} - (\psi_{2,a} - \psi_1) = 25.5$ kJ/kg

- Turbine: $q = 0,\ w_{t,s} = (h_3 - h_{4,s}),\ w_{t,a} = \eta_t w_{t,s} = (h_3 - h_{4,a})$

$\Rightarrow$ $w_{t,a} = 388$ kJ/kg, $I_{c,turb} = -w_{t,a} - (\psi_{4,a} - \psi_3) = 28.1$ kJ/kg

$\Rightarrow$ $w_{net} = w_{t,a} + w_{c,a} = 146.1$ kJ/kg

$\Rightarrow$ $\eta = \frac{w_{net}}{q_{comb}} = 0.232$ ◀

$\Rightarrow$ $\epsilon = \frac{w_{net}}{\Phi_Q} = 0.373$ ◀

- Energy balance: $q - w = 483.7,\ h_{4,a} - h_1 = 483.7$ kJ/kg
- Exergy balance:

$\psi_{4,a} - \psi_1 = 191.5,\ \phi_Q - w_{net} - I_{c,total} = 191.5$ kJ/kg

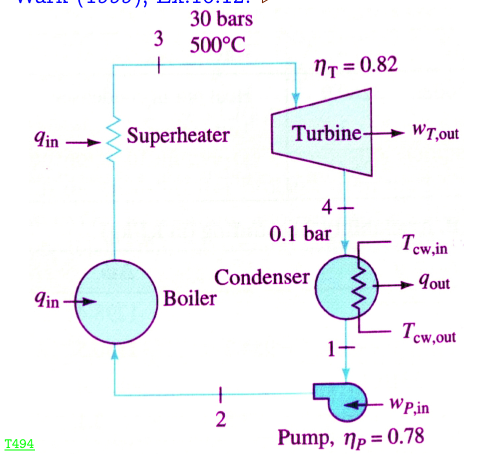
```
Energy Analysis:
w_ca                =  -2.4208E+02 [kJ/kg]
w_ta                =   3.8819E+02 [kJ/kg]
w_net               =   1.4611E+02 [kJ/kg]
q_in_comb           =   6.2985E+02 [kJ/kg]
e_in                =   8.6874E+02 [kJ/kg]
e_out               =   8.6874E+02 [kJ/kg]
eta                 =   2.3198E-01 [-]

Exergy Analysis:
compressor          =   2.1661E+02 [kJ/kg]
combustor           =   3.9124E+02 [kJ/kg]
turbine             =  -4.1633E+02 [kJ/kg]
incoming fluid      =  -1.1141E+00 [kJ/kg]
outgoing fluid      =   1.9040E+02 [kJ/kg]
sum d_psi           =   0.0000E+00 [kJ/kg]
i_c                 =   2.5466E+01 [kJ/kg]
i_t                 =   2.8143E+01 [kJ/kg]
i                   =   5.3609E+01 [kJ/kg]
epsilon             =   3.7346E-01 [-]
```

T1433

Simple Steam Power Cycle Analysis

Wark (1999), Ex.16.12: ▷



- Energy:
  $q - w = \Delta h + \Delta ke^{0} + \Delta pe^{0}$
- Exergy:
  $\Delta\psi = \Phi_Q - w_u - I\,cv$
- $\eta_p = \frac{w_{p,s}}{w_{p,a}} = \frac{h_{2s}-h_1}{h_{2a}-h_1}$
- $\eta_t = \frac{w_{t,a}}{w_{t,s}} = \frac{h_{4a}-h_3}{h_{4s}-h_3}$
- $w_{p,s} = (h_1 - h_{2,s}) = \frac{P_1 - P_2}{\rho_1}$

T494

- pump: $q = 0,\ w_{p,a} = w_{p,s}/\eta_p$

$\Rightarrow w_{p,a} = -3.87$ kJ/kg, $I_{c,pump} = -w_{p,a} - (\psi_{2,a} - \psi_1) = 0.80$ kJ/kg

- Boiler: $w = 0,\ I_{c,comb} = 0$ (generally assumed).

$\Rightarrow q_{comb} = h_3 - h_{2a} = 3262.0$ kJ/kg, $\Phi_Q = \psi_3 - \psi_{2a} = 1300.0$ kJ/kg

- Turbine: $q = 0,\ w_{t,s} = (h_3 - h_{4,s}),\ w_{t,a} = \eta_t w_{t,s} = (h_3 - h_{4,a})$

$\Rightarrow w_{t,a} = 954.9$ kJ/kg, $I_{c,turb} = -w_{t,a} - (\psi_{4,a} - \psi_3) = 190.5$ kJ/kg

$\Rightarrow w_{net} = w_{t,a} + w_{c,a} = 951.1$ kJ/kg

$\Rightarrow \eta = \frac{w_{net,out}}{q_{comb}} = 0.291$ ◀

$\Rightarrow \epsilon = \frac{w_{net,out}}{\Phi_Q} = 0.731$ ◀

- Condenser:
  $q_{cond} = h_1 - h_{4,a} = -2310,\ \psi_{cond} = \psi_1 - \psi_{4,a} = -157.1$ kJ/kg
- Energy balance: $q - w = 3200 - 2310 - 951 = 0$
- Exergy balance: $\phi_Q - w_{net} - I_{c,total} = 1300 - 157 - 951 - 191 = 0$

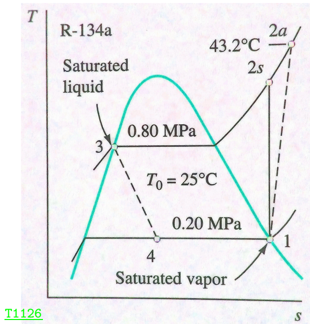

```
Energy Analysis:
Pump                = -3.870E+00 [kJ/kg]
Boiler              =  3.262E+03 [kJ/kg]
Turbine             =  9.549E+02 [kJ/kg]
Condenser           = -2.310E+03 [kJ/kg]
Net heat            =  9.511E+02 [kJ/kg]
Net work            =  9.511E+02 [kJ/kg]
Net energy in       =  3.265E+03 [kJ/kg]
Net energy out      =  3.265E+03 [kJ/kg]
eta                 =  2.916E-01 [-]

Exergy Analysis:
Pump                =  3.075E+00 [kJ/kg]
Boiler              =  1.299E+03 [kJ/kg]
Turbine             = -1.151E+03 [kJ/kg]
Condenser           = -1.507E+02 [kJ/kg]
Sum of d_psi        =  5.821E-14 [kJ/kg]
i_p                 =  7.954E-01 [kJ/kg]
i_t                 =  1.959E+02 [kJ/kg]
i                   =  1.967E+02 [kJ/kg]
epsilon             =  7.324E-01 [-]
```

T1434

Refrigeration Cycle Analysis

Wark (1999), Ex. 17-7 ▷ Saturated R-134a vapour enters the compressor at 0.2 MPa and leaves the condenser as saturated liquid at 0.8 MPa. Vapour leaves the irreversible compressor at 43.2°C. Estimate (a) COP, (b) Effectiveness of the cycle. Also, prepare energy & exergy balance sheet.



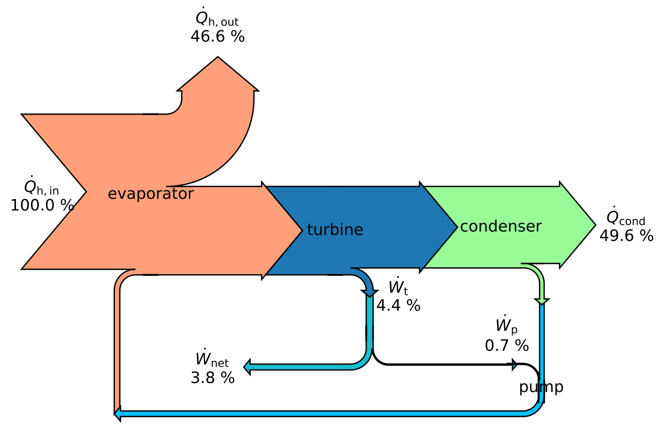
T1126

```
q_evap                  =   1.4897E+02 [kJ/kg]
q_cond                  =  -1.8425E+02 [kJ/kg]
w_comp                  =  -3.5276E+01 [kJ/kg]
COP                     =   4.2230E+00 [-]
epsilon                 =   5.6307E-01 [-]

Energy Analysis:
w_comp                  = -3.528E+01
q_cond                  = -1.842E+02
q_evap                  =  1.490E+02
q_evap - q_cond         =  3.332E+02

Exergy Analysis:
d_psi_comp              =  2.910E+01
d_psi_cond              = -4.059E+00
d_psi_evap              = -1.986E+01
d_psi_exp               = -5.181E+00
                        =  1.135E+01
```

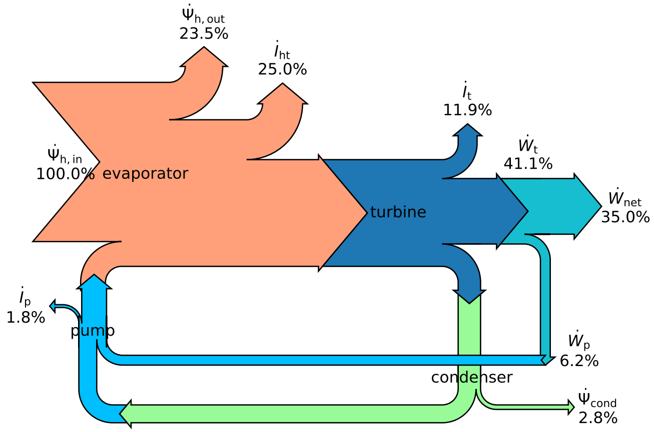
T1127



T1431

https://doi.org/10.1115/1.4050261

Energy flow in the WHR system at optimal condition for T_s = 100°C using R1216.



T1432

https://doi.org/10.1115/1.4050261

Exergy flow in the WHR system at optimal condition for T_s = 100°C using R1216.