Exergy(火用)or Availability
"Understanding engineering thermo"

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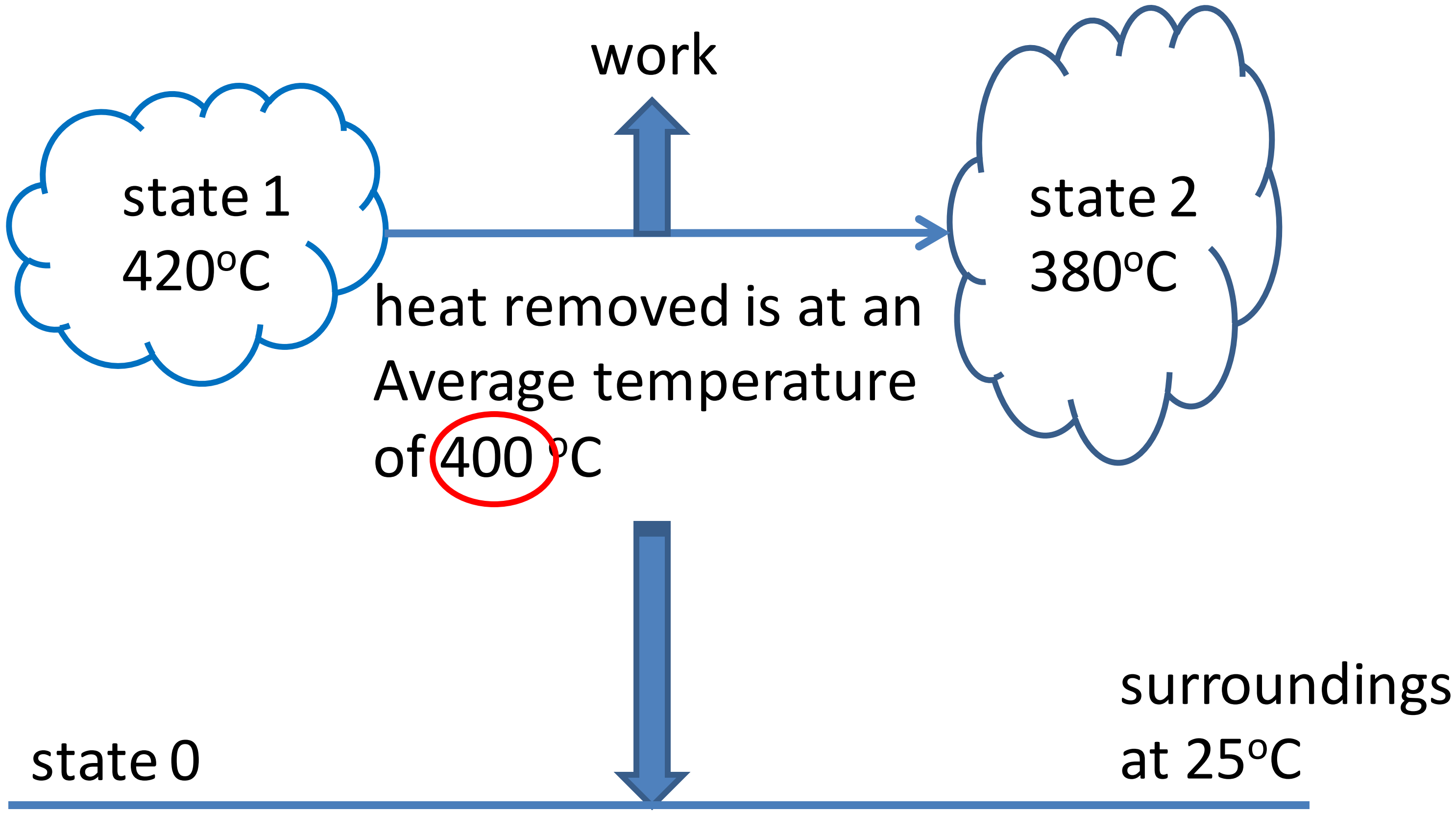
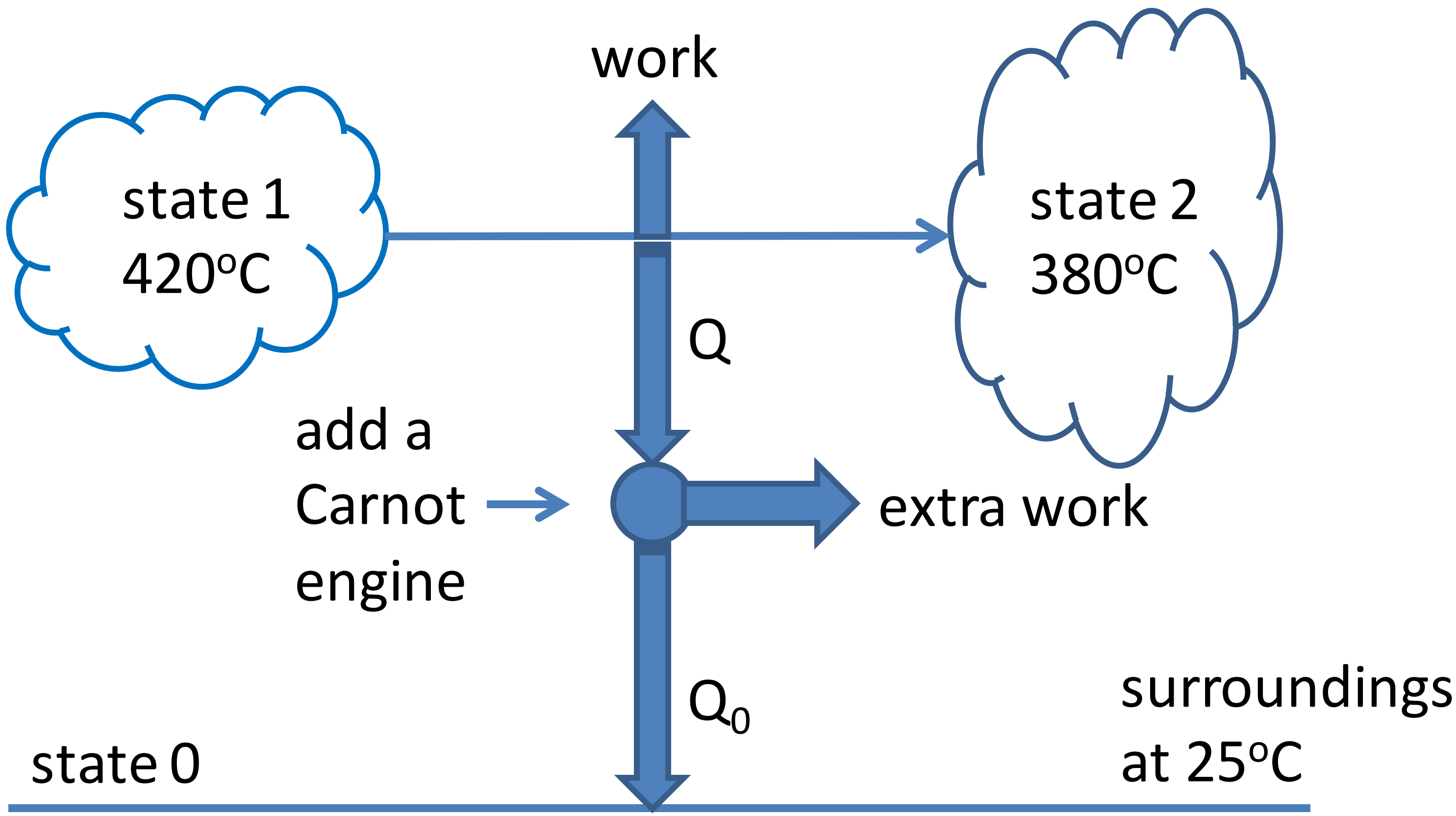

work
state 1
420^{o}C
state 2
380^{o}C
heat removed is at an
Average temperature
of 400 ^{o}C
surroundings
at 25^{o}C
state 0

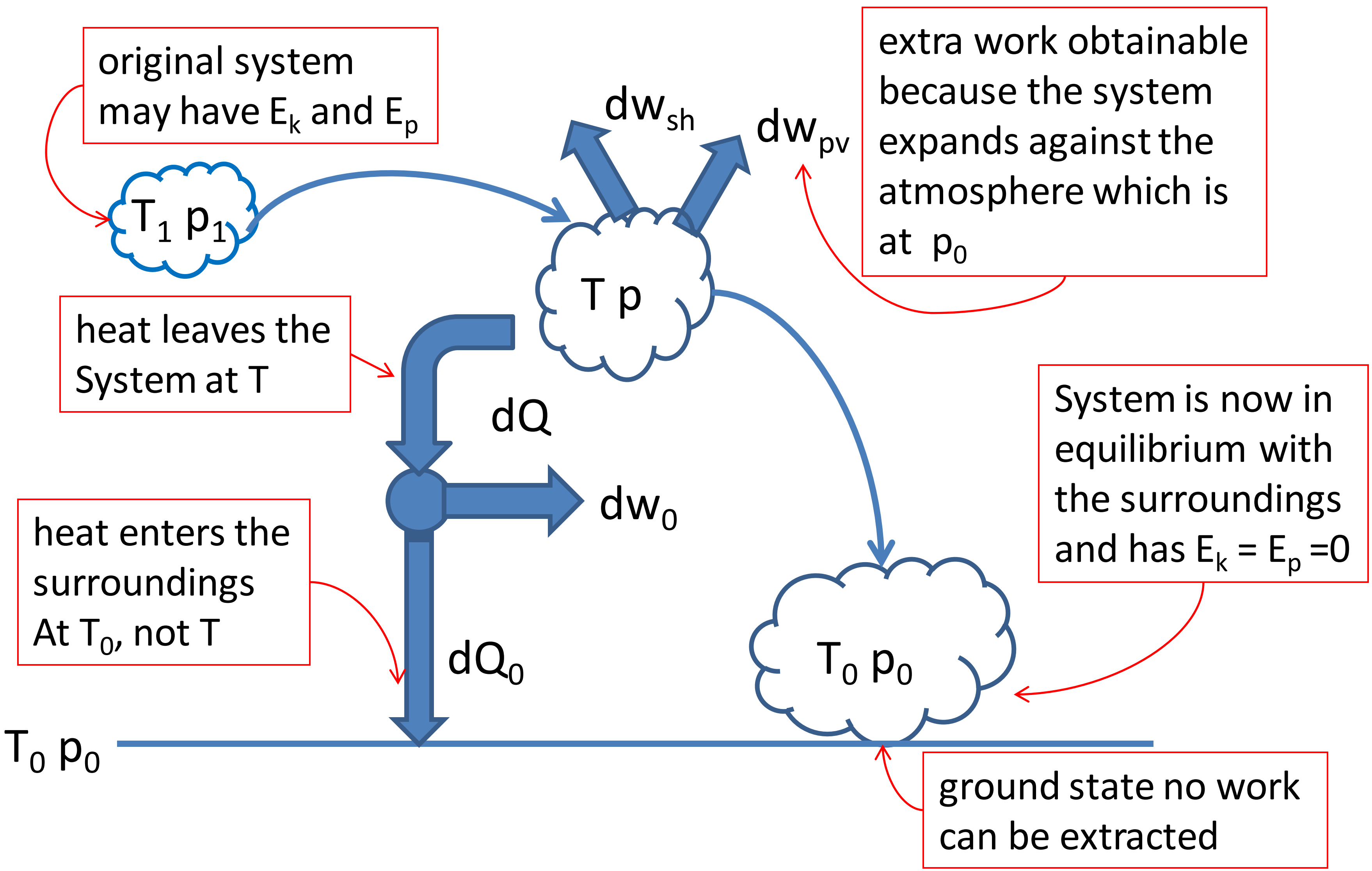


To get true maximum available work, all the heat to be rejected from the system has to be rejected at the temperature of the surroundings.

- Similarly, if the system and surroundings are at different pressures and if the system expands, then to minimize the nonuseful pV work, the expansion should always be done at the pressure of the surroundings.
- The maximum extractable work depends on three quantities: the states of the system , 1, 2 and the state of the surroundings, 0.
- This work concept was first mentioned by J.C. Maxwell in his “theory of Heat”
- To distinguish it from all other forms of work, Rant coined a new term “exergy”, to represent this concept.

EXERGY OF BATCH SYSTEM, $W_{EX,BATCH}$

- $W_{ex,1\rightarrow 0,batch}$: Consider a system at T_1, p_1 and having E_{p1} and E_{k1}, while the surroundings are at T_0, p_0.



received by surroundings

from Carnot engine, since $\frac{|Q_0|}{|Q|} = \frac{T_0}{T}, \quad \frac{d|Q_0|}{d|Q|} = \frac{T_0}{T}$

given up by the system

then $d|Q_0| = T_0 \frac{d|Q|}{T} = T_0 dS$

of system

of surroundings

- Consider a very small (differential) move of the system (at T, p) towards equilibrium. The total work produced,

work in pushing back
The atmosphere, dW_{pv}

$$dW_{total} = dW_{sh} + p_0 dv + dW_0$$

work obtained from
the Carnot engine

both available shaft work
or the exergy

$$d|Q_0| = T_0 \frac{d|Q|}{T} = T_0 dS$$

from the 1st law, $dE = dQ_0 - dW_{total}$

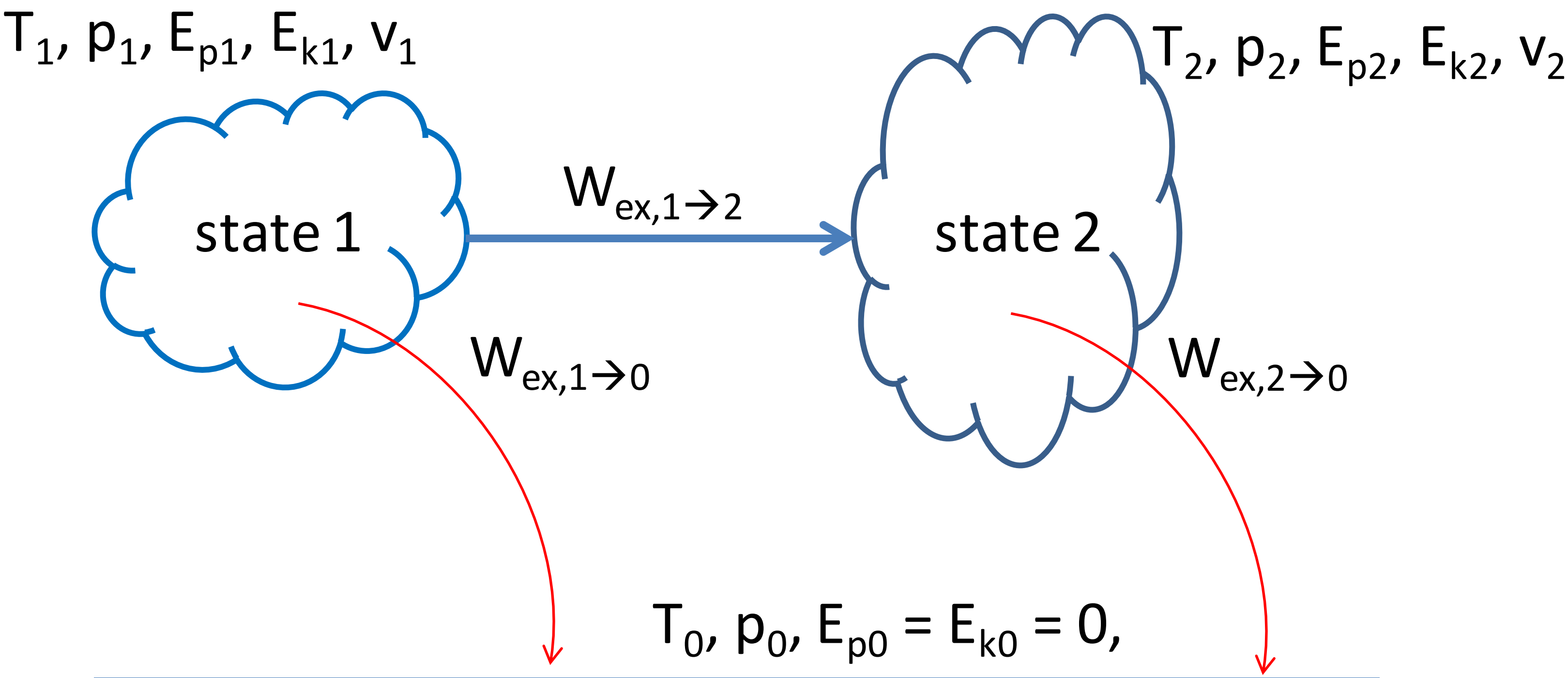
therefore, $dW_{ex} = dW_{sh} + dW_0 = -dE + T_0 S - p_0 dv$

- For the whole progression of changes for the system from T_1, p_1, E_{p1}, E_{k1} to T_0, p_0 with $E_{p0} = E_{k0} = 0$,
- We have

$$W_{ex,1\rightarrow 0,batch} = -(U_0 - E_1) + T_0(S_0 - S_1) - p_0(v_0 - v_1)$$

$$U_1 + E_{p1} + E_{k1}$$

- $W_{ex,1\rightarrow 2,batch}$



$$W_{ex,1\rightarrow 2} = W_{ex,1\rightarrow 0} - W_{ex,2\rightarrow 0}$$

$$\boxed{W_{ex,1\rightarrow 2,batch} = -(E_2 - E_1) + T_0(S_2 - S_1) - p_0(v_2 - v_1)}$$

$$U_2 + E_{p2} + E_{k2}$$

- Actual and lost work in real changes, batch system

$$\text{recall} \quad W_{ex,1\rightarrow 2,batch} = -(E_2 - E_1) + T_0(S_2 - S_1) - p_0(v_2 - v_1)$$

$$(E_2 - E_1) = T_0(S_2 - S_1) - W_{ex,1\rightarrow 2,batch} - p_0(v_2 - v_1)$$

do not depend on the path

$$\text{actual work}: \Delta E_{1\rightarrow 2} = Q_{\substack{actual\\ to\,surr}} - W_{\substack{actual\\ to\,surr}}$$

$$dW_{total} = (dW_{sh} + dW_0) + p_0 dv$$

$$\text{then} \quad W_{sh,lost,1\rightarrow 2} = W_{ex,1\rightarrow 2} - W_{sh,actual,1\rightarrow 2}$$

$$= T_0(S_2 - S_1) + T_0\Delta S_{surr}$$

$$= T_0\Delta S_{syst} + T_0\Delta S_{surr}$$

$$W_{sh,lost} = T_0\Delta S_{total}$$

$$d|Q_0| = T_0\frac{d|Q|}{T} = T_0 dS$$

Example I

- The little community of East Zilch, TX owns an enormous underground reservoir—not of oil, not of natural gas, but of waste gas (volume of gas in reservoir = 10^{12} m^3, c_p=36 J/mol/K, p=9.95 atm, T=237^oC, mω=0.03 kg/mol).
  - Ideally, how much useful work can be gotten from this gas?
  - If East Zilch can sell electricity to the power company at 3.6₵/kW/hr, and if their energy extraction plant is 10% efficient, want is the value of the gas in the reservoir?

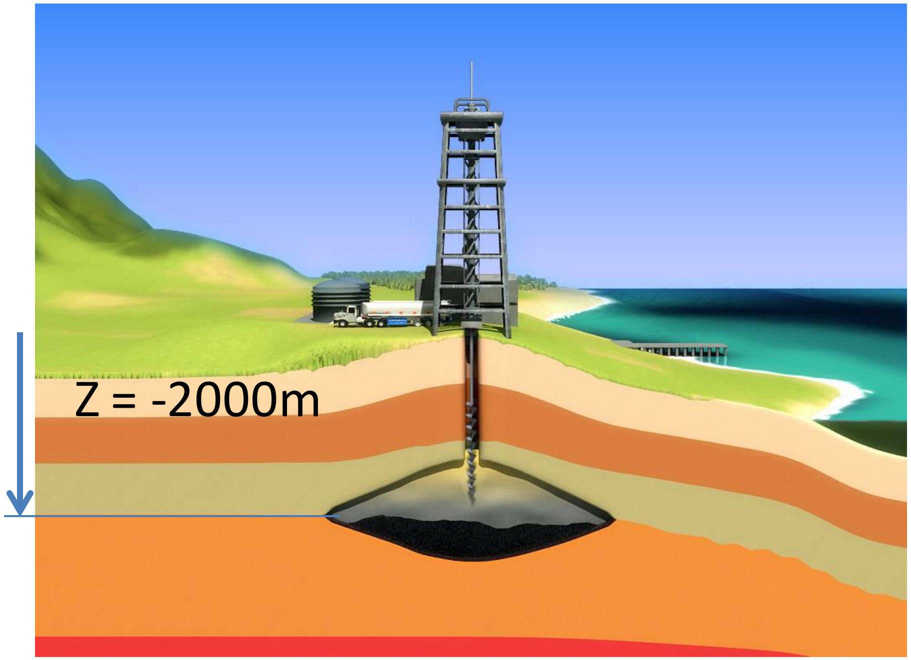
- This is a batch of gas,
- Recall

Reservoir is under ground, it is certainly not zero, but Assume to be negligible

$$W_{ex,1\rightarrow 0,batch} = -\left[(U_0 + E_{p0} + E_{k0}) - (U_1 + E_{p1} + E_{k1})\right] + T_0(S_0 - S_1) - p_0(v_0 - v_1)$$

($E_{p0} \rightarrow 0$, $E_{k0} \rightarrow 0$, $E_{k1} \rightarrow 0$)

$$W_{ex,1\rightarrow 0} = -\left[nc_v(T_0 - T_1)\right] + T_0 n\left(c_p \ln\frac{T_0}{T_1} - R\ln\frac{p_0}{p_1}\right) - p_0(v_0 - v_1)$$



$$n = \frac{p_1 v_1}{RT_1} = 2.378\times 10^{14} \ \ \text{mol}$$

$$c_v = 36 - 8.314 = 27.686 \ \ \text{J/mol}\cdot\text{K}$$

$$v_0 = (10^{12})\left(\frac{9.95}{1}\right)\left(\frac{300}{510}\right) = 5.853\times 10^{12} \ \ \text{m}^3$$

$$W_{ex,1\rightarrow 0} = 8.9083\times 10^{17} \ \ \text{J}$$

$$\$ = 890 \ \ \text{million}$$

Example II

- If E_p assume not to be negligible

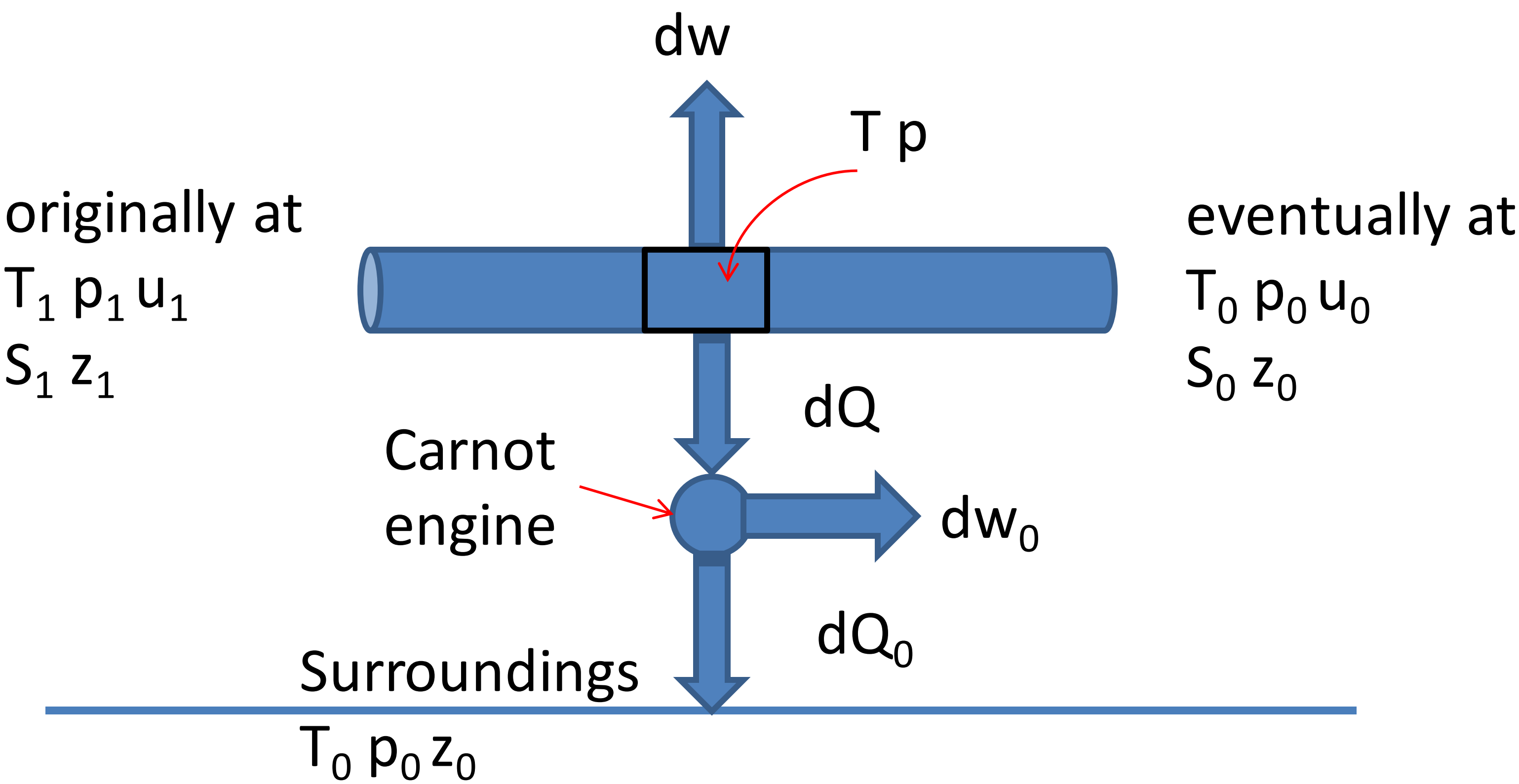
$$E_{p,1\rightarrow 0} = E_{p0} - E_{p1} = mg(z_0 - z_1) = 1.3983 \times 10^{17} \ \ J$$

$$W_{ex,1\rightarrow 0} = 8.9083 \times 10^{17} - 1.3983 \times 10^{17} = 7.51 \times 10^{17} \ \ J$$

$$\$ = 140 \ \ \text{million}$$

- This means, the potential energy should not always be ignored.

EXERGY IN FLOW SYSTEMS



- Recall

$$W_{ex,1\to 0,batch} = -\left[(U_0 + E_{p0} + E_{k0}) - (U_1 + E_{p1} + E_{k1})\right] + T_0(S_0 - S_1) - p_0(v_0 - v_1)$$

- Therefore,

$$W_{ex,1\to 0} = -\left[(H + E_p + E_k)_0 - (H + E_p + E_k)_1\right] + T_0(S_0 - S_1)$$

$$W_{ex,1\to 2} = -\left[(H + E_p + E_k)_2 - (H + E_p + E_k)_1\right] + T_0(S_2 - S_1)$$

- Recall

$$W_{sh,lost,1\to 2} = W_{ex,1\to 2} - W_{sh,actual,1\to 2}$$

$$Q_{rev} - (\Delta h + \Delta E_p + \Delta E_k)$$

$$Q_{actual\ to\ surroundings} - (\Delta h + \Delta E_p + \Delta E_k)$$

$$= Q_{rev} - Q_{actual}$$

$$= T_0(S_2 - S_1) + T_0 \Delta S_{surr}$$

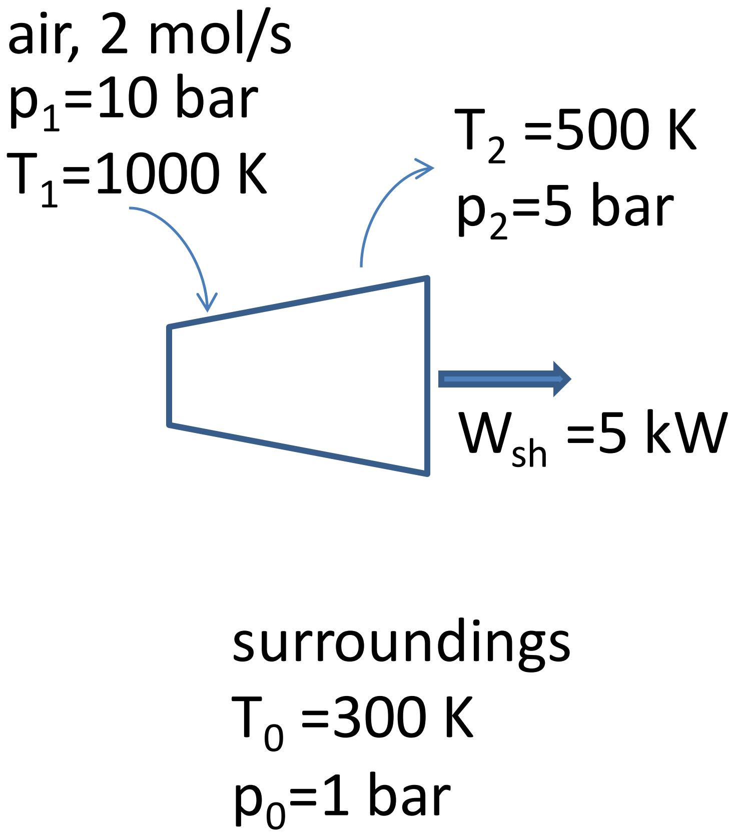
- And

$$W_{sh,lost} = T_0 \Delta S_{total}$$

- Recap

$$W_{ex,1\to 0} = W_{ex,2\to 0} + W_{sh,actual,1\to 2} + W_{sh,lost,1\to 2}$$

Example III



- A stream of 2 mol/s of air goes from 1000 K and 10 bar to 500 K and 5 bar while doing 5.0 kW of work. Surroundings are 300 K and 1 bar. What is the lost work for this process?

- Recall

$$W_{ex,1\to 2} = -\left[(H+E_p+E_k)_2 - (H+E_p+E_k)_1\right] + T_0(S_2 - S_1)$$

$$w_{ex,1\to 2} = -\left[h_2 - h_1\right] + T_0(s_2 - s_1)$$

$$= c_p(T_1 - T_2) + T_0\left(c_p \ln\frac{T_2}{T_1} - R\ln\frac{p_2}{p_1}\right)$$

$$= 10228 \text{ J/mol}$$

- Available power

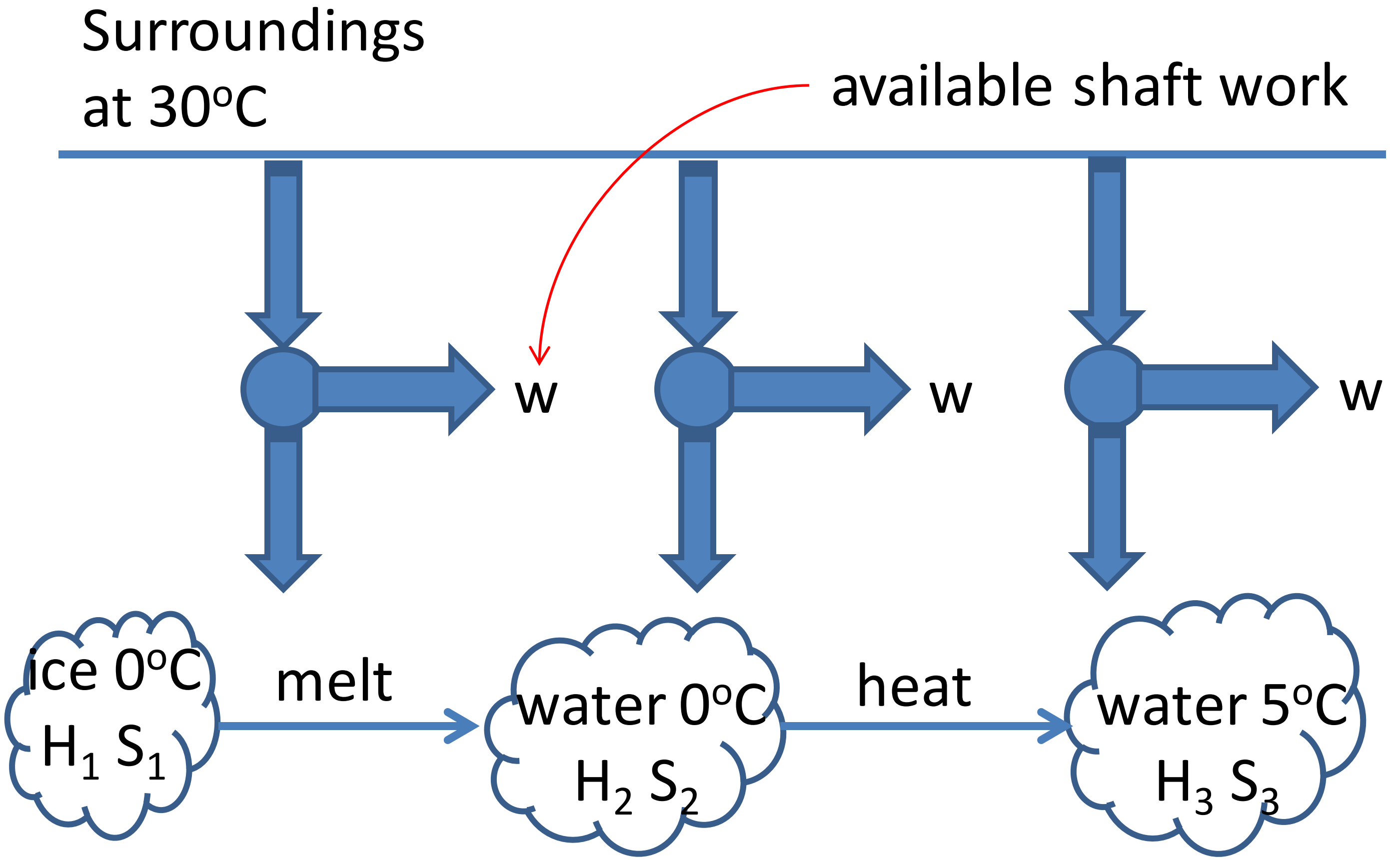
$$\dot{W}_{ex,1\to 2} = (10228)(2) = 20.5 \text{ kW}$$

- The actual power production is 5 kW, so

$$\dot{W}_{sh,lost} = 20.5 - 5.0 = 15.5 \text{ kW}$$

Example IV

- Saudi Arabia, a hot dry country (T_{ave}=30^oC), plans to lasso icebergs in Antarctica, two them to Jiddah Harbor, melt and store the water at 5^oC, and thereby supply the country with fresh water. But one can produce work, electricity, and air conditioning in addition to fresh water during the melting process. If they do not try to recover this available work, how much power do they waste if they bring in a 10^6 ton iceberg every three weeks?



- Since we are only interested in the overall 1→3 change, we can bypass state 2.
- Consider this to be a steady state, $\Delta E_p = \Delta E_k = 0$

- Therefore,

$$w_{ex,1\rightarrow 3} = -\left[(h+e_p+e_k)_3 - (h+e_p+e_k)_1\right] + T_0(s_3 - s_1)$$

- From the reference tables

h_1=-333.43 kJ/kg h_3=20.98 kJ/kg

s_1=-1.221 kJ/kg/K s_3=0.0761 kJ/kg/K

- Hence,

$$w_{ex,1\rightarrow 3} = 38.61 \text{ kJ/kg}$$

$$w_{lost} = 38.61 \text{ kJ/kg}$$

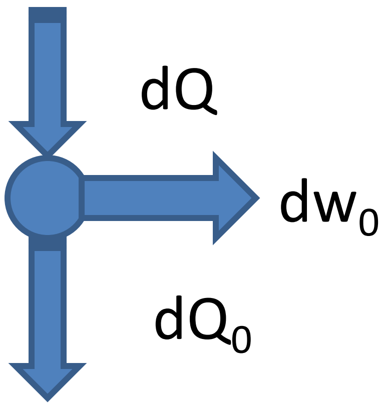
$$w_{ex} = w_{lost} + w_{actual}$$

$$\dot{W}_{lost} = (38.61\ )\left(\frac{1000\text{kg}}{\text{ton}}\right)\left(\frac{10^6 \text{ tons}}{21\text{days}}\right)\left(\frac{1\text{ day}}{24\times 3600\text{s}}\right)$$

$$= 21280\,\frac{\text{kJ}}{\text{s}} = 21.3 \text{ MW}$$

recap

- The availability of heat (exergy of heat)



$$w_{carnot} = Q - Q_0$$

$$w_{carnot} = \int T ds - \int T_0 ds$$

$$Ex_{heat} = \int T ds - \int T_0 ds$$

$$\Delta Ex_{heat} = Q_{rev} - \int T_0 ds$$

2nd law

- The availability of work (exergy of work)

$$\Delta Ex_{work} = W_{rev} - \int p_0 dv$$

- The total exergy is that exergy that can be extracted through heat and work processes

$$\Delta Ex_{system} = \Delta Ex_{heat} - \Delta Ex_{work}$$

- exergy of the system becomes

$$\Delta Ex_{system} = \left(Q_{rev} - T_0 \int ds\right) - \left(W_{rev} - \int p_0 dv\right)$$

$$= \left(Q_{rev} - W_{rev}\right) - \left(T_0 \int ds - \int p_0 dv\right)$$

1st law

$$\Delta Ex_{system} = \Delta E - \left(T_0 \int ds - \int p_0 dv\right)$$

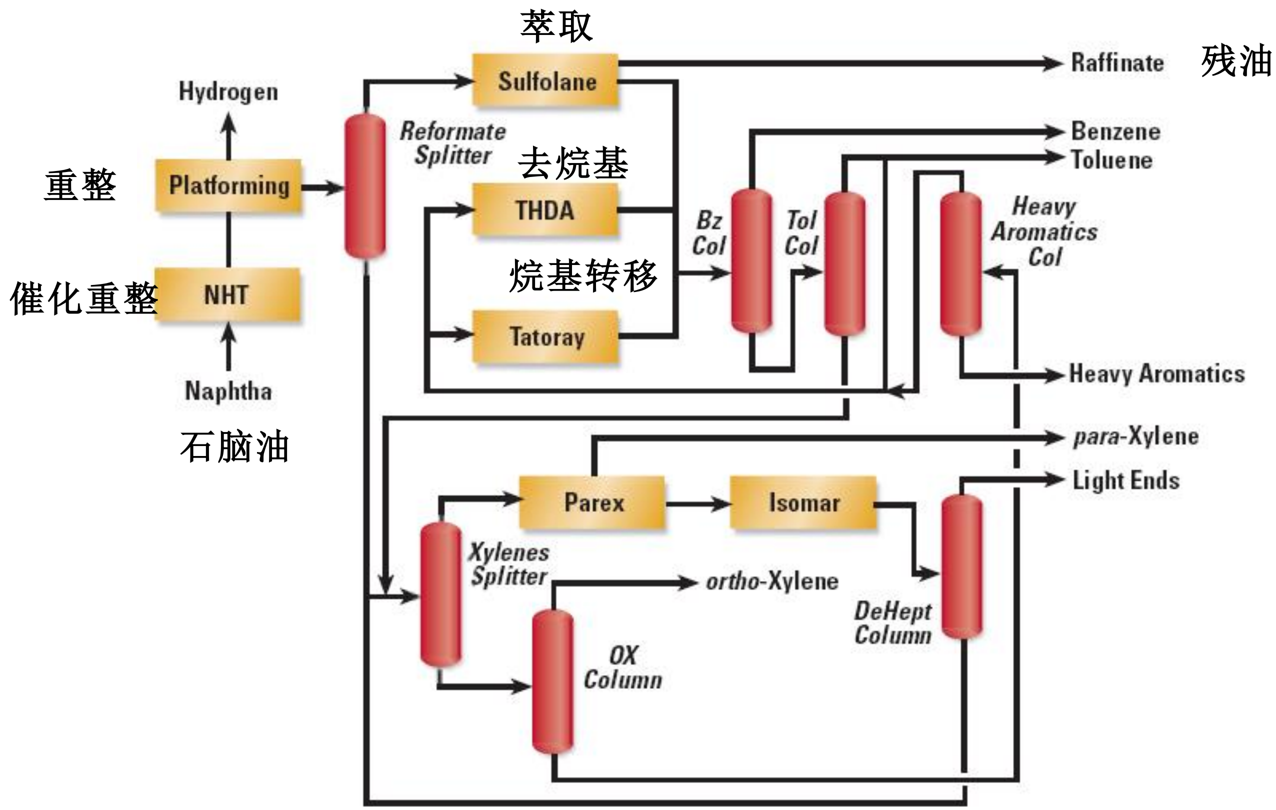
- Finally $\Delta Ex_{system} = \Delta U - \int p_0 dv - T_0 \int ds + \Delta e_p + \Delta e_k$
- Closed: $W_{ex,1\rightarrow 0,batch} = -(U_0 - E_1) + T_0(S_0 - S_1) - p_0(v_0 - v_1)$
- Flow: $W_{ex,1\rightarrow 0} = -\left[(H + E_p + E_k)_0 - (H + E_p + E_k)_1\right] + T_0(S_0 - S_1)$

Exergy

- In distillation columns, this work is supplied by heat being injected at the reboiler q_{reb} and rejected at the condenser q_{cond}. The net work available from the heat energy (or the net exergy from the heat transferred) is:

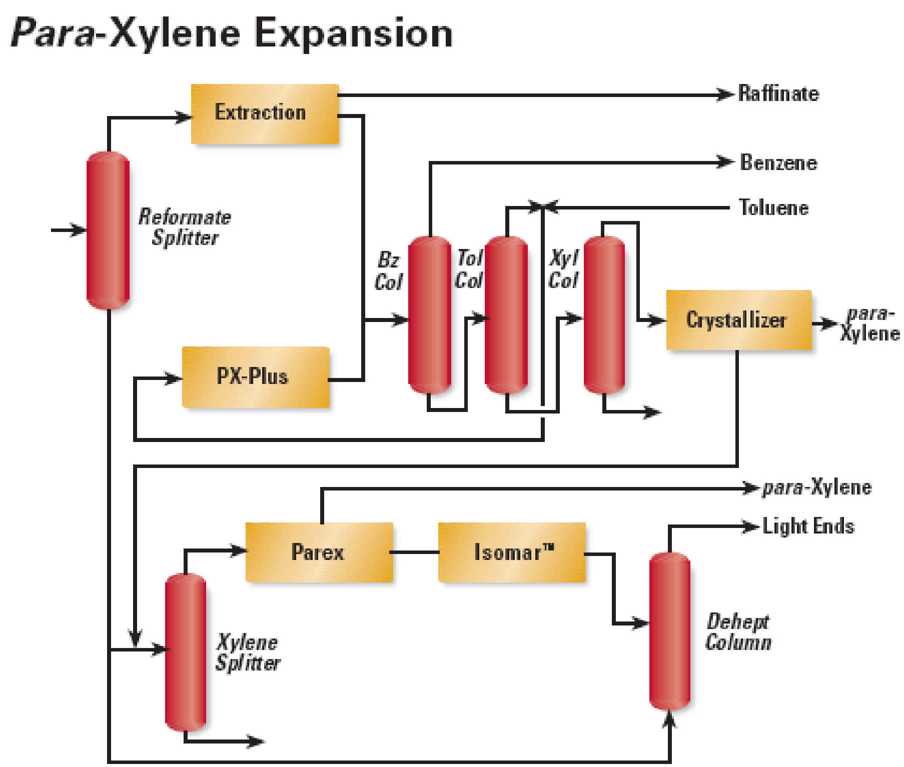
$$Ex_{heat} = q_{reb}\left(1 - \frac{T_0}{T_{reb}}\right) - q_{cond}\left(1 - \frac{T_0}{T_{cond}}\right)$$

UOP芳烃联合工艺



萃取
Sulfolane
Raffinate
残油
Hydrogen
Reformate Splitter
去烷基
重整
Platforming
THDA
Benzene
Toluene
Bz Col
Tol Col
Heavy Aromatics Col
催化重整
NHT
烷基转移
Tatoray
Heavy Aromatics
Naphtha
石脑油
para-Xylene
Light Ends
Parex
Isomar
Xylenes Splitter
ortho-Xylene
DeHept Column
OX Column

UOP芳烃联合工艺

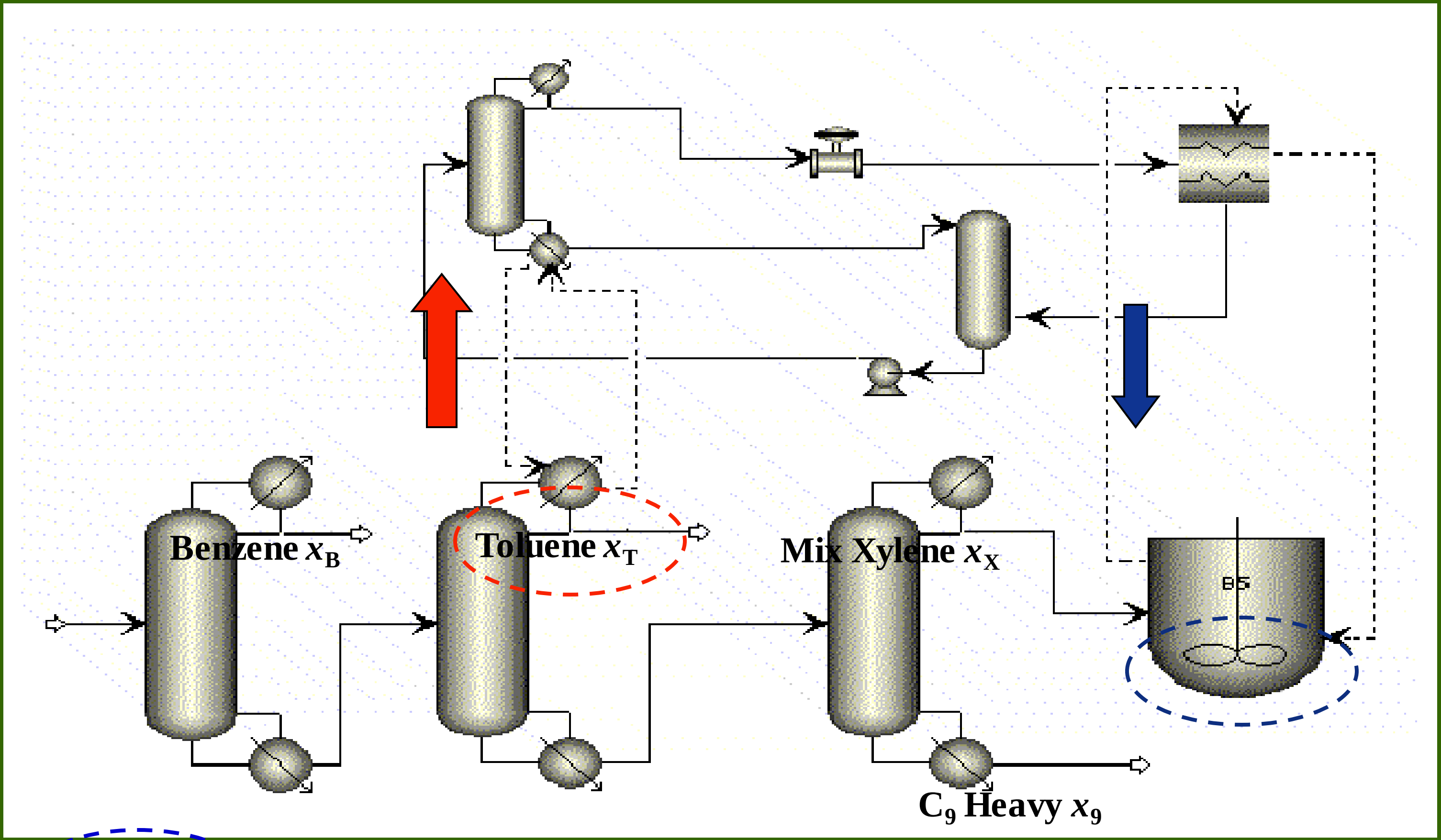


Para-Xylene Expansion
Extraction
Raffinate
Benzene
Toluene
Reformate Splitter
Bz Col
Tol Col
Xyl Col
Crystallizer
para-Xylene
PX-Plus
para-Xylene
Light Ends
Parex
Isomar™
Xylene Splitter
Dehept Column

Assess if the waste heat from the toluene tower is enough

Feed Stream:

Benzene x_B
Toluene x_T
Mix Xylene x_X
C_9 Heavy x_9



$$\frac{Q_{Crystallization}}{Q_{Toluene}} = \frac{[144kJ/(kg\ mixed\ xylenes)] \times [0.15(kg\ mixed\ xylenes)/(kg\ CSTDP\ product)]}{[319kJ/(kg\ toluene)] \times [0.70(kg\ toluene)/(kg\ CSTDP\ product)]} \approx 0.097$$

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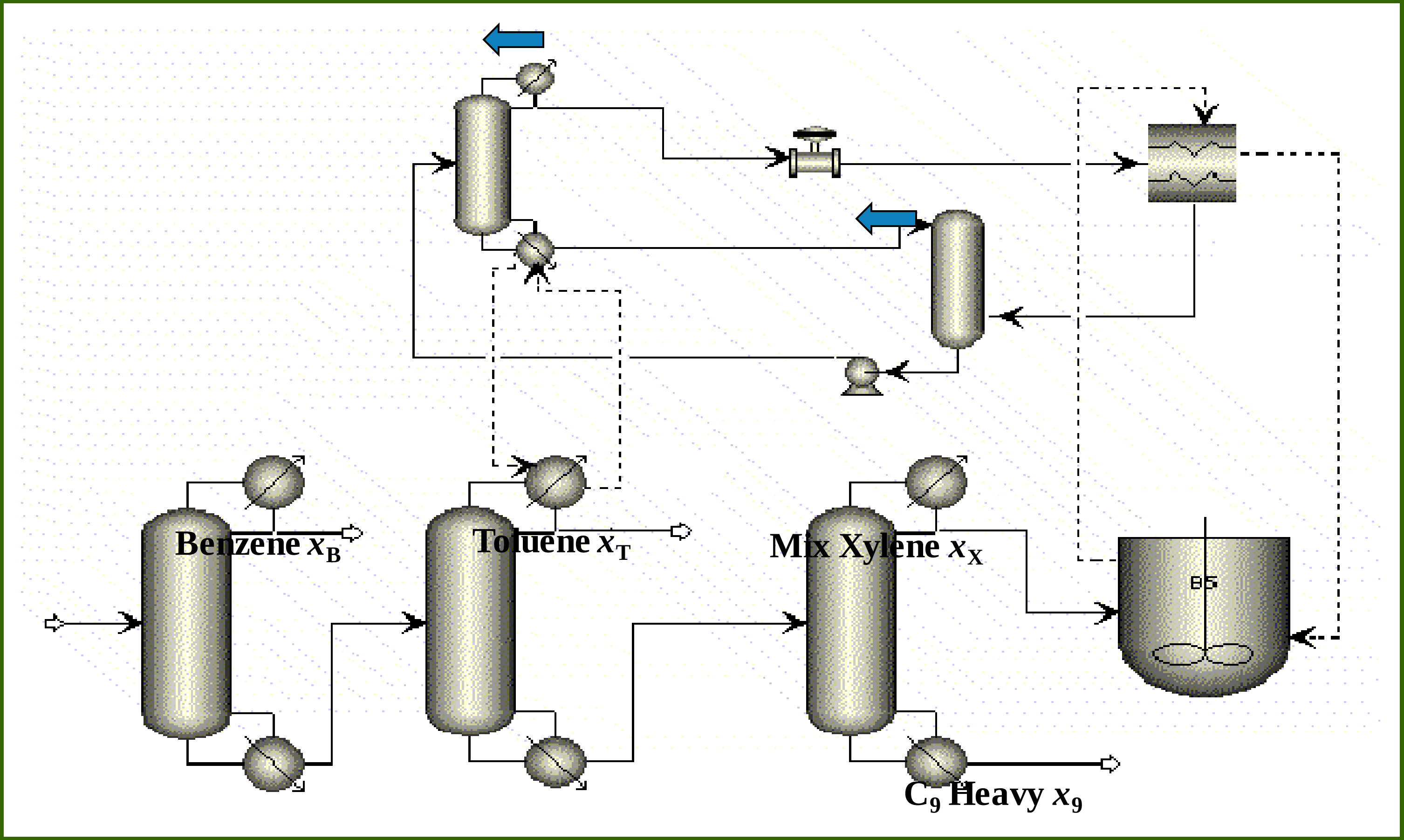

Feed Stream:

- Benzene x_B
- Toluene x_T
- Mix Xylene x_X
- C_9 Heavy x_9

$$\frac{Q_{\text{Crystallization}}}{Q_{\text{Toluene}}} = \frac{[144\text{kJ}/(\text{kg mixed xylenes})] \times [0.15(\text{kg mixed xylenes})/(\text{kg CSTDP product})]}{[319\text{kJ}/(\text{kg toluene})] \times [0.70(\text{kg toluene})/(\text{kg CSTDP product})]} \approx 0.097$$