rod: slow cooling $\Delta S = m\int_{T_r}^{T_f} \frac{c_p dT}{T} = mc_p \ln\frac{T_f}{T_r}$

$= 100\,g \cdot 2\frac{J}{g\,K} \cdot \ln\frac{300}{800} = -196\frac{J}{K}$

bath: exchange of heat with const.-T object @ 300 K: $\Delta S = \frac{Q}{T} = \frac{-mc_p(T_f - T_r)}{T_b} =$

$= 100g \cdot 2\frac{J}{gK} \cdot 500\,K \cdot \frac{1}{300\,K} = 333\frac{J}{K}$

Universe: $\Delta S = \Delta S_{rod} + \Delta S_{bath} = +137\frac{J}{K}$ (>0, irrev. process)

For <u>reversible</u> processes only: $\boxed{\Delta S_{universe} = 0}$

(since heat flows occur in pairs across boundaries at the same temperature)

for all real (irreversible) processes: $\boxed{\Delta S_{universe} > 0}$

Reversible Processes are "the best"

(when considering the amount of work produced by a process, or the amount of net work input required by a process; they are also infinitely slow, so not very good from a practical point of view)

$\Delta S_{universe} = \Delta S_{system} + \Delta S_{environment} \geq 0$

$\updownarrow$

$=$ only for reversible

$dS_{universe} = dS_{system} + dS_{environment} \geq 0$

$= -\frac{\delta Q}{T_{env}}$ (2)

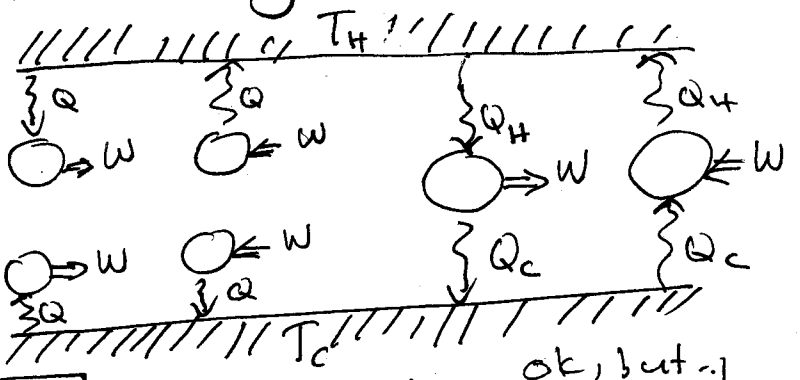
1st Law: $dE_{system} = \delta Q + \delta W$ (1)

(1)+(2) $$dS + \frac{\delta W - dE}{T_{env}} \geq 0 \Rightarrow -\delta W \leq T_{env} dS - dE \quad (6.27)$$

$-\delta W$ is the net work amount produced by the system for changes dS and dE in its properties (state) For reversible processes, the equality holds, for Irreversible ones, we get less work out.

(For work input, write 6.27 as $\delta W \geq dE - T_{env} dS$
For irreversible processes, one needs more work input.)

Heat Engines (Carnot)



reservoir of const. T

engine

⇒ W work

⇝ Q heat [+ if input to engine]

engine undergoes a cycle with no net (internal) change

NOT possible $\Delta S_{univ} < 0$

OK

ok, but...

2nd Law imposes limits on performance

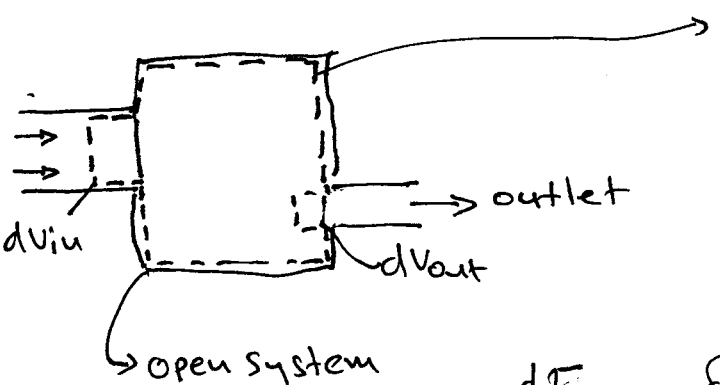
For thermal engines that operate reversibly: $Q_H + Q_c + W = 0$

$$\Delta S_{universe} = 0 \Rightarrow -\frac{Q_H}{T_H} - \frac{Q_c}{T_c} = 0 \Rightarrow \frac{Q_H}{T_H} = -\frac{Q_c}{T_c} \Rightarrow$$

$$\Rightarrow \frac{Q_H}{T_H} = \frac{Q_H + W}{T_c} \Rightarrow \frac{T_c}{T_H} = \frac{Q_H + W}{Q_H} \Rightarrow -\frac{W}{Q_H} = \boxed{\frac{T_H - T_c}{T_H} = \eta}$$

η is the thermal efficiency (Carnot)

Open Systems



$dE_c = \delta Q_c + \delta W_c$ (c = closed system / no subscript = open system)

$dE_c = dE - dm_{in}\hat{e}_{in} + dm_{out}\hat{e}_{out}$

$\delta Q_c = \delta Q \qquad \delta W_c = \delta W + P_{in}dV_{in} - P_{out}dV_{out}$

$\Rightarrow dE = \delta Q + \delta W + \hat{e}_{in}dm_{in} - \hat{e}_{out}dm_{out} + dm_{in}\hat{v}_{in}P_{in} - dm_{out}\hat{v}_{out}P_{out}$

Setting $\hat{e} + P\hat{v} = \hat{h}$ (^ is mass-based spec. property)

$\therefore \boxed{dE = \delta Q + \delta W + \hat{h}_{in}dm_{in} - \hat{h}_{out}dm_{out}}$

1st Law, open systems

Note that this balance is written from the point of view of the open system. If the open system is at <u>steady state</u>, there is no internal change:

$$\dot{Q} + \dot{W} + \sum_{in}\hat{h}_{in}\dot{m}_{in} - \sum_{out}\hat{h}_{out}\dot{m}_{out} = 0$$

(written in terms of rates, mass basis)

Could also have potential + kinetic energy changes for the inlet/outlet streams

For $\dot{Q} = \dot{W} = 0$, single stream, steady state

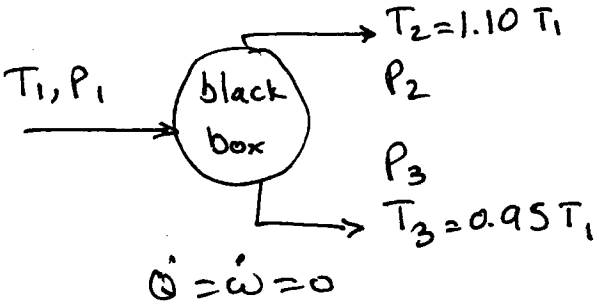
$\hat{h}_{in} = \hat{h}_{out}$ or $h_{in} = h_{out}$

For open systems, the entropy balance is

$$\dot{S}_{world} = \sum_{out} \dot{m}_{out} \hat{S}_{out} - \sum_{in} \dot{m}_{in} \hat{S}_{in} - \frac{\dot{Q}}{T_{env}} \geq 0$$

Note that outlet streams appear (+ sign) and inlet streams disappear (− sign). $\dot{Q}$ is the heat input to the system.

Example 6.3



$P_2 = P_3 = P$

What is min P_1/P to make operation of this device possible?

$C_p = 5R/2$ $\quad u, h = f(T \text{ only})$

Change of state of ideal gas: from $T_1, v_1 \rightarrow T_2, v_2$

$$du = Tds - Pdv \Rightarrow Tds = C_v dT + Pdv \Rightarrow ds = C_v \frac{dT}{T} + \frac{R dv}{v}$$

$$\Rightarrow \Delta s = C_v \ln \frac{T_2}{T} + R \ln \frac{V_2}{V_1} = C_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}$$

1st Law balance, steady-state

$$0 = \cancel{\dot{Q}} + \cancel{\dot{W}} + \dot{m}_1 \hat{h}_1 - \dot{m}_2 \hat{h}_2 - \dot{m}_3 \hat{h}_3 \quad (1)$$

For ideal gas, T-indep. C_v, C_p $\quad h = C_p T$ [+ const] $\quad u = C_v T$ [+ const] can ignore

$$(1) \Rightarrow \dot{m}_1 T_1 = \dot{m}_2 T_2 + \dot{m}_3 T_3 \Rightarrow$$

$$(2)\ T_1 = \lambda T_2 + (1-\lambda) T_3 \qquad \lambda = \frac{\dot{m}_2}{\dot{m}_1} \quad \text{Solve } (2) \Rightarrow \lambda = 1/3$$

2nd Law balance for best (reversible) process

$$\dot{S}_{world} = 0 = \dot{m}_2 \hat{S}_2 + \dot{m}_3 \hat{S}_3 - \dot{m}_1 \hat{S}_1 \Rightarrow$$

2 3 1

$$\left[c_p \ln\frac{T_2}{T_1} - R\ln\frac{P}{P_1}\right] + 2\left[c_p \ln\frac{T_3}{T_1} - R\ln\frac{P}{P_1}\right] = 0$$

$$\Rightarrow \frac{5R}{2}\cdot \ln(1.10) + 2\cdot\frac{5R}{2}\cdot\ln(0.95) = 3R\ln\frac{P}{P_1} \Rightarrow$$

$$\ln\frac{P}{P_1} = -0.006 \Rightarrow P = 0.994\,P_1$$

Note typo in book for this example