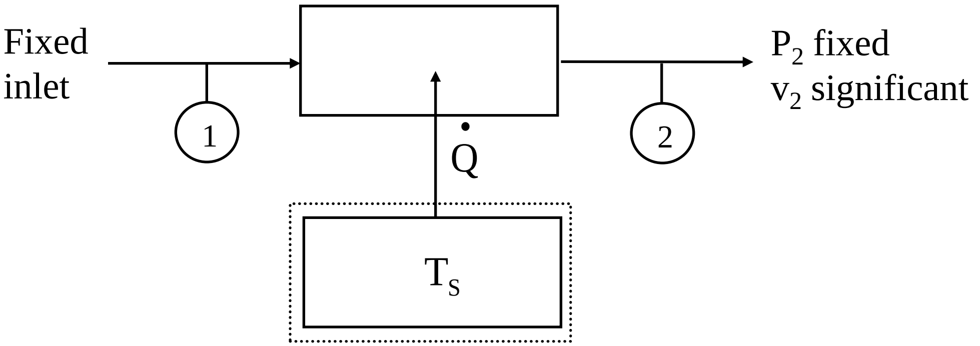
A Thrusting Device

Example: A Thrusting Device
Objective: to produce thrust



Given: 1) State (1) P_1, T_1 fixed
2) P_2 fixed, $P_2 < P_1$

Question: What state (2) do we want to maximize the thrust?

E.B.:
$$\dot{Q} - (0) = \cancelto{0}{\frac{dE}{dt}} + \dot{m}_2\left(h_2 + \frac{v_2^2}{2g_c}\right) - \dot{m}_1\left(h_1 + \frac{v_1^2}{2g_c}\right)$$

2nd Law:
$$\dot{S}_{gen} = \cancelto{0}{\frac{dS}{dt}} - \left(\frac{\dot{Q}}{T_S}\right) + \dot{m}_2 s_2 - \dot{m}_1 s_1$$

Eliminate $\dot{Q}$:

$$\dot{Q} = T_S \dot{m}(s_2 - s_1) - T_S \dot{S}_{gen}$$

$$\frac{\dot{Q}}{\dot{m}} = T_S(s_2 - s_1) - T_S \frac{\dot{S}_{gen}}{\dot{m}}$$

Combining the equations:

$$\left(h_2 + \frac{v_2^2}{2g_c}\right) - \left(h_1 + \frac{v_1^2}{2g_c}\right) = T_S(s_2 - s_1) - T_S \frac{\dot{S}_{gen}}{\dot{m}}$$

How do we maximize v_2?

Let $\dot{S}_{gen} \rightarrow 0$

Then: $$\left(\frac{v_2^2}{2g_c}\right) = \left(\frac{v_1^2}{2g_c}\right) + (h_1 - T_S s_1) - (h_2 - T_S s_2)$$

Thus, neglecting $\left(\frac{v_1^2}{2g_c}\right)$: $$\left(\frac{v_2^2}{2g_c}\right) = (b_1 - b_2)$$

What state (2) should be chosen?

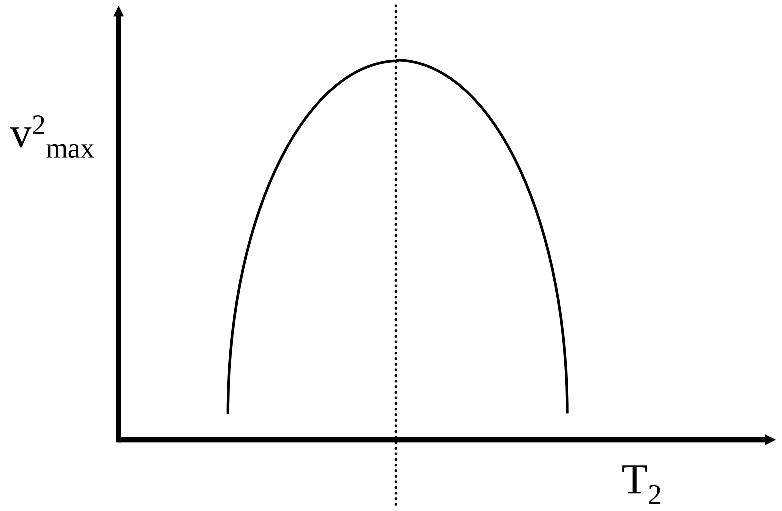
Assume ideal gas:

$$h_2 - h_1 = C_P(T_2 - T_1) \quad \& \quad s_2 - s_1 = C_P \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{P_2}{P_1}\right)$$

$$\left(\frac{v_2^2}{2g_c}\right) = C_P(T_1 - T_2) - T_S\left[C_P \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{P_2}{P_1}\right)\right]$$

$C_P(T)$ is <u>monotonically increasing</u>

For P_1, T_1, P_2 fixed:

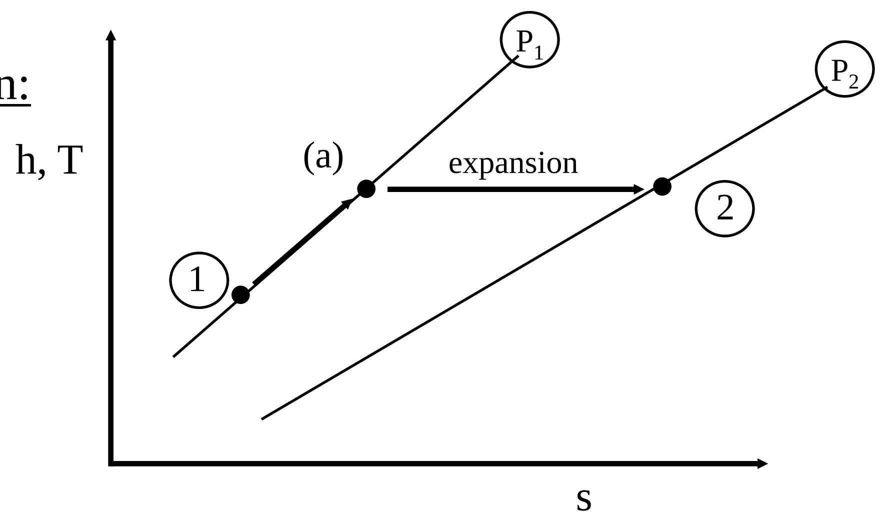


Differentiate with respect to T_2 :

$$\frac{d\left(\frac{1}{2} v_2^2\right)}{dT_2} = -C_P + T_S C_P \frac{1}{T_2} = 0$$

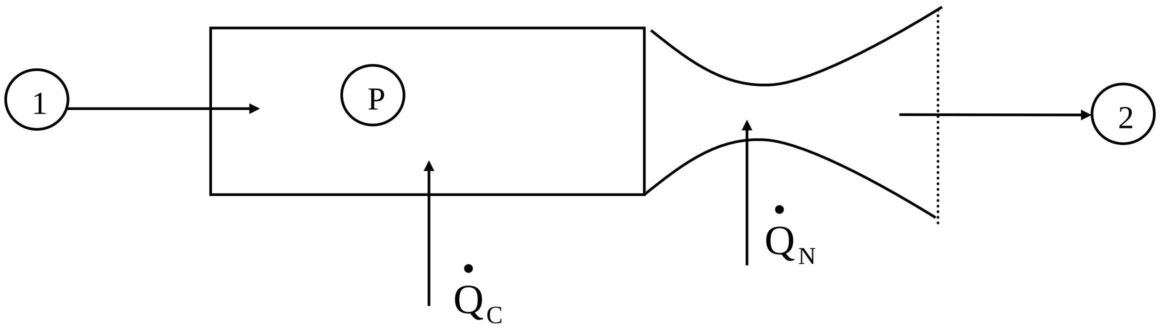
Thus : $\quad T_{2max} = T_S$

Ramification:



What is suggested is that you supply heat as the highest possible temperature!

How do we accomplish this?

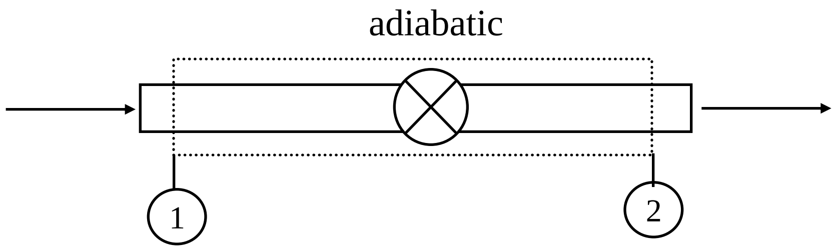


Did we seek equilibrium with environment?

No, actually we sought maximum disequilibrium with environment!

Viscous Pipe Flow

Example: Irreversibility in Viscous Pipe Flow



$$\text{1st Law:}\quad \dot{m}h_1 = \dot{m}h_2$$

$$h_1 = h_2$$

$$\text{2nd Law:}\quad \dot{P}_S + \dot{m}s_1 = \dot{m}s_2 + \cancel{\frac{ds}{dt}}^{\,0}$$

$$\dot{P}_S = \dot{m}(s_2 - s_1)$$

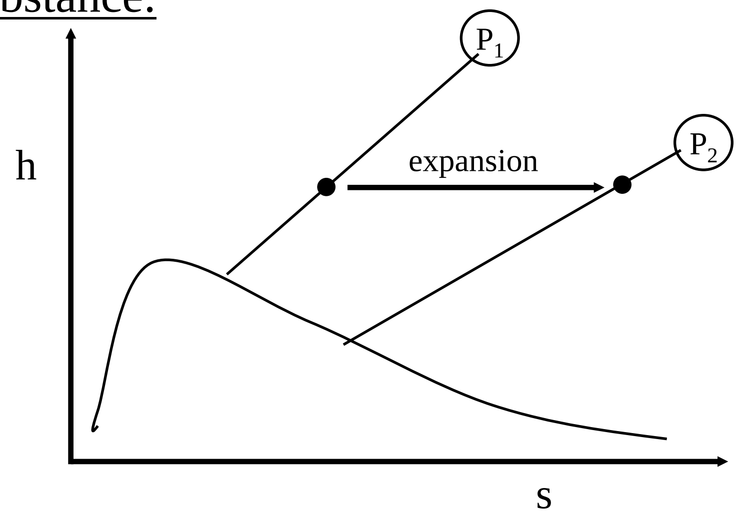
Recall that for any pure, simple compressible susbstance:

dh = Tds + vdP

Since dh = 0 for adiabatic flow:

$$ds = -\left(\frac{v}{T}\right)dP$$

$$s_2 - s_1 = \left[\int_{P_2}^{P_1}\left(\frac{v}{T}\right)dP\right]\Bigg|_{h=const}$$



In general both T and P may change. Changes in temperature associated with viscous dissipation, i.e. conversion of mechanical energy to internal thermal energy, therefore degradation of available mechanical power.

Specialization:

Case (1) : Perfect Gas

1st Law : $$h_2 - h_1 = 0$$

For Constant C_P : $$C_P (T_2 - T_1) = 0 \qquad \therefore T_2 = T_1$$

$$Pv = RT \qquad \therefore \frac{v}{T} = \frac{R}{P}$$

$$s_2 - s_1 = \int_{P_2}^{P_1} R \frac{dP}{P} = R \ln\left(\frac{P_1}{P_2}\right)$$

$$\dot{P}_s = \dot{m} R \ln\left(\frac{P_1}{P_2}\right) = \dot{m} C_P \ln\left[\left(\frac{P_1}{P_2}\right)^{\frac{k-1}{k}}\right]$$

Now if $\Delta P = P_1 - P_2 << P$

$$\frac{P_1}{P_2} = \frac{\Delta P + P_2}{P_2} = \frac{\Delta P}{P_2} + 1 = \frac{\Delta P}{P_1 - \Delta P} + 1 \cong \frac{\Delta P}{P_1} + 1$$

$$\dot{P}_s \cong \dot{m} R \ln\left(1 + \frac{\Delta P}{P_1}\right) \cong {}^{*}\dot{m} R \ln\left(\frac{\Delta P}{P_1}\right) \cong \dot{m}\left(\frac{\Delta P}{\rho_1 T_1}\right)$$

* Recall : $\ln(1+x) = x - \frac{1}{2}x^2 + \frac{1}{3}x^3 + \cdots$ for $-1 < x \le 1$ so for x very small, $\ln(1+x) \cong x$

Case (2): Incompressible Liquid

$$s_2 - s_1 = \int_{P_2}^{P_1} \left(\frac{v}{T} \right) dP$$

$$Tds = du + P\cancel{dv} \quad (\rightarrow 0)$$

Now: $$ds = \frac{du}{T} = C_V \frac{dT}{T}$$

and also: $$Tds = dh - vdP$$

$$ds = -\frac{v}{T} dP; \qquad dh = 0$$

$\therefore$ $$-\frac{v}{T} dP = C_V \frac{dT}{T}$$

$$-vdP = C_V dT$$

since $v = \text{const}$: $$\frac{1}{\rho} \int_{P_2}^{P_1} dP = C_V \int_{T_1}^{T_2} dT$$

$$\left[\frac{P_1 - P_2}{\rho} \right] = C_V (T_2 - T_1) \quad \Rightarrow$$

General result for an I.C.L. undergoing <u>isenthalpic</u> process

divide by T_1: $$\left[\frac{P_1 - P_2}{T_1 \rho} \right] = C_V \left(\frac{T_2}{T_1} - 1 \right)$$

$$s_2 - s_1 = C_V \int_{T_1}^{T_2} \frac{dT}{T} = C_V \ln\left(\frac{T_2}{T_1}\right)$$

$$s_2 - s_1 = C \ln\left[\frac{\Delta P}{\rho\, C\, T_1} + 1\right]$$

$$\dot{P}_S = \dot{m}\,(s_2 - s_1) = \dot{m}\, C \ln\left[\frac{\Delta P}{\rho\, C\, T_1} + 1\right]$$

now if $\quad \frac{\Delta P}{\rho\, C\, T_1} << 1 \quad$ (very small)

$$\dot{P}_S = \dot{m}\,(s_2 - s_1) \cong \dot{m}\, C \frac{\Delta P}{\rho\, C\, T_1} = \dot{m} \frac{\Delta P}{\rho\, T_1}$$

Thus: $\quad \dot{P}_S \cong \frac{\dot{m}}{T_1}\left[\frac{\Delta P}{\rho}\right]$

Recall from the Perfect Gas equation :

$$\dot{P}_S \cong \dot{m} R \left(\frac{\Delta P}{P_1} \right)$$

but $P_1 = \rho_1 R T_1$

$$\therefore \quad \dot{P}_S = \frac{\dot{m}}{T_1} \left[\frac{\Delta P}{\rho_1} \right]$$

The perfect gas and the incompressible liquid equations are the same. What is implied?

$$\left(\text{remember we said } \frac{\Delta P}{\rho_1} << 1 \right)$$

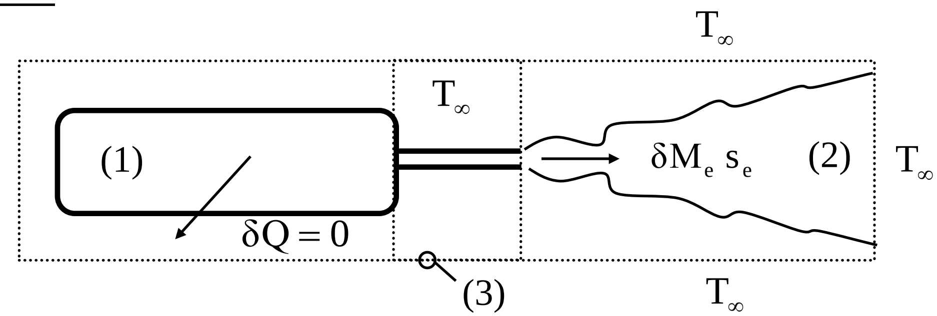
Thus note : Lost Work, or $\dot{I}$

$$\left\{ \frac{T_1 \dot{P}_S}{\dot{m}} = \frac{\Delta P}{\rho_1} \right\} = \dot{I}, \quad \text{irreversibility rate}$$

$$\left(\frac{J}{kg} \right) x \frac{\$}{J} = \frac{\$}{kg}$$

Discharge of a Vessel

Example: Discharge of an Adiabatic Tank



(1) $\delta P_S = d(M s) + \delta M_e\ s_e$

but: $dM + \delta M_e = 0; \quad dM = -\delta\delta\ _e$

or: $\delta P_{S1} = s\, dM + \delta M_e\ s_e = 0$ becauseentropyis constant

Entropy is not produced in the tank. It is a reversible process.

(2) In thefree jet

$$\delta P_{S2} + s_\infty\ \delta M_{entrained} + \delta M_e\ s_e = \frac{dS_{jet}}{dt} + \left(\delta M_{entrained} + \delta M_e\right) s_\infty$$

$$\delta P_{S2} = \frac{dS_{jet}}{dt} \overset{0}{} + \delta M_e\left(s_\infty - s_e\right)$$

for an ideal gas:

$$s_2 - s_1 = C_P \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{P_2}{P_1}\right)$$

Therefore:

$$\delta P_{S2} = \delta M_e \left[C_P \ln\left(\frac{T_\infty}{T_e}\right) - R\ln\left(\frac{P_\infty}{P_e}\right) \right]$$

Now: $T_e < T_\infty$

$P_e > P_\infty$

Where is entropy generated and what is the manifestation?

Ultimately, the ability to perform mechanical work is lost and entropy was produced.

What does the <u>energy balance</u> tell us:

$$\underbrace{\delta M_e \left(h_e + \frac{v_e^2}{2g} \right)}_{(1)} + \delta M_{entrained} \left(h_{\infty-} + \frac{v_{entrained}^2}{2g} \right) = \underbrace{\left(\delta M_e + \delta M_{entrained} \right) \left(h_{\infty+} + \frac{v_\infty^2}{2g} \right)}_{(2)}$$

(1) Energy available as kinetic energy of the flow

(2) Energy available as kinetic energy of the flow, but <u>less</u> specific kinetic energy, i.e. kinetic energy per unit mass flow. A <u>lower quality</u> energy.

Introduction to Availability

Some Remarks about Availability or Exergy

- The quality of energy is the potential of that energy to produce useful work

- The work potential of a given quality of energy is defined as the maximum possible useful work that can be obtained from that in a given environment

- When energy changes its form or is transferred from one system to an another:
  - the total amount of energy is constant (1st Law)
  - the potential for producing useful work is reduced forever (2nd Law)

Goals of Engineering Thermodynamics:

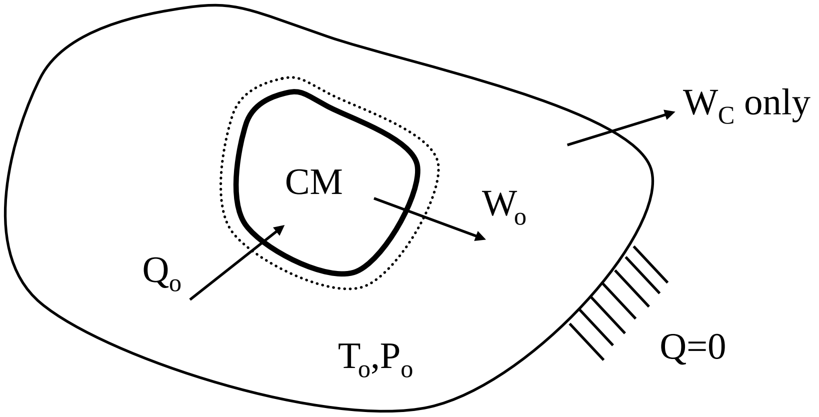
- Optimize methods for converting various forms of energy into work

- Optimize the use of work interactions to bring about desired results

- Minimize loss in work potential of a system even in the absence of work interactions

Total Availability of a System without Flow

A Combined System (Moran, Ch. 3, 1989)



$V_{combined} = V + V^o =$ constant (note: V^o may change)

Analysis: for the combined system: undergoing state change to dead state

E.B. $W_C = -\Delta E_C$

where $\Delta E_C = \Delta E + \Delta E^o$

thus $\Delta E_C = (U^o - E) + \Delta U^o$

Now, from Gibbs equation:

$$T_o \Delta S^o = \Delta U^o + P_o \Delta V^o$$

thus: $\Delta U^o = T_o \Delta S^o - P_o \Delta V^o$

Combining :

$$W_C = -\left[(U^o - E) + (T_o \Delta S^o - P_o \Delta V^o)\right]$$

Now, since $\Delta V^o = -\Delta V = (V_o - V)$

then : $W_C = (E - U^o) + P_o (V - V_o) - T_o \Delta S^o$

2nd Law : combined system

$$P_{S,C} = \Delta S_C = \Delta S + S^o$$

or $P_{S,C} = (S_o - S) + \Delta S^o$

Combining :

$$W_C = \left\{(E - U^o) + P_o (V - V_o) - T_o (S - S_o)\right\} - T_o P_{S,C}$$

Thus :

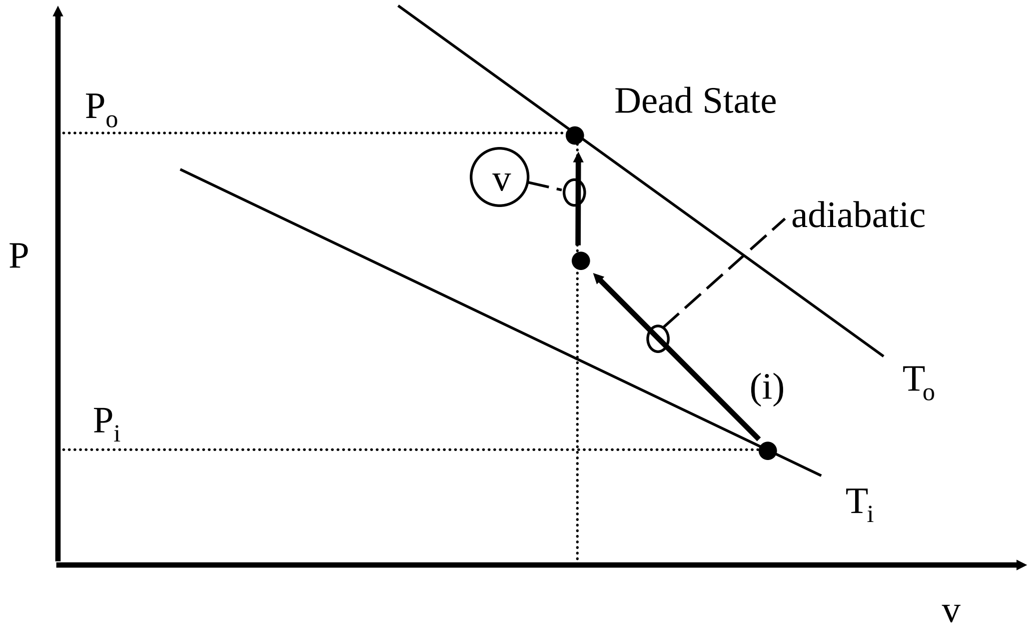
$$W_C \leq W_C, \max$$

where

$$W_C, \max = (E - U^o) + P_o (V - V_o) - T_o (S - S_o)$$

$$A = W_C, \max$$

Example of a Process:



i-a: adiabatic process

a-o: constant volume process

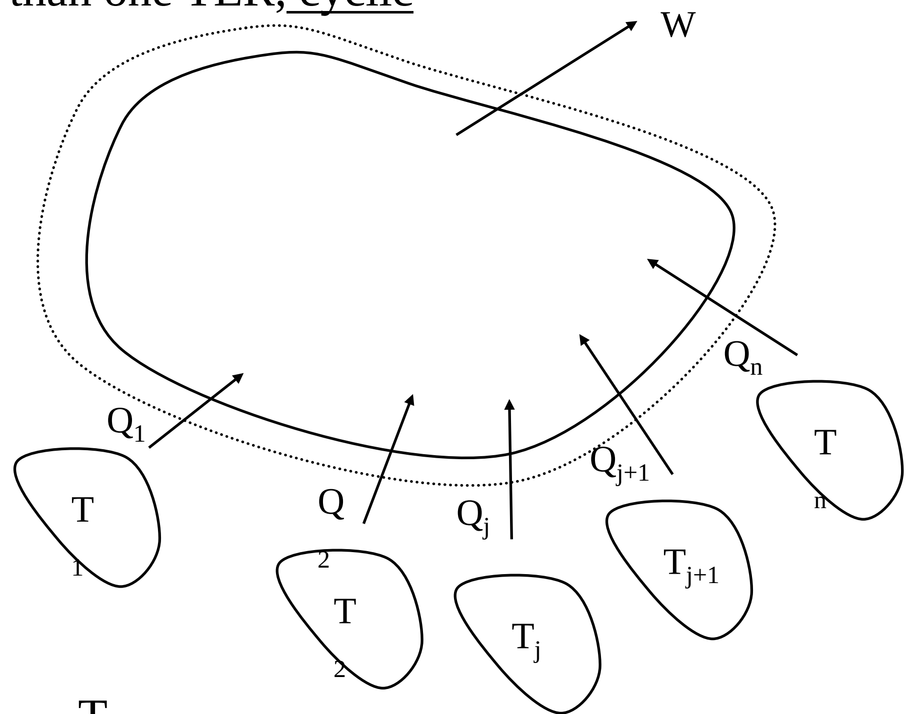
Requirements to find the Availability:

• All internally reversible processes, both system & surroundings?

Availability of a Closed Cyclic System

Availability - Closed System: Cyclic

A system, closed, communicating with more than one TER, cyclic



$$\text{E.B.}: \qquad W = \sum_{i=1}^{n} Q_i$$

$$\text{2nd Law}: \quad P_S = -\sum_{i=1}^{n} \left(\frac{Q}{T}\right)_i \geq 0$$

Let Q_j be the "floating" term:

$$T_j\, P_S + \sum_{i=1}^{j-1} Q_i \frac{T_j}{T_i} + \sum_{i=j+1}^{n} Q_i \frac{T_j}{T_i} = -Q_j$$

Conbining :

$$W = \sum_{i=1}^{j-1} Q_i + \sum_{i=j+1}^{n} Q_i - \sum_{i=1}^{j-1} Q_i \frac{T_j}{T_i} - \sum_{i=j+1}^{n} Q_i \frac{T_j}{T_i} - T_j\, P_S$$

or :

$$W = \sum_{i=1}^{j-1} Q_i \left(1 - \frac{T_j}{T_i}\right) + \sum_{i=j+1}^{n} Q_i \left(1 - \frac{T_j}{T_i}\right) - T_j\, P_S$$

Thus we note:

$$W_{max} = \underbrace{\sum_{i=1}^{j-1} Q_i\left(1-\frac{T_j}{T_i}\right) + \sum_{i=j+1}^{n} Q_i\left(1-\frac{T_j}{T_i}\right)}_{\text{*Bejan calls } \dot{Q}\left(1-\frac{T_o}{T_i}\right) \text{ exergy content of heat transfer}}$$

W_{max} = A = availability referenced to T_j, of heat transfer interactions.

Also note:

$W_{lost} = W_{max} - W = T_j P_S$ Gouy-Stodola theorem (see Bejan)

Sometimes called I = irreversibility see Wark

Remarks:

W_{max} obtained when system undergoes an internally reversible process.

Dead State

- The particular state of the system when it is in thermal & mechanical equilibrium with its environment.
- At the dead state, the system is at (T_o, P_o)
- Restricted dead state does not allow mass mixing with the environment.

Remarks:

Lost available work is a relative quantity that depends upon choice of reference reservoir temperature.

The reference reservoir is the one whose heat transfer interaction floats (changes) as the irreversibility and work output of a system change.

Now since P_S does not depend on reference temperature

$$P_S = -\sum_{i=1}^{n} \left(\frac{Q}{T}\right)_i$$

then $$W_{lost\ j} = T_j\ P_S$$

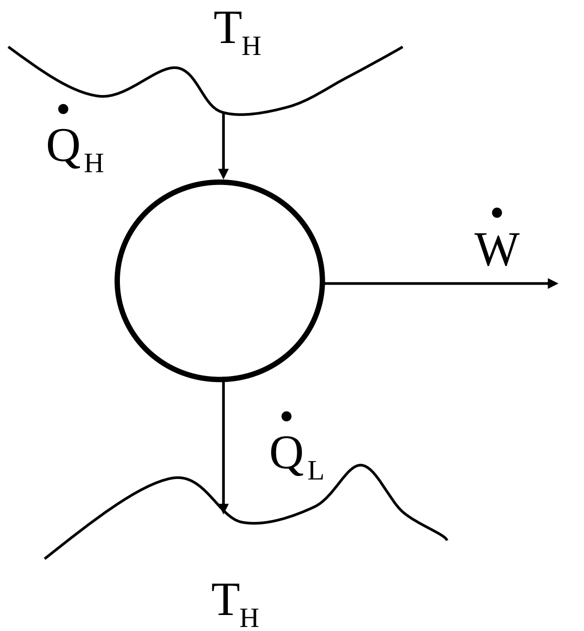
and $$W_{lost\ o} = T_o\ P_S$$

Therefore: $$W_{lost\ j} = \frac{T_j}{T_o} W_{lost\ o}$$

Final Remarks:

- W_{lost}; depends upon convention and usage
- P_S depends solely on irreversibility
- To design systems for which destruction of availability work is minimized, the entropy produced must be minimized.

Example: A 2T Engine



1st Law: $\dot{Q}_H - \dot{Q}_L - \dot{W} = 0$

2nd Law: $P_S + \frac{Q_H}{T_H} = \frac{Q_L}{T_L}$

$$P_S = \frac{Q_L}{T_L} - \frac{Q_H}{T_H} \geq 0$$

For a reversible engine

$$\dot{Q}_{H\,rev} - \dot{Q}_{L\,rev} = \dot{W}_{max}$$

$$\cancelto{0}{P_S} = \frac{Q_{L\,rev}}{T_L} - \frac{Q_{H\,rev}}{T_H} = 0$$

Now, compare performance of actual heat engine to reversible engine based on equal heat input

$$\dot{Q}_H = \dot{Q}_{H\,max}$$

$$\dot{W}_{lost} = \dot{W}_{max} - \dot{W} = \dot{Q}_{H\,rev} - \dot{Q}_{L\,rev} - \left[\dot{Q}_H - \dot{Q}_L\right] = -\dot{Q}_{L\,rev} + \dot{Q}_L$$

$$\dot{W}_{lost} = \dot{Q}_L - \frac{T_L}{T_H}\dot{Q}_H = T_L\left[\frac{\dot{Q}_L}{T_L} - \frac{\dot{Q}_H}{T_H}\right] = T_L\ P_S$$

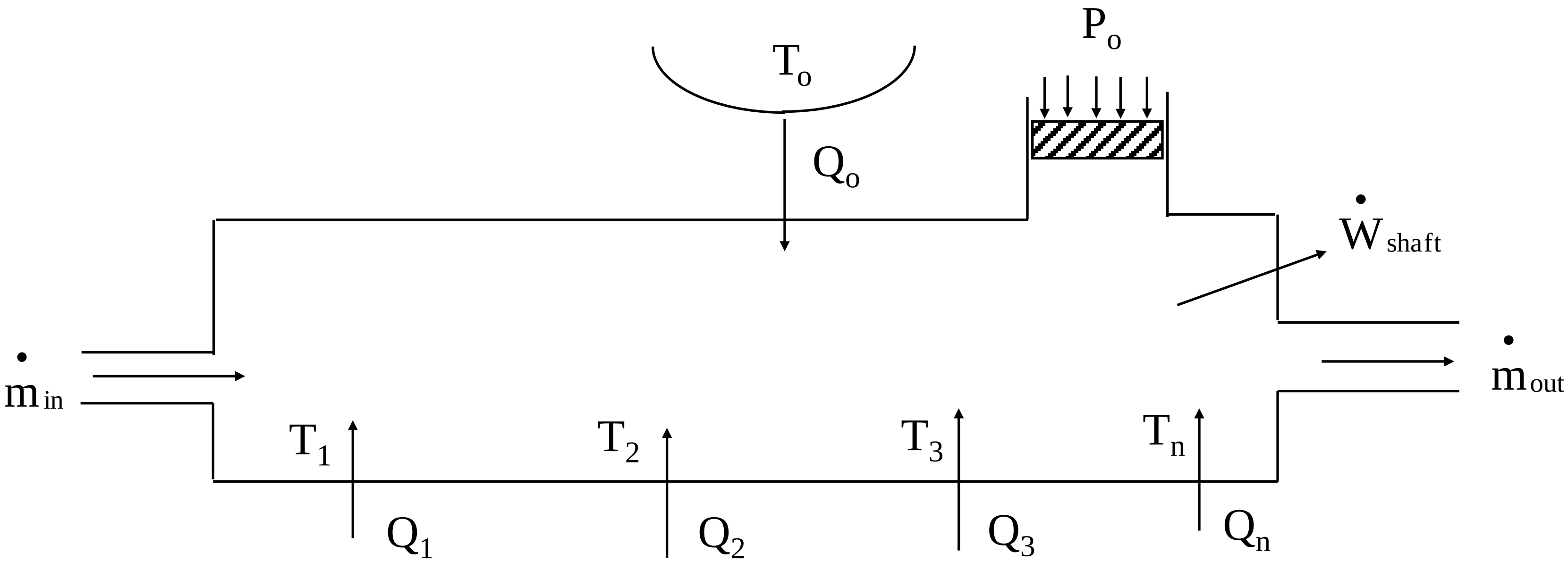
In this case, what is the floating reservoir?

Answer: Reservoir at T_L, thus $T_L = T_j$ in the general analysis.

Comment: evaluating $\dot{W}$ and $\dot{W}_{max}$ based on equal $\dot{Q}_H$ means $\dot{Q}_L$ varies with irreversibility of the engine.

Steady Flow Availabilty [Exergy]

(see Bejan p. 129 & Wark Chap 3



Environment at dead state (T_o , P_o)

1st Law: $$\frac{dE}{dt} = \sum_{i=1}^{n} \dot{Q}_i - \dot{W}_{tot} + \sum_{in} \dot{m}\, h^o - \sum_{out} \dot{m}\, h^o + \dot{Q}_o$$

where: $$h^o = \left[h + \frac{v^2}{2} + g\, z \right]$$

2nd Law: $$\dot{\sigma}_S = \frac{dS}{dt} - \sum_{i=1}^{n} \frac{\dot{Q}_i}{T_i} + \sum_{in} \dot{m}\, s - \sum_{out} \dot{m}\, s + \frac{\dot{Q}_o}{T_o}$$

Combine 1st & 2nd laws to eliminate $\dot{Q}_o$:

$$\dot{W}_{tot} = -\frac{d}{dt}\left[E - T_o S\right] + \sum_{i=1}^{n} \left(1 - \frac{T_o}{T_i}\right) \dot{Q}_i + \sum_{in} \dot{m}\,(h^o - T_o s) - \sum_{out} \dot{m}\,(h^o - T_o s) - T_o\, \dot{\sigma}_S$$

Thus: $\dot{W}_{rev} - \dot{W}_{tot} = T_o\, \dot{\sigma}_S \geq 0$

$T_o\, \dot{\sigma}_S$ is lost work or $\dot{I}$ (irreversibility)

This is the <u>"lost work theorem"</u>

<u>Conclusions:</u>

(a) entropy produced is proportional to available work destroyed

(b) upper limit of work transfer rate can be found by letting $\dot{\sigma}_S \rightarrow 0$, reversible process

For Steady Flow:

$$\dot{W} = \sum_{i=1}^{n}\left(1 - \frac{T_o}{T_i}\right)\dot{Q}_i + \sum_{in}\dot{m}\,b - \sum_{out}\dot{m}\,b - T_o\,\dot{\sigma}_S$$

where $b = h^o - T_o s = e_x$

[compare to Wark eq. 3.43] Wark assumes work inflow

Flow Availability or Exergy:

Define flow availability:

$$\psi = b - b_o = \left(h^o - T_o s\right) - \left(h_o^o - T_o s\right); \qquad \text{Bejan uses} \quad e_x = \psi$$

where h_o^o is evaluated at the system dead state.

Thus re-writing:

$$\dot{W}_{rev} = \sum_{i=1}^{n}\left(1 - \frac{T_o}{T_i}\right)\dot{Q}_i + \sum_{k=1}^{m}\left[\left(\dot{m}\,\psi\right)_{in} - \left(\dot{m}\,\psi\right)_{out}\right]_k$$

or

$$\dot{W}_{rev} = \underbrace{\sum_{i=1}^{n}\left(1 - \frac{T_o}{T_i}\right)\dot{Q}_i + \sum_{k=1}^{m}\left(\dot{m}\,\psi\right)_{in}}_{\text{exergy inflow}} - \underbrace{\sum_{k=1}^{m}\left(\dot{m}\,\psi\right)_{out}}_{\text{exergy outflow}} - \underbrace{T_o\,\dot{\sigma}_S}_{\text{destroyed exergy}}$$

Other definitions:

$$\dot{\Phi}_Q = \dot{E}_Q = \left(1 - \frac{T_o}{T_i}\right)\dot{Q}_i \text{ is Availability or exergy of } \dot{Q}$$

ψ is Availability of flow (e_x)

$$\dot{I} = T_o\,\dot{\sigma}_S$$

Example: Flow availability for ideal gas

$$e_{x2} - e_{x1} = \psi_2 - \psi_1 = (h_2 - h_1) - T_o(s_2 - s_1)$$

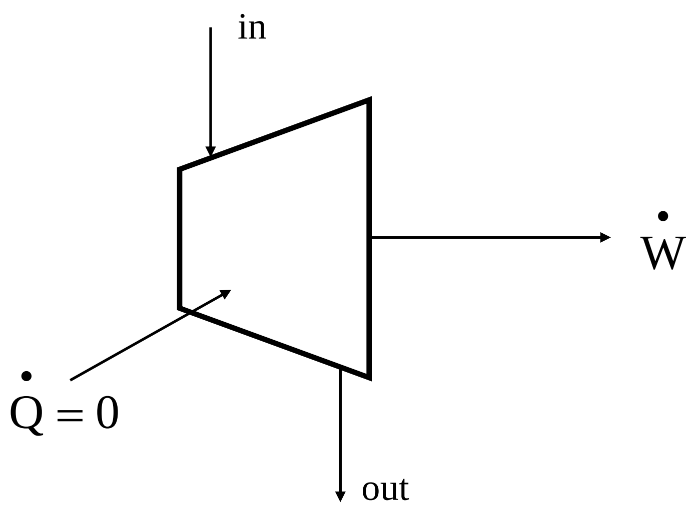
$$\frac{\psi}{C_P T_o} = \frac{T}{T_o} - \ln\left(\frac{T}{T_o}\right) + \ln\left(\frac{P}{P_o}\right)^{\frac{k-1}{k}}$$

Thus we may write:

$$\dot{W}_{actual} = \dot{\Phi}_Q + \sum_{in}\dot{m}\,\psi - \sum_{out}\dot{m}\,\psi - \dot{I} = \dot{E}_Q + \sum_{in}\dot{m}\,e_x - \sum_{out}\dot{m}\,e_x - \dot{E}_{w\,lost}$$

Examples:

Turbine



SSSF availability balance:

$$\dot{W} = \left(\dot{m}\psi\right)_{in} - \left(\dot{m}\psi\right)_{out} - \dot{I}$$

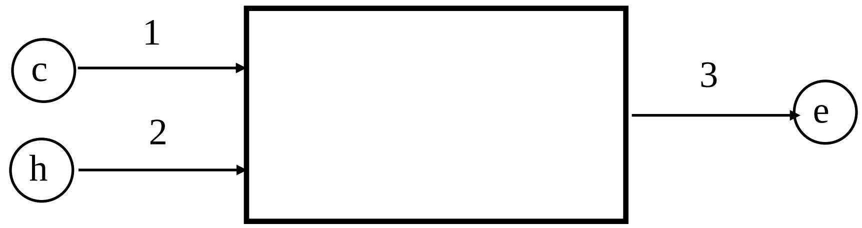
Turbine effectiveness: [2nd Law effectiveness]

$$\varepsilon_t = \frac{\dot{W}_{actual}}{\left(\dot{m}\psi\right)_{in} - \left(\dot{m}\psi\right)_{out}} = \left[\frac{\dot{w}}{\psi_{in} - \psi_{out}}\right] = \frac{\dot{w}}{\dot{w} - \dot{i}}$$

Is this the same as isentropic efficiency?

Examples:

Heat Exchange with Mixing



$$\dot{m}_1 + \dot{m}_2 = \dot{m}_3$$

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 - \dot{m}_3 h_3 = 0$$

$$\left(\dot{m}\,\psi\right)_1 + \left(\dot{m}\,\psi\right)_2 - \left(\dot{m}\,\psi\right)_3 - \dot{I} = 0$$

$$\text{Combine:}\ \dot{m}_h(\psi_3 - \psi_3) = \dot{m}_c(\psi_3 - \psi_1) + \dot{I}$$

$$\text{Thus:}\qquad \varepsilon = \frac{\dot{m}_c(\psi_3 - \psi_1)}{\dot{m}_h(\psi_3 - \psi_3)}$$

$$\text{or}\qquad \dot{m}_1\psi_1 + \dot{m}_2\psi_2 = \left(\dot{m}_1 + \dot{m}_2\right)\psi_3 + \dot{I}$$

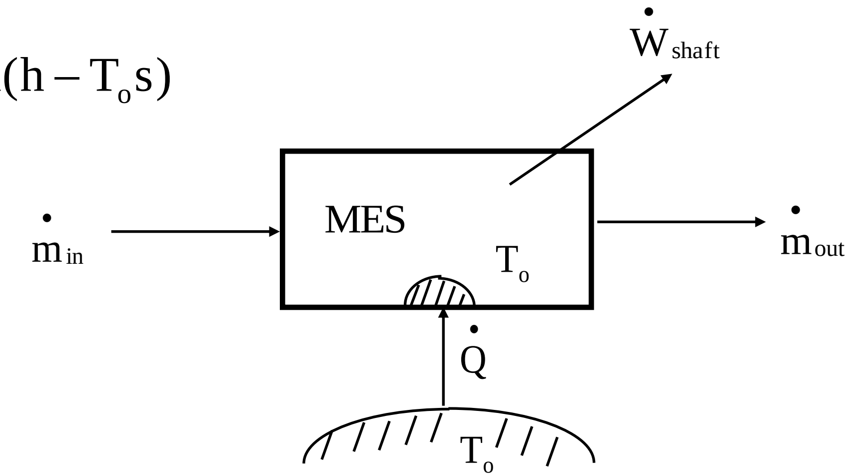
$$\varepsilon = \frac{\text{output}}{\text{input}} = \frac{\left(\dot{m}_1 + \dot{m}_2\right)\psi_3}{\left(\dot{m}_1\psi_1 + \dot{m}_2\psi_2\right)}$$

Availability [Exergy] Analysis of Steady Flow Processes:

we showed before:

$$\dot{W}_{shaft\ max} = \sum_{in} \dot{m}(h - T_o s) - \sum_{out} \dot{m}(h - T_o s)$$

$$= \sum_{in} \dot{m}\, b - \sum_{out} \dot{m}\, b$$

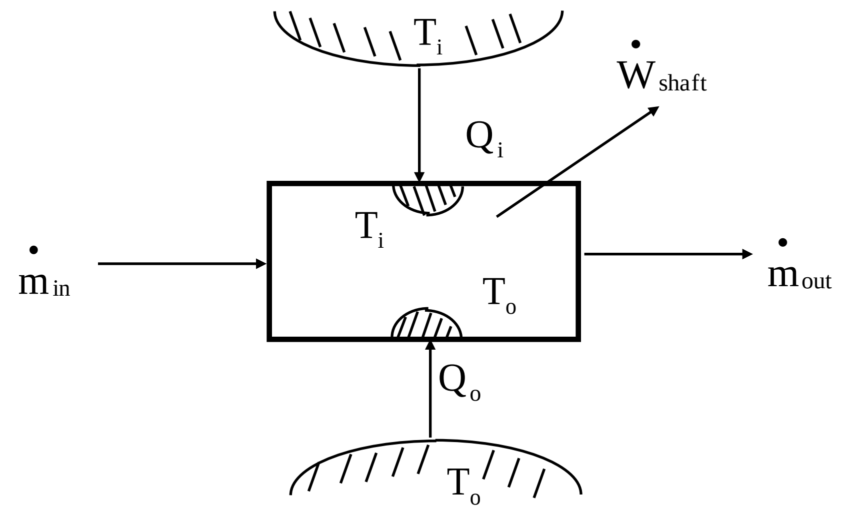


where: $b = h - T_o s$

Steady flow availability function

When T_o is specified, b is a thermodynamic property of the system.

Now Consider:



$$\dot{W} = \sum_{i} \dot{Q}_i + \dot{Q}_o - \sum_{in} \dot{m}\, h - \sum_{out} \dot{m}\, h$$

$$P_S = -\sum_{i} \frac{\dot{Q}_i}{T_i} - \frac{\dot{Q}_o}{T_o} - \sum_{in} \dot{m}\, s - \sum_{out} \dot{m}\, s$$

For a <u>reversible system:</u>

$$\text{1st Law:} \qquad \dot{W}_{max} = \sum_i \dot{Q}_i + \dot{Q}_{o\,rev} + \sum_{in} \dot{m}\,h - \sum_{out} \dot{m}\,h$$

$$\text{2nd Law:} \qquad P_S = 0 = -\sum_i \frac{\dot{Q}_i}{T_i} - \frac{\dot{Q}_{o\,rev}}{T_o} - \sum_{in} \dot{m}\,s + \sum_{out} \dot{m}\,s$$

Eliminating $\dot{Q}_{o\,rev}$

$$\dot{W}_{max} = \dot{W} + \dot{W}_{lost\,o} = \sum_i \dot{Q}_i \left(1 - \frac{T_o}{T_i}\right) + \sum_{in} \dot{m}\,(h - T_o s) - \sum_{out} \dot{m}\,(h - T_o s)$$

$h - T_o s = b =$ "<u>steady flow availability function</u>"

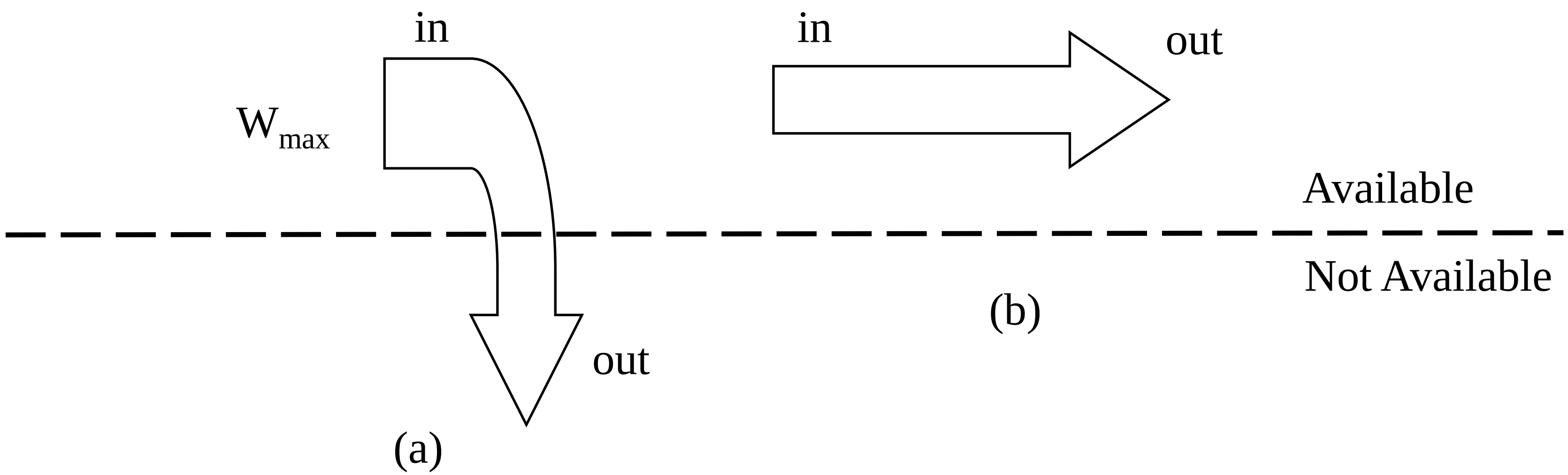
$\dot{Q}_i \left(1 - \frac{T_o}{T_i}\right)$ = "<u>availability</u> of the heat transfer interaction $\dot{Q}_i$, T_i with respect to reference reservoir T_o,
i.e. capacity of the heat transfer interaction to do useful work.

Obviously, heat transfer availability for a reservoir $\dot{Q}_i$, T_i with respect to T_o is <u>zero</u>!

Exergy: $e_x = h - h_o - T_o (s - s_o)$

where h_o , s_o , T_o are referred to the dead state ambient conditions

Example: [Bejan Fig 2.6, p.33]



(a) Exergy of outgoing stream is zero.

W_{max} = exergy content of inflow stream.

Lost Work Theorem Applied to Cycles

It is obvious that:

Maximum delivery of available mechanical power:

$$\dot{W}_{rev} = \sum_{i=1}^{n} \dot{Q}_i \left(1 - \frac{T_o}{T_i}\right) = \left(\dot{E}_W\right)_{rev}$$

The heat transfer interaction $\dot{Q}_i$ can affect ability to perform work if $T_i \neq T_o$.

To use exergy notation:

$$\dot{E}_Q = \dot{Q}_i \left(1 - \frac{T_o}{T_i}\right)$$

= available work (exergy) content of the heat transfer interaction; heat transfer is reversible.

Also called "availability"

Thus:

$$\dot{W}_{lost} = \left[\sum_{i=1}^{n} \left(\dot{E}_Q\right)\right] - \dot{E}_W$$

Heat Engine

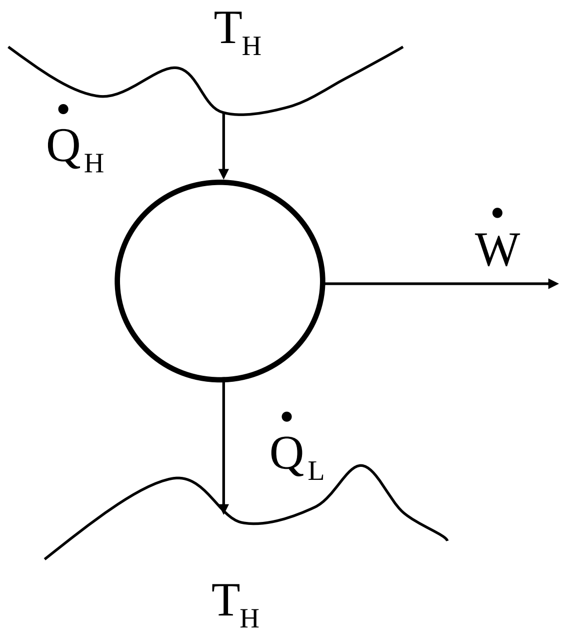
$$1\text{st Law}: \quad Q_H - Q_L - W = 0$$

$$2\text{nd Law}: \quad \dot{P}_S = \frac{Q_L}{T_L} - \frac{Q_H}{T_H} \geq 0$$

Let T_L be the environment temperature:
(T_o eliminated between 1st and 2nd laws)

$$\dot{W}_{lost} = \dot{E}_{Q_H} - \dot{E}_W$$

$$\dot{W}_{lost} = \dot{Q}_H\left(1 - \frac{T_L}{T_H}\right) - \dot{W}_{max}$$



Note: The exergy is referred to the state $T_L(T_o)$; this is eliminated between the equations

Restricted Dead State

Equilibrium (mechanical & thermal) state with environment

T_o = 298.15 K P_o=0.101325 Mpa

Advantage of Exergy Analysis

"What is available work (exergy) content of a stream that is not in thermal and mechanical equilibrium with its environment?"

Answer: for environment being only thermal reservoir:

$$\dot{W}_{rev,T_o\ only} = \dot{m}\, e_x$$