



## MODULE 8

# Availability and Irreversibility



## IRREVERSIBILITY



The entropy of a system plus its surroundings (i.e. an isolated system) can never decrease (2nd law).

The second law states:

$$(\Delta S)_{system} + (\Delta S)_{surr} = 0 \text{ where } \Delta = \textit{final - initial}$$

**> 0 irreversible (real world)**  
**= 0 reversible (frictionless, ideal)**

In an ideal case if  $Q$  is the heat supplied from a source at  $T$ , its availability or the maximum work it can deliver is  $Q(1-T_0/T)$  where  $T_0$  is the temperature of the surroundings. Invariably it will be less than this value. The difference is termed as irreversibility.

Availability = Maximum possible work - Irreversibility

$$W_{\text{useful}} = W_{\text{rev}} - I$$



Irreversibility can also be construed as the amount of work to be done to restore the system to the original state.

Eg: If air at 10 bar is throttled to 1 bar, the irreversibility will be  $p v \ln(10)$  which is the work required to get 10 bar back. Here  $p$  is 1 bar and  $v$  is the specific volume at this condition.

Note that the system has been restored to the original state but not the surroundings Therefore increase in entropy will be

$R \ln 10.$

Combining I & II laws

$$Tds \geq \Delta u + \delta W$$

equality sign being for the reversible process. It implies that the amount of heat energy to be supplied in a real process is larger than the thermodynamic limit.



## Second Law of Thermodynamics

- Irreversible Processes increase the entropy of the universe
- Reversible Processes do not effect the entropy of the universe
- Impossible Processes decrease the entropy of the universe

$$\Delta S_{universe} = 0$$

Entropy Generation in the universe is a measure of lost work

$$\Delta S_{Universe} = \Delta S_{System} + \Delta S_{Surroundings}$$

The losses will keep increasing

The sin keeps accumulating

Damage to environment keeps increasing

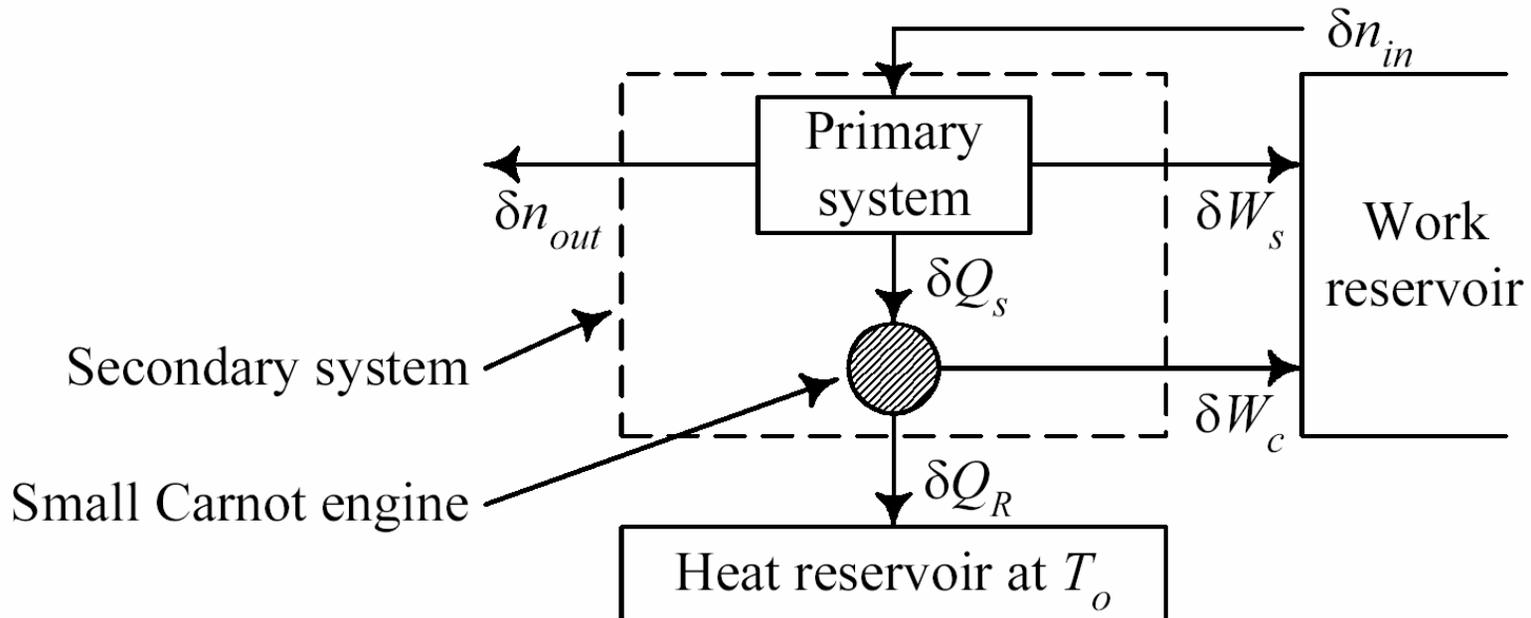
When the entropy of the universe goes so high, then some one has to come and set it right. **HE SAYS HE WILL COME.** Every religion confirms this.

Let us all wait.

**Cheer up, things are not that bad yet!!**



# Ideal maximum work – Availability or Exergy



Consider a fully reversible process with no dissipative effects – that is all work is transferred without loss and all heat is transferred using an ideal Carnot process to generate additional work.



# Availability or Exergy (cont...)



The resulting maximum work in Secondary system given by

$$\Delta B = H_{out} - H_{in} - T_o (S_{out} - S_{in}) = \Delta H - T_o \Delta S$$

$\Delta B$  = change in availability or exergy

= maximum work output or minimum work input

$$\Delta B = \Delta H - T_o \Delta S \Big|_{T_{out}, P_{out}}^{T_{in}, P_{in}}$$

Normally,  $T_{out}, P_{out}$  = ambient or dead state condition =  $T_o, P_o$



# Availability or Exergy (cont...)



Clearly, the availability  $B$  is a state function in the strictest mathematical sense so the maximum (or minimum) work associated with any steady state process is also independent of the path.

Availability:

- *Yields the maximum work producing potential or the minimum work requirement of a process*
- *Allows evaluation and quantitative comparison of options in a sustainability context*



# Exergy analysis



Exergy analysis is a formalised way of applying availability theory to engineering installations such as power generating plants. Energy (First Law) analysis keeps track of the heat and work transfers but does not indicate the source and magnitude of the irreversible entropy creation. Exergy (Second Law) analysis provides this information. It is useful in indicating where research resources can be directed to best advantage.

## Steady-flow exergy equation

The specific *steady-flow availability function* is defined by,

$$b = h - T_0 s$$

- $T_0$  is the temperature of a heat reservoir (usually the environment).
- The datum level for  $b$  (the state at which  $b = 0$ ) depends on the datum levels for  $h$  and  $s$ . These can be chosen arbitrarily because it is only differences in  $h$ ,  $s$  and  $b$  which are meaningful.



## Steady-flow exergy equation....(cont.)

- When a fluid is at equilibrium with the environment, it has zero potential for doing work
- It would therefore be physically meaningful if  $b$  were zero at this condition.
- This will not be so unless  $h$  and  $s$  also happen to be zero. Rather than change the  $h$  and  $s$  datum levels in all the different thermodynamic tables, we choose instead to replace the *availability function* with a new quantity called the *exergy*.
- When the fluid is at equilibrium with the environment it is said to be in its *dead state* ( $p_D, T_D$ ).
- The dead state is usually taken as  $p_D = 1$  bar and  $T_D = 25$  °C (which coincides with what is known as the ‘standard state’).
- The *specific steady-flow exergy*  $e$  is then defined as the difference between the actual value of  $b$  and its value  $b_D$  at the dead state,

$$e = b - b_D = (h - T_0 s) - (h_D - T_0 s_D)$$

where  $h_D$  and  $s_D$  are the fluid specific enthalpy and entropy at ( $p_D, T_D$ ). Hence,  $e_D = 0$ .



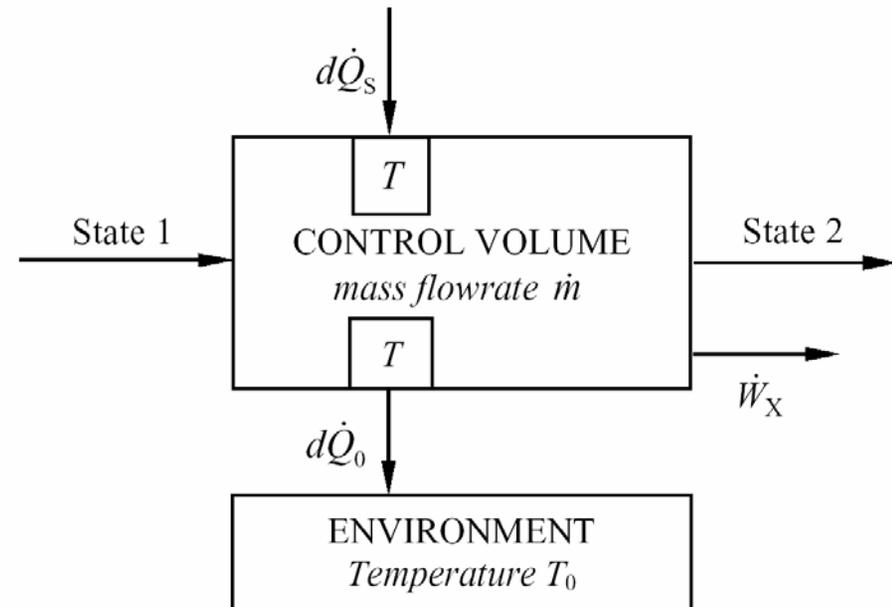
## Steady-flow exergy equation....(cont.)



- The *steady-flow exergy* of a fluid at a given state is therefore the maximum power which could be obtained by taking the fluid, in steady-flow, from the given state to the dead state (allowing heat transfer only with the environment at  $T_0$ ).
- Although this confers a certain absolute status on  $e$ , it is important to appreciate that the only truly meaningful quantities are changes in  $e$  and  $b$  and that these are equal,  $(e_2 - e_1) = (b_2 - b_1)$ .

The figure shows a device such as a turbine, boiler, condenser, etc. The device may produce shaft power  $\dot{W}_X$  and there may be a heat transfer  $d\dot{Q}_0$  between the control volume at local temperature  $T$  and the environment at  $T_0$ .

Also indicated is a possible heat transfer  $d\dot{Q}_s$  between an unspecified heat source and the control volume. The work and heat transfers are positive in the direction of the arrows.





## Steady-flow exergy equation....(cont.)



Neglecting changes in KE and PE between inlet and outlet states, the steady-flow energy and entropy equations applied to the control volume are :

$$\dot{m}(h_2 - h_1) = \int_1^2 d\dot{Q}_S - \int_1^2 d\dot{Q}_0 - \dot{W}_X \quad (1)$$

$$\dot{m}(s_2 - s_1) = \int_1^2 \frac{d\dot{Q}_S}{T} - \int_1^2 \frac{d\dot{Q}_0}{T} + \Delta\dot{S}_{irrev} \quad (2)$$

where  $\Delta\dot{S}_{irrev}$  is the rate of entropy creation in the control volume due to irreversibilities. Mulyiplying eq. (2) by  $T_0$  and subtracting from eq. (1), we obtain,

$$\dot{m}[(h_2 - T_0 s_2) - (h_1 - T_0 s_1)] = \int_1^2 \left(1 - \frac{T_0}{T}\right) d\dot{Q}_S - \dot{W}_X - T_0 \Delta\dot{S}_{irrev} - \int_1^2 \left(1 - \frac{T_0}{T}\right) d\dot{Q}_0$$



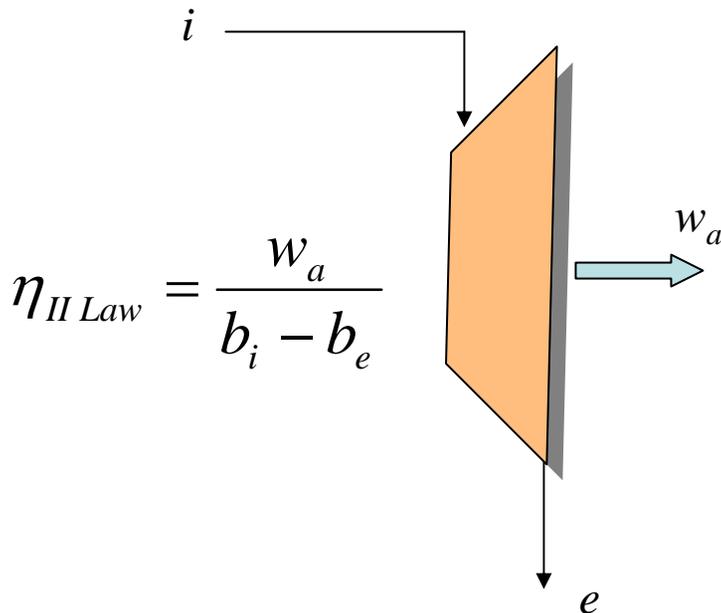
# Second Law Efficiency



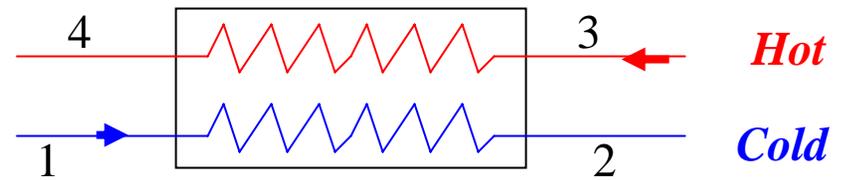
The general definition of second law efficiency of a process can be obtained in terms of change in availability during the process:

$$\text{Second Law Efficiency} = \eta_{II \text{ Law}} = \frac{\text{Production of availability}}{\text{Destruction of availability}}$$

*Steam Turbine*



*Heat Exchanger*



$$\eta_{II \text{ Law}} = \frac{\dot{m}_1(b_2 - b_1)}{\dot{m}_3(b_3 - b_4)}$$