5

Energy

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5.1 Introduction

- Exergy is the maximum useful work that could be obtained from the system at a given state in a specified environment. In other words the exergy of a system is the maximum useful Work possible during a process that brings the system into equilibrium with a heat reservoir. When the surroundings are the reservoir, exergy is the potential of a system to cause change as it achieves equilibrium with its environment.
- Exergy is then the energy that is available to be used. Therefore, it is also called the availability or available energy. After the system and surroundings reach equilibrium the exergy becomes zero.
- Anergy is the energy which is not utilizable and rejected to the surroundings. It is also called unavailable energy.
- For any thermodynamics system,

Energy supplied = Work done + Heat rejected
= Available energy + Unavailable energy
= Exergy + Anergy

5.2 Basic Definitions

1) **Available Energy**
- It is maximum portion of energy which can be converted into work by reversible processes which reduce the system to a dead state.

2) **Unavailable Energy**
- It is that portion of energy which cannot be converted into work even by reversible process which reduces system in a state of equilibrium. That energy is rejected to sink.

3) **Dead State**
- When system comes to complete equilibrium with its environment there is no energy difference exists to promote further work is called dead state.

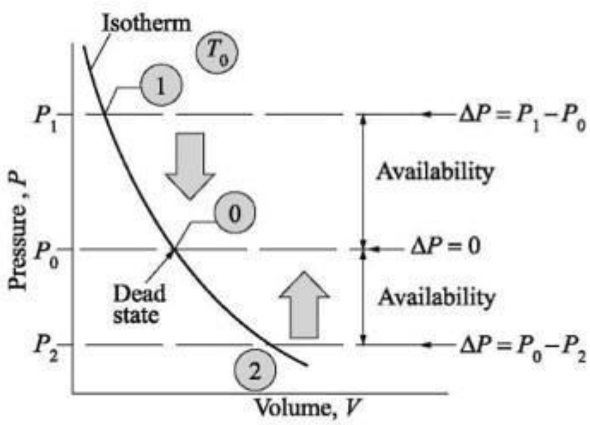

Fig.5.1 - Representation of Dead State and Availability

5.3 Exergy (Available Energy) referred to a cycle

1) **Exergy referred to infinite heat source**
- As shown in Fig. represents a reversible engine that operates between a constant temperature reservoir at temperature T and a sink at temperature T_0.
- Heat Q supplied by the reservoir and the available work W_{max}.

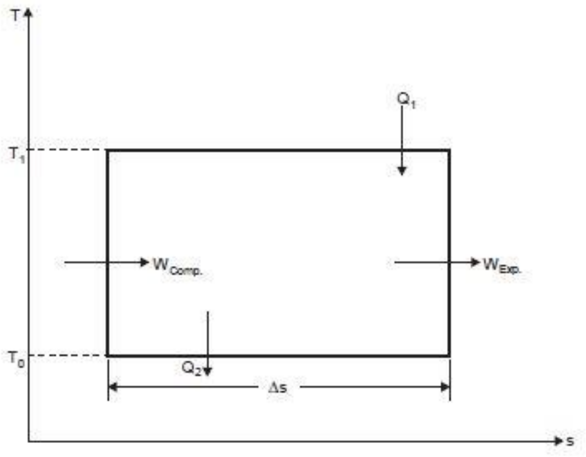

Fig.5.2 - Available and unavailable energy heat withdrawn from an infinite reservoir

- Efficiency of the reversible heat engine,

$$\eta = 1 - \frac{T_0}{T} = \frac{W_{max}}{Q} \quad \textit{Eq. (5.1)}$$

$$W_{max} = Q\left(1 - \frac{T_0}{T}\right) \quad \textit{Eq. (5.2)}$$

$$W_{max} = Q - \frac{Q}{T}T_0 \quad \textit{Eq. (5.3)}$$

$$W_{max} = Q - T_0 ds \quad \textit{Eq. (5.4)}$$

$$Q = W_{max} + T_0 ds \quad \textit{Eq. (5.5)}$$

- But, we know that Heat supplied = available energy + Unavailable energy

$$Q = W_{max} + UE$$

- From above equation, Unavailable energy UE = T_0dS
- W_{max} is the availability and on *T-S* diagram it is given by the area 1-2-3-4. The area 3-4-5-6 represents the unavailable portion of the heat supplied to the engine.
- Unavailable energy is the energy rejected from the engine, and hence represents the portion of heat supplied that cannot be converted into work. The unavailable energy equals the product of the lowest temperature of heat rejection and the change of entropy of the system during the process of heat supply.

2) Exergy referred to finite heat source/ Lost work-Exergy destruction in heat transfer process

- Consider certain quantity of heat Q transfer from a system at constant temperature T_1 to another system at constant temperature T_0 ($T_1 > T_0$) as shown in Fig. Before heat is transfer, the energy Q is available at T_1 and ambient temperature is T_0.

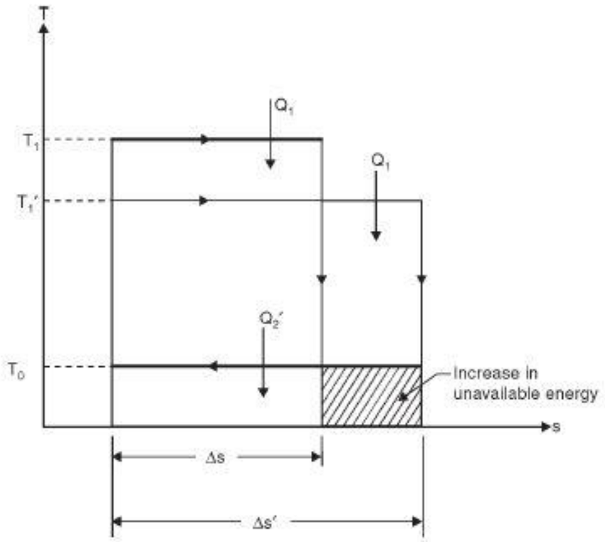

Fig.5.3 - Decrease in available energy due to heat transfer through a finite temperature difference

- Initial available energy is given by,

$$(AE_1) = Q\left(1 - \frac{T_0}{T_1}\right) \qquad \textit{Eq. (5.6)}$$

- After heat transfer, the energy Q is available at T_2 and again the ambient temperature is T_0.
- Final available energy is given by,

$$(AE_2) = Q\left(1 - \frac{T_0}{T_2}\right) \qquad \textit{Eq. (5.7)}$$

Change in available energy = $(AE_1) - (AE_2)$

$$= Q\left(1 - \frac{T_0}{T_1}\right) - Q\left(1 - \frac{T_0}{T_2}\right) \qquad \textit{Eq. (5.8)}$$

$$= T_0\left[-\frac{Q}{T_1} + \frac{Q}{T_2}\right] \qquad \textit{Eq. (5.9)}$$

- Where, dS_{net} is the net change in the entropy of the combination of the two interacting systems. This total entropy change is called entropy of universe or entropy production. Since the heat transfer has been through a finite temperature difference, the process is irreversible, *i.e.*, $dS_{net} > 0$ and hence there is loss or decrease of available energy.

5.4 Exergy (availability) of the closed system

- Consider a piston-cylinder arrangement (closed system) in which the fluid expanding reversibly from initial state of p_1, V_1, T_1 to final atmospheric state of $p_{0,}$ V_0,$T_{0.}$ During this process, fluid produces work W_{fluid} and rejects heat Q to atmosphere. To find the maximum work done, we will assume that the heat Q rejected by the system is utilized in reversible Carnot engine producing work W_{engjne} and rejecting part of heat Q_0 to atmosphere at temperature T_0, as shown in *Fig.5.6 - Two heat engines that have the same thermal efficiency* practically this would be possible by having infinite number of reversible engines arranged in parallel, each one receiving heat at a different constant temperature but each one rejecting heat at atmospheric temperature T_0.
- **Following are the heat and work interactions take place in given system:**
- Expansion work $(W_{\exp})$:
- The fluid expands and expansion work $W_{\exp}$ is obtained. From the principal of energy conservation,

$$\delta Q = \delta W + \delta U \qquad \textit{Eq. (5.10)}$$

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$$-Q = W_{exp} + (U_0 - U_1) \qquad Eq. (5.11)$$

- Negative sign indicate that heat leaves the system

$$W_{exp} = (U_1 - U_0) - Q \qquad Eq. (5.12)$$

- **Engine work:**
- Heat rejected by piston cylinder assembly may be utilized to run reversible heat engine which receives. The work done by the engine is given by,

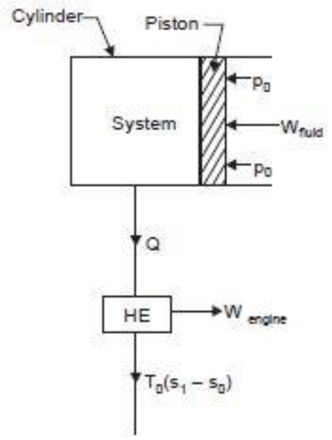

Fig.5.4 - Availability of non flow (closed) system

$$W_{eng} = Q\left(1 - \frac{T_0}{T_1}\right) \qquad Eq. (5.13)$$

$$W_{eng} = Q - T_0(S_1 - S_0) \qquad Eq. (5.14)$$

- **Maximum work:**
- The summation of expansion work W_{exp} and the engine work W_{eng} gives maximum obtainable from the given arrangement,

$$W_{max} = W_{exp} + W_{eng} \qquad Eq. (5.15)$$

$$= (U_1 - U_0) - Q + Q - T_0(S_1 - S_0) \qquad Eq. (5.16)$$

- **Surrounding work:**
- When the piston moving outwards has to spend a work in pushing the atmosphere against its own pressure. This work, which may be called as the surroundings work is simply dissipated, and such is not useful.

$$W_{max} = (U_1 - T_0S_1) - (U_0 - T_0S_0) \qquad Eq. (5.17)$$

5.5 Exergy (availability) of steady flow open system

- Consider a flow of fluid through a open system as shown in fig. The working fluid enter the system at section 1 (p_1, v_1, T_1, U_1, C_1) and leave the system at section (p_0, v_0, T_0, U_0, C_0) and passing at a steady rate. Let the system rejects heat Q, which for getting maximum work should be passed through a reversible engine.
- Steady flow energy equation may written as,

$$U_1 + P_1V_1 + m\frac{C_1^2}{2} + mg\,Z_1 - Q = U_0 + P_0V_0 + m\frac{C_0^2}{2} + mg\,Z_0 - W_s \qquad Eq. (5.18)$$

- Neglecting kinetic and potential energy changes,

$$U_1 + P_1V_1 - Q = U_0 + P_0V_0 + W_s \qquad Eq. (5.19)$$

$$H_1 - Q = H_0 + W_s \qquad Eq. (5.20)$$

$$W_s = (H_1 - H_0) - Q \qquad \text{Eq. (5.21)}$$

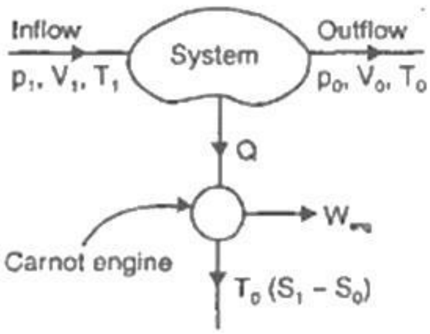

Fig.5.5 - Availability of open flow system

- The heat Q rejected by the system may be utilized to run a reversible heat engine. The work output from this engine is,

$$W_{eng} = Q\left(1 - \frac{T_0}{T_1}\right) \qquad \text{Eq. (5.22)}$$

$$W_{eng} = Q - T_0(S_1 - S_0) \qquad \text{Eq. (5.23)}$$

- Maximum available useful work or net work is given by,

$$W_{max} = W_s + W_{eng} \qquad \text{Eq. (5.24)}$$

$$= (H_1 - H_0) - Q + Q - T_0(S_1 - S_0) \qquad \text{Eq. (5.25)}$$

$$= (H_1 - T_0 S_1) - (H_0 - T_0 S_0) \qquad \text{Eq. (5.26)}$$

5.6 Second law efficiency or effectiveness

- Normally, performance of a process or device is measured with help of thermal efficiency or coefficient of performance. They are defined on basis of first law and hence it is referred to as the first law efficiency. But, this first law efficiency is not a measure of the fraction of maximum work actually utilized. Therefore, there is need to define a second law efficiency as the *ratio of the actual thermal efficiency to the maximum possible thermal efficiency under same condition*.
- Consider two heat engines, both having a thermal efficiency of 30 %, as shown in *Fig.5.6 - Two heat engines that have the same thermal efficiency*. One of the engines (engine A) is supplied with heat from a source at 600 K, and the other one (engine B) from a source at 1000 K. Both engines reject heat to a medium at 300 K. At first glance, both engines seem to convert to work the same fraction of heat that they receive; thus they are performing equally well. When we take a second look at these engines in light of the second law of thermodynamics, however, we see a totally different picture. These engines, at best, can perform as reversible engines, in which case their efficiencies would be,

$$\eta_{rev\,A} = \left(1 - \frac{T_L}{T_H}\right) = 1 - \frac{300}{600} = 50\ \% \qquad \text{Eq. (5.27)}$$

$$\eta_{rev\,B} = \left(1 - \frac{T_L}{T_H}\right) = 1 - \frac{300}{1000} = 70\ \% \qquad \text{Eq. (5.28)}$$

- Now it is becoming apparent that engine *B* has a greater work potential available to it (70 % of the heat supplied as compared to 50% for engine *A*), and thus should do a lot better than engine *A*.

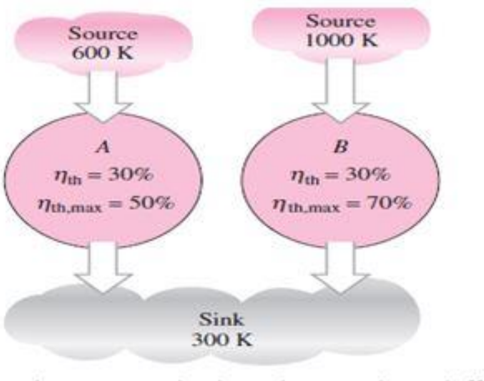

Fig.5.6 - Two heat engines that have the same thermal efficiency

- Therefore, we can say that engine *B* is performing poorly relative to engine *A* even though both have the same thermal efficiency. It is obvious from this example that the first-law efficiency alone is not a realistic measure of performance of engineering devices. To overcome this deficiency, we define second-law efficiency.
- Second-law efficiency is defined as the ratio of the actual thermal efficiency to the maximum possible (reversible) thermal efficiency under the same conditions.

$$\varepsilon = \frac{\eta_{th}}{\eta_{rev}} \qquad \text{Eq. (5.29)}$$

- Based on this definition, the second-law efficiencies of the two heat engines discussed above are,

$$\varepsilon = \frac{\eta_{th}}{\eta_{rev}} = \frac{0.30}{0.50} = 0.60 \qquad \text{Eq. (5.30)}$$

$$\varepsilon = \frac{\eta_{th}}{\eta_{rev}} = \frac{0.30}{0.70} = 0.42 \qquad \text{Eq. (5.31)}$$

– It means that engine 1 is converting 60 % of the available work potential to useful work. And for engine 2 is 42.85 %.

5.7 Cause of irreversibility

- The irreversibility of a process may be due to either one or both of the following,

1) Lack of equilibrium (mechanical, chemical or thermal equilibrium) during the process

(i) Heat transfer through a finite temperature difference:

- We know that the reversible process in which heat is transferred through an infinitesimal temperature difference would require an infinite amount of time or infinite area. But, all actual heat transfer process are taken place through a finite temperature difference and so irreversible. Hence heat transfer take place greater temperature difference, the greater is the irreversibility.

(ii) Lack of pressure equilibrium within the system or between system and surroundings:

- When pressure difference exists within the system or between system and surroundings, then both the system and its surrounding or only system will undergo a change of state. The reverse process of this process is not possible without producing any other effect.

(iii) Free expansion:

– The process of free expansion is irreversible.

2) Irreversibility due to dissipative effects

- Some time the work is converted into molecular internal energy through the agency of such phenomena as friction, viscosity, inelasticity, electric resistance and magnetic hysteris. These effects are called dissipative effects, and this effects increases irreversibility of a process.

(i) Friction:

- In case of brake, kinetic energy of flywheel is converted into molecular internal energy due to friction. However, the conversion of this increase in molecular internal energy into kinetic energy within the system to cause the wheel to rotate is not possible.

(ii) Stirring work:

- When paddle wheel rotates in the insulated container, work may be transferred into a system. The work transferred is dissipated adiabatically into an increase in the molecular internal energy of (i.e. increase in the temperature of fluid). The same amount of work produce by the system at the expense of its molecular internal energy and temperature of the system goes down, is not possible. So stirring work is irreversible process.

(iii)Transfer of electricity through a resistor:

- The flow of electric current through a wire represents work transfer. The part of the work transfer is stored as an increase in the internal energy of the wire and remainder leaves the system as heat. The reverse process, the conversion of heat into electric work is not possible.

5.8 Types of Irreversibilities

1) **External irreversibilities:**

- These are associated with dissipating effects outside the working fluid, i.e. Mechanical friction occurring during a process due to some external source.

2) **Internal irreversibilities**

- These are associated with dissipating effects within the working fluid

3) **Mechanical irreversibilities**

- It is generally associated with friction between fluid molecules, friction between fluid and mechanical parts, friction between mechanical parts and atmosphere.

4) **Thermal irreversibilities**

- It is associated with heat transfer due to finite temperature difference between the parts of system or between system and surrounding.

5.9 Irreversibility and guoy-stodala theorem

a) ***Irreversibility of closed system***

– **It is defined as the** difference between the maximum work output from the system and the expansion work.

$$I = \left[\left((U_1 - T_0S_1) - (U_0 - T_0S_0)\right)\right] - [-Q - (U_0 - U_1)] \quad \text{Eq. (5.32)}$$

$$I = T_0 ds_{sys} + Q \quad \text{Eq. (5.33)}$$

- Change in entropy of environment due to addition of heat Q at constant atmospheric temperature T_0.

$$ds_{surr} = \frac{Q}{T_0} \quad \text{Eq. (5.34)}$$

$$Q = T_0 ds_{surr} \quad \text{Eq. (5.35)}$$

$$I = T_0 ds_{sys} + Q \quad \text{Eq. (5.36)}$$

$$I = T_0 ds_{sys} + T_0 ds_{surr} \quad \text{Eq. (5.37)}$$

$$I = T_0 ds_{universe} \quad \text{Eq. (5.38)}$$

b) ***Irreversibility refers to steady flow system:***

$$I = \left[\left((H_1 - T_0S_1) - (H_0 - T_0S_0)\right)\right] - [(H_1 - H_0) - Q] \quad \textit{Eq. (5.39)}$$

$$I = T_0(S_0 - S_1) + Q \quad \textit{Eq. (5.40)}$$

$$I = T_0 ds_{sys} + T_0 ds_{surr} \quad \textit{Eq. (5.41)}$$

$$I = T_0 ds_{universe} \quad \textit{Eq. (5.42)}$$

Gouy-stodala Theorem:

- The rate of loss of exergy (available energy) in a process is proportional to the rate to the rate of entropy generation.

$$I = W_{lost} = T_0 ds_{universe} = T_0 ds_{generation} \quad \textit{Eq. (5.43)}$$

5.10 Reference Books

1. Thermal Science and Engineering by D. S. Kumar
2. Engineering Thermodynamics by R. K. Rajput