Advanced Thermodynamics and Combustion
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Module - 02
Entropy and Exergy
Lecture - 08
Exergy Analysis (Part I)

Dear learners. Greetings from IIT, Guwahati. We are in this course Advanced Thermodynamics and Combustions, module 2 Entropy and Exergy.

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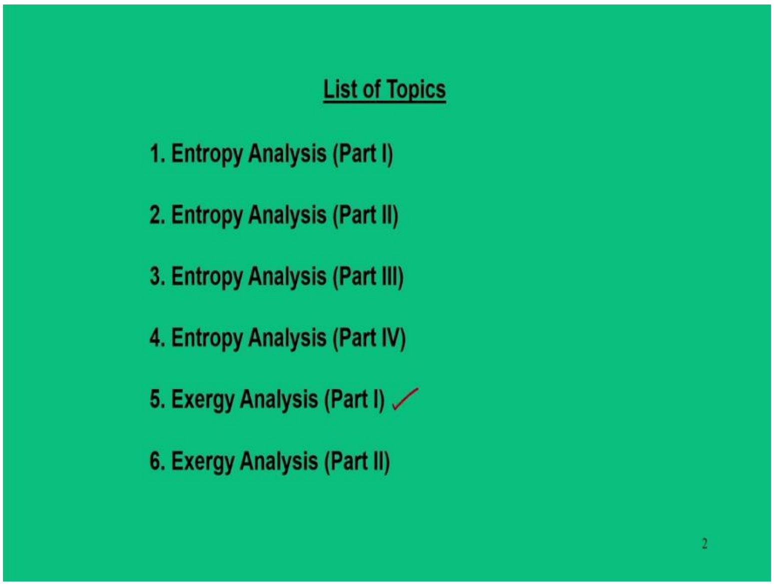

List of Topics

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6. Exergy Analysis (Part II)

Till this point of time we have covered the entropy analysis with four lectures. Now in the next two lectures we will discuss about exergy analysis. Now we are in the module 2 lecture number 5 exergy analysis part I. So, this will be lecture number 5.

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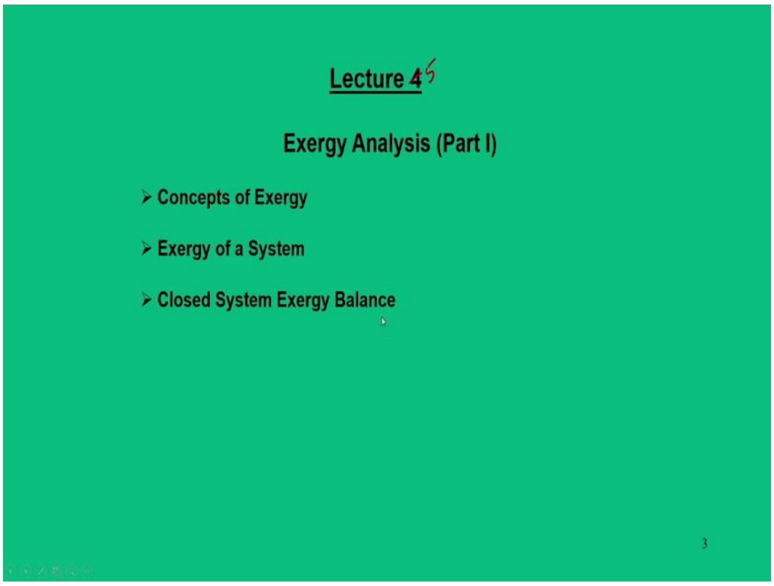

Lecture 4 5

Exergy Analysis (Part I)

- Concepts of Exergy
- Exergy of a System
- Closed System Exergy Balance

And in this lecture we will be discussing about the concepts of exergy, exergy of a system and closed system exergy balance.

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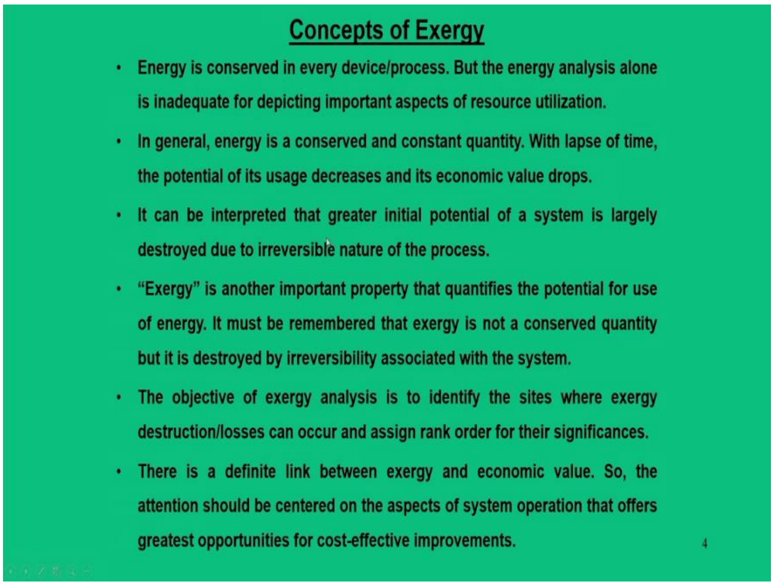

Concepts of Exergy

- Energy is conserved in every device/process. But the energy analysis alone is inadequate for depicting important aspects of resource utilization.
- In general, energy is a conserved and constant quantity. With lapse of time, the potential of its usage decreases and its economic value drops.
- It can be interpreted that greater initial potential of a system is largely destroyed due to irreversible nature of the process.
- “Exergy” is another important property that quantifies the potential for use of energy. It must be remembered that exergy is not a conserved quantity but it is destroyed by irreversibility associated with the system.
- The objective of exergy analysis is to identify the sites where exergy destruction/losses can occur and assign rank order for their significances.
- There is a definite link between exergy and economic value. So, the attention should be centered on the aspects of system operation that offers greatest opportunities for cost-effective improvements.

So, let us discuss something on the concept of exergy. Till this point of time we all know from the first law of thermodynamics that energy is a conserved property and it is conserved for every device and processes. But the energy analysis alone is inadequate for depicting many important aspects of resource utilizations.

So, in some sense it may happen that energy may have certain potential or not. For example, in the second law we discussed that work is considered to be high grade energy, heat is considered to be low grade energy. And in a sense that there is a relative potential exist between the quality of the energy. So, the analysis of exergy gives us the idea whether proper utilization of energy is done or not.

So, what we can say that although the energy is a conserved property and it is a constant quantity, but with lapse of time the potential of its usage decreases or degrades which means that its economic value drops. So, it can be interpreted that a greater initial potential of the system is largely destroyed due to the irreversibility nature of the process.

So, means that energy degrades with time and it degrades due to the irreversible nature of the process. So, to have another understanding, the quantification of energy we represent in another term and in fact, this is also a thermodynamic property which is known as exergy. So, this exergy quantifies the potential use of energy. So, it must be remembered that exergy is not a conserved quantity, but whereas, energy is always conserved.

This exergy is destroyed by the irreversibility associated with the systems. So, with the time instead of calculating energy we must calculate exergy. So, this will tell you whether there is a work potential exist for that nature of energy. So, the objective of exergy analysis is to identify the sites where exergy destruction or losses can occur and we can assign a rank order in their significance.

For example we may have many situations like 10 kJ of work available and we also can have 10 kJ of heat is available at 20C or it may be 300C or it may be 1000C. So, what is the relative ranking between all these sources of energy. So, this can be possible through the exergy analysis.

So, the exergy analysis provides a definite link between the economic value and the energy of the system. So, in our discussions the attention is centered for the aspects of system operations that offers greatest opportunities for a cost effective improvements. Now to analyze the concept of energy let us refer to this particular figure.

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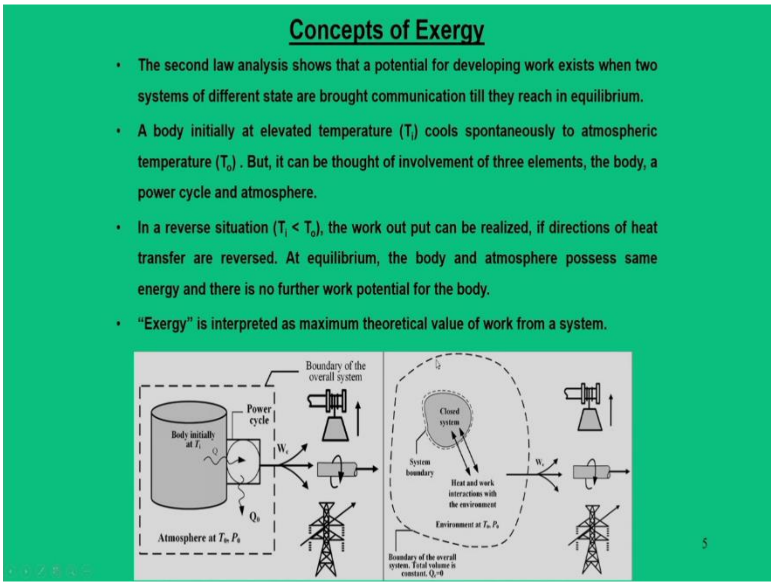

Concepts of Exergy

- The second law analysis shows that a potential for developing work exists when two systems of different state are brought communication till they reach in equilibrium.
- A body initially at elevated temperature (T_i) cools spontaneously to atmospheric temperature (T_o) . But, it can be thought of involvement of three elements, the body, a power cycle and atmosphere.
- In a reverse situation ($T_i < T_o$), the work out put can be realized, if directions of heat transfer are reversed. At equilibrium, the body and atmosphere possess same energy and there is no further work potential for the body.
- "Exergy" is interpreted as maximum theoretical value of work from a system.

So, what we have seen here in this figure that we have a body which is initially at temperature T_i and we want to extract the work potential or we want to quantify its work potential. So, for that purpose it must reject heat to the atmospheres. So, the body which is at initial temperature T_i and whereas, we have this atmosphere and typically we call this as surroundings, it is maintained at temperature T_0 and p_0.

So, what we can say about this that in order to extract work potential from this body; that means, this work potential needs to be evaluated with respect to atmospheric conditions or atmospheric parameters. So, to do that we can think about a power cycle that can run in between. So, that means, as if we are evaluating the Carnot cycle which operates between the initial temperature T_i and atmospheric temperature T_0.

And we are getting the work output from this power cycle. So, as long as $T_i > T_0$ we can get the work output from the systems, but if in a reverse situation if $T_i < T_0$, our directions of heat should be reversed; that means, there will be requirement of work input into the system and such a particular concepts can be visualized that as if we have a closed system.

This closed systems interacts with environment or in this case we call this as a surroundings in the mode of heat or work transfer. And this system and surroundings in this case body and the atmosphere, it constitutes the combined systems or that combined system analysis is what we do in the exergy analysis. Now in the process of maximizing the theoretical output of work we interpret this energy as exergy.

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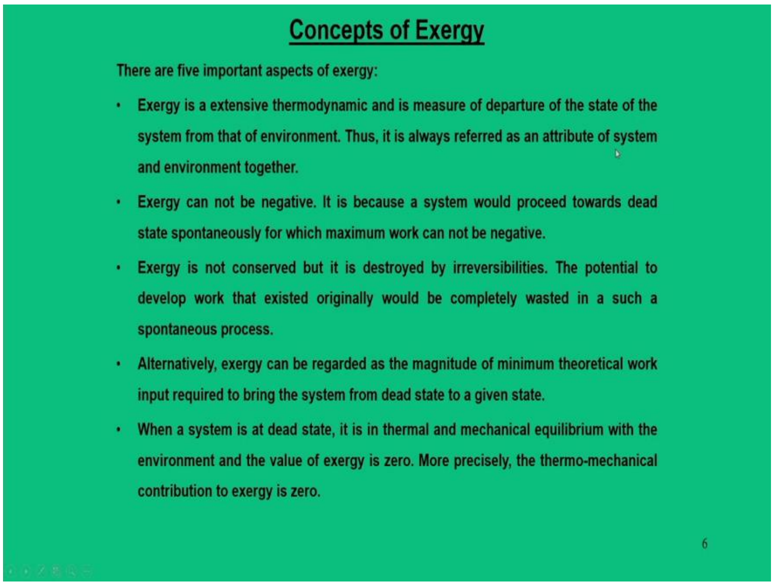

Concepts of Exergy

There are five important aspects of exergy:

- Exergy is a extensive thermodynamic and is measure of departure of the state of the system from that of environment. Thus, it is always referred as an attribute of system and environment together.
- Exergy can not be negative. It is because a system would proceed towards dead state spontaneously for which maximum work can not be negative.
- Exergy is not conserved but it is destroyed by irreversibilities. The potential to develop work that existed originally would be completely wasted in a such a spontaneous process.
- Alternatively, exergy can be regarded as the magnitude of minimum theoretical work input required to bring the system from dead state to a given state.
- When a system is at dead state, it is in thermal and mechanical equilibrium with the environment and the value of exergy is zero. More precisely, the thermo-mechanical contribution to exergy is zero.

Now, we will talk about the important aspects of exergy. In fact, there are five important aspects of exergy. So, we will discuss them one by one. The first one is that exergy is a extensive thermodynamic property and it is a measure of departure of the state of the systems from that environment. So that means, when you do exergy analysis we must take system and the surroundings or environment together.

So, it is always referred as attribute of the system and surrounding together. Exergy cannot be negative. So, it is because that system would always proceeds towards the dead state; I will talk about what you mean by dead state in the subsequent slides. So, it means that system would always proceed towards the dead states spontaneously for which maximum work cannot be negative.

For example a candle light keeps on burning as long as it is getting its power source. Otherwise with time, its work potential goes on reducing or in terms of producing the light. So, what we can say is that it is a spontaneous process and since it is a spontaneous process this the exergy cannot be negative. Already I have emphasized that exergy is a non conserved properties.

But it is destroyed by the irreversibilities associated with the systems, but the potential of potential to develop work that existed originally would be completely wasted in a such a spontaneous process. That is what I said that exergy cannot be negative. An alternative way of representing exergy is that that exergy can be regarded as the magnitude of minimum theoretical work input required to bring the systems from the dead state to the given states.

So, in our previous analysis we say that system is going from any arbitrary states to a dead state; that means, dead state means with the surrounding conditions means properties matches to the surrounding temperatures or it is in equilibrium with the surroundings or environment. So, that is what we call as a dead state. Now when the system is at dead state it means that it is in thermal and mechanical equilibrium with the environment and the value of exergy is 0. So, precisely the thermo mechanical contribution to exergy is 0 at equilibrium state.

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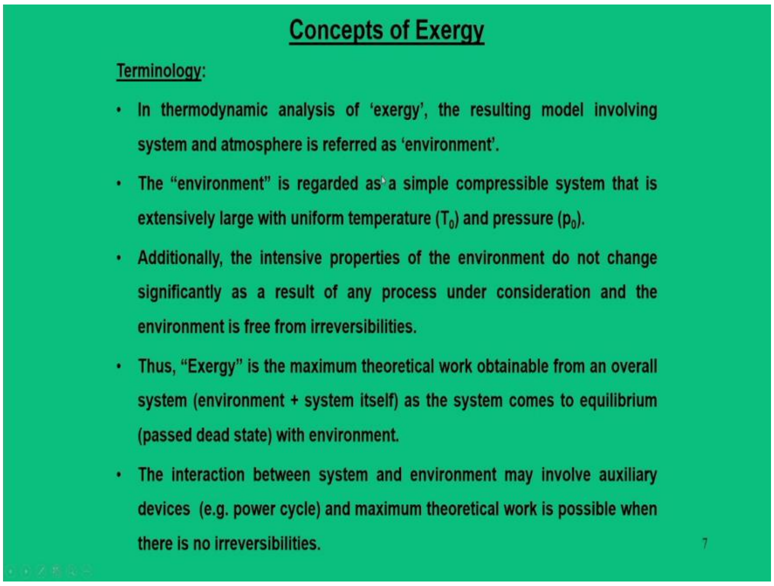

Concepts of Exergy

Terminology:

- In thermodynamic analysis of 'exergy', the resulting model involving system and atmosphere is referred as 'environment'.
- The "environment" is regarded as a simple compressible system that is extensively large with uniform temperature (T_0) and pressure (p_0).
- Additionally, the intensive properties of the environment do not change significantly as a result of any process under consideration and the environment is free from irreversibilities.
- Thus, "Exergy" is the maximum theoretical work obtainable from an overall system (environment + system itself) as the system comes to equilibrium (passed dead state) with environment.
- The interaction between system and environment may involve auxiliary devices (e.g. power cycle) and maximum theoretical work is possible when there is no irreversibilities.

Now, before you go for the exergy analysis, let me discuss some terminology that we are going to use. The first one is that we are using the word environment or surroundings. So, the thermodynamic analysis of exergy the resulting model will involve systems plus atmosphere together and this atmosphere is referred as the environment.

So, the word environment is nothing but a simple thermodynamic compressible systems which has uniform pressure p_0 and temperature T_0, additionally the intensive properties of the environment do not change significantly as a result of any process under considerations. So, in other words we are going to say that the environment is free from irreversibilities.

So, the exergy by considering the system and environment together is the maximum theoretical work obtainable from the overall systems and here we will use the overall systems which means environment and the system itself. As the systems comes to the equilibrium or means when the system comes to the equilibrium it means it has passed the dead state with environment.

The interaction between the system and environment also may involve certain power cycles; I mean to get the theoretical work we need some power cycles with no irreversibilities. So, these terminology system and environment together we are going to analyze the effect of the combined system. So, the first analysis that we are going to do is that exergy of a systems.

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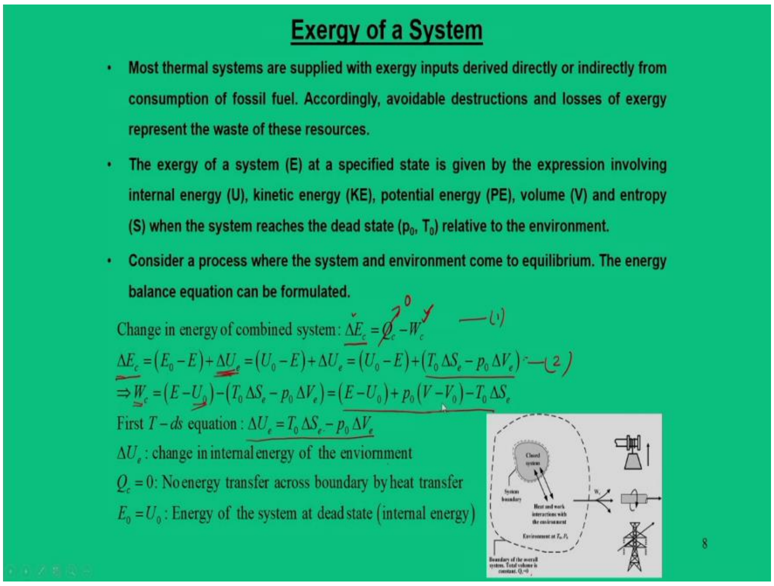

Exergy of a System

- Most thermal systems are supplied with exergy inputs derived directly or indirectly from consumption of fossil fuel. Accordingly, avoidable destructions and losses of exergy represent the waste of these resources.
- The exergy of a system (E) at a specified state is given by the expression involving internal energy (U), kinetic energy (KE), potential energy (PE), volume (V) and entropy (S) when the system reaches the dead state (p_0, T_0) relative to the environment.
- Consider a process where the system and environment come to equilibrium. The energy balance equation can be formulated.

Change in energy of combined system: $\underline{\Delta E_c} = \overset{0}{\cancel{Q_c}} - W_c \quad —(1)$

$\Delta E_c = (E_0 - E) + \Delta U_e = (U_0 - E) + \Delta U_e = (U_0 - E) + \underline{(T_0 \Delta S_e - p_0 \Delta V_e)} \quad —(2)$

$\Rightarrow W_c = (E - U_0) - (T_0 \Delta S_e - p_0 \Delta V_e) = \underline{(E - U_0) + p_0(V - V_0) - T_0 \Delta S_e}$

First $T-ds$ equation : $\underline{\Delta U_e = T_0 \Delta S_e - p_0 \Delta V_e}$

ΔU_e : change in internal energy of the enviornment

$Q_c = 0$: No energy transfer across boundary by heat transfer

$E_0 = U_0$: Energy of the system at dead state (internal energy)

So, in this case if you refer to this figure the simplified form that we can have a closed systems, this closed system has certain boundary and environment is at certain conditions. So, the system is interacting with surroundings and side by side the integrated system involving system and surroundings produces some work in the form of shaft work.

And if you look at the overall systems, the overall system has total volume that remains constant, but the overall system does not encounter any heat transfers. So, with this philosophy we are going to discuss about the exergy of the systems. In fact, such a process normally occurs in a thermal power plants or thermal power systems that involves the energy contents from the fossil fuel.

And for these things we analyze the destruction or losses of energy or what energy that goes as a waste from these resources. Now to calculate the exergy of the systems we need certain expressions that involves the internal energy U, kinetic energy KE and then potential energy PE, volume, entropy of the system and the dead state situations.

Dead state situation means ambient pressure p_0 and temperature T_0. So, we are now considering a process in which the system and some environment are in equilibrium and for that thing we are going to calculate the energy balance equations. So, for this combined system shown in this figure. The first expression that you can write is that change in the energy of the combined systems, your c stands for the combined systems.

So, as you can see that combined system there is no heat interactions this Q_c is 0. So, we have left with $\Delta E_c = -W_c$ and in fact, our main goal is to find out this W_c . Now another way of representing the change in the energy of the combined system ΔE_c is nothing but your E_0 which is the initial energy and that is nothing but the U_0 that is the total internal energy at the dead state.

And E is the energy at any arbitrary states and $\Delta E_c = (E_0 - E) + \Delta U_e = (U_0 - E) + \Delta U_e$. So, now, this ΔU_e is the change in the internal energy of the environment, this can be interpreted in terms of the first TdS equations that is $\Delta U_e = T_0 \Delta S_e - p_0 \Delta V_e$. So, here e stands for the environment.

Now, after getting this expression of ΔE_c, from this now if I say this is equation 1, then this is this is equation 2, then when I put equation 2 in 1 then I will get $W_c = (E - U_0) + p_0(V - V_0) - T_0 \Delta S_e$. So, the work potential or exergy of the systems we can represent in this form.

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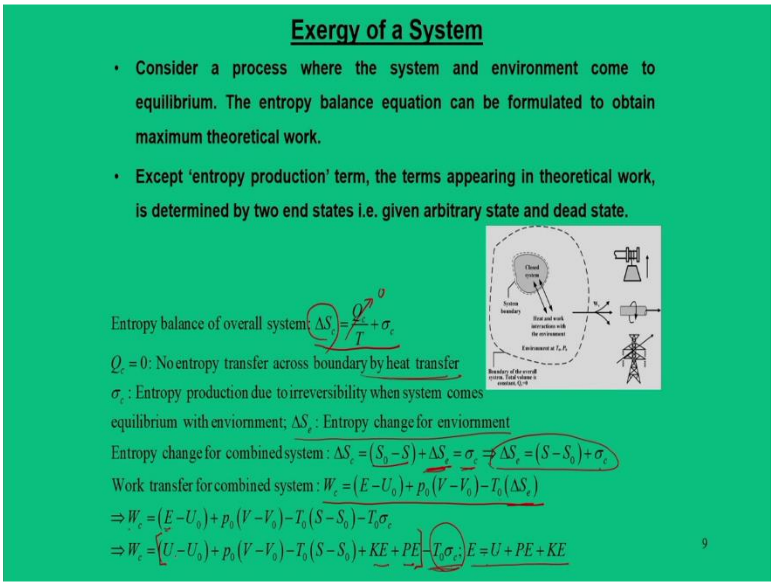

Exergy of a System

- Consider a process where the system and environment come to equilibrium. The entropy balance equation can be formulated to obtain maximum theoretical work.
- Except 'entropy production' term, the terms appearing in theoretical work, is determined by two end states i.e. given arbitrary state and dead state.

Entropy balance of overall system: $\boxed{\Delta S_c} = \cancel{\frac{Q_c}{T}}^{0} + \sigma_c$

$Q_c = 0$: No entropy transfer across boundary by heat transfer

σ_c : Entropy production due to irreversibility when system comes equilibrium with enviornment; ΔS_e : Entropy change for enviornment

Entropy change for combined system : $\Delta S_c = (S_0 - S) + \Delta S_e = \sigma_c \Rightarrow \boxed{\Delta S_e = (S - S_0) + \sigma_c}$

Work transfer for combined system : $W_c = (E - U_0) + p_0(V - V_0) - T_0(\Delta S_e)$

$\Rightarrow W_c = (E - U_0) + p_0(V - V_0) - T_0(S - S_0) - T_0\sigma_c$

$\Rightarrow W_c = \left[(U - U_0) + p_0(V - V_0) - T_0(S - S_0) + KE + PE\right] - \boxed{T_0\sigma_c}; E = U + PE + KE$

Now, for the same the situation what we did in the previous slide? It was the energy balance. Now we will be talking about the entropy balance. So, for the same figure we can write or recall the entropy balance of the overall system $\Delta S_c = \frac{Q_c}{T} + \sigma_c$. Now this $\frac{Q_c}{T}$ is 0, because no entropy transfer across the boundary by heat transfer.

So, we are left with the σ_c which is nothing but entropy production due to irreversibility when the system is in equilibrium with the environment. And ΔS_e is the entropy change of the environment. So, we are now going to calculate what is this ΔS_c. So, $S_c = (S_0 - S) + \Delta S_e = \sigma_c$, I mean this is for the system and this is for the environment and that is equal to σ_c.

So, from this equations we can get $\Delta S_e = (S - S_0) + \sigma_c$. So, if you recall our previous energy balance equations for the same figure we have already derived the expressions for the work transfer of the combined systems. Now on this work transfer from the combined systems we are now going to introduce what is this ΔS_e that is change in the entropy of the environment.

Now, when I put it, then we are left with an expressions of $W_c = (E - U_0) + p_0(V - V_0) - T_0(S - S_0) - T_0\sigma_c$. So, now let us see what is the E?

E is nothing but combination of U + PE + KE; that means, internal energy, potential energy and kinetic energy. Now when I put this expression here finally, we land off in getting the exergy of the systems which has terms like $W_c = (U - U_0) + p_0(V - V_0) - T_0(S - S_0) + KE + PE - T_0\sigma_c$. And this $T_0\sigma_c$ is nothing but the entropy production due to irreversibility.

So, you can see this particular expression that this is the work that we are going to extract from this closed systems, but since σ_c is always a positive quantity, this particular term kills the amount of work or exergy.

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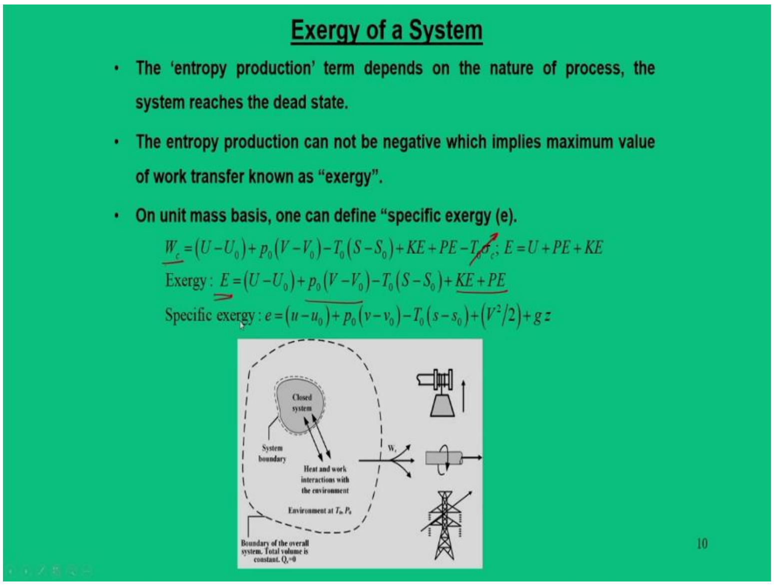

Exergy of a System

- The 'entropy production' term depends on the nature of process, the system reaches the dead state.
- The entropy production can not be negative which implies maximum value of work transfer known as "exergy".
- On unit mass basis, one can define "specific exergy (e).

$\underline{W_c} = (U - U_0) + p_0(V - V_0) - T_0(S - S_0) + KE + PE - \cancel{T_0\sigma_c}$; $E = U + PE + KE$

Exergy: $\underline{E} = (U - U_0) + \underline{p_0(V - V_0)} - T_0(S - S_0) + \underline{KE + PE}$

Specific exergy: $e = (u - u_0) + p_0(v - v_0) - T_0(s - s_0) + (V^2/2) + gz$

So, if I interpret that maximum possible work then I must neglect this term; not neglect rather I will say that this irreversibility should be absent. So, when I say irreversibility is absent. So, we represent this W_c as exergy E. So, now, onwards we will be using exergy term as E which is the combination of internal energy for the system and the dead state and $p_0(V - V_0)$; that means, flow work we can say and $T_0(S - S_0) + KE + PE$.

Many a times we are also representing the exergy as a unit mass systems we call this as a specific exergy.

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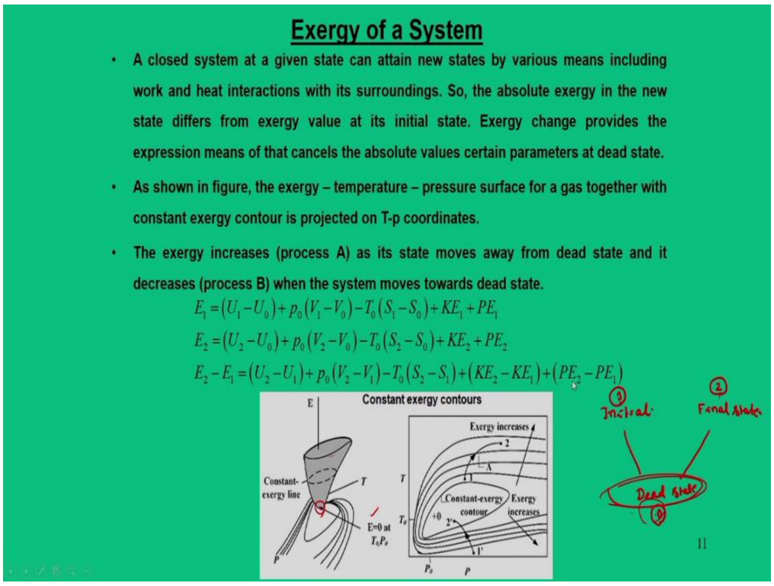

Exergy of a System

- A closed system at a given state can attain new states by various means including work and heat interactions with its surroundings. So, the absolute exergy in the new state differs from exergy value at its initial state. Exergy change provides the expression means of that cancels the absolute values certain parameters at dead state.
- As shown in figure, the exergy – temperature – pressure surface for a gas together with constant exergy contour is projected on T-p coordinates.
- The exergy increases (process A) as its state moves away from dead state and it decreases (process B) when the system moves towards dead state.

$$E_1 = (U_1 - U_0) + p_0(V_1 - V_0) - T_0(S_1 - S_0) + KE_1 + PE_1$$

$$E_2 = (U_2 - U_0) + p_0(V_2 - V_0) - T_0(S_2 - S_0) + KE_2 + PE_2$$

$$E_2 - E_1 = (U_2 - U_1) + p_0(V_2 - V_1) - T_0(S_2 - S_1) + (KE_2 - KE_1) + (PE_2 - PE_1)$$

Constant exergy contours

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Now, let us see that another viewpoint; that means, we have talked about this exergy analysis in the pressure temperature coordinates and basically if you want to put them in a graphical way what does it represent to us. So, the closed systems at a given state can attain new states by various means including work and heat interactions with surroundings.

So, we can say that exergy can increase or decrease depending on the values of irreversibility of associated at any instant of time. So, the absolute exergy of the new states different from the exergy value from the initial states.

Hence we have to find out the exergy change which provides the expressions for means that cancel the absolute value for certain parameters of the dead state. How you are going to do that? So, refer this particular figure that it is plotted that in a three axis systems one is pressure, temperature axis and exergy axis. And we have put the exergy contours.

So, what we see that this exergy contours; that means, exergy is 0 when the system is at dead state. Now slowly if you evolve; that means, any arbitrary plane would represent the constant exergy line and if you put in a two dimensional form that is pressure temperature plot first plot we are getting a constant exergy contour.

And if a systems goes from 1 to 2; that means, from the dead state to the any arbitrary state then its exergy content increases and when the system goes from its arbitrary state to a dead state its exergy content decreases. So, this is how you view the exergy temperature pressure surface for a gas together with the constant and exergy contour projected on a TP coordinates.

So, many a times we say that dead state; that means, with respect to system and the environment, we view three situations; that means, system has an initial state and system will have a final state. So, initial state we refer as 1 final state we refer as 2, but both these initial states is interacting with dead state and it is referred as 0.

So, basically we calculate the exergy change from 1 to 0 or 2 to 0 or in other words if you just bypass this dead state; that means, if you want to find out the exergy change between 1 and 2 it is easy for us that if you quantify this $E_2 - E_1 = (U_2 - U_1) + p_0(V_2 - V_1) - T_0(S_2 - S_1) + (KE_2 - KE_1) + (PE_2 - PE_1)$.

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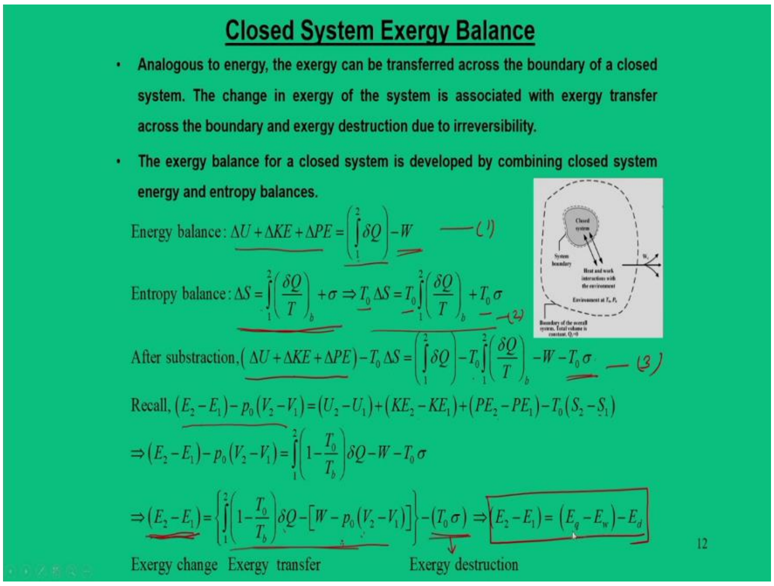

Closed System Exergy Balance

- Analogous to energy, the exergy can be transferred across the boundary of a closed system. The change in exergy of the system is associated with exergy transfer across the boundary and exergy destruction due to irreversibility.
- The exergy balance for a closed system is developed by combining closed system energy and entropy balances.

Energy balance: $\Delta U + \Delta KE + \Delta PE = \left(\int_1^2 \delta Q\right) - W$ — (1)

Entropy balance: $\Delta S = \int_1^2 \left(\frac{\delta Q}{T}\right)_b + \sigma \Rightarrow T_0 \Delta S = T_0 \int_1^2 \left(\frac{\delta Q}{T}\right)_b + T_0 \sigma$ — (2)

After substraction, $(\Delta U + \Delta KE + \Delta PE) - T_0 \Delta S = \left(\int_1^2 \delta Q\right) - T_0 \int_1^2 \left(\frac{\delta Q}{T}\right)_b - W - T_0 \sigma$ — (3)

Recall, $(E_2 - E_1) - p_0(V_2 - V_1) = (U_2 - U_1) + (KE_2 - KE_1) + (PE_2 - PE_1) - T_0(S_2 - S_1)$

$$\Rightarrow (E_2 - E_1) - p_0(V_2 - V_1) = \int_1^2 \left(1 - \frac{T_0}{T_b}\right)\delta Q - W - T_0 \sigma$$

$$\Rightarrow \underbrace{(E_2 - E_1)}_{\text{Exergy change}} = \underbrace{\left\{\int_1^2 \left(1 - \frac{T_0}{T_b}\right)\delta Q - [W - p_0(V_2 - V_1)]\right\}}_{\text{Exergy transfer}} - \underbrace{(T_0 \sigma)}_{\text{Exergy destruction}} \Rightarrow \boxed{(E_2 - E_1) = (E_q - E_w) - E_d}$$

The next point that we are going to discuss is the closed system exergy balance. So, that point of time we have discussed at exergy of the system. Now we have to say that like we did the energy balance from the first law and we will be also looking at the exergy balance. Now to study the exergy balance we need to revoke the first law and second law together.

So, from this again with respect to same figure the energy balance equations can be written as $\Delta U + \Delta KE + \Delta PE = \left(\int_1^2 \delta Q\right) - W$. So, this is how the energy balance equation looks like.

Now, if you recall the entropy balance equations this is the second equation that is $\mathit{\Delta} S = \int_1^2 \left(\frac{\delta Q}{T}\right)_b + \sigma$. Now in this equation you multiply T_0 on the both sides. So, we arrive at the $T_0 \mathit{\Delta} S = T_0 \int_1^2 \left(\frac{\delta Q}{T}\right)_b + T_0\sigma$. Now we have first equation and we have second equation. Now when you subtract we get the third equation.

So, in this particular equations we say that we have energy term, we have entropy term we have work transfer, we have heat transfer term and we have entropy production term. Now if you recall our previous analysis we did this expressions. $\Delta E - p\Delta V = (\mathit{\Delta} U + \mathit{\Delta} KE + \Delta PE) - T_0 \mathit{\Delta} S$. So, from this these two equations we can now find out what is the value of exergy transfer.

So, in other words after simplifying these expressions these are all proper self explanatory we land off having this exergy transfer or change for the system at state 2 and 1 we call this as exergy change and it involves the exergy transfer. $\left(E_2 - E_1\right) = \left\{\int_1^2 \left(1 - \frac{T_0}{T_b}\right) \delta Q - \left[W - p_0\left(V_2 - V_1\right)\right]\right\} - \left(T_0\sigma\right)$. Now the change happens due to the exergy transfer, this exergy transfer can take place by 2 means 1 is through by heat transfer other is through work transfer.

So, second expression is $T_0\sigma$ and we interpret this term as exergy destructions. So, in a simplified form we write $(E_2 - E_1) = \left(E_q - E_w\right) - E_d$; that means, exergy transfer due to heat transfer and work transfer minus exergy destruction ok. So, this is the final basic expressions that we rewrite here.

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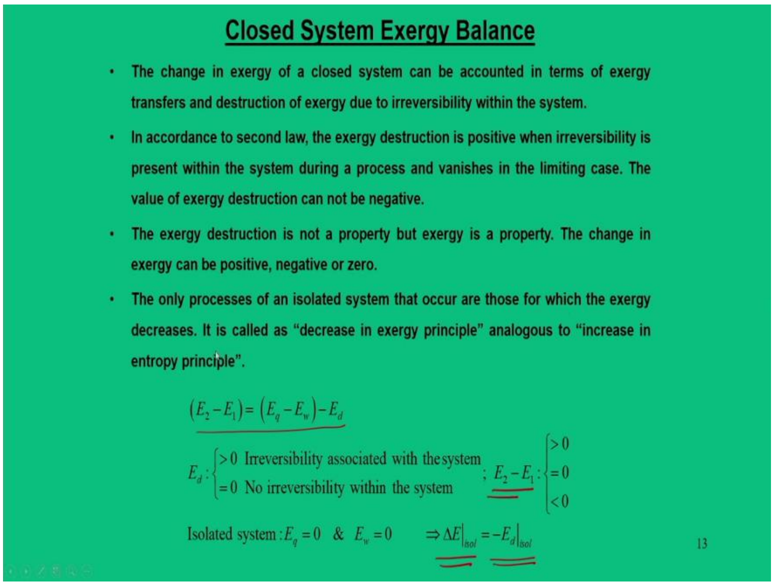

Closed System Exergy Balance

- The change in exergy of a closed system can be accounted in terms of exergy transfers and destruction of exergy due to irreversibility within the system.
- In accordance to second law, the exergy destruction is positive when irreversibility is present within the system during a process and vanishes in the limiting case. The value of exergy destruction can not be negative.
- The exergy destruction is not a property but exergy is a property. The change in exergy can be positive, negative or zero.
- The only processes of an isolated system that occur are those for which the exergy decreases. It is called as "decrease in exergy principle" analogous to "increase in entropy principle".

$$\underline{(E_2-E_1)=(E_q-E_w)-E_d}$$

$$E_d:\begin{cases}>0 & \text{Irreversibility associated with the system}\\ =0 & \text{No irreversibility within the system}\end{cases}\;;\ \underline{\underline{E_2-E_1}}:\begin{cases}>0\\ =0\\ <0\end{cases}$$

$$\text{Isolated system}: E_q=0\ \ \&\ \ E_w=0 \qquad \Rightarrow \underline{\underline{\Delta E|_{isol}}} = \underline{\underline{-E_d|_{isol}}}$$

Now, here these equations has a very significant repercussions. First thing we are going to see here that this exergy change $(E_2 - E_1) = (E_q - E_w) - E_d$, Ed is nothing but exergy destruction. So, this E_d can have 0 or it can be greater than 0. So, when it is 0 it means there is no irreversibility associated with the systems.

And when it is greater than 0; that means, there is always an irreversibility that is associated with the systems; that means, we say that exergy of the system drops. Now from this we can rightly point out that this is the options that are available for exergy destructions, but what happens to exergy change; that means, $E_2 - E_1 : \begin{cases} > 0 \\ = 0. \\ < 0 \end{cases}$

So, there are three possibilities for exergy change for a any given systems. Now we already mentioned that for an isolated system. So, when we define this isolated system in thermodynamics sense that it does not involve any heat transfer, it does not involve in the work transfer. So, $E_q = 0 \& E_w = 0 \Rightarrow \Delta E|_{isol} = -E_d|_{isol}$ that means exergy destruction for the isolated systems. So, exergy of an isolated systems always decreases and this is called as decrease in the exergy principle. And this is an analogous terminology that we recall that increase in the entropy principle. So, the second law analysis of increase in the entropy principle is interpreted as decrease in the exergy principle.

And final consequence that we can write that the only processes of an isolated system that can occur are those for which exergy decreases.

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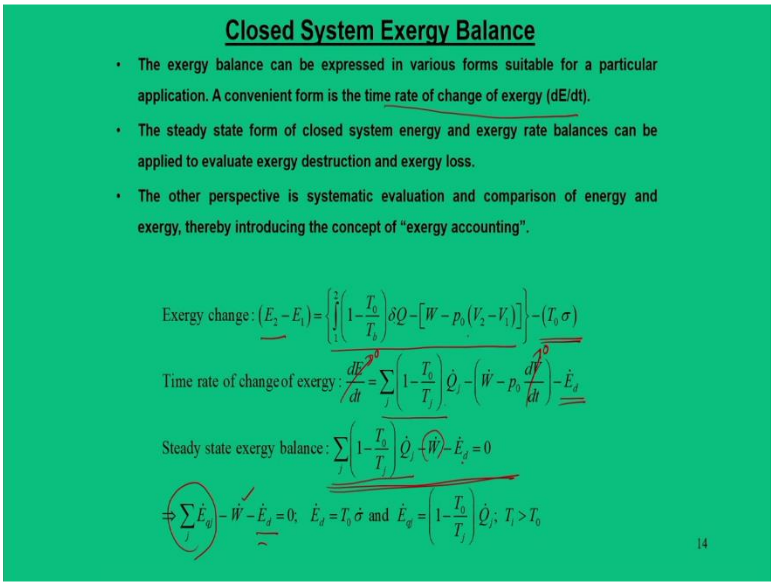

Closed System Exergy Balance

- The exergy balance can be expressed in various forms suitable for a particular application. A convenient form is the time rate of change of exergy (dE/dt).
- The steady state form of closed system energy and exergy rate balances can be applied to evaluate exergy destruction and exergy loss.
- The other perspective is systematic evaluation and comparison of energy and exergy, thereby introducing the concept of "exergy accounting".

Exergy change: $(E_2 - E_1) = \left\{ \int_1^2 \left(1 - \frac{T_0}{T_b}\right) \delta Q - [W - p_0(V_2 - V_1)] \right\} - (T_0 \sigma)$

Time rate of change of exergy: $\frac{\cancelto{0}{dE}}{dt} = \sum_j \left(1 - \frac{T_0}{T_j}\right) \dot{Q}_j - \left(\dot{W} - p_0 \frac{\cancelto{0}{dV}}{dt}\right) - \dot{E}_d$

Steady state exergy balance: $\sum_j \left(1 - \frac{T_0}{T_j}\right) \dot{Q}_j - \dot{W} - \dot{E}_d = 0$

$\Rightarrow \sum_j \dot{E}_{qj} - \dot{W} - \dot{E}_d = 0; \quad \dot{E}_d = T_0 \dot{\sigma}$ and $\dot{E}_{qj} = \left(1 - \frac{T_0}{T_j}\right) \dot{Q}_j; \; T_i > T_0$

And moving further we are now going to talk about exergy balance with respect to time or many times we call this as a time rate of change of exergy $\frac{dE}{dt}$. So, same expressions is evaluated in a different way. But here we say that this exergy change, this is exergy transfer due to heat and due to work and this is exergy destruction. $(E_2 - E_1) = \left\{ \int_1^2 \left(1 - \frac{T_0}{T_b}\right) \delta Q - [W - p_0(V_2 - V_1)] \right\} - (T_0 \sigma)$.

So, in this equation if you find out what is this $\frac{dE}{dt}$, then we can make this integrals that can be represented through summations for exergy transfer by heat and exergy transfer by work and exergy destructions. $\frac{dE}{dt} = \sum_j \left(1 - \frac{T_0}{T_j}\right) \dot{Q}_j - \left(\dot{W} - p_0 \frac{dV}{dt}\right) - \dot{E}_d$. And in a steady state situations this particular term vanishes and finally, we get the steady state exergy balance in this form which involves that there are multiple ways that a system can interact with the environment or surroundings through different inlets or outlets. So that means, there are multiple exit and entry of the systems. $\sum_j \left(1 - \frac{T_0}{T_j}\right) \dot{Q}_j - \dot{W} - \dot{E}_d = 0$

And for which we represent this exergy transfer due to heat transfer as $\dot{E}_{qj}$. $\sum_j \dot{E}_{qj} - \dot{W} - \dot{E}_d = 0$. And the exergy transfer the due to work remains as it is. Ultimately what we are trying to say that the exergy transfer that is $\dot{E}_{qj}$ is mainly functions of temperatures at which the system exist and with respect to environment. So, why you insist more on exergy with respect to heat because heat is a low grade energy and complete conversion of low grade energy to high grade energy is not possible.

So; that means, if you interpret this heat in terms of work then to have maximum work we need to recall this exergy study. So, that is the entire philosophy of this consideration for a closed system exergy balance.

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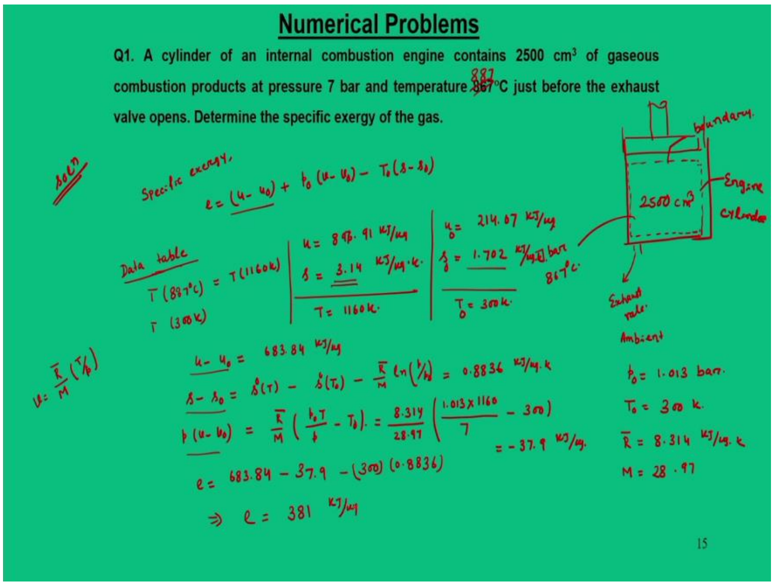

Numerical Problems

Q1. A cylinder of an internal combustion engine contains 2500 cm³ of gaseous combustion products at pressure 7 bar and temperature $\overset{887}{\cancel{867}}$°C just before the exhaust valve opens. Determine the specific exergy of the gas.

Sol

Specific exergy,

$e = \underline{(u - u_0)} + p_0 (v - v_0) - T_0 (s - s_0)$

Data table

$T(887°C) = T(1160K)$

$T(300K)$

$u = 897.91$ kJ/kg

$s^0 = \underline{\underline{3.14}}$ kJ/kg·K

$T = 1160K$

$u_0 = 214.07$ kJ/kg

$s^0_0 = \underline{1.702}$ kJ/kg·K, bar

$T_0 = 300K$

$v = \frac{\bar{R}}{M}\left(\frac{T}{p}\right)$

$\underline{u - u_0} = 683.84$ kJ/kg

$\underline{s - s_0} = s^0(T) - s^0(T_0) - \frac{\bar{R}}{M} \ln\left(\frac{p}{p_0}\right) = 0.8836$ kJ/kg·K

$\underline{p(v - v_0)} = \frac{\bar{R}}{M}\left(\frac{p_0 T}{p} - T_0\right) = \frac{8.314}{28.97}\left(\frac{1.013 \times 1160}{7} - 300\right)$

$= -37.9$ kJ/kg.

$e = 683.84 - 37.9 - (300)(0.8836)$

$\Rightarrow e = 381$ kJ/kg

Ambient

$p_0 = 1.013$ bar.

$T_0 = 300$ K.

$\bar{R} = 8.314$ kJ/kg·K

$M = 28.97$

So, now we are at the end of this particular lecture we are now going to look into some numerical problems which will clarify some of our understanding and the first one which we are going to discuss is the exergy study for an IC engine. Normally when you say internal combustion engines we are very familiar that exhaust of an engine carries lot of energy.

And of course, these exhaust are associated with lot of energy and if you want to quantify that we have to find the work potential of that exhaust gas energy. So, the problem that talks about that we have a IC engines in which cylinder has a size of 2500 cm^3. And this cylinder has some combustion products which has pressure 7 bar and temperature 867C and before the exhaust valve opens. That means, before the exhaust valve opens the combustion products is at 7 bar and 867C.

At that particular instant or initial state we have to find out the specific exergy of the gas. To recall this study let me draw this simple schematic diagram of an IC engine combustion chamber. So, we have a closed system which is nothing but the engine cylinder and this is nothing but the boundary that contains the combustion products and we have the pistons on the top, somewhere we can say there is an exhaust valve.

Just before the exhaust of the engine the conditions were 7 bar, 867C. So, we need to calculate the specific exergy for this gas. So, we can recall this expression for specific exergy $e = (u - u_0) + p_0(v - v_0) - T_0(s - s_0)$. So, prior to this let me recall this ambient condition.

So, since no data is given. So, I can say that ambient conditions can be recalled as p_0 is 1 bar or 1.013 bar and T_0 is 300 K. So, we have two situations to calculate all these numbers, we have to refer the data table. This data table is to be referred for the temperatures T at 867C and temperature at 300K.

Instead, I will write it as 887. So, 887C which is equivalent to temperature at 1160K. So, referring to this data table we are going to find out $U = 897.91\ kJ/kg$ and your entropy is equal to $3.14\ kJ/kg - K$. Now again at $T_0 = 300\ K$ we can find out $U_0 = 214.07 \frac{kJ}{kg}; s_0 = 1.702\ kJ/kg - K$.

So, data given so, we know $u - u_0 = 683.84\ kJ/kg$. Then $s - s_0$ expression we can recall that is entropy of the arbitrary system and the dead state that is nothing but $s(T) - s(T_0) - \frac{\bar{R}}{M} \ln\left(\frac{p}{p_0}\right)$.

Where your $\bar{R}$ is universal gas constant which is $8.314\ kJ/kg - K,$ M is the molecular weight and this molecular weight we can directly take an assumptions that they are almost analogous to air we can say 28.97. Now considering this and putting this number we have $s - s_0 = 08836\ kJ/kg - K$.

Then next term we can find out $p(v - v_0)$. So, before you go for this let us recall what is v. From the ideal gas equation of state we can write$v = \frac{\bar{R}}{M}\left(\frac{T}{p}\right)$, now putting this we can write as $p(v - v_0) = \frac{\bar{R}}{M}\left(\frac{p_0 T}{p} - T_0\right)$. So, here we know all the number.

So, this becomes $\frac{8.314}{28.97}\left(\frac{1.013\times1160}{7}-300\right)=-37.9\ kJ/kg$. So, once we have this $e = 683.34-37.9-300\times0.8836=381\ kJ/kg$. So, it means that the exhaust gas has substantial amount of exergy which is 381 kJ/kg.

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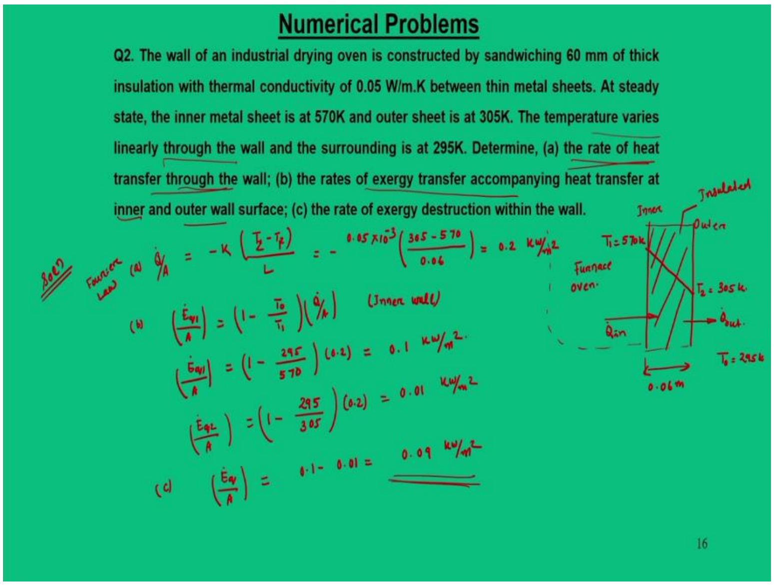

Numerical Problems

Q2. The wall of an industrial drying oven is constructed by sandwiching 60 mm of thick insulation with thermal conductivity of 0.05 W/m.K between thin metal sheets. At steady state, the inner metal sheet is at 570K and outer sheet is at 305K. The temperature varies linearly through the wall and the surrounding is at 295K. Determine, (a) the rate of heat transfer through the wall; (b) the rates of exergy transfer accompanying heat transfer at inner and outer wall surface; (c) the rate of exergy destruction within the wall.

Soln

Fourier Law (a) $\dot{Q}/A = -K\left(\frac{T_2-T_1}{L}\right) = -0.05\times10^{-3}\left(\frac{305-570}{0.06}\right) = 0.2\ kW/m^2$

(b) $\left(\frac{\dot{E}_{q1}}{A}\right) = \left(1-\frac{T_0}{T_1}\right)\left(\dot{Q}/A\right)$ (Inner wall)

$\left(\frac{\dot{E}_{q1}}{A}\right) = \left(1-\frac{295}{570}\right)(0.2) = 0.1\ kW/m^2.$

$\left(\frac{\dot{E}_{q2}}{A}\right) = \left(1-\frac{295}{305}\right)(0.2) = 0.01\ kW/m^2$

(c) $\left(\frac{\dot{E}_{q}}{A}\right) = 0.1-0.01 = \underline{\underline{0.09\ kW/m^2}}$

And the similar line we are now going to solve the second problem which is mainly on the exergy balance for the closed system. So, what the problem talks about is that in many industrial situations there is a heat generated in a furnace and we ensure that heat should not come out. So, that means, we provide sufficient insulation that heat should not come out and we have some arbitrary ambient conditions which is atmospheric conditions.

So, this is what we do that in a furnace we expect that energy should not come out, but to do that we require the wall design for the furnace. Now here we have to do some kind of exergy auditing which says that we must take into account the world design such a way there will be the minimal transfer of loss or energy loss to the surroundings.

So, with this philosophy or we can say auditing of the exergy and this exergy transfer is mainly due to heat transfer because the furnace is normally is at very high temperatures. So, the problem statement that gives here that wall of an industrial drying oven is constructed by sandwiching 60 mm of thick insulation with thermal conductivity of 0.05 W/m-K between the thin metal sheets.

At steady state the inner metal sheet is at 570K, outer seat is at 305K. The temperature varies linearly through the wall to the surroundings and the surrounding is at 295K. We need to determine the rate of heat transfer through the wall, rate of exergy transfer accompanying the heat transfer at the inner wall and the outer wall then exergy destruction within the wall.

So, a schematic environment that I will be looking at that its nothing but our emphasis should be focused on a wall or you can say there may be furnace and oven has wall this wall is insulated and its thickness is 0.06 m, inner wall of this oven is we can say T_1 570K and outer wall is let us say at T_2 305 K and ambient that is surroundings T0 is 295 K.

Now, across this wall the temperature drops linearly that is what it is given. And in this case what we can say the flow of heat? We can say Q_{in} and this is Q_{out} that is for inner wall and for the outer wall. So, the first expression that we are going to find out what is the rate of heat transfer through the wall.

So, to find the rate of heat transfer through the wall we recall that we have to find $\frac{\dot{Q}}{A}$; that means, we let us say heat flux and we have to recall this as from the Fourier lawr. That is nothing but $\frac{\dot{Q}}{A} = -\frac{k(T_2 - T_1)}{L} = \frac{(-0.05 \times 10^{-3})(305-570)}{0.06} = 0.2\ kW/m^2$.

Second answer rate of exergy transfer accompanying heat transfers. So, you have to recall the exergy due to heat transfer.

We can say $\frac{\dot{E}_{q/1}}{A}$. So, here 1 stands for inner wall. So, it is nothing but $\left(1 - \frac{T}{T_0}\right)\frac{\dot{Q}}{A}$. So, this is for inner wall. So, we know that the inner wall is at 570 K. So, we can say $\frac{\dot{E}_{q/1}}{A} = \left(1 - \frac{295}{570}\right) 0.2 = 0.1\ kW/m^2$.

Then this is accompanying by heat transfer at the inner wall and for the outer wall we can write $\frac{\dot{E}_{q/2}}{A} = \left(1 - \frac{295}{305}\right) 0.2 = 0.01\ kW/m^2$. So, we got the second answer and third answer is exergy destructions.

So, we say $\frac{\dot{E}_q}{A} = 0.1 - 0.01 = 0.09\ kW/m^2$. So, this says that we have a substantial amount of exergy destruction and that exergy destruction is maybe quite sometimes it is unavoidable and this exergy destruction needs to be minimized.

So, this can be minimized by improving the thermal conductivity of the insulation materials. So, these two problems gives us some glimpses that how exergy destruction is a significant parameter in many industrial processes. So, with this I will conclude.

Thank you for your attention.