Thermal Physics
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Lecture - 33
First Law of Thermodynamics

Hello and welcome back to another lecture on this NPTEL course of thermal physics. Now, as promised, we will continue from where we have left in the last class. So, we will be basically discussing internal energy once again. Now, the basic concept of internal energy has been discussed to some extent in the last class where we said that internal energy, I have basically given you one example of an internal energy.

That is let us say if we have a gas assembly, the thermal energy associated with each degree of freedom of the gas particles which we have discussed in details, when we were discussing kinetic theory or classical equipartition theorem. That energy is an example of internal energy.

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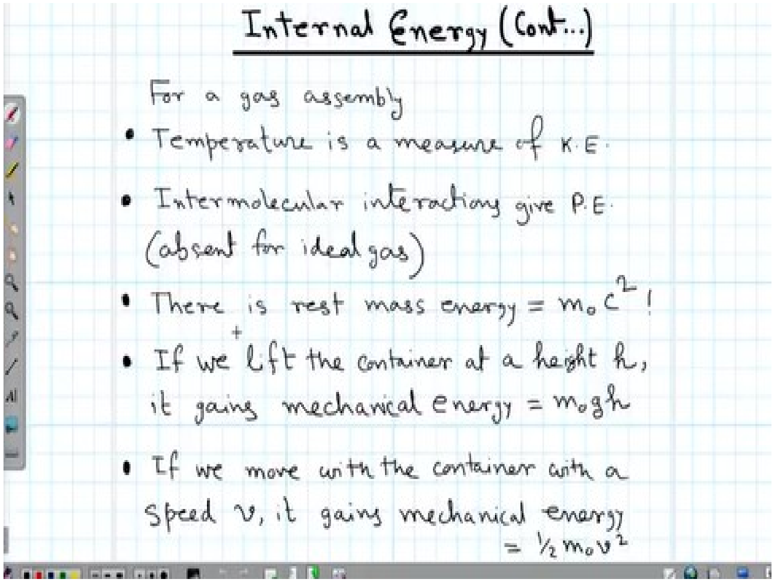

Internal Energy (Cont..)

For a gas assembly

- Temperature is a measure of K.E.
- Intermolecular interactions give P.E. (absent for ideal gas)
- There is rest mass energy = $m_0 c^2$!
- If we lift the container at a height h, it gains mechanical energy = $m_0 g h$
- If we move with the container with a speed v, it gains mechanical energy = $\frac{1}{2} m_0 v^2$

Now, let us look once again into the example of gases assembly. We have what are the other possible energies that are gases assembly might have. So, of course, we have temperature, which is a measure of kinetic energy, classical equipartition theorem. Then we have intermolecular interaction giving rise to potential energy which is absent in ideal gas. But we have seen that in real gases, this potential energy that intermolecular interaction is actually present.

And that gives you some kind of a pressure reduction when it comes to comparison with ideal gas. Now, of course, there are other sources of energy for example, there is rest mass energy. We are all familiar with this famous Einstein relation of E is equal to mc squared. Going by this for gas assembly where the total mass is m 0 we have m 0 c squared amount of energy which is also some form of internal energy of the system.

Now, let us say the gases inside a container. Of course, it is, I mean we talk about closed gases assembly though it will lift the container at a height h. It gains the mechanical energy the gases assembly forget about the mass of the continent the gas assembly which has a mass m 0, it gains a mechanical energy of m 0 g h. And then if we start moving the gas assembly the box which are the container which contains the gas with the speed v.

It gains a mechanical energy which is the potential kinetic energy once again it is half m v 0 squared. So, this is the mechanical potential energy, this is the mechanical kinetic energy, this is the rest mass energy and of course, we have internal kinetic energy that is associated with the temperature by equipartition theorem and the internal potential energy for which we have not written an explicit expression, but it is available it is possible to write that.

So, out of this all these are internal energy it is there, if you want to exploit the gas assembly. Let us start so, we have to assume that there is a h and with the finite h the gases assembly moving with a finite speed v then all these five forms of energy these are present in the gas assembly. The simple question is, can we really call all of it the internal energy in the context of thermodynamics? The answer is no.

Only the first two, this one and this one, which I am marking with red, these can be called the potential or the internal energy when it comes to the context of classical thermodynamics. So, only these two types of energy will be of our interest. And this is what we talk about when we talk over this is what we discuss. This is what we talk about when we discuss internal energy of a gas assembly. So, basically the energy that it associated with thermal vibration or intermolecular interaction.

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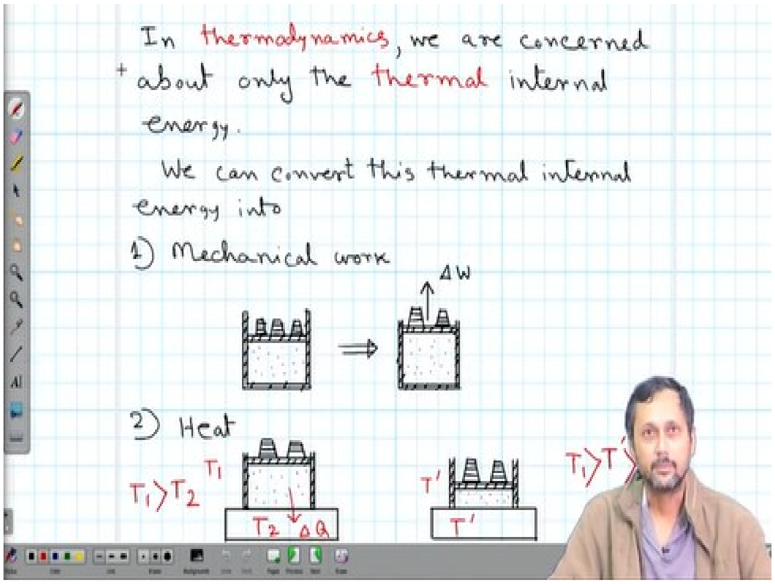

In thermodynamics, we are concerned about only the thermal internal energy.

We can convert this thermal internal energy into

1) Mechanical work

2) Heat

Now, this internal energy whichever is this thermal internal energy or the thermal internal energy that we talked about. Of course, the potential energy is called is also part of this thermal internal energy but it is not exactly correlated with the temperature there is a relation of course, but it is not exactly correlated with the temperature. And it that way it is not thermal quote and quote in nature, but this is also very important in case of thermodynamics.

Because in certain cases we; have to deal with molecular interaction, so, only these two parts. Now, this internal energy which we are talking about, it can be converted into either mechanical work or heat and vice versa. For example, if I take this piston arrangement when we have enclosed gas, I have three let us say three such works to make it keep it in equilibrium. Now, if I lift one weight from here, what happens? The pressure of this side will be more as compared to this side.

So, the weight was there to balance the pressure. Now, the pressure is gone or the weight is gone now, the pressure will be more and the piston will be moving outwards. So, that means, there will be equivalent delta W or d w amount of work or delta W amount of work which is done by this gas assembly. Now, we have not supplied any other energy to this gas assembly. So, we can conclude that this work what whatever is done by the gas assembly is taking place in the expense of the internal energy.

So, that means, we can conclude that under expansion the internal energy of these gases only decreases. So, the reverse process is also true. Now, if we compress these gas assembly from here to here and please remember we are always considering ISO necessarily quasi-static process and we are at this point we are not talking about the dissipative forces. So, now this one is a reversible change reversible once again it is a quote and quote reversible.

Because two reversible changes as I have said is the combination of infinitesimal displacements which will never end, but this is a quasi-static process. But we can still consider it to be an reversible process, where at least the initial and the final state is in thermodynamic equilibrium. Now, if I put this word back, so it will; the process will revert. So, that way it will also go in this direction. So, if I put back this way, we will get back this state.

So, that means internal energy so that basically means compression or doing mechanical work on the system by putting this weight we are doing mechanical work on the system and in this case, work is done by the system. So, if I reverse this process so that means if we do work on the system is the internal energy will once again increase. Similarly, let us assume that we have a system where all three sides are okay so, here we have taken a thermally insulated system.

Here we have thermally insulated system, but let us say this side is that on the bottom wall is diathermic in nature and it is in contact with another object finite size object which is at a temperature T 2 whereas, the gas assemblies are at a temperature T 1 which is greater than T 2. Now what will happen? We all know from zeroth law of thermodynamics is that the temperature equilibrium temperature must equilibrate.

That is the condition of thermal one of the primary condition for equilibrium. So, once the temperature I am sorry, I should not say it is the condition of equilibrium that happens at equilibrium that the temperature becomes equal. So, if we keep this long enough, if we let these two systems in contact with each other to equilibrium that means if we just keep it there for a long time the temperature of both the gas and the object will be something T prime which is intermediate to T 1 and T 2.

Now in the process what will happen? We are not changing the pressure on this system. So, what we are doing is? Basically, we are taking away heat in order to increase the temperature from T 2 to T prime. And we will see that the system compresses at the same time the temperature goes down. As the temperature goes down, we know that the internal energy of the system goes down but because at least for gas assembly let it be real gas not an ideal gas.

Even then there is this half getting contribution for the kinetic energy of the gas molecule for each gas molecule. So, that is why solid 3 half K T basically. Let us say it is a non-ideal monatomic gas let us 3 half K T whatever I think you understand what ever tries to say that reduces. So, the total kinetic energy reduces that means the internal energy reduces in the cost of heat.

So, the reverse process is also true if we heat up this heat up or gas assembly, the internal energy increases. The temperature increases as a result the internal energy increases.

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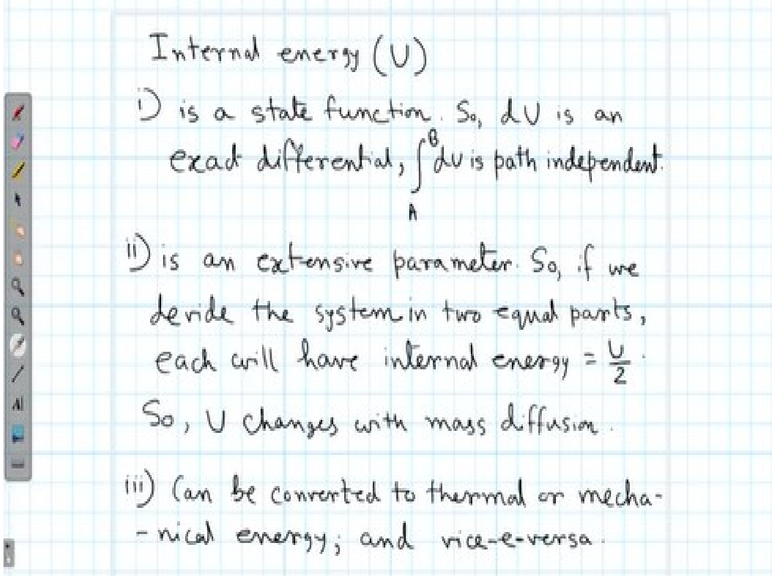

Internal energy (U)

i) is a state function. So, dU is an exact differential, $\int_A^B dU$ is path independent.

ii) is an extensive parameter. So, if we devide the system in two equal parts, each will have internal energy $= \frac{U}{2}$.

So, U changes with mass diffusion.

iii) Can be converted to thermal or mechanical energy; and vice-e-versa.

So, once again let us summarize the properties of internal energy U. This is a state function that is also very important that dU is the exact differential. So, the integration A to B dU is path independent. Unlike the work mechanical work which is a path dependent phenomena dU is a path integral dU is a path independent phenomena because it is a state function. So, internal energy is one example of thermodynamic state function.

This is an extensive parameter that is also a very crucial point. So, let me underline this. So, state function and extensive parameters. So, these are this is also a very important point that means, if we divide the system into 2 equal half any system let us say it has internal energy U, so the internal energy of each half will be U by 2 exactly. So, U changes with so at the same time we can conclude that U changes with mass diffusion.

What do you mean by this? That means, if we somehow take out molecules from the system in this assembly, let us say let us say a fusion is a process that we have already discussed where from a gas assembly the mass the gas molecules escape there is a small hole. So, in the process of diffusion internal energy will decrease. Similarly, in the reverse process, if we can push in more particles inside gas assembly the internal energy will increase.

So, these are because this is an extensive parameter and as we have already discussed that internal energy can be converted to thermal or mechanical energy and vice versa.

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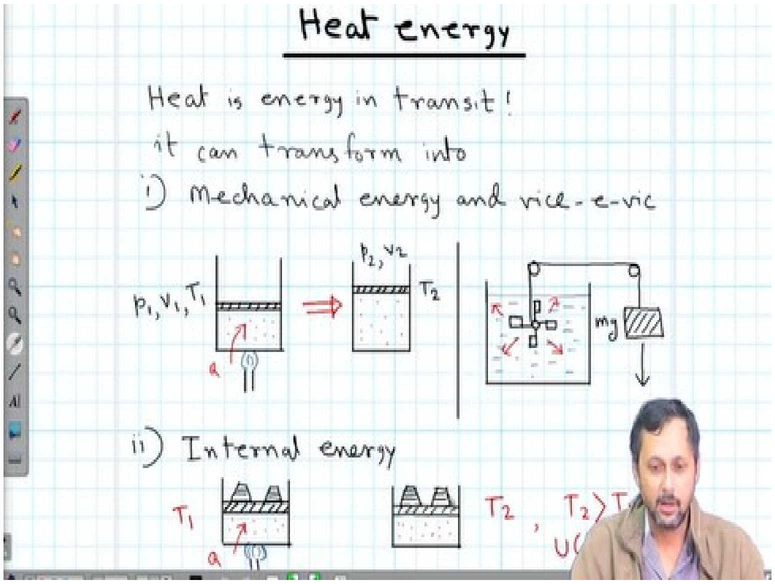

Heat energy

Heat is energy in transit!

it can transform into

i) Mechanical energy and vice-e-vic

ii) Internal energy

So, now let us move to the next topic, which is heat energy. Now, heat energy is something that we have discussed either not directly maybe but indirectly throughout this course, so far. We all know that heat is a form of energy, but I will just take it one step forward and I will call it the call heat is the energy in transit. Now, this is a very important point because we cannot actually measure the total heat that is preserved inside a system.

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So, let us say I have this bottle of water. So, I have this bottle of water I cannot tell you what is the total heat that is absorbed in this bottle or in this water or in this whole system? If I considered this whole thing as a system but if I now change the temperature of this by if I take this water out separately, put it inside a calorie meter and try to heat it up. Then by looking at the temperature difference.

I think you are all familiar with the calorimeter arrangement from it is a very simple experiment. So, why temperature difference? I can tell you exactly what amount of heat has gone inside or if it is cooling, I can tell you what amount of heat has been taken out from this water. But we cannot can never say what is the exact amount of heat present inside.

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So, let us use the water. Now as like internal energy heat can also be converted into mechanical energy and vice versa. For example, if I just put a flame under this piston arrangement which is initially let us say at equilibrium the pressure here and the weight here the balance each other. If

I do not do anything to it, if I do not put any extra weight then the volume will increase. Similarly, the temperature might also increase by some extent.

So, in this case this is an example where the heat actually gives you mechanical energy and given that the temperature might also increase slightly, the internal energy is also changing. So, although we are just talking about heat so here by heat, we can change internal energy as well and we have seen that. Let us talk about this experiment which is actually a very famous experiment in the early days by Lord Kelvin.

Where he has measured the amount not only him there are other very famous scientist who also set up this type of experiment where we have inside an isolated chamber. Let us say there is an isolated chamber outside this whole setup. There is a wheel which rotates inside a bucket of water or pool of water and there is a mechanical weight which is connected through pulley. Now if the mechanical weight is dropping then it this one will be rotating.

This field will be rotating and as a result the temperature the heat this is primarily mechanical energy. And it was observed that by the process of movement of this pulley, the temperature of the water was also changing or rising slightly small amount but measurable change. So, this is a classic example by which mechanical energy could be converted to heat energy. I mean there are many other ways of doing it, if you just rub your hands, we are all familiar to it.

If we rub our hands basically mechanical energy will convert to heat energy and we will feel a little warm in the pump. But in this particular experiment, this was the first time when mechanical equivalent of heat was very carefully measured. Then we have internal energy, which once again if we in the first example, if I now put some weight. So, that the piston cannot move outside, then what happens? Temperature changes.

Now, in this case T 2 will be definitely more than T 1. Similarly, U at T 2 will be greater than U at T 1. So, we have mechanical energy to heat and heat energy to mechanical energy and vital vice versa, internal energy to heat energy and vice versa. As I have already said in the previous example, when we have this scenario then the temperature will drop, internal energy will drop. So, basically in here U corresponding to T prime will be less as compared to U corresponding to T 2.

And here U corresponding to T 2 is greater than U corresponding to T 1. So, now we see that work, mechanical work, internal energy and heat energy, they are all converting to each other. So, these are convertible forms of energy. So, primarily what is going from one part to the other or one part of the system to the other is the heat energy and this is why it is called the energy in transit.

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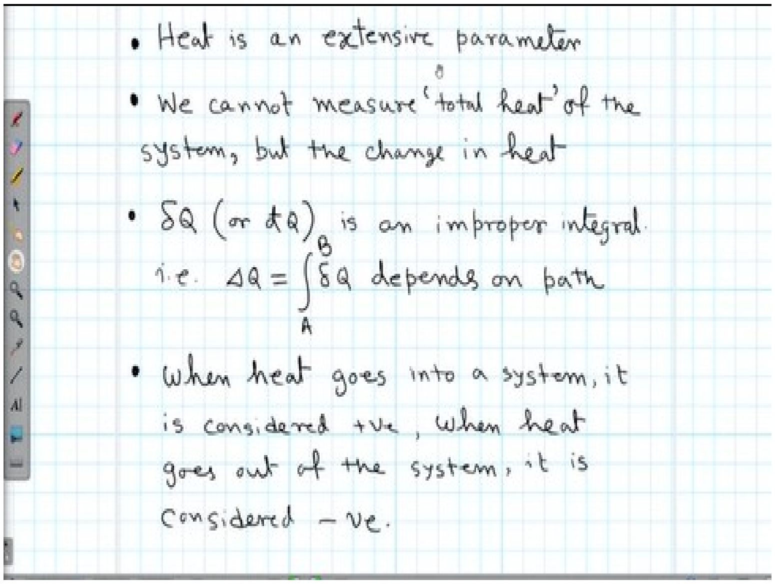

- Heat is an extensive parameter
- We cannot measure 'total heat' of the system, but the change in heat
- δQ (or $đQ$) is an improper integral.
  i.e. $\Delta Q = \int_A^B \delta Q$ depends on path
- When heat goes into a system, it is considered +ve, when heat goes out of the system, it is considered −ve.

Now, there is comes so some more properties of heat. Heat is an extensive parameter because if we have a system if I divide the system the heat will be divided. And as I have said we cannot measure total heat but the change in heat and delta Q or d cut Q is an improper integral that means the integration there are delta dQ or there sorry capital delta Q which is an integration A to B dQ is dependent on the path.

And by convention if a system accepts heat thermodynamic system in question accepts it, we call this positive. When heat goes out of the system, we call it negative. Exactly the; way we have defined positive work and negative work we have also defined positive heat and negative heat.

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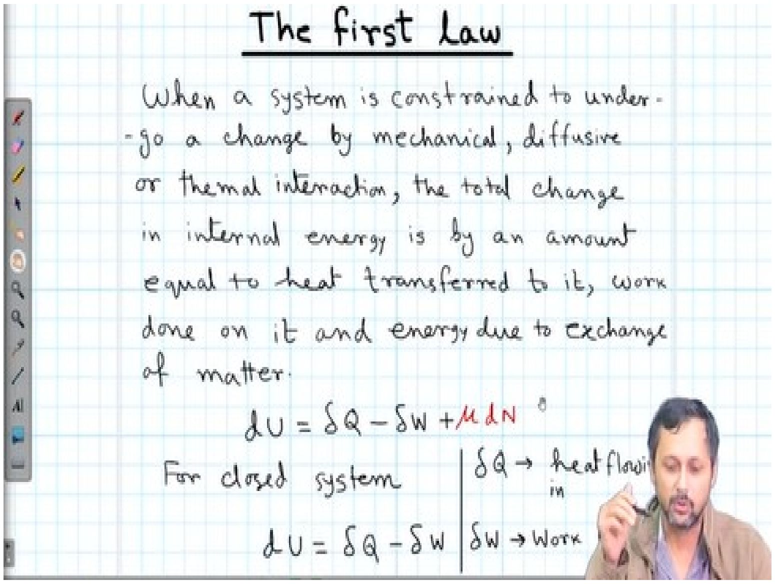

The first Law

When a system is constrained to under-go a change by mechanical, diffusive or themal interaction, the total change in internal energy is by an amount equal to heat transferred to it, work done on it and energy due to exchange of matter.

$$dU = \delta Q - \delta W + \mu\, dN$$

For closed system

$$dU = \delta Q - \delta W$$

$\delta Q \rightarrow$ heat flowi in

$\delta W \rightarrow$ Work

Please keep this definition in mind because the next thing we are going to discuss is the first law of thermodynamics which has this particular mathematical form. Please remember that the exact sign of delta Q and delta W is extremely important. I think you are all familiar with the first law and because first law is nothing but the energy conservation principle in a slightly different representation. So, here I am not going through the statement of the first law.

So, by the time we have discussed whatever we have discussed over one thing is very clear from that. The internal energy the work done and heat energy, they are all convertible to each other. Now, the equation that summarizes this interconversion is the first law the mathematical form of law which says dU = dQ - dW + mu dN and now this mu dN is something that is valid only for a closed system.

So, as we are sorry, this is valid only for an open system when molecules can move in or out of the system. This mu is called the chemical potential and the dN is the number of molecules that is changing. We are not going to discuss this part for now, because we are not talking about open systems as of now. So, we will just focus on the first two terms of this and we will lie for a closed system that dU = dQ - dW with the notation that dQ is the heat that is flowing in the system.

And dW is the work by the system, minus dW is the work done on the system. So, you have to be very careful about the sign or the convention that we are following. Otherwise, there is always a sign error in writing the mathematical form of the first law, keep this in mind. Because this is something that is important in order to understand. Now so we will keep talking about this law. And once again, let me tell you so that is what the statement I am going to make now is valid for all three laws or other all four laws of thermodynamics.

That says system energy or the laws of thermodynamics cannot be proven. So, this a primarily based on observation and so far, no experiment could disprove these laws. So, that is the best treatment we have in hand and we can safely say because these laws has not been determined. Not only that, these laws could not be disproved, but also based on these laws, the second first law and the second law and subsequently the third law so many deductions has been made.

And so many inventions has been made that typically we can consider those laws beyond question. But anyway, I mean, if you think you have any doubts, you are free to think in that line. We can always discuss whether is there any formal way of formal proof is necessary or not, but this is more of a philosophical discussion. So, in reality there is no proof for this law. But there has not been it could not be disproven as of now.

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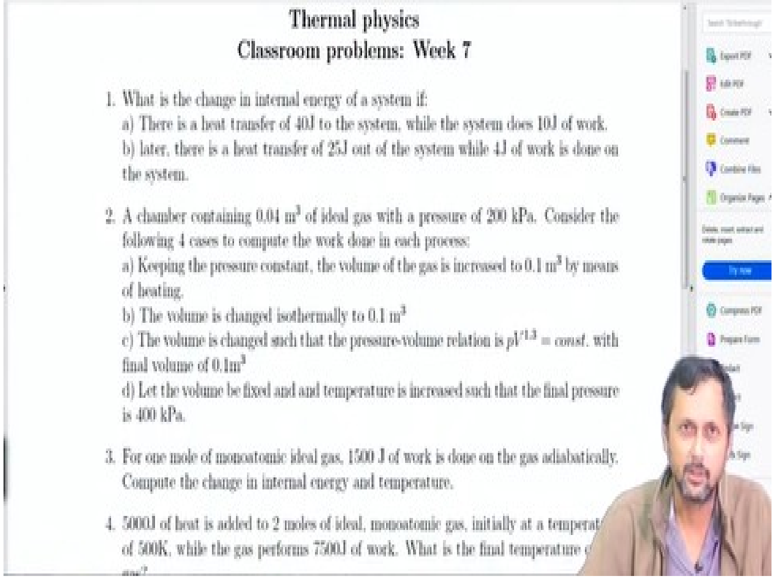

Thermal physics
Classroom problems: Week 7

1. What is the change in internal energy of a system if:
   a) There is a heat transfer of 40J to the system, while the system does 10J of work.
   b) later, there is a heat transfer of 25J out of the system while 4J of work is done on the system.
2. A chamber containing 0.04 m^3 of ideal gas with a pressure of 200 kPa. Consider the following 4 cases to compute the work done in each process:
   a) Keeping the pressure constant, the volume of the gas is increased to 0.1 m^3 by means of heating.
   b) The volume is changed isothermally to 0.1 m^3
   c) The volume is changed such that the pressure-volume relation is $pV^{1.3} = const.$ with final volume of 0.1m^3
   d) Let the volume be fixed and and temperature is increased such that the final pressure is 400 kPa.
3. For one mole of monoatomic ideal gas, 1500 J of work is done on the gas adiabatically. Compute the change in internal energy and temperature.
4. 5000J of heat is added to 2 moles of ideal, monoatomic gas, initially at a temperat of 500K, while the gas performs 7500J of work. What is the final temperature

So, now it is time to focus on the problem set. This is the first time we are talking about problems in today's lecture on this week's lecture. So, the first problem is a very simple kind, what is the change of internal energy of the system if there is a heat transfer of 40 Joules to the system, while the system does 10 Joules of work. And later, there is a heat transfer of 25 Joules out of the system while 4 Joules of work is done on the system. So, let us look into the first case.

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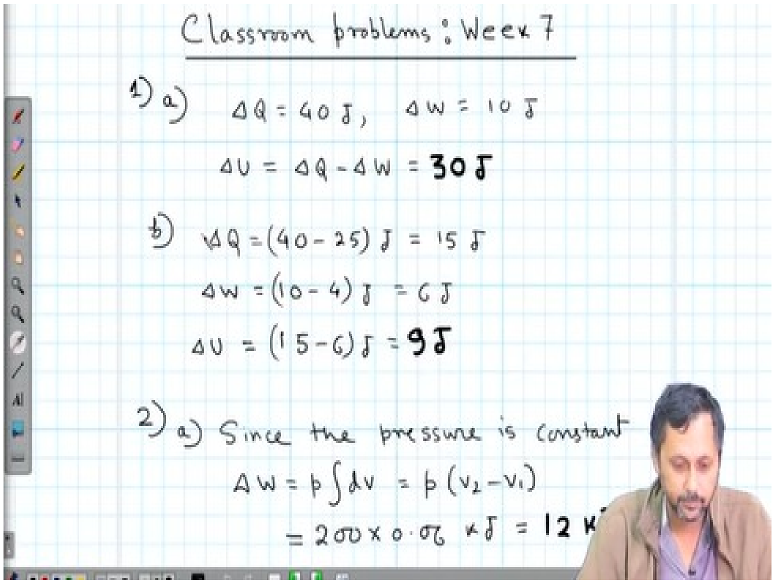

Classroom problems : Week 7

1) a) $\Delta Q = 40\ J, \quad \Delta W = 10\ J$

$\Delta U = \Delta Q - \Delta W = \mathbf{30\ J}$

b) $\Delta Q = (40 - 25)\ J = 15\ J$

$\Delta W = (10 - 4)\ J = 6\ J$

$\Delta U = (15 - 6)\ J = \mathbf{9\ J}$

2) a) Since the pressure is constant

$\Delta W = p \int dV = p(V_2 - V_1)$

$= 200 \times 0.06\ kJ = \mathbf{12\ K}$

We have delta Q is equal to 40 Joules which is going into the system delta W is equal to 10 Joules which is work done by the system. So, this is also very important, it is said done, while the system does 10 Joules of work. So, 10 Joules is the work done by the system. So, $dU = dW - dQ$ which is equal to 30 Joules. Now, for the next part, we have a transfer of 25 Joules out of the system, while 4 Joules of work is done on the system.

So, already there was initially 40 Joules to the system now heat of 25 Joules is transferred out of the system. So, total 40 minus 25 Joules which is equal to minus 50 Joules that goes in the system. And now, the system does 4 Joules of work. So, that means sorry system while 4 Joules of work is done on the system. So, previously, 10 Joules of work was done by the system. Now 4 Joules of work is done on the system.

So, altogether it is 6 Joules by the system. So, dU is equal to 15 minus 6 Joules, which is equal to 9 Joules. The next problem; the last problem for today's lecture a chamber containing 0.04 meter cube of ideal gas with the pressure of 200 kPa. Considered the; following four cases to compute the work in each process. So, I will get the volume and pressure is given no temperature is given, we have to consider for different cases to compute the work done.

Keeping the pressure constant, the volume of the gas is increase 2.1 meter cube by means of heating. So, it is a isobaric process. Now in an isobaric process, what happens? Delta W is equal to delta P dV integration P dV and in an isobaric process P is equal to constant. So, that is taken out of the integral. So, it is P v 2 minus v 1 of course, we are integrating from one to two. So, this is the initial and the final step so, it is v 2 minus v 1.

Now, P is 200 kilo Pascal's and v 2 minus v 1 is equal to 0.06 meter cube which makes it 200 into 0.06 kilojoules which is equal to 12 kilojoules. So, this is the answer to the first part. Now, for the second part, we have the volume is changed isothermally 0.1 meter cubed. See once again this is also this example also talks about the processes three processes both in both in all three cases the final volume is 0.1 meter cubed. So, I mean not exactly the same state function. So, let us look into isothermal process.

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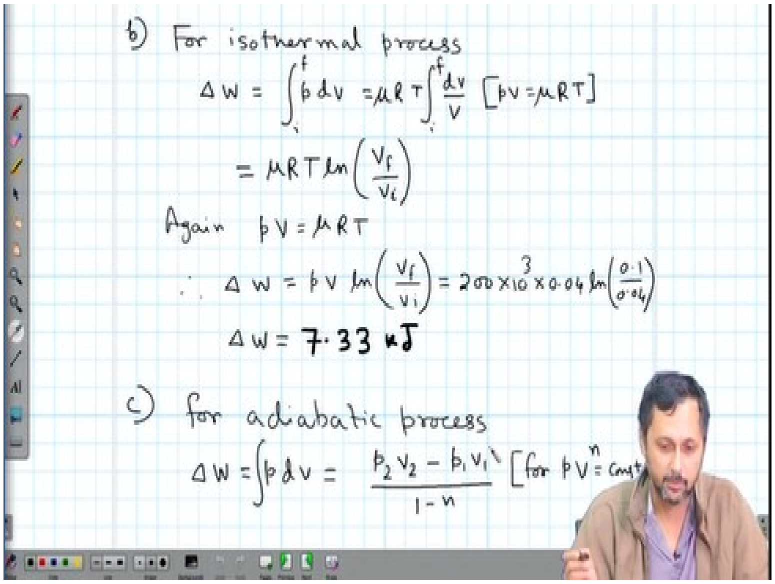

b) For isothermal process

$$\Delta W = \int_i^f p\,dv = \mu R T \int_i^f \frac{dv}{v} \quad [pv = \mu R T]$$

$$= \mu R T \ln\left(\frac{V_f}{V_i}\right)$$

Again $pV = \mu R T$

$$\therefore \Delta W = pV \ln\left(\frac{V_f}{V_i}\right) = 200 \times 10^3 \times 0.04 \ln\left(\frac{0.1}{0.04}\right)$$

$$\Delta W = 7.33 \text{ kJ}$$

c) for adiabatic process

$$\Delta W = \int p\,dv = \frac{p_2 V_2 - p_1 V_1}{1-n} \quad [\text{for } pV^n = \text{Const}$$

Now, in this isothermal process what happens? delta w is equal to i to f p d v remember p v is equal to mu RT. so, we can write p is equal to mu what T by v which is mu RT and this is an isothermal process. So, T is constant, mu is once again the number of moles i to f d v by v.

Please do not confuse between this mu and the chemical potential which we have just discussed. So, for most part we will be solved rather only maybe one or two lectures will be discussing chemical potential.

So, in other than that, mu is the number of moles that is present. So, this is mu RT log V f minus V i. And please remember this expression, this is the work done for an isothermal process by an ideal gas. If the equation of state changes, then of course, this has to be recalculated, but otherwise this is the expression. And once again, p V is equal to mu RT, we have mu RT here so, we can just substitute it with p V.

So, we have delta w is equal to p V ln V f minus V i which after simplification is 3.33 kilojoules. See the volume is changed such that the pressure volume relation is p V to the power 1.3 is equal to constant with final volume of 0.01 meter cubed. So, once again, we have the same final volume, but this time it will go through a polytroph. Now, for the polytrophic process should not call it an adiabatic actually it is a I should call it a polytrophic process.

I will correct that delta w is equal to p d v p 2 minus p v 2 p 2 v 2 minus p 1 v 1 divided by 1 by n where the processes p V to the power n is equal to constant. So, I have not proved this I will prove that maybe in one of the later classes or you can also try it yourself and see.

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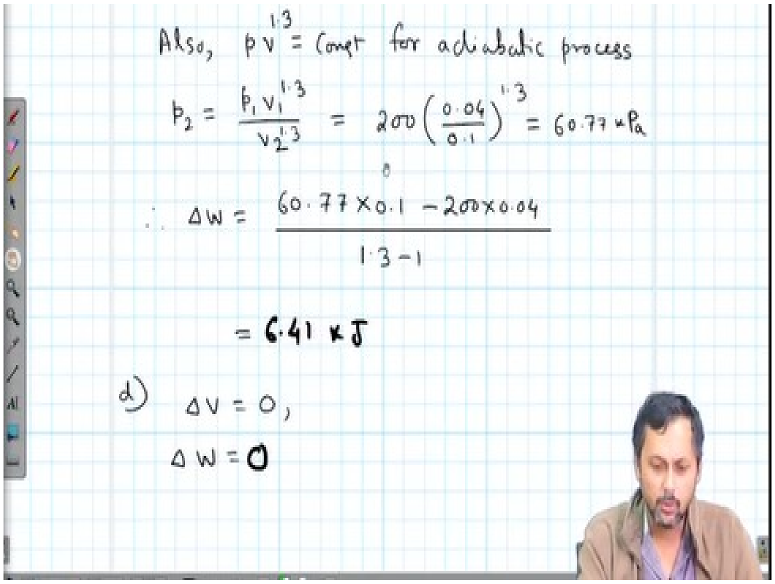

Also, $pV^{1.3} = \text{Const}$ for adiabatic process

$$p_2 = \frac{p_1 V_1^{1.3}}{V_2^{1.3}} = 200\left(\frac{0.04}{0.1}\right)^{1.3} = 60.77\,\text{kPa}$$

$$\therefore \Delta W = \frac{60.77 \times 0.1 - 200 \times 0.04}{1.3 - 1}$$

$$= 6.41\,\text{kJ}$$

d) $\Delta V = 0,$

$\Delta W = 0$

Now, putting also we have p V to the power 1 3rd is equal to constant sorry once again I should not write should be a polytrophic. So, p 2 is equal to p 1 v 1 to the power 1.3 divided by v 2 to the power 1.3 which is 200 divided into 0.04 divided by 0.1 to the power 1 3rd. And on simplification we have 60.77 kPa. So, delta w which is this minus this divided by 1 minus n ideally, it is 1 minus n. So, I am just putting n - 1 which is once again as a convention whether it is on the system or by the system.

In this case the work is done by the system as the volume is increasing. So, it is has to be positive. I think this expression comes with a minus sign. If I have 1 minus n other words it is n minus 1. I will check that. So, final answer is 6.41 kilo Joules. And for the last part, let the volume is fixed and the temperature is increases the final pressure is 400 kPa. Now in this case, because there is no volume change, d V = 0 we have d w is equal to 0. So, that is where we stop today.

We will we have to solve two more problems for this particular chapter. And also, we have to continue our discussion about the first law of thermodynamics. So, we will do that in the remaining two lectures. And also, we will talk about elastic modulus, certain systems, some certain thermodynamic system and their relationship with the specific heat and other things that will be coming in the next two lectures. Thank you.