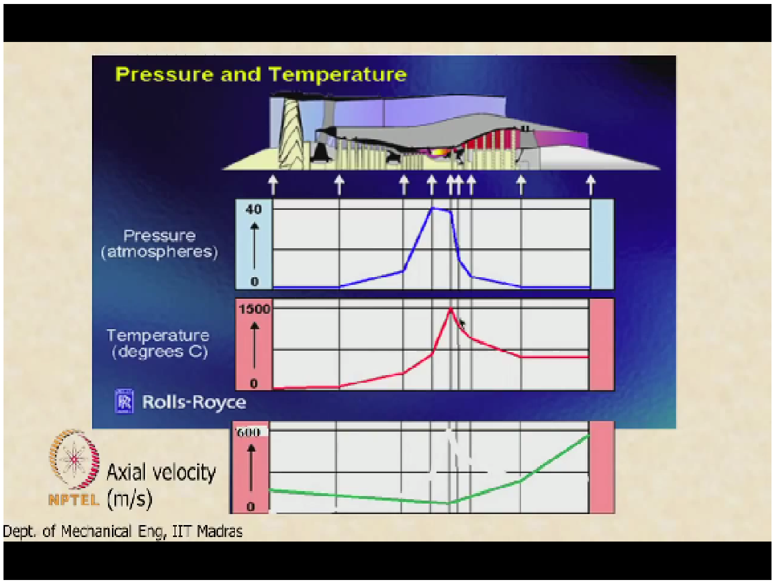
Gas Dynamics and Propulsion
Dr. Babu Viswanathan
Department of Mechanical Engineering
Indian Institute of Technology - Madras

Lecture – 02
Introduction / Fundamental Ideas

So in the last class, we were looking at the various components in the engine.

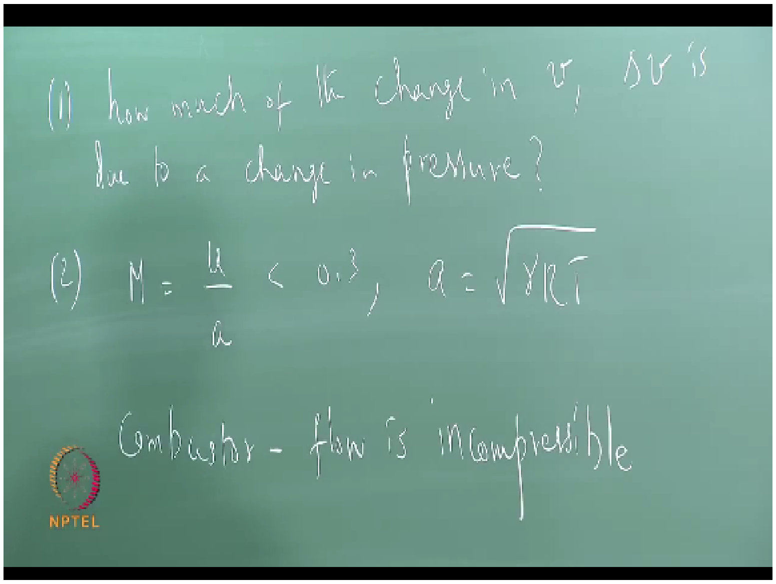
(Refer Slide Time: 00:15)



Pressure and Temperature

And we were trying to identify which component is handling compressibility flow or in which component is compressibility effect very significant and we have looked at, we used 2 criteria to decide whether compressibility effect is significant or not.

(Refer Slide Time: 00:35)



(1) how much of the change in v, Δv is due to a change in pressure?

(2) $M = \frac{u}{a} < 0.3$, $a = \sqrt{\gamma R T}$

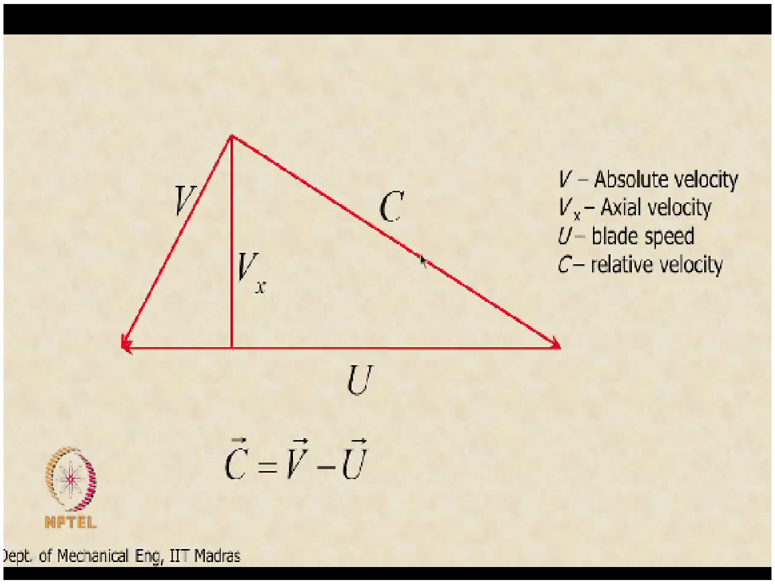
Combustor - flow is incompressible

The first one was, how much of the change in specific volume, namely delta v is due to the change in pressure, this was one condition that we used. The other one was that the Mach number which is the velocity, flow speed/speed of sound to be approximately < 0.3, that was our consideration, with the speed of sound being given as square root of gamma RT and based on this condition, we decided that the combustor, essentially in the combustor, flow is incompressible.

We were looking at the compressor and the turbine part of the engine, the fan, the compressor and the turbine part of the engine and based on the axial velocity, we see that the Mach number based on axial velocity is going to be relatively low because the temperature keeps increasing and as the temperature increases, the speed of sound also increases but the axial velocity more or less is remaining constant or decreasing.

So which means that the Mach number is going to decrease, so it would suggest based on criterion 2, that in the compressor and turbine, the flow should be incompressible. However, based on criterion one and based on this curve that we have here, the increase in pressure and the increase in temperature, we are able to see that is going to be the significant (()) (02:21) change in density or specific volume due to pressure which seems to suggest that compressibility effect is significant. So the second one is saying compressibility effect may not be significant. First one says compressibility effect is significant.

(Refer Slide Time: 02:34)

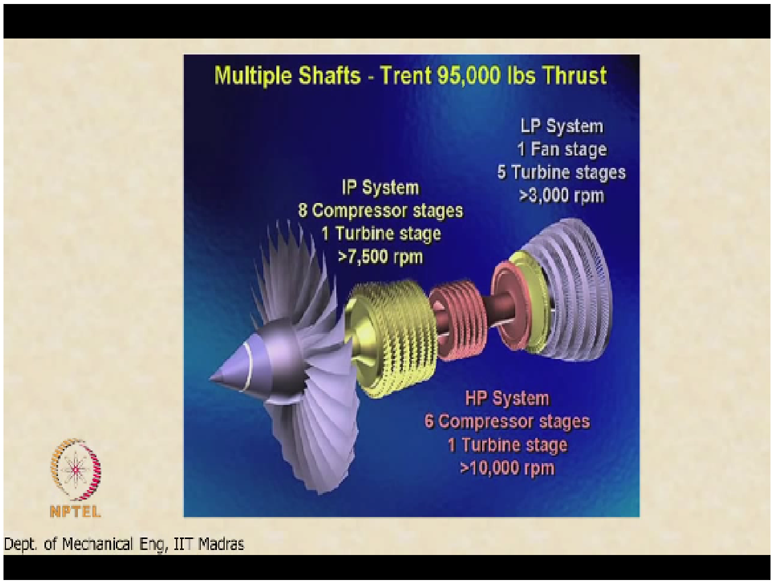


V – Absolute velocity
V_x – Axial velocity
U – blade speed
C – relative velocity

$$\vec{C}=\vec{V}-\vec{U}$$

This disagreement is due to the fact that we actually use only the axial velocity and in the case of turbo-machinery, we need to use relative velocity or vector difference of the absolute velocity and the blade velocity which is the relative velocity, is quite high in these cases. In fact, in the fan blade, the flow is actually subsonic at the root of the blade and is actually supersonic at the tip of the blade, that will be based on relative velocity, the speed is subsonic at the root and supersonic at the tip which is why these are called transonic fan blades, okay.

(Refer Slide Time: 03:11)



Multiple Shafts - Trent 95,000 lbs Thrust

LP System
1 Fan stage
5 Turbine stages
>3,000 rpm

IP System
8 Compressor stages
1 Turbine stage
>7,500 rpm

HP System
6 Compressor stages
1 Turbine stage
>10,000 rpm

Even in the other parts of the engine, we can see the RPM. We can see that for example, the fan spins at an RPM of 3000 and there is a huge variation in the Mach number from root to tip and the next system which is the intermediate pressure system, spins at a speed of about 7500 RPM and so if you calculate the velocity, relative velocity based on the speed, for this case also, the Mach number will be more than 0.3, right and the high-pressure system spins at an rpm of around 10,000 and we can see that the blade speed is even higher for that.

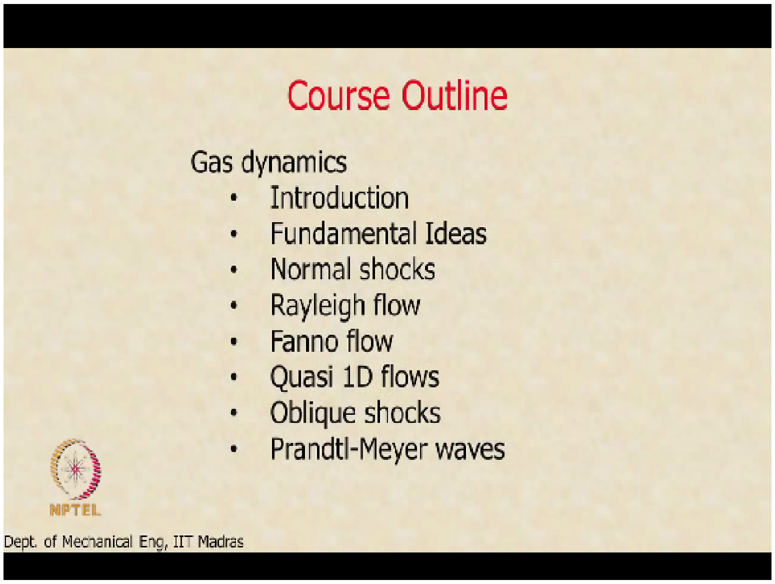
So which means that based on relative velocity, both the criteria, based on relative velocity, second criterion says that the flow, compressibility effect is going to be significant. First criterion also states the same thing. So there is really no disagreement. So when it comes to applying this criterion for turbo-machinery, we must be very careful and use the correct velocity which is the relative velocity for these cases.

In the nozzle which is located over here as we can see, the velocity increases and the temperature also decreases, although it is not clearly visible in this scale, the temperature decreases since the fluid undergoes an expansion process. So the Mach number increases in the nozzle to reasonably high subsonic values perhaps even Mach number 1 due to 2 reasons, one is the increase in the velocity and 2, the decrease in the speed of sound due to the decreasing temperature.

So both these effects together cause the Mach number to increase to values probably equal to the speed of sound at the exit of the nozzle. So this tells us that if we go back to this, so this tells us that the flow or compressibility effect is minimal in the combustor but compressibility effect is significant in the fan and the compressor and compressibility effect is also significant in the turbine and the nozzle, right.

Except for the combustor, compressibility effect is significant in the fan, compressor, turbine and nozzle which is why we are going to study gas dynamics first because compressibility effects are significant in almost all components except the combustor, that is why we are going to study, start the course with gas dynamics, okay.

(Refer Slide Time: 05:31)



Course Outline

Gas dynamics

- Introduction
- Fundamental Ideas
- Normal shocks
- Rayleigh flow
- Fanno flow
- Quasi 1D flows
- Oblique shocks
- Prandtl-Meyer waves

Dept. of Mechanical Eng, IIT Madras

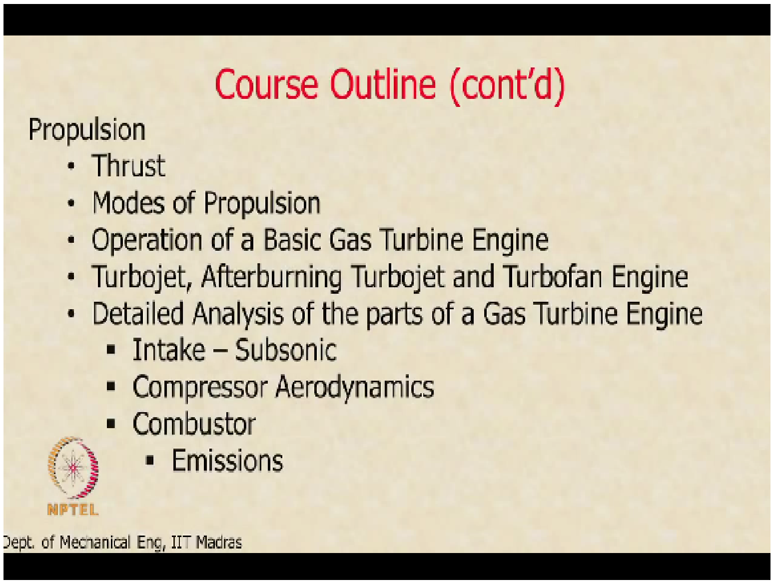
So we will first take a look at the introduction which we have already done. The introduction basically pertains to how do we assess compressibility whether the compressibility is significant or not in a flow that we have already done and we then move on to fundamental ideas, right and then normal shocks. We will look at Rayleigh flow, flow with heat addition.

So in this particular chapter, we will show that if compressibility effects are not significant and if you add heat to a flow and the pressure remains constant, if compressibility effect is significant and you add heat to such a flow, then the pressure also increases along with the temperature, right. We will show that in this case this is followed by Fanno flow where we have flow with friction which is also very important and occurs in many practical applications.

Then we will look at Quasi 1-dimensional flows. The first 2 categories, the first 3 flows, normal shock, Rayleigh flow and Fanno flow would be 1D flow. Then we go to Quasi 1-dimensional flow where we allow for some variation in the other direction also. This would be typically flow-through nozzles, flow through blade passages and so on. We then follow it up with study of Oblique shocks which also occurs in many turbo-machinery applications like the ones that we are looking at.

This is followed by Prandtl-Meyer waves. So Oblique shock is basically a compression wave. The Prandtl-Meyer wave can be both compression and expansion based but it is an isotropic process in contrast to the Oblique shock which is not an isotropic process. So we will discuss these things first.

(Refer Slide Time: 07:05)



Course Outline (cont'd)

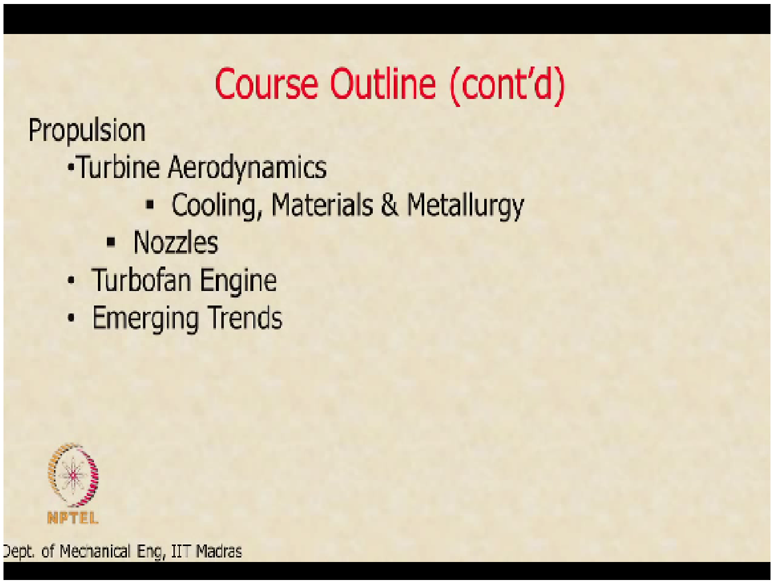
Propulsion
- Thrust
- Modes of Propulsion
- Operation of a Basic Gas Turbine Engine
- Turbojet, Afterburning Turbojet and Turbofan Engine
- Detailed Analysis of the parts of a Gas Turbine Engine
  - Intake – Subsonic
  - Compressor Aerodynamics
  - Combustor
    - Emissions

Dept. of Mechanical Eng, IIT Madras

This will be followed by our discussion on propulsion. So we start with the concept of thrust. We then look at different modes of propulsion. Basically, we will look at propeller versus jet as different modes of propulsion. Then we will look at the operation of a basic gas-turbine engine, right. This will be followed by a discussion of turbojet, the afterburning turbojet and the turbofan engine.

So these are all basically derivatives of the turbojet engine and we will look at the different parts of the gas-turbine engine, namely the intake, the compressor, the combustor and in the combustor, we will look at emissions particularly.

(Refer Slide Time: 07:43)



Course Outline (cont'd)

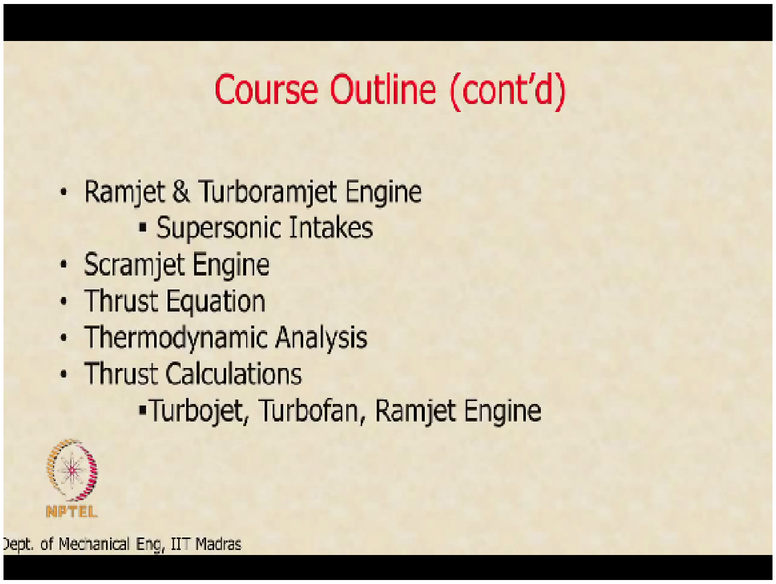
Propulsion
- Turbine Aerodynamics
    - Cooling, Materials & Metallurgy
  - Nozzles
- Turbofan Engine
- Emerging Trends

Dept. of Mechanical Eng, IIT Madras

Then we will look at turbine in which the cooling materials and metallurgy is very important. Unless you cool the blades, you will not be able to handle the combustor, the post-combustion gases which are coming at very high temperatures. So we need to do special things for the turbine blades to make them operate in such a harsh environment.

Then we look at nozzles and then we move on to turbofan engine where the additional component is the fan and the fan nozzle. We will discuss that. We will look at emerging trends in the industry, what is the latest and the greatest in the industry in terms of propulsion technology, what are the concepts that are being pursued.

(Refer Slide Time: 08:24)



Course Outline (cont'd)

- Ramjet & Turboramjet Engine
    - Supersonic Intakes
- Scramjet Engine
- Thrust Equation
- Thermodynamic Analysis
- Thrust Calculations
    - Turbojet, Turbofan, Ramjet Engine

Dept. of Mechanical Eng, IIT Madras

We will discuss that, then we will move onto the Ramjet and Turboramjet engine. Now these are, the ramjet engine for example is an engine without any moving parts which means that the intake plays a very critical role in compressing the air. If you remember, we said that 2 things have to be done in Jet propulsion, right. One is increasingly the enthalpy and then converting the enthalpy to thrust.

Increasing the enthalpy required has to increase the pressure and the temperature. Now in a ramjet, the pressure is increased not by using a compressor but by decelerating the air because it is moving at such high speeds, if you decelerate the air properly, that can actually translate into a pressure rise. So it operates without any compressor which means you do not need a turbine also, right but the intake has to be designed extremely carefully to make sure that you are able to get the kind of pressure rise that you are looking for.

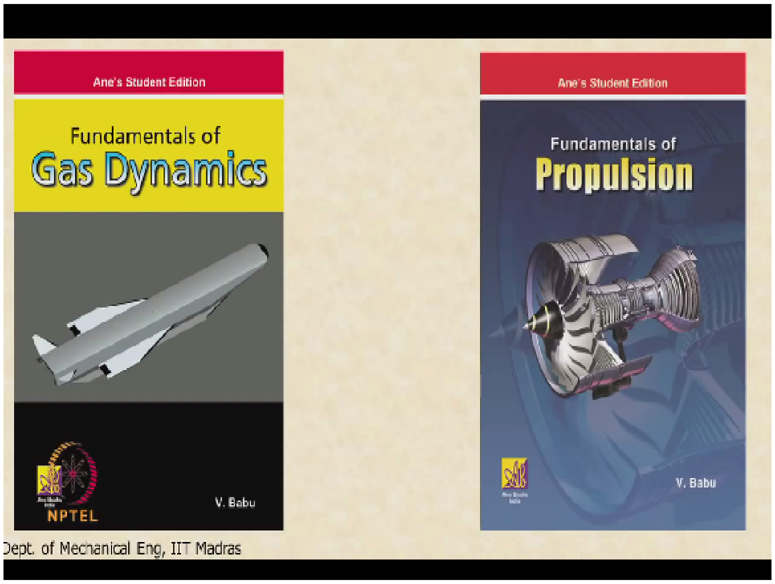
So that is why we have identified supersonic intakes as a special topic for discussion. We will take a look at a scramjet engine, just a brief idea about the scramjet engine, some of the issues involved in scramjet engine and so on. Then we will go to the thrust equation, we will drive the thrust equation for the various engines, right. The idea is to calculate thrust produced by the engine and thrust specific fuel consumption. How much fuel does it require to produce? Let us say 1 kilonewton of thrust and those are the 2 quantities which are of interest.

So we will do thermodynamic analysis, we will develop an equation for calculating thrust and then we will actually use the equation to calculate the thrust produced by a turbojet engine, turbofan engines and ramjet engines, okay. In the first 2 cases, we will take engines which are actually in service today, actual engines in service and we will do thrust calculation for those engines so that this is not some conceptual engine that we are working on but actual production engines.

And we will compare the result from a thrust calculation with what the manufacturer reports. The manufacturers may report that this engine, if you remember I showed the Rolls-Royce engine. They said this produces 250 kilonewtons of thrust for example. We will actually do a calculation of that engine and see whether it produces 250 kilonewtons or not and we will write to compare some of the other performance matrix of that engine with what the manufacturer reports, okay.

Broadly speaking that is what we are going to do in the course. So we start with gas dynamics, the importance of gas dynamics is brought out clearly. So now we will do gas dynamics then move on to propulsion, okay. Any questions?

(Refer Slide Time: 10:47)



Ane's Student Edition

Fundamentals of
Gas Dynamics

NPTEL

V. Babu

Ane's Student Edition

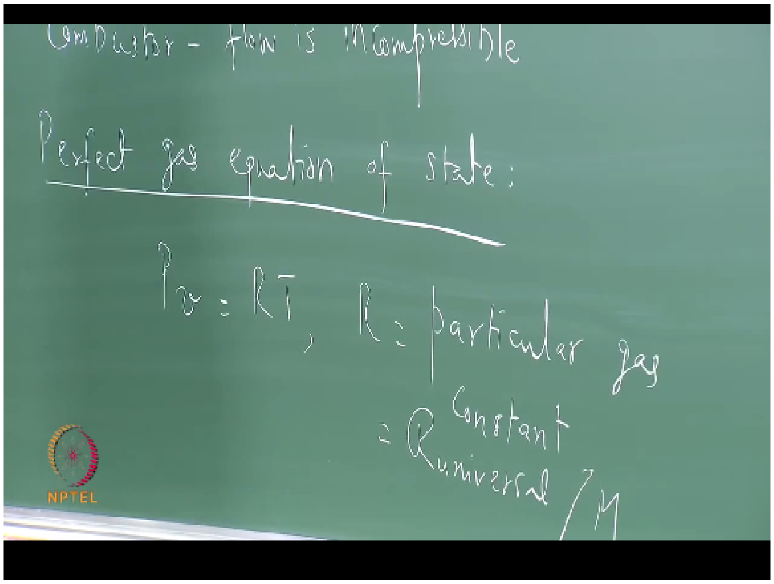
Fundamentals of
Propulsion

V. Babu

Dept. of Mechanical Eng, IIT Madras

We will follow 2 textbooks, Fundamentals of Gas Dynamics and Fundamental of propulsion. The exercise problems will be taken from the book but the examples will also be taken from the book. So we will basically teach from these 2 textbooks, okay. So we have already discussed the notion of a compressibility.

(Refer Slide Time: 11:24)



Combustor - flow is incompressible

Perfect gas equation of state:

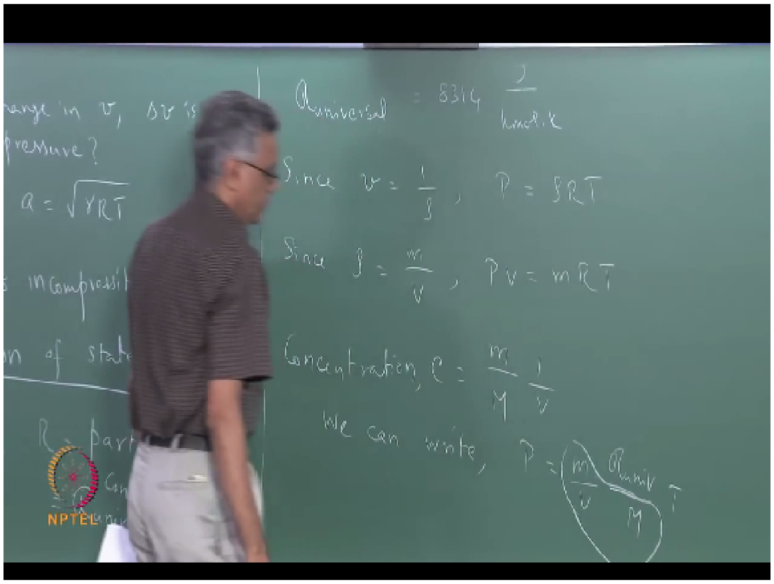
$Pv = RT$, R = particular gas constant

$= R_{universal}/M$

We now move onto the next topic which is perfect gas equation of state. The equation of state for a perfect gas can be written as Pv=RT where P is the pressure and v is the specific volume. Now this gas constant R is actually the particular gas constant and this is equal to the universal gas constant/the molecule weight of the gas, this is not the universal gas constant but it is the particular gas constant which is universal gas constant/the molecule weight of the gas, okay.

For air for example, we will take the molecular weight to be 28.8 kilogram per kilomole. P here is the temperature. In the later part of the course, we will actually refer to this temperature as the static temperature, okay. For now, temperature is sufficient and pressure is also sufficient but as we go along, we will start calling the pressure, static pressure. We will start calling the temperature, static temperature, okay and I will make that definition clear as we go along.

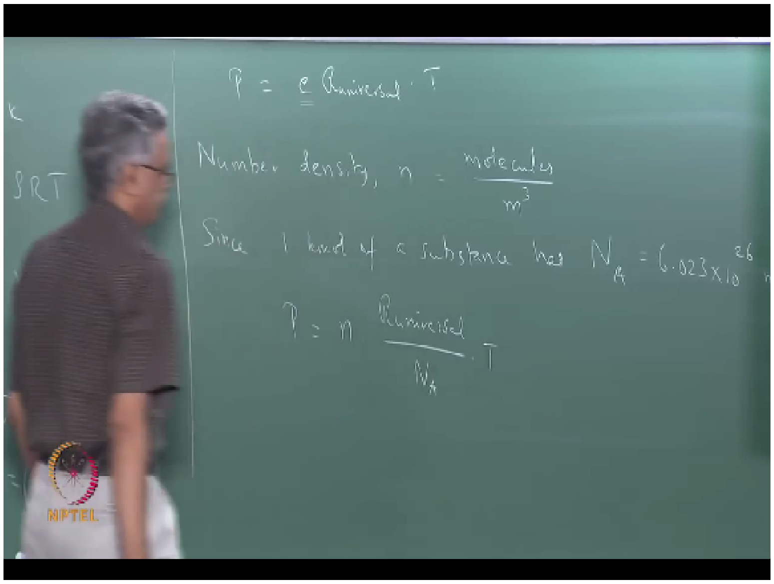
(Refer Slide Time: 12:57)



So R universal of course is 8314 Kmol Kelvin. This equation can be written in many different forms and if you use the fact that the specific volume is the reciprocal of the mass density, we can write P=rho*R*T, right where the rho is the mass density in units of kg per meter cube or if I make use of the fact that the mass density rho itself is equal to the mass of the gas/the volume that it occupies, I can write this equation of state as Pv=m*R*T.

Now the concentration C, it can also be written in terms of concentration. So concentration C is defined as the mass of the gas/the molecular weight per unit volume. So this is in units of kilomole per cubic metre and in terms of the concentration, we can write P=m... and if you recognise the fact that M/molecule weight, this quantity is = C.

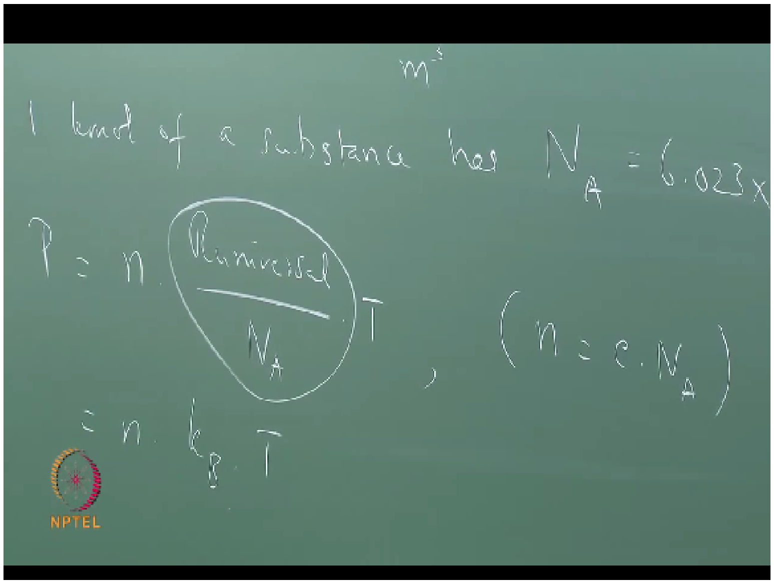
(Refer Slide Time: 14:50)



I can write this equation as P=CR universal*T. It is also possible to replace the concentration, it is quite useful in certain types of applications to write this, not in terms of concentration but in terms of something called a number density, okay. Number density N is defined like this. M is actually in units of, it tracts molecules per unit volume and since 1 kilomole of a substance as how many molecules?

Avogadro number of molecules, right. So since 1 kilomole of a substance Avogadro number of molecules which is nothing but 6.023*10 to the 26 molecules as Avogadro number of molecules. I can actually rewrite this equation as P= n*R universal/Na*T. So I have replaced the concentration with, let me write it like this. So n, the quantity n=C*N Avogadro.

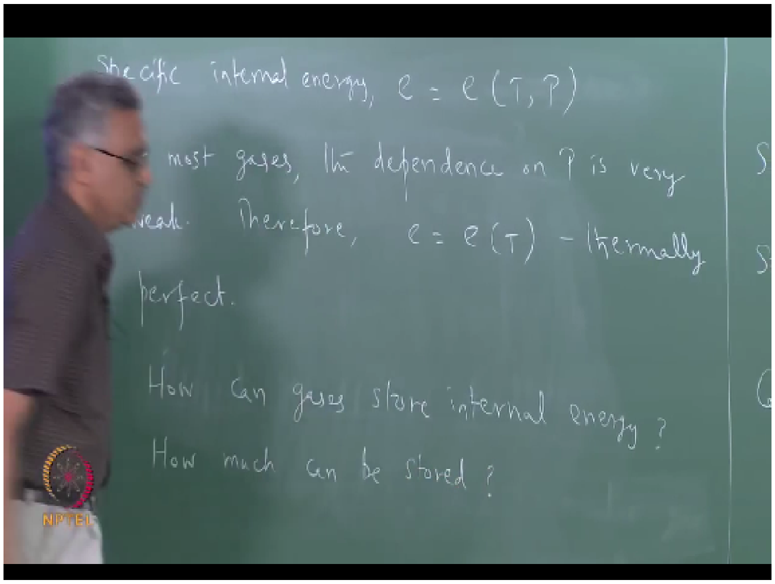
(Refer Slide Time: 16:51)



Now this quantity here is nothing but the Boltzmann's constant. So I can write this as n*kB*T. So P=n*kB*T is a form of the perfect gas equation which is very useful in many applications including flow of plasmas and so on. Now we need to know one more thing before we can proceed. So we know how to relate the pressure, temperature and specific volume of the perfect gas.

We also need to know how to calculate changes in internal energy of a perfect gas as it undergoes certain flow processes. Let us see how we do that. As we discussed earlier, the internal energy of a perfect gas is also a function of temperature and pressure. Let us see how this works. Just like we said that the specific volume of a perfect gas is a function of temperature and pressure, v=v of T, P.

(Refer Slide Time: 17:49)



Specific internal energy, $e = e(T, P)$

most gases, the dependence on P is very weak. Therefore, $e = e(T)$ - thermally perfect.

How can gases store internal energy?

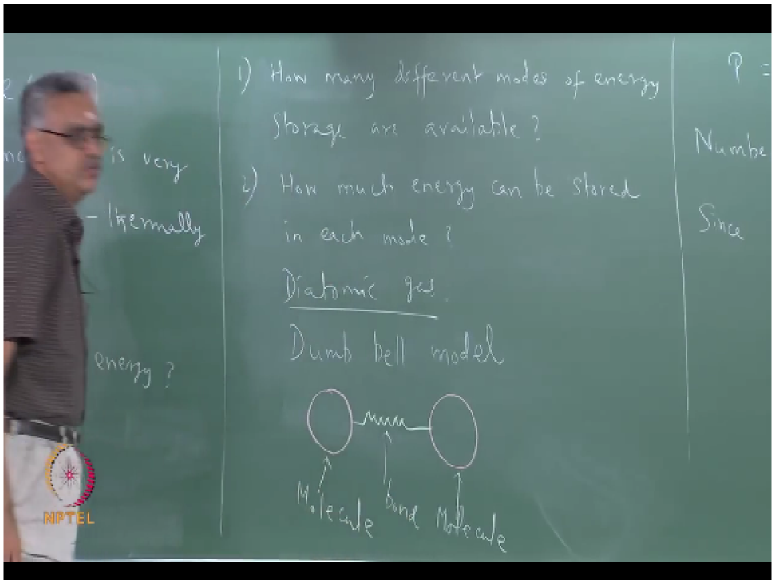
How much can be stored?

We can also say that the specific internal energy which we will denote as e, is also a function of T and P, where T is the temperature and P is the pressure. Now for most gases, it turns out that the dependants on P is very weak which means that the internal energy is a strong function of temperature but a very weak function of pressure. So this means that I can write the internal energy as a function only of temperature.

For all practical purposes, I can ignore the dependence on pressure and say that it is a function only of temperature, right. Such gases are called thermally perfect gases. So gases for which the internal energy is a function only of temperature are called thermally perfect gases. Now depending upon the nature of this function, we can make a further idealisation which is what we are going to do next. So now we are going to examine how the internal energy depends on temperature.

What sort of a function is it? Is it a linear function, polynomial? quadratic. How does it depend on are more complicated function? So that is what we are going to look at next. Okay. Now when we do that, we need to look at 2 things, okay. How can... store internal energy and how much... So these are the 2 things that we need to know. How do actually gases store internal energy? So gases store internal energy in different modes. So the question that we wish to answer is the following.

(Refer Slide Time: 20:18)



1) How many different modes of energy storage are available?

2) How much energy can be stored in each mode?

Diatomic gas

Dumb bell model

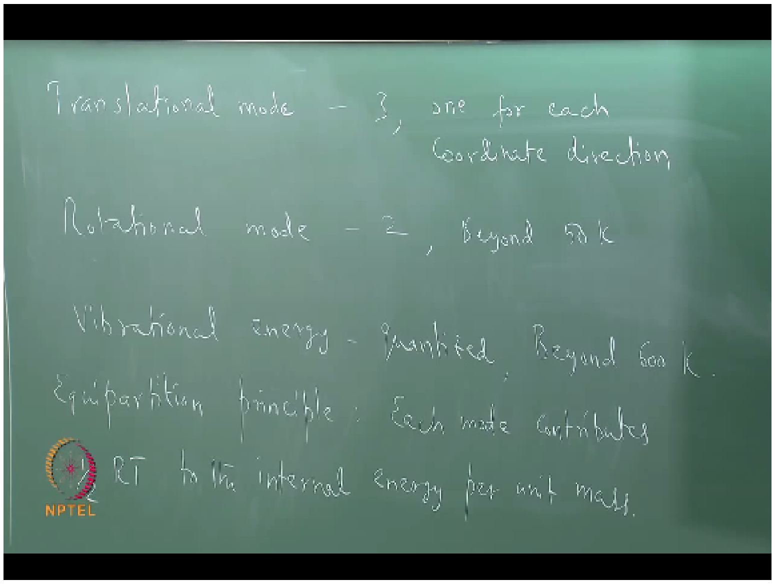
If I rewrite this, I can write the first question as how many different modes of energy storage are available and questionable number 2, How much can be stored in each mode? The answer to the first question depends upon the nature of the gas. Let us say that we have a diatomic gas. This is easy to visualise actually than a monatomic gas, right. Let us say that we have a diatomic gas, right. Diatomic gas can be represented or depicted using the so-called dumbbell model, right.

We have all seen this exercise equipment dumbbell. So this is used to represent diatomic gas. So let us say that we have, this is 1 molecule, this is another molecule and the 2 are connected by through bonds, okay. So this is 1 molecule, this is another molecule and this is a bond which connects the 2 molecules. This is called the dumbbell model, okay. So if you think about the diatomic gas, let us say that it is at a temperature of 0 Kelvin.

If it is at a temperature of 0 Kelvin, no internal energy is stored in the molecules. It is at a state of 0 energy. Let us say that we slightly raise the temperature of the gas. The molecules, what do they do? The molecules begin to move, right. They begin to move with a translational kinetic energy. That is what happens first. So what does the first mode that we are talking about, the first mode in which the molecules can take up energy is the translational mode, right.

So let us look at translational modes. Let us write down. So the first question is how many modes are available. So we are going to list out the modes that are available for storing energy by a molecule. The first mode as we said is the translational mode, right.

(Refer Slide Time: 23:04)



Translational mode – 3, one for each Coordinate direction

Rotational mode – 2, Beyond 50 K

Vibrational energy – Quantized, Beyond 600 K.

Equipartition principle: Each mode contributes $\frac{1}{2}$ RT to the internal energy per unit mass.

So translational mode. Now when you say a translational mode, what exactly do I mean by that? Because when a gas molecule absorbs this energy, it is not constrained to move only in 1 coordinate direction. It can move this way, it can move in this coordinate direction, it can also move in this coordinate direction. That means it can acquire translational kinetic energy in each one of these 3 coordinate directions, right.

So translational mode is the name of the mode and within translational mode, it can actually have 3 in number. So it can store translational mode in 3 in number, one for each coordinate direction. So we have heated the gas now and as we keep heating the gas, it absorbs the energy and the molecules begin to move around with translational kinetic energy. Now as I keep doing this, the molecules are moving and when I reach a temperature of about 15, till now the molecules are only moving with translational energy.

When I reach a temperature of let us say 50 Kelvin or so in most cases, then these molecules because the energy is too much, the temperature is too much, so the molecules in addition to moving around, also begin to, they begin to rotate. Now till 50 Kelvin, the molecules are only translating. Now as you keep adding energy beyond 50, the molecules also slowly begin to spin like this, right.

So now the molecules can also absorb the energy through rotational kinetic energy, right, that is the next mode that comes into play. 50 Kelvin is high enough for the rotational mode to become excited. This is what it is technically called, the rotational modes become excited. So now we have rotational mode also in which the molecules can store energy. Now how many rotational modes can be there, right.

One would think that again 3 rotational modes should be there because the molecules can spin like this, right. So you have a molecule, it can spin like this, the molecules can also spin about this axis and the molecules can spin about this axis but if you look at the nature of the molecule, when it spins like this, it can have considerable energy. Now if it spins like this also, it can have considerable energy.

But when the molecules spin about their own common axis like this, the energy is very small because the moment of inertia of the molecule is very small. So effectively rotation gives only 2 modes. When the molecules rotate like this, they can have considerable energy or if they rotate like this, they can have considerable energy. Not when they rotate like this because the moment of inertia is very small as you know rotational kinetic energy is 1/2I omega square.

So I is very small, so the amount of energy that can be stored in this way is very small. So rotation effectively gives rise to only 2 modes. This is beyond 50 Kelvin, right, beyond about approximately 50 Kelvin for most diatomic gases. Now let us say that we keep increasing the temperature, we keep increasing the temperature. Now molecules are translating, they are also now rotating in both the directions.

When you begin to exceed 600 Kelvin, the temperature is high enough that now this bond which actually acts like a spring, begins to vibrate. Now the vibrational mode begins to get excited, right. So in addition to moving and rotating, now it can also vibrate like this. So now it can store energy in the form of vibrational energy, right. So that is the next mode that comes into play. Now vibrational energy we cannot really count because the energy levels of the vibrational energy are quantised.

So depending upon how many levels we can excite, say if we go to 700 Kelvin, probably 10 vibrational levels can be excited. If you go to 1000 Kelvin, may be 15. When you go to 2000, all the vibrational levels that are possible for a diatomic molecule will get fully excited, right. So this is quantised, so we cannot really give this a priority and this happens beyond 600 Kelvin. So you can see that the internal energy of the molecules for the kind of temperature ranges that we are looking at is going to have translation modes 3 in number, rotational modes 2 in number and vibrational modes.

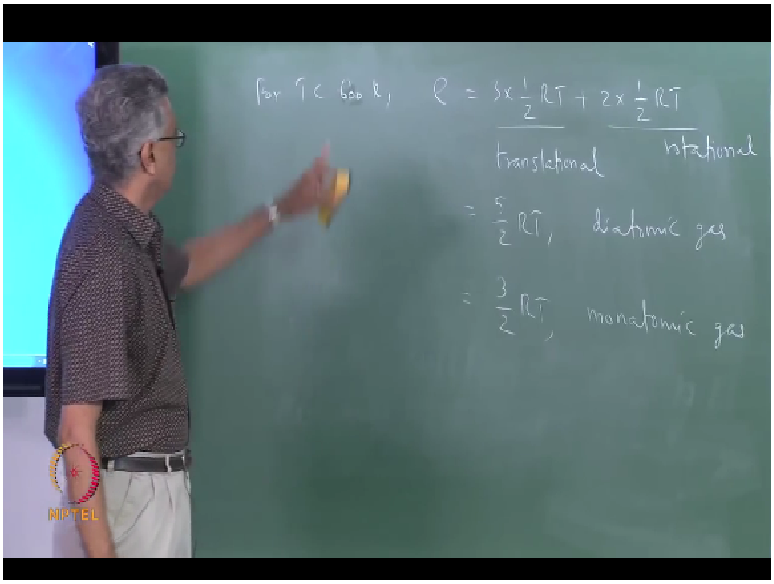
Vibrational modes, we will not actually consider for the sake of the course because this allows us to make certain simplifications, okay. So this tells us the number of modes in which the energy can be stored. So that answers the first question. Now we are going to look at the second question, okay. Second question can be answered by using equipartition principle. Equipartition principle comes from classical theory and it is not entirely correct but it is good enough for our purposes.

Equipartition principle states that each mode contributes 1/2RT to the internal energy per unit mass, okay. Actually we said that these energy levels are quantised. In reality, these energy levels are also quantised. These are also quantised but the spacing between the levels are so small that for all intents and purposes, the quantisation is not visible. So we essential assume it to be continuous and use classical theory for describing this, okay.

In reality, these are also quantised. In fact, when people realised that higher temperatures, they were not able to account for this energy that was one of the most important things that actually brought out the birth of quantum mechanics, when somethings could not be explained using classical theory, this being one of that. This was the beginning of quantum mechanics, that was when people realised that we cannot store energy continuously, that it is quantised, right.

So we will not go into this part of it, we will try to stay in this part of this and we will use actually equipartition theory to calculate our internal energy. So this answers our second question. First question, how many modes, we have now. Second question, how much can be stored per mode, that is answered by this.

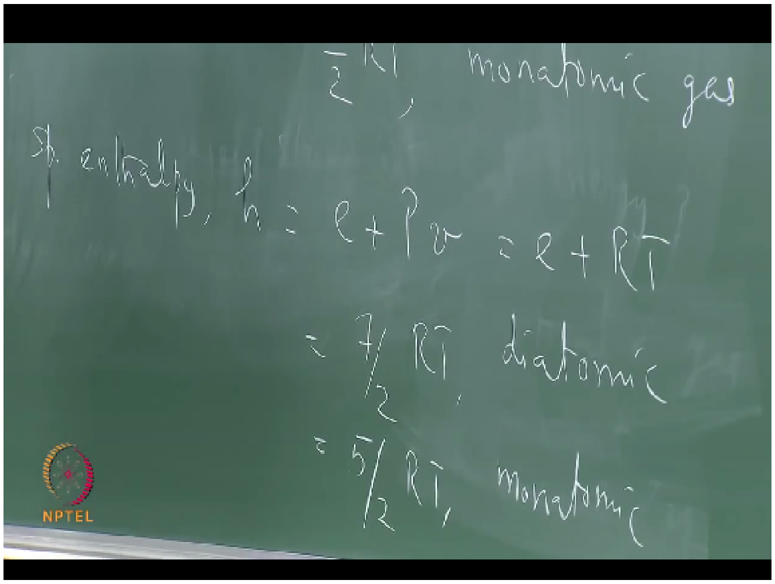
(Refer Slide Time: 30:57)



So if we stay at temperatures below 600 Kelvin or so, for temperature < 600 Kelvin, I can say that e, the specific internal energy for a diatomic gas, for a diatomic gas, it is going to have 5 degrees of freedom. So I am going to have 3*1/2RT from translational mode +2*1/2RT from rotational mode. So this is translation mode and this is rotational. So this is = 5/2RT for a diatomic gas, right.

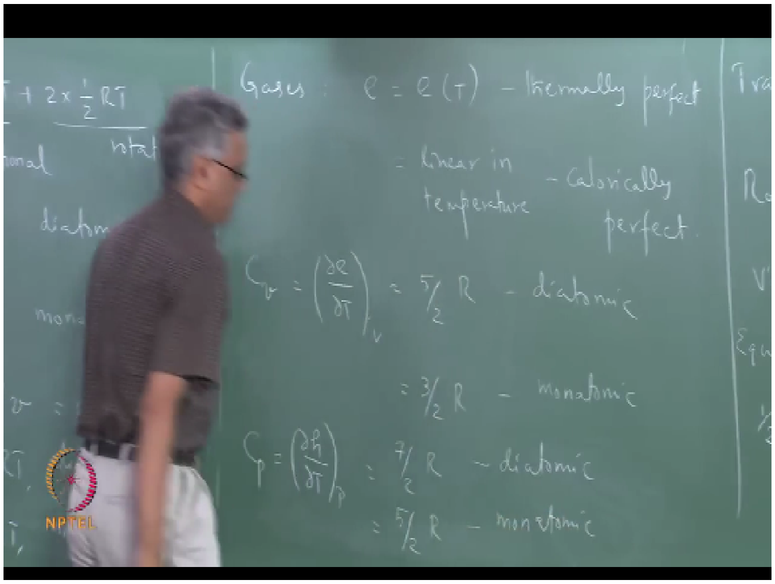
Now if you think about a monatomic gas, we can easily see that a monatomic gas in which these things are absent, will have only kinetic energy, right. We will have only kinetic energy, there will be no rotational or vibrational energy. So we can easily write down that this is going to be 3 halves, so 3 modes of translational kinetic energy. So far a monatomic gas, e is going to be 3/2RT, right. So that is the internal energy.

(Refer Slide Time: 32:28)



The specific enthalpy as we know h is nothing but e+Pv and since the gas obeys perfect gas equation of state, I can write this as e+RT. so the specific enthalpy of a diatomic gas is going to be 5/2RT+RT which is nothing but 7/2RT and 5/2RT for a monatomic gas.

(Refer Slide Time: 33:34)

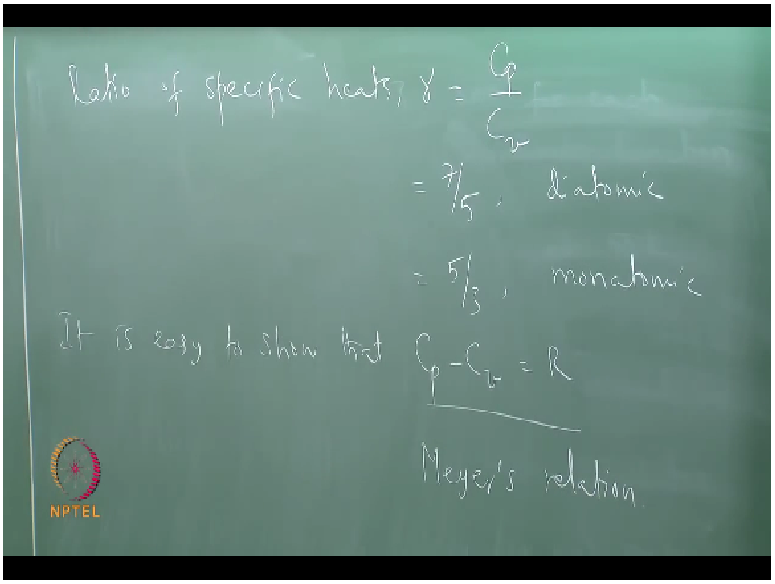


So if you remember we said that for gases for which the internal energy is a function of temperature only, these are called thermally perfect gases and we can see from here that not only is the internal energy a function of temperature only, it is also a linear function of temperature as you can see. Internal energy is a linear function of temperature. So such gases are called calorically perfect also, okay.

So if e is linear in temperature and these are called, such gases are called calorically perfect and in our course, we will assume the gases to be caloric perfect throughout that allows us to calculate the internal energy using such formulas. So having calculated the specific internal energy and the specific enthalpy, I can write Cv which is nothing but partial e partial T or constant volume is also, okay, right.

So this is going to be nothing but 5/2R for a diatomic gas and this is going to be = 3/2R for a monatomic gas and similarly for Cp also, so I can write Cp which is nothing but partial h partial T, this is = 7/2R for a diatomic gas and is = 5/2R for a monatomic gas which then allows me to calculate or determine the ratio of specific heats of the gases which is a very important quantity in gas dynamics.

(Refer Slide Time: 36:08)



Ratio of specific heats, $\gamma = \frac{C_p}{C_v}$

$= 7/5$, diatomic

$= 5/3$, monatomic

It is easy to show that $\underline{C_p - C_v = R}$

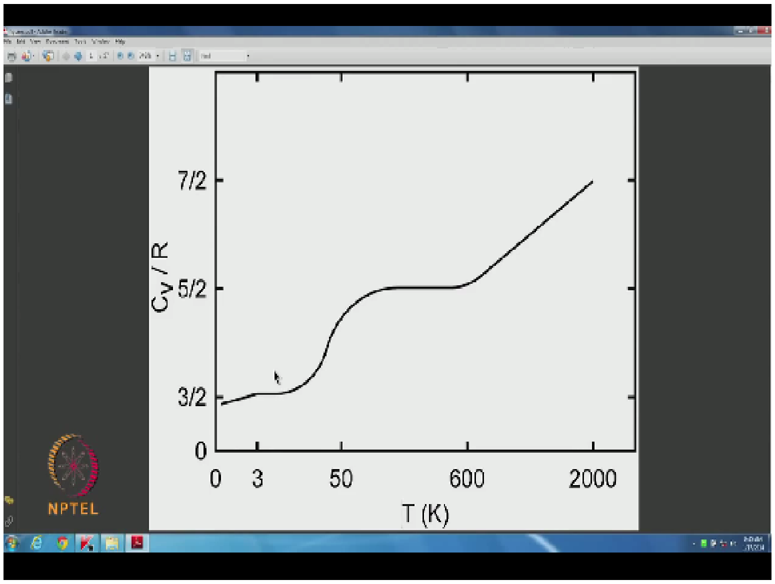
Meyer's relation

So the ratio of specific heats gamma, for a diatomic gas, ratios are, for any gas, the ratio of specific heat is nothing but Cp/Cv and if you use these expressions for Cp and Cv, we have that Cp/Cv for a diatomic gas is 7/2 and it is = 5/3 for a monatomic gas. **“Professor - student conversation starts**” 7/5. I am sorry it is 7/5, thank you, **“Professor - student conversation ends”**

7/5th for a diatomic gas and 5/3rds for a monatomic gas and since we use air as the working substance in all our calculations, we will assume gamma to be 1.4 throughout. 7/5th for most diatomic gases actually, it is quite a good approximation, we can use that quite well. It is also easy to show from this relationships, Cp-Cv=R which is the so called Meyer's relation, okay. Any questions?

So the variation of Cp and Cv with temperature can be seen from here. Let us take a look at that.

(Refer Slide Time: 37:52)



So here you are looking at variation of Cp, I am sorry Cv/R with temperature and we can see that initially the translational mode gets excited and the amount of energy that we can store increases until it reaches 3/2, right. So that corresponds to 3 degrees of translational mode. So it becomes 3/2 at about temperatures around 3 Kelvin for a gas. So at about 3 Kelvin, the translational mode is fully excited.

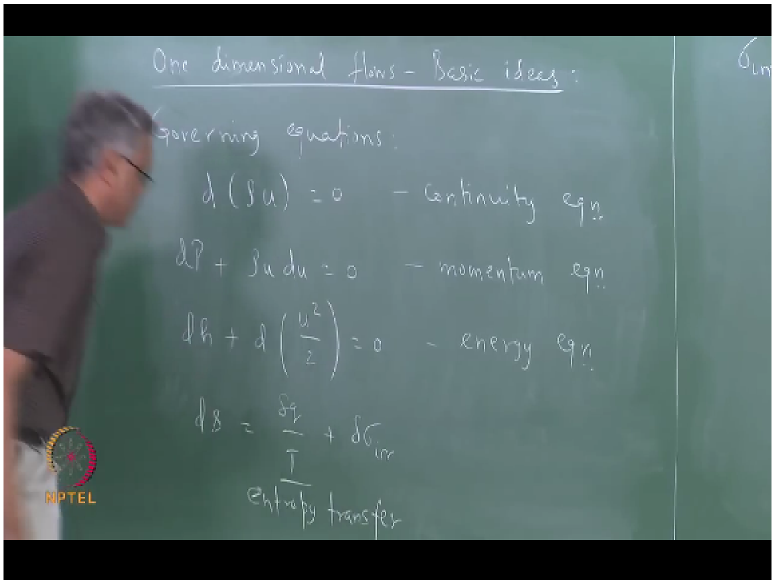
Then as we keep increasing the temperature, it remains at 3/2 and then it begins to increase as the rotational modes begin to get excited and once we reached temperatures beyond 50 Kelvin, the amount of energy that is stored in rotational mode is also reaching a maximum. So now the molecules are rotating and they are with the highest possible kinetic energies and then it reaches till about 600 Kelvin.

You can see that Cv/R remains constant at 5/2. Now once we go beyond 600, we can see that the energy that can be stored in vibrational modes begins to increase and the curve continues to increase this way. Then as we keep going, additional modes of energy like electronic modes become available for the gas to store the energy in. But we will stay in this range of temperature about 50 to 600 Kelvin where the Cv/R is constant and is = 5/2R.

So the calorically perfect assumption is valid in this region and that is the region in which we will stay mostly, okay. Even if the temperatures become high for the purposes of this course, we can essentially assume the Cv to be constant and we can do calculations that way or use slightly different values for combustion gases which can be at higher temperature. Later on when we do calculations, engine calculations, the gases that come out of the combustor are at higher temperature.

So Cv is not 5, Cv/R is not 5/2 for that gas. We will assume a slightly different value for that and do our calculations, okay. It is a good enough approximation, okay. So that completes our introduction, introductory ideas in the gas dynamics. What we will do next is look at some basic concepts. One-dimensional flow basic concepts, let us do that.

(Refer Slide Time: 40:26)



One dimensional flows - Basic ideas:

Governing equations:

$d(\rho u) = 0$ - Continuity eqn.

$dP + \rho u\, du = 0$ - momentum eqn.

$dh + d\left(\frac{u^2}{2}\right) = 0$ - energy eqn.

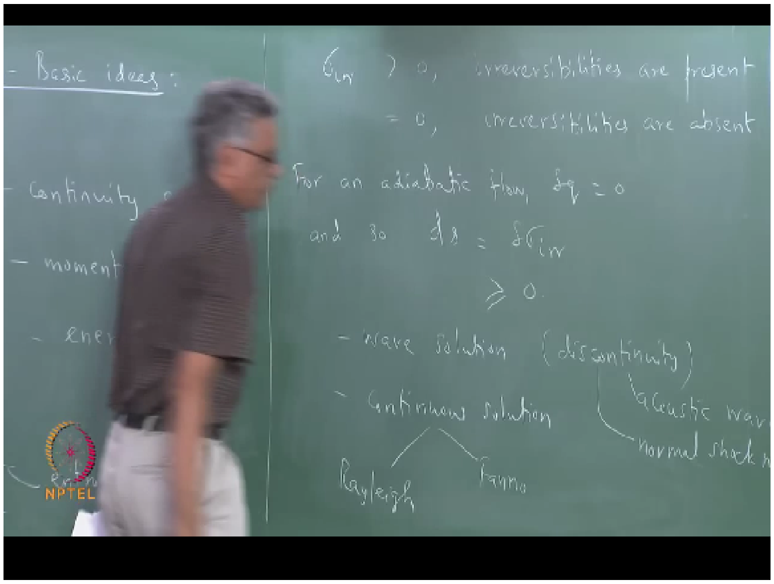
$$ds = \underbrace{\frac{\delta q}{T}}_{\text{entropy transfer}} + \delta\sigma_{irr}$$

So we start with 1-dimensional flows. So the governing equations for 1-dimensional compressible flow, 4 governing equations are available. First one is the mass conservation equation which says that, so this is the so-called continuity equation. Rho is the mass density and u the velocity. There is only one velocity component because we are looking at a 1-dimensional flow, right.

Now the momentum equation can be written like this, dP+rho udu=0, this is the moment equation, P is the pressure and the energy equation looks like this, dh+d of ... 2=0, this is the energy equation. Notice that here, we assume the fluid to be a calorically perfect fluid without any viscosity. So there is no effect due to viscosity of the fluid and the fluid is also calorically perfect, right, h is the specific enthalpy.

This is the energy equation. In addition to this in such flows, we also need to write down the change in specific entropy, ds, can be written as delta q/T+delta sigma irreversibility. Sigma reversibility is the entropy that is produced due to irreversibilities in the flow and it is non-0 and positive when there is irreversibility in the flow and it is = 0 when there no irreversibilities in the flow. Let us write that down.

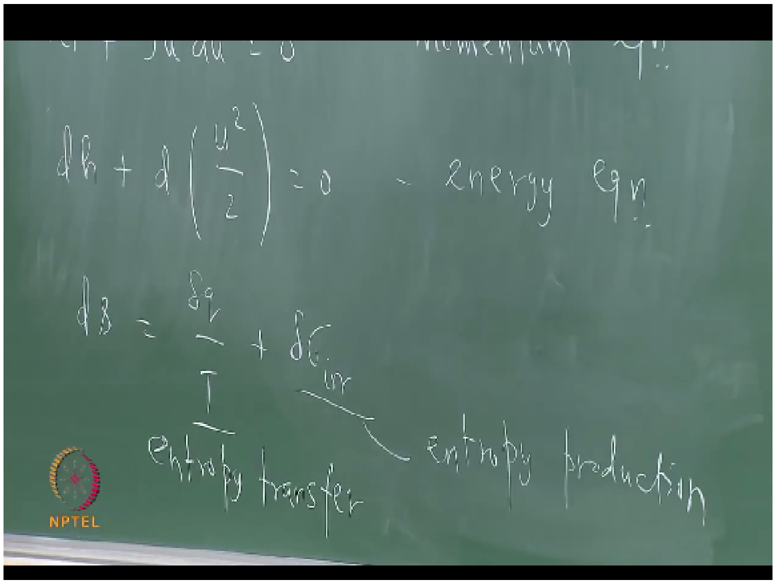
(Refer Slide Time: 42:54)



Is > 0, then irreversibility is not present and it is = 0 when irreversible or we can also say irreversibility are absent. We can say... This is not a quantity that can be measured but it allows us to determine whether entropy is going to increase or remains the same in the flow, right. We can use other means of calculating entropy changes in the flow but this gives us a very good idea of which direction entropy change is going to go, okay.

The first term here talks about entropy. This is due to heat interactions. So this mean this is the entropy that we are transferring to the flow or taking away from the flow, right. If you give heat to the flow, then its entropy as you can see is going to increase, delta q is positive. So that means this is entropy transfer. If you remove heat from the flow, then the entropy in the flow is going to decrease. So this is the entropy transfer.

(Refer Slide Time: 44:24)



And the second term is entropy production, right. If there are irreversibilities in the flow, then that is going to generate entropy and if there are no irreversibilities in the flow, then there is no generation of entropy. So entropy change in a flow as you go from one point to another, it is due to 2 things, one entropy transfers, another one entropy production, right. If it was an adiabatic flow, then there is no entropy transfer, delta q is 0, right.

So that means for an adiabatic flow, the entropy can only increase or remain the same. There is no question of decreasing for an entropy for an adiabatic flow. So for an adiabatic flow, delta q is 0 and so ds is... So ds can increase or at best remain the same, okay because sigma is always positive or = 0. So that means entropy in an adiabatic flow can increase or remain the same, okay.

So these are the 4 governing equations for the flow and we are going to look at in one after other, solutions to this governing equation. These governing equations permit different types of solutions, okay and we are going to, some other types of solutions that they permit is that, wave solution is permitted. So why wave is actually a discontinuity. Flow properties I have the wave have a certain value, flow properties downstream wave have a certain value.

So the wave itself is a discontinuity. Gas dynamics is probably the only application where discontinuous solutions are permitted, okay. So this is a discontinuous solution, discontinuity. Other solutions are also permitted. These are continuous solutions for example, the wave solution will encompass things like an acoustic wave propagation or it can also be a normal shockwave

and the continuous solutions, under continuous solutions, we are going to look at Rayleigh flow and Fanno flow. So these are the 4 solutions that we will look at one after the other, okay. 2 under the category of wave or discontinuous solutions and 2 under the category of continuous solutions which is going to be Rayleigh flow or Fanno flow, okay. We will pick this up in the next class.