Gasdynamics:
Fundamentals and Applications
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Lecture-01
Introduction

Welcome to the course on gas dynamics fundamentals and applications. Gas dynamics treats the compressible nature of flow in gases. So, it is while the fluid flow equations remain same additional complexities and considerations have to be taken due to compressible nature where density becomes a variable and it changes as the flow happens and this is typical of gases.

So, many interesting features and flow starts coming up due to the compressible nature of gases and when they flow and especially when speeds become high. So, in this course we will cover various aspects of this. In this lecture we will give an introduction mainly through images and videos, many of them captured in our laboratories of the flow of gases at high speeds where compressibility is important.

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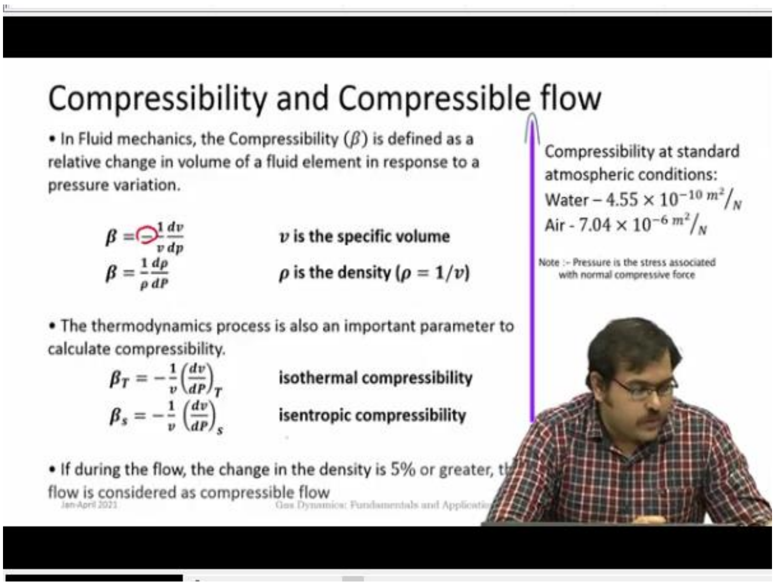

So, even before we go there, first we have to understand what do we mean by compressibility, compressible flow and so on. So, in fluid mechanics the compressibility is defined as the change of volume of a fluid element in response to the pressure applied upon it. So, when you apply pressure, pressure is compressive force. So, based on that volume will change, it will try to shrink.

How much does that volume shrink! And that is the basic definition of compressibility. So, mathematically it is represented as $\boldsymbol{\beta = -\frac{1}{v}\frac{dv}{dp}}$ where $\boldsymbol{v}$ is the specific volume, it can also be represented in terms of density because density is nothing but $\mathbf{1}/\boldsymbol{v}$. So, it becomes $\boldsymbol{\frac{1}{\rho}\frac{d\rho}{dP}}$, because pressure when you apply pressure generally the volume will decrease.

So, you have a negative sign for volume but density will increase. So, for any particular fluid we can define the compressibility and compressibility just tells us how compressible that fluid is, how much its volumes will change not only is this basic definition important we will also see in compressible flows.

And in gas dynamics that there is a close relationship between these definitions and the thermodynamic process that is used to achieve a certain change. So, in this case compressing a certain volume can happen either in an isothermal way or in an isentropic way. In isothermal way there is a certain amount of heat transfer involved while in isentropic compression the heat transfer is not there and accordingly the definition of compressibility can be defined as an isothermal compressibility or an isentropic compressibility.

So, more of these processes and how they are important in describing compressible flows we will see in actual chapters that we go ahead. So, now let us just compare two very common fluids that we know, one is water and the other is air and at normal standard atmospheric conditions what is their compressibility? If you compare them, you can see that the compressibility of air of water is in the range of 10^{-10}.

While for air it is in the order of 10^{-6}. So, water is almost like negligible, so you treat water in almost all cases as an incompressible fluid or constant density fluid that what is normally done and flow involving such liquids and waters you treat them as incompressible flow. But on the other hand, if you look at air it is 10^{-6} that is it is at least 10000 times more compressible than water.

So, when flow of air happens then there is a possibility that during the flow density can change then that flow becomes a flow where compressible effects become important. Normally in fluid mechanics in the first course on fluid mechanics one would have come across incompressible flows where density is taken as constant, all of you must be aware of the Bernoulli's equation where you consider density as a constant.

And you would have done several applications of that equation, but now when we come to cases when compressible effects become important then Bernoulli equation for a constant density flow is not applicable in such scenarios. So, whenever this change in density during the flow changes in density become important it is greater than 5% then the flow is considered as a compressible flow.

So, even in air which is a gas and it has significant compressibility if the velocities are small and corresponding changes to density as the flow changes if they are small then you can still consider the flow of air as an incompressible flow. So, this distinction between fluids which are dominantly compressible and have significant compressibility and a compressible flow when do you need to consider compressibility effects one should be really aware of. Air flowing at very low velocities like 10 m/s 20 m/s is not generally you need not consider the compressibility effects.

But air flowing at something like 200 m/s, 400 m/s then compressibility effects is very important. So, there must be something really important which can quantify when compressibility is important when it is not important.

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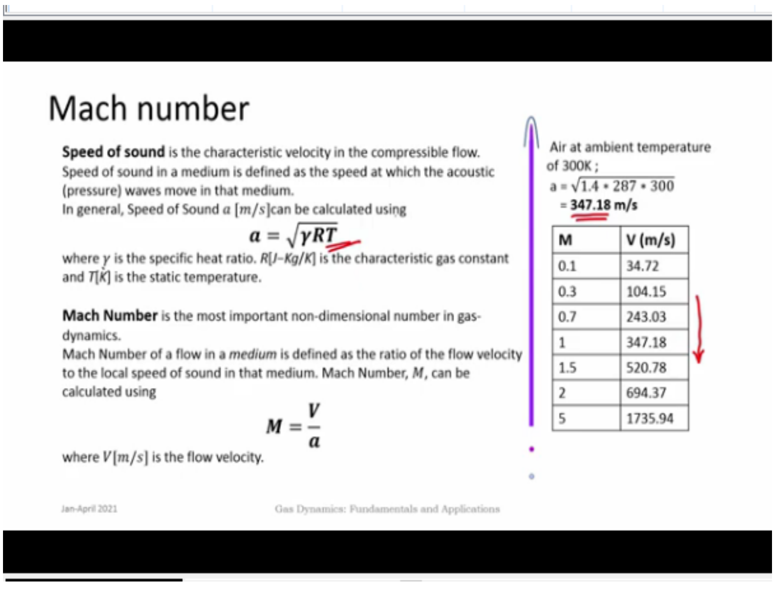

And you will find in compressible flows that speed of sound is a very important parameter, it is a characteristic velocity, you will also find that propagation of waves, how they affect the medium and so on and the flow velocity versus speed of sound. All of these concepts become important in compressible flows. So, the speed of sound is just the speed at which acoustic waves move in that medium.

And it is a local property and it is defined as it has a formula for a perfect gas which is $\sqrt{(\gamma RT)}$, which is given over here, R is the specific gas constant and T is the static temperature. Now if you know the speed of sound then the ratio of velocity of air to speed of sound in that it is again a local quantity at that particular point is known as the mach number.

And it is the you can consider the single most important non-dimensional number in compressible flows in gas dynamics and we will be referring to mach number almost in all the classes from now and from this moment onwards. So, now we had just now discussed that the speed at which the flow moves will decide whether compressible flows are important or not important?

And that can be really put in terms of mach number generally it is considered that if the mach number of the flow is greater than 0.3, then compressibility effects become important, if it is less than 0.3 you can still consider it as an incompressible flow and you can continue to do the analysis. So, for air at room temperature at say temperature of about 300 kelvin the speed of sound is 347 meter per second.

So, you can see that if you have a mach number of 0.1 it is about 34 meter per second and the mach number of 0.3 beyond which compressibility becomes important is about 104 meter per second. So, beyond 100 meter per second can be considered as compressible flow with an ambient temperature of 300 kelvin. So, you should really look at mach number, see if the mach number is greater than 0.3, then compressibility is important. If it is less than 0.3 then it is not so important. So, now that we have an idea of what do we mean by compressible flows and compressibility. Now how important are these flows?

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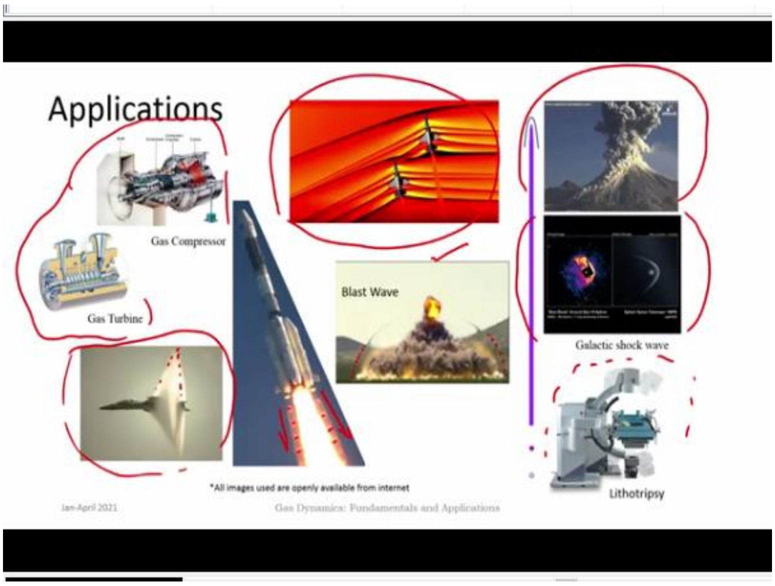

So, if you look at that they are widespread actually they find them everywhere and they have been there all the time right from natural flows to all the way to current engineering applications and future research and many interesting aspects of these flows in general flow in gases is compressible and there are several interesting phenomena that occur as the speed of the flow increases with respect to the speed of sound.

An important phenomena that occurs at velocity is greater than the speed of sound known as supersonic flows is the phenomenon of shock waves. Now these are special flow features which are very thin extremely thin, they are so thin that you can consider them almost as discontinuities and across which there is a sudden jump in pressure, temperature and density and there is a reduction in velocity.

They are the means by which supersonic flows respond to certain flow conditions or if there is a flow turn and so on and we will go through in fact majority of discussions in gas dynamics will involve shock waves and their interactions and how they behave in certain flow scenarios and so on and these waves are found everywhere and in any sort of compressible flow where you expect the velocities to go beyond the speed of sound.

In nature they are very much present in cases like the explosive volcano that is described over here or even in the universe these shock waves are quite common and you find them because majority of the gases that are there they behave in compressible manner and you can move with extremely high velocities. So, you can find shock waves there. So, in nature it is quite common.

But really in engineering and in applications where we started to find use of or rather these phenomena occurring frequently are initially they would have been seen when explosions happen when there is a sudden deposition of large amounts of energy, then such waves are formed and they are known as blast waves which is a one form of the shock wave essentially they are a shock wave and they move supersonic speeds.

For example it is shown in this particular picture an explosion happens and you can see just at the outer periphery here a wave that moves and this moves at very high speed and it is a very sharp wave front and there is a large pressure jump that appears across it and it can cause significant, it is the first wave that causes quite a good amount of damage. So, probably compressible flows other places naturally which would have occurred is thunder claps and so on.

But really more detailed studies in 2 compressible flows began early on with trying to extract energy like steam power and steam turbines, steam engines and so on there you really observed the compressible nature of flow and at those points of time in history a lot of things about thermodynamics and fluid flows were also not so well developed and they were developing at that point aspects like supersonic flow in nozzles and so on were developed at during those times the de laval nozzle was an important invention in the context of steam turbines.

And this compressible gas flow and at high velocities is still a matter of importance for energy applications in gas turbine, gas compressors so on and today we are looking at doing higher and higher amounts of energy conversion with compact machines, with greater efficiency, higher temperatures, then compressibility effects become even more predominant.

Really the way this field really took off is when the flight and space age began because in those times when one has to go beyond the atmosphere of earth, then you really have to provide significant velocities and then we really see the effects of compressible flow and here there are 2 pictures of aircrafts, one at this bottom left corner which is very nice picture where you have a flight which is going at what is known as transonic mach numbers which is mach numbers close to speed of sound.

And there is a pocket of supersonic flow that develops and gets terminated by a shock forming a kind of a condensation cloud and this is nicely visualized in this particular photographs. This kind of flight is very common any transport aircraft, civilian aircraft, passenger aircraft flies at mach numbers of between 0.7, 0.8 and that is clearly in the domain of compressible flows.

Here in the middle and on the top part is another interesting photograph that shows the features of shock waves around aircrafts which are flying at supersonic speeds, you would have heard that when objects move at supersonic speeds you first see them and hear them much later and there are reasons why that happens and we will soon learn about them in this course why such phenomena happens, you would have heard about sonic booms and so on which are parts of this course.

And when one considers a rocket moving very quickly to the upper parts of the atmosphere here there is a snapshot from one of ISRO’s own rocket and here you can see it is ejecting out extremely high velocity, high temperature gases, they are in supersonic speeds which is visualized by these shock waves which can be seen at specific locations, why they occur and how are they important is something that we deal with in this course?

So, there are numerous applications of compressible flows and in modern times they have these special waves, these shock waves have been turned into useful applications like biomedical applications for removing kidney stones using lithotripsers and so on. So, not only is there, they are present naturally, there are several engineering applications, there are also applications in medicine biology and so on. So, really it has a wide range of applications.

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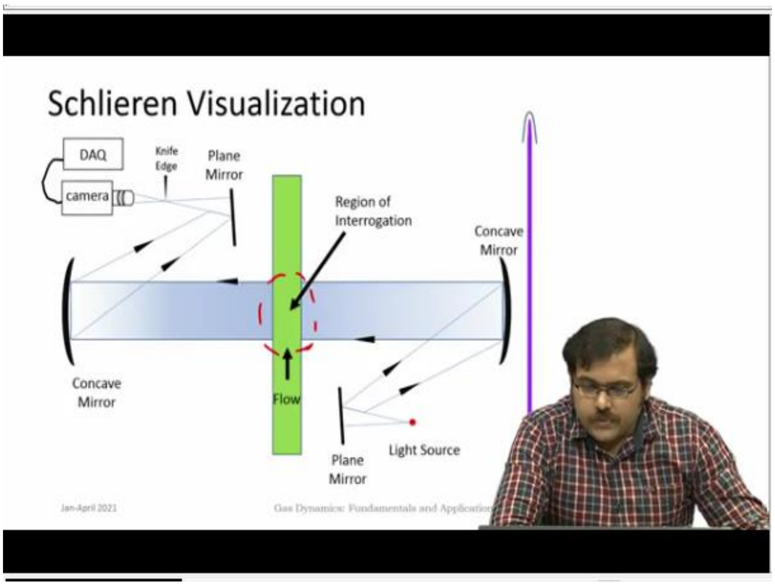

So, what we will do today that provides us the motivation to learn gas dynamics compressible flows going to the details but today we will just look at images and understand what are the important physical features that are there in such flows, what is important, what we learn here and so on providing you further motivation to learn this particularly interesting subject.

And before I go into those images they are taken using a special method known as the schlieren visualization and I just explain what is the schlieren visualization? The schlieren is a technique that captures variations of density in a medium. So, variations of density vary the refractive index and as a consequence a beam of light going through a region where there are large density changes bends significantly.

So, what we see here is a setup that is typically used in experimental labs where there is a light source and the beam the light from the light source is made into a parallel beam using concave mirrors our lenses can also be used and this beam is passed into a region of interrogation where there is a flow happening where density gradients or density changes are present.

Then the light is collected and focused back onto a sharp knife edge which acts like a sort of a filter filtering out certain deflected rays which move towards the knife edge. So, that we can visualize what have moved away from the knife edge and what has moved into the knife edge and then it is captured using a camera. Since compressible flows involve large changes in density these large changes in density can be readily captured using schlieren, in fact schlieren is so widely used to study compressible flow.

So, we will be watching several schlieren images as well as videos in some cases which were taken in the laboratory of hypersonic and shockwave research in Indian institute of science.

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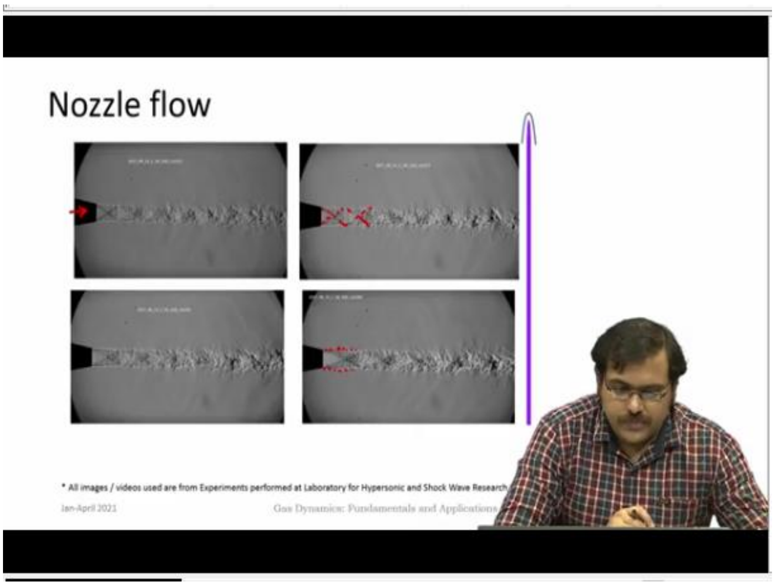

And I have to really acknowledge all my colleagues who have worked with us in the lab as well as many students who have been a part of this work these different works which have enabled us to show such excellent images over here and here in this case you see a nozzle flow and if you look at its structure this is not very different from the one you saw at the edge of the rocket because this is a supersonic flow.

So, you can see the flow is happening from left to right and this nozzle produces supersonic flow of mach number about 2 and here the pressure at which the nozzle is being supplied is changed. This is in some sense similar to what happens to the rocket as it ascends up to into the upper layers of the atmosphere, there the ambient pressure reduces as you go higher and higher.

So, the way the jet behaves as it comes out changes as the pressure ratio between the ambient and the supply pressure keep changing. So, here is some images that shows what happens, in this case we are increasing supply pressure and so initially the supply pressure is quite smaller and you have significant x kind of marks which are dark, you can observe it here these are nothing but shock waves which are present in supersonic flow.

Here the shock waves come about as the jet responds to the ambient pressure. Now as the pressure keeps increasing there is possibility that the jet can further expand in the atmosphere, so you see that towards the end which is at a much higher pressure, there is a slight expansion of the jet. So, we will study these various operating regimes of flows through nozzles from nozzles and so on in this particular course.

So, variable area ducts how does flow happen in variable area ducts what happens to flow once it comes out of the nozzle, what if it is subsonic?, what is it if it is supersonic so on and so forth. **(Video Starts: 26:16)** This is a particular video of when there is a sudden deposition of energy then you get shock waves to call it by the exact name it is a kind of blast wave.

This is produced by compressed gases suddenly being pushed out in a laboratory experiment and these waves travel very quickly faster than the speed of sound and you can see the sharp front, the sharp front is due to the shock wave. So, we will study about shock waves and if you take any particular ray then almost the shock wave is normal to that particular ray. So, we will study about various types of shock waves, normal shocks, oblique shocks and so on.

And what is the pressure ratio? How does mach number change or velocity change across the shock and so on. This is an important sort of example of what is known as moving shock where the shock moves inside the duct if the shock wave is present can consider it as a stationary shock also. So, these are some aspects which we will go in detail in this course. **(Video Ends: 27:49)**

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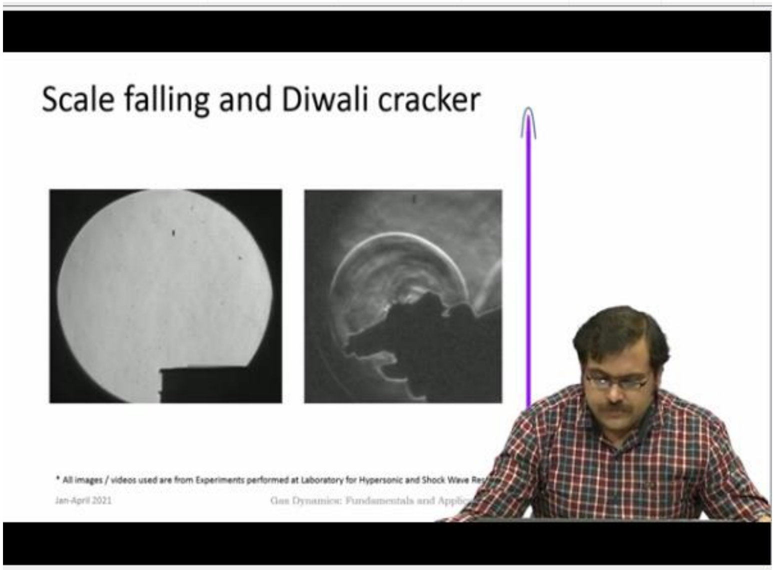

So, just to give a perspective here is our comparative experiments between on the left hand side is a very loud sound which can start to leave is nothing but a scale suddenly falling. So, you can see this scale falling and it creates a wave and the wave can be visualized. This is a strong wave acoustic wave loud sound, it can start to leave, but it is it just travels at the speed of sound itself it is not really a shock wave.

But on the other hand here on the right side you have another device which is also quite calm and it is a diwali pataka, it is just a firecracker used in the festivals and you see that when this fire cracker is lit and when it is fired you really get a very significantly sharp front which is typical to shock waves of course this shock is much milder as compared to what would be produced in the previous slide what we saw.

But even then this is not in any way as small as a scale falling which is even a scale falling itself is a quite a loud sound, a metal scale falling but what you see here is a diwali pataka and that produces really a very strong pressure wave which is more closer to a shock wave.

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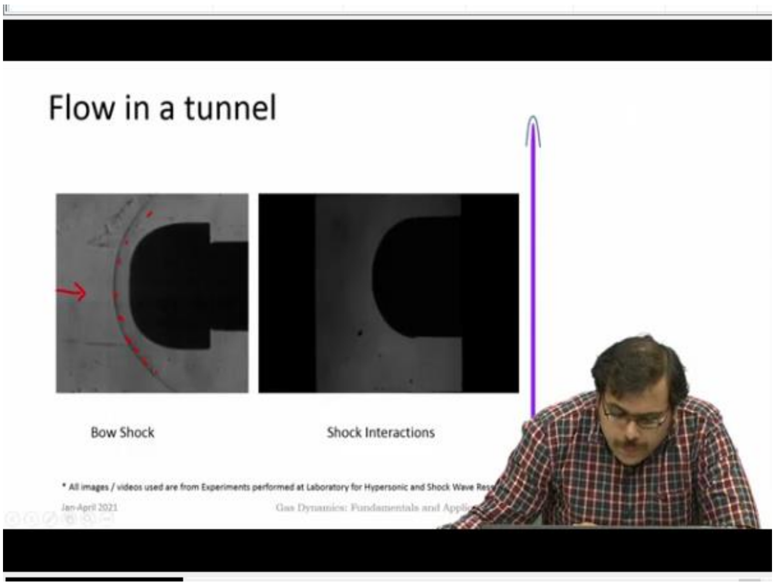

So, now we will see more of typical bodies which are similar to objects that move through air at very high speeds. This is a very blunt kind of a shape semi a hemispherical shape and a supersonic flow is flowing over it from left to right and this supersonic flow when it flows past such bodies abruptly it has to change its speed because on the body the flow has to come relatively at rest to the body.

And this sudden change in velocity is accomplished using a shock wave which is well visible over here that this kind of a shock has a bow like structure, it is called a bow shock and in this particular video on the right what you see is an interaction when you have multiple bodies like what you saw which is typical to a spacecraft or a rocket you have many components, then shock waves from different components can interact with each other. So, this video shows such an interaction.

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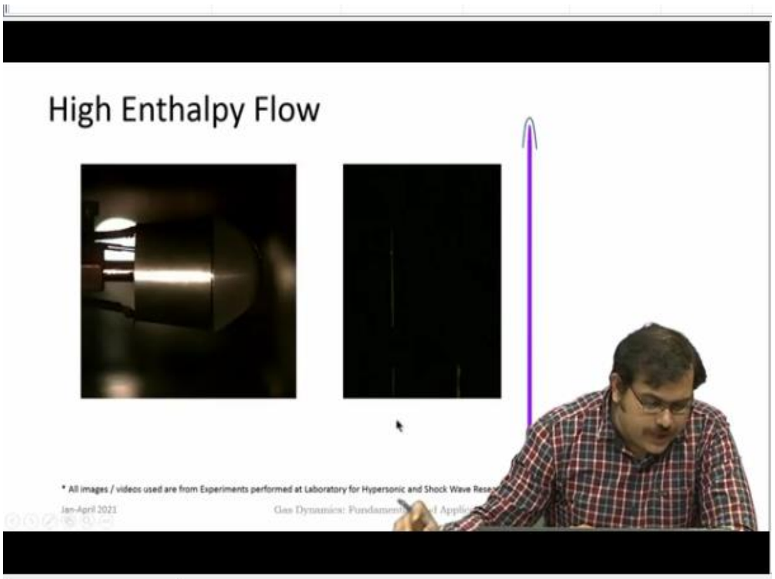

And further if you look at even high speed flows so you find that the velocity increases so high that if you produce any change to velocity it also brings about a huge change in other thermodynamic variables of course density changes, here even temperature changes significantly and it can change to such an extent that you can have very, very high temperature gas and the temperatures will be so high that it will start radiating and you can get a glow. **(Video Starts: 32:22)**

And this is what is seen over here this is typical to re-entry kind of flow scenarios when some object like a space capsule re-enters the earth's atmosphere, then its energies are so high that it can glow and temperatures can become very high. Then the important question is how do we save the vehicle from such high temperatures, how do we protect it thermal protection systems and so on?

So, in compressible flows on one hand you have subsonic flows, supersonic flows and this comes very high enthalpy flows which are also called as hypersonic flows, where certain important aspects like high temperature effects become important. On the right hand side is another visualization where you can see, further see the radiating gas ahead of bodies in very high speed flows.

Here the speeds are close to 1 or 2 km/s, it is not in meters per second anymore. So, I hope these images and videos would have given idea about many, many interesting features that appear in compressible flows. **(Video Ends: 33:54)**

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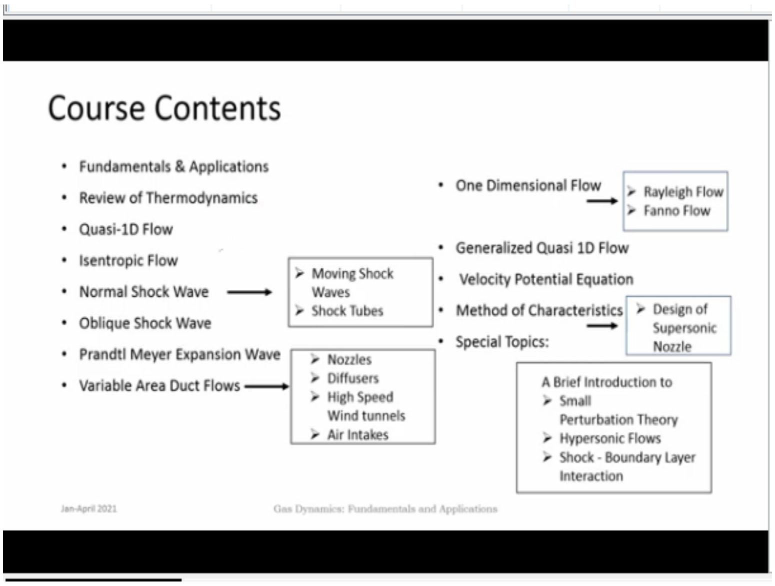

Therefore we have in this course many aspects of what we just saw and in the course of this course we look at all these different phenomena. Since the density is a variable there is additional equations that need to be applied besides the fluid flow equations and there is a close interaction between energy of the flow and changes in velocity and so on. Therefore thermodynamics becomes an important part.

So, you have to use both thermodynamics and fluid dynamics. So, we will begin our discussions with a review of thermodynamics. So, this being a course in compressible flow it is expected that you know fluid dynamics and thermodynamics well you would have undergone a first course in fluid dynamics and thermodynamics. So, these flow equations and thermodynamic equations we will just review will not go into too much detail we will take what is necessary for discussions in our class of gas dynamics.

But please do go through them and revise them then you will understand this course even better and typically these flows the first way to or understand the flows and analyze them is using what is known as a control volume approach and look at very simple cases like isentropic flows and specific flow features like normal shock waves, oblique shock waves and some of their applications in certain devices known as shock tubes.

And we will go into details of how flow happens through varying area ducts and look into certain applications like nozzles diffusers how they are applied in high speed wind tunnels or air intakes and look also into flows where there is a long duct and there is friction inside the duct as the fluid flow goes along which is nothing but similar to pipe flow which is known as Fanno flow and also cases where you can have heat addition happening or heat removal happening, heat transfer happening in a constant area duct.

So, that is known as Rayleigh flow, in all these cases density is a variable and you need not only mass and momentum conversation but also energy conservation and finally we will come to looking at flow fields in general particularly 2 dimensional flow fields we look at some special methods which can be used to design supersonic nozzles and a brief introduction in special topics to aspects like small perturbation theory, hypersonic flows which are flows at which very high enthalpies and high velocities are present and shock boundary layer interactions.

So, with this we have a sort of complete good presentation about what is basic understanding of compressible flows which can be used in practice or and help you understand different engineering applications in the domain. So, in the next class we will look at what is meant by different flow regimes in compressible flow, what do we mean by subsonic flow, what do we mean by supersonic flow and so on. So, we will meet in the next class, thank you.