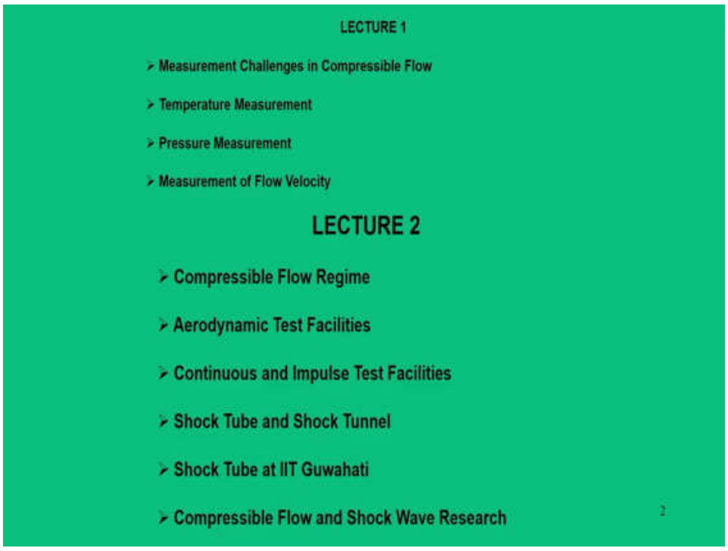
Fundamentals of Compressible Flow
Prof. Niranjan Sahoo
Department of Mechanical Engineering
Indian Institute of Technology, Guwahati

Module – 08
Lecture – 02
Measurement Diagnostics and Experimental Facilities for Compressible Flow

Welcome to this course Fundamentals of Compressible Flow. We are in the module 8, and this is the 2nd lecture. The title of this module is Measurement Diagnostics and Experimental Facilities for Compressible Flow.

(Refer Slide Time: 00:47)



So, in the last lecture, we concentrated mostly on measurement methods, where we talked about challenges in executing these measurements and localized measurements in terms of pressure, temperature and flow velocity.

In this lecture, we will focus mostly on testing facilities with respect to compressible flow. So, the contents for this lectures are as follows, first, we will see that what are the different compressible flow regime. In fact, we have already discussed in our previous modules about this flow regime.

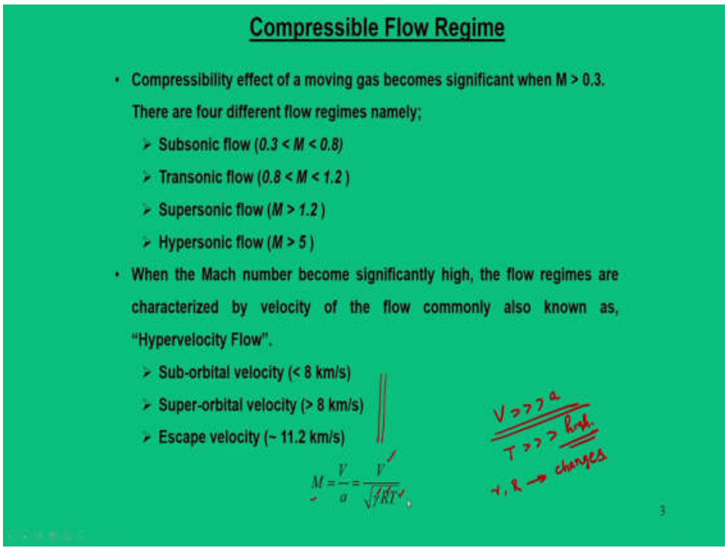
Then, based on this flow regime these test facilities are different. So, we will discuss about aerodynamic test facilities. I use the word aerodynamic because in most of these compressible flow facilities are attend by aerodynamic scientists.

Then, out of this aerodynamic test facilities there are some facilities which are continuous type or impulse type. Means, some facilities they run in a continuous mode, but other facilities they just run in a blow down mode; that means, for one test when the experiment is over then we have to rework on the second test. But where are in the continuous mode, as long as the flow continues in the tunnel, we can take the measurements.

And in particular with respect to our course, I will just discuss about the fundamentals of a shock tube and shock tunnel because this is the simplest type of one dimensional tool that can be used in the laboratory as a impulsive device. Then, I will just give you a brief introduction about the shock tube facilities located at IIT Guwahati in the Mechanical Engineering Department.

And in the last, I will conclude this course with a philosophy that how a compressible flow knowledge will help in conducting research in the area of shock waves, what are the revenues or research focus that is available that one can create his passion in conducting this research.

(Refer Slide Time: 03:45)



Now, let us talk about this compressible flow regime. We all know that till this point of time that compressible flows are characterized when the Mach number of the flow is more than 0.3. And based on this Mach number, the flow regimes are classified as subsonic flow in which Mach number lies between 0.3 and 0.8. Transonic flow where Mach number lies between 0.8 and 1.2. Supersonic flow, any Mach number that goes more than 1.2, we categorize that as supersonic flow. Hypersonic flow when the Mach number goes more than 5.

And the major challenge is that once you cross this limit of hypersonic flow many a times the Mach number role is irrelevant and on many situations we define the flows in terms of its velocity. We call as hypervelocity flows. So, if you look at this expression of Mach number, it is equal to the speed of the body with respect to speed of sound.

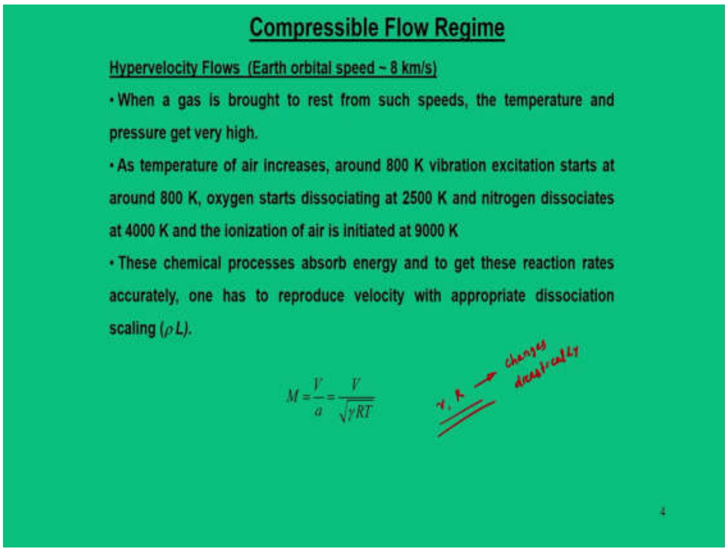
Now, what happens in the limit of subsonic transonic or supersonic or low supersonic Mach numbers? The speed of sound normally does not change because temperature change is not drastical and because the temperature does not change and the medium that is air has almost no change in its characteristics property. Like, there is not significant change in the specific ratio for air or characteristics gas constant.

But, what happens when the velocity becomes very high and it becomes more than speed of sound? So, that is one part this Mach number also changes. And because of this temperature is also very high because the body encounters normal shock. And moreover the properties of the medium that is γ and R changes.

So, effectively in the expression of Mach number, the velocity changes, γ changes, R changes, temperature changes. So, everything that changes, but we really do not know why this change in Mach number takes place or which particular effect has significant role in changing the Mach number. So, in that case, people try to express the high velocity or hypersonic flow Mach number may be more than 10 and above in terms of its velocity.

So, we categorize them as suborbital velocity less than 8 km/s, super orbital velocity where the it is if it is more than 8 km/s and in fact, we all know there is a word escape velocity that is 11.2 km/s. That means, when you go to this particular regime the appropriate way of discussing about the velocity of the body is in terms of velocity not Mach number because all these parameters V, gamma and R and T changes drastically.

(Refer Slide Time: 07:37)

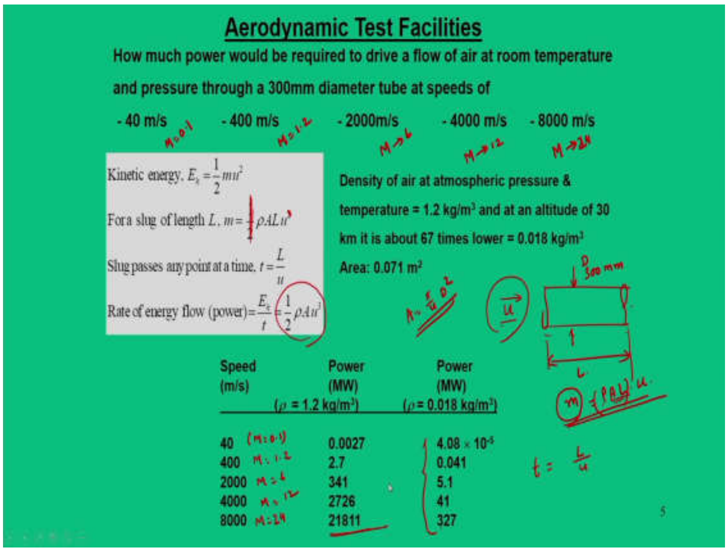


Now, what happens? Specific characteristics of a hyper velocity happens when the speed goes nearly about 8 km/s. So, in such cases, the temperature and pressure becomes very high.

Now, once the temperature becomes very high the vibration excitation mode starts, so at around 800°K and close to 2500°K oxygen starts dissociating and close to 4000°K nitrogen starts dissociating and close to 9000°K the ionization of air is initiated. In fact, air consists of mostly nitrogen and oxygen and those gases are not in their stable state. And because this is not the stable state we can say γ, R changes drastically. Hence, there is no role of Mach number rather we interpret in terms of velocity that is one angle.

Second angle there are lot of chemistry and chemical process that are involved, that absorb the energy and the reaction rates are also difficult to predict. So, in such cases, it is appropriate to infer the velocity as a parameter rather than Mach number. In fact, people have discussed about dissociation scaling in their chemical reaction in hypervelocity flows. But anyway that is not on our topic of discussion. But our main focus is that under this flow regimes how the aerodynamic test facilities can be classified.

(Refer Slide Time: 09:55)



But before you move for the aerodynamic facilities, in fact, design of any facilities requires a lot of power. So, when you talk about aerodynamic ground base facilities, we must know that what type of power requirement we need to establish such facilities. A simple calculation will tell us that what type of parameters or power that we require.

The question that comes in our mind that how much power would be required to drive a flow of air at room temperature and pressure because we are operating at atmospheric conditions, while passing the air through 300mm diameter tube. And we are using a tube of 300mm diameter and we want to have a speed 40m/s, this is about close to Mach 0.1 and 400m/s this is about Mach 1.2, 2000m/s this is closely about Mach 6, 4000m/s Mach 12, and 8000m/s Mach 24.

So, these are the broad regime of Mach number that we are going to see. So, we have fixed its velocity and Mach number and we want to find out that how much power do you require. Now, we have two options, one is we are going to create an environment which is atmospheric in nature in which the density is about 1.2 kg /m^3 that is at sea level density.

Now, if you want to simulate a high altitude conditions let us say we are talking about a 30km altitude where density is 67 times lower, so you talked about a density of 0.018 kg /m^3. So, in other words, if I pose the problem like this that for a given set of dimensions of facilities and we are changing the speed, but we are operating at different densities.

So, to calculate this, the power requirement is normally decided through the kinetic energy which we can say $E_k = \frac{1}{2}mu^2$. So, m you can put a for a slug of length L. So, we can see that there we have a pipe of 300 mm diameter and it has a length L. So, for this length L then you have a slug of mass m. This mass we can write as its ρALu. So, this is volume density into flow velocity u. So, mass flow rate becomes this.

Now, once I say slug of mass, then we can say that if you are talking about a speed u and we can say that this particular slug of mass will take a time t that is nothing but L/u, to cross this length. So, this slug of mass at any time t will be L/ u, so based on that you can reframe that problem that the power requirement will be $\frac{E_k}{t} = \frac{1}{2}\rho Au^3$. This is the working formula that can give us an estimate that what is the power requirement.

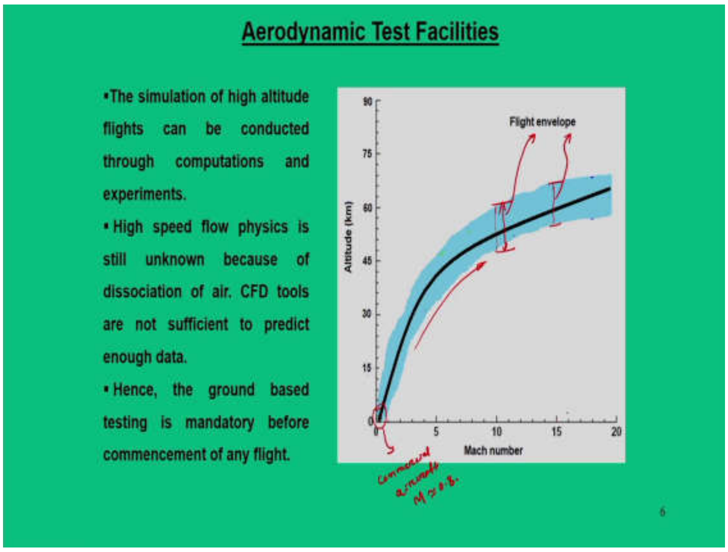
So, here we know that what is area that $A = \frac{\pi}{4}D^2$; D is about these 300 mm diameter. Now, putting all this numbers we are going to work out what is the power requirement. So, the power requirement is calculated in two situations, one is conventional density mode that is ρ is equal to 1.2 kg/m^3 other is the high altitude conditions where density is about 0.018 kg/m^3.

If you look at these numbers, so for 40 m/s that is for M is equal to 0.1, we can see that the power requirement; This is typically a low speed mode is about 0.0027 MW which is very less, but if you go to 8000 m/s that is Mach 24 then this power requirement is huge, that is about 21811 MW.

But whereas, this number reduces drastically when I use the value density as 0.018 kg/m^3. So, this gives a clear cut indication that if I reduce density then I can go for higher speeds. So, that is the reason all flight vehicles they look for a right altitude to go at higher speed.

So, likewise for other speeds like Mach 1.2, Mach 6, Mach 12, we can find the power requirement. That means, if you are able to reduce the density of the gas, then we are able to travel higher speeds.

(Refer Slide Time: 17:00)



So, based on this we can have a altitude Mach number plot that way if you want to go at higher Mach number we have to increase the altitude. Now, here the aerodynamic challenge comes into picture because at low subsonic speed, even in fact the commercial aircraft this is the location for which we have commercial aircraft flies.

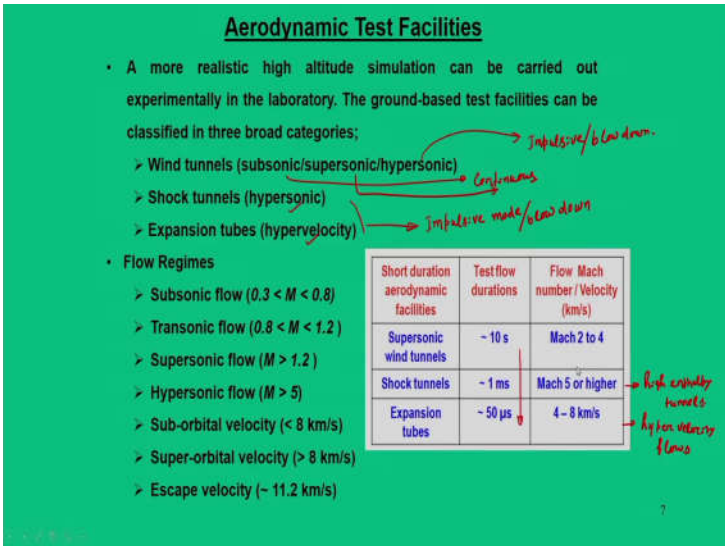
And, typically these are Mach numbers in the range of 0.6-0.8. So, the Mach number is order of 0.8. And these altitude at are at very less that is within maybe 10 km altitude. But if you want to go higher speeds or higher Mach number, then you have to climb this altitude. So, that is what this curve talks about a attitude Mach number plot; that means, if you have to go higher Mach number you have to climb in altitude.

And, in fact, for a given Mach number if you want to operate these are the level of altitudes that we call this as a flight envelope. For this Mach number, we may have this is the domain in which the flight suit. This means, that if you want to operate your flight at Mach 15, then your range of altitude can be fixed. So, in this mode normally all the flight vehicles operate. But the real challenge that happens that how do you simulate these high altitude conditions in the laboratory. This is what the aerodynamic scientist or test facilities require.

In fact, our main intention is that we have to create a high altitude conditions in the laboratory. Now, one can do those things through computations, but when you talk about very high speeds when the conditions of dissociation of air, the flow physics is not clear.

In fact, most of the CFD tools are not sufficient to predict this data. So, what we require is a ground based testing is mandatory for simulating high altitude conditions; at least we will be able to get a real time data.

(Refer Slide Time: 19:44)



So, with this the different flight regimes between subsonic to may be hypersonic flow and then towards this hypervelocity flows. We have classified the ground based aerodynamic facilities in 3 broad categories, one is wind tunnels. This wind tunnels can be subsonic mode, supersonic mode or hypersonic mode.

Now, here the word continuous mode and impulsive mode is predominant because mostly these subsonic wind tunnels they operate in continuous mode. And to some extent this supersonic wind tunnel can or can be continuous, but when you say hypersonic wind tunnel it is a kind of impulsive mode or blow down mode.

And, but all other shock tunnels like when you talk about hypersonic speed and expansion tube when you talk about hyper velocity speed, they work on impulsive or blow down mode.

By impulsive mode I mean that for a given test there is a very limited time available to us and within that time one has to complete this experiment. But in a continuous mode we need not have to worry about the time because the facility gives continuous flow conditions and we have enough time to do our measurements.

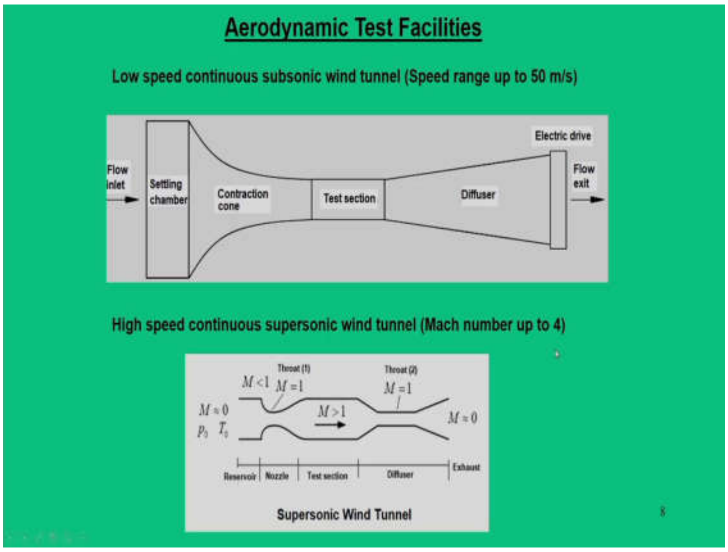
So, in this way the short duration aerodynamic facilities are classified as supersonic wind tunnels, shock tunnels, expansion tubes. And I have mentioned their typical range of Mach number in which these tests are carried out because for example, if we want to conduct the flow Mach number in the range of 2 to 4, mostly supersonic, we have to use supersonic wind tunnel. This is how I have explained how a supersonic tunnel works in my previous module.

But if you want to operate at this Mach number these facilities can provide data for 10 seconds. So, test flow deviation is 10 second means your entire measurement diagnostics should be over within the test durations. But what happens? That if you want to go for higher Mach number the supersonic wind tunnel will require huge power. So, this is not a preferred options when you go for higher Mach number.

So, in that case you have to choose these other modes that we call this as a shock tunnels and this is we call as enthalpy based tunnels, where we can go very high Mach number, but our available test time will reduce. That means, from 10 seconds the test time reduces to about 1 milliseconds. So, in other words it means that we have to conduct all our measurements within 1 millisecond time frame. And when you go to expansion tubes that is we say that hypervelocity flows, then the test time further reduces to 50 microseconds.

But we can have the hypervelocity flows in the range of 4 to 8 km/s. So, this is the challenge that lies that the test time reduces as and when your Mach number increases. So, this is the main challenge for aerodynamic engineers that we have to decide which tunnel we are going to use and based on their testing Mach number.

(Refer Slide Time: 24:29)



So, likewise I will just give some introduction that what are the facilities available so far. We have a low speed continuous subsonic wind tunnel, where speed range is about 50 m/s. Typical way of operation is that this is a very fundamental wind tunnel where we have electric drive that is in terms of fan and motor.

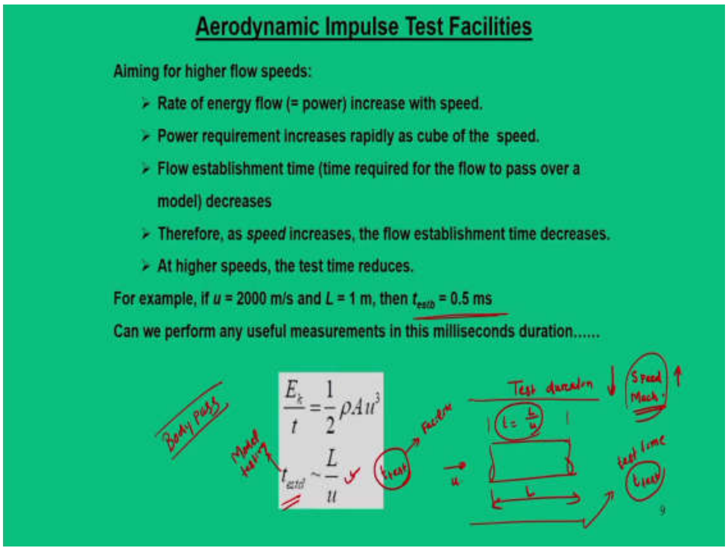
This fan and motor rotates, when it rotates it sucks the air from the other end. When the flow gets into the tunnel, it enters to settling chamber where the flow gets settled in the sense that we get a total flow and those flow you try to contract, allow into a nozzle mode where your velocity is increased.

So, this velocity increase and decrease that can be controlled through the contraction zone and we get desired flow velocity. So, I am saying 50 m/s means we can operate the tunnel that is up to maximum 50 m/s that is you can test a model at 10 m/s, 20 m/s, likewise the conditions can be controlled here.

Then, the gas or the air after testing is over, it enters to into a diffuser and finally, comes out. So, as long as your electric drive is there, it is rotating you are getting the flow. So, there is no question of measurement diagnostics in trouble because we have enough time to do the testing.

But when you go for supersonic wind tunnel like we discussed in the last module, where we have a reservoir, so that means, instead of this drive we have a storage vessel that have sufficient pressure and temperature and this is allowed into a nozzle that gives desired Mach number in the test section. And finally, the flow is slowed down in a diffuser before going to the outer exit. So, in this range in a supersonic wind tunnel we can go up to Mach number of 4.

(Refer Slide Time: 26:59)



But, what happens if you aim for very high flow speeds? So, as I said that when you go for high flow speeds your test duration decreases when speed increases or Mach number increases.

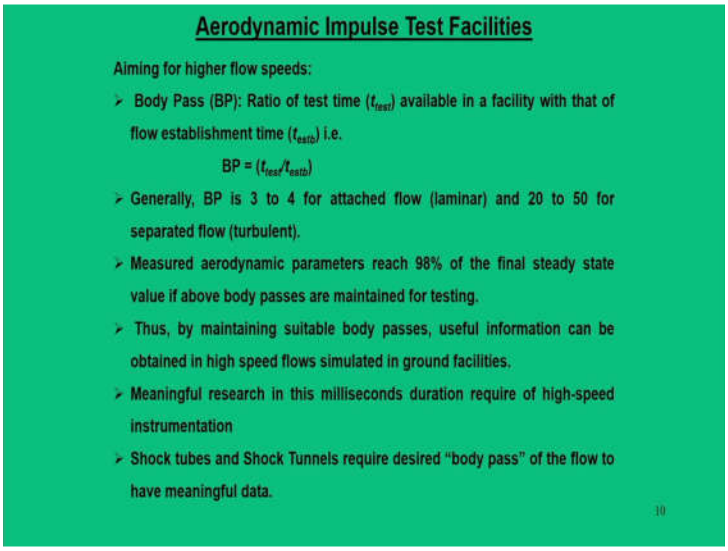
So, this gives a real pose of problem that whether we get enough time to do our testing. So, for that purpose we define a term which is called as flow establishment time. So, we are looking at a length L of the model and we are talking about a speed u. So, one can find that how much time it takes to cross this L length. So, time t is equal to L/u. So, we call this as flow establishment time. And when I am putting this model in a test section the facility will give you a test time, we say testing time.

So, you have two time, now, one is testing time which is controlled through facility; establishment time is obtained through model testing. So, these two times bear a definite correlations and that correlation we call this as a body pass. Means that to do the testing we must know that certain body pass of the flow should crossover the given model. This is one aspect.

Second aspect is that what we see is that the power requirement becomes huge as the cube of the speed, so that means, when I use a wind tunnel for hypersonic Mach number my power requirement will be very huge which is not at all feasible. But we will get a test time about 10 second, but when I do the same testing in a shock tunnel, the test time reduces to a millisecond, but what I compromise is that I can operate that tunnel at low power.

So, based on this philosophy a judgment is made that depending on your requirement of the model and the flow Mach number we decide the test facilities. So, for example, when your speed is about 2 km/s, length is 1m; your establishment time will be 0.5 milliseconds. Now, in this 0.5 millisecond if your test time is less than this then there is no role of doing that testing because by the time will get a 1 body pass flow, the test flow will be over.

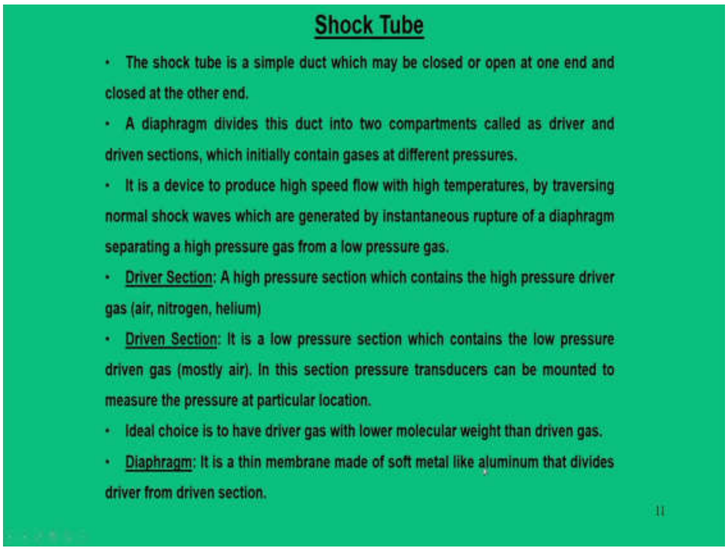
(Refer Slide Time: 30:56)



So, this is the reason that we define a term which is called a body pass that is the ratio of test time available in a facility to that of flow establishment time. So, a body pass of 3 to 4 is required for a attached flow that is laminar and 20 to 50 is required for a turbulent flow. That means, if I expect a laminar flow I must allow a 3 to 4 body pass to pass over the body, so that I can do our measurement testing without any difficulties. So, we require suitable body pass to have a meaningful data.

In this philosophy, the shock tubes and shock tunnels require a body pass because they are impulsive facilities, they have very less time, considering these aspects the shock tube and shock tunnel require sufficient number of body pass.

(Refer Slide Time: 32:00)



So, now, in our discussion today, although there are many facilities are available, but I will discuss about very important facilities which is a shock tube. And it is considered as a impulsive facility where test times are very less, may be less than a millisecond. Why I said a shock tube because it is a simple one dimensional tube, and does not have any complicacy or extra attachments and in fact, it follows the philosophy of one dimensional flow what we have discussed so far in our course.

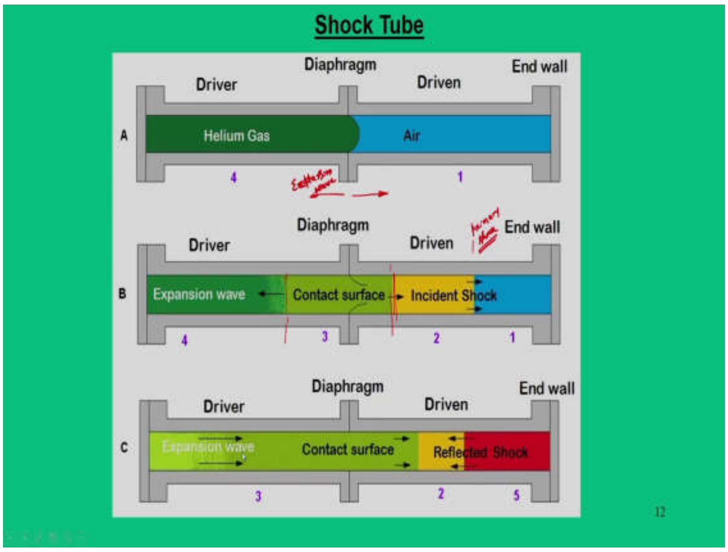
So, to introduce that topic we say that shock tube is a simple duct which may be closed or open at one end, but closed at other end; that means, one end is always closed, other end may be opened or closed. It has two sections mainly driver and driven sections, and a diaphragm that separates ducts into two apartment called as driver and driven sections, and these diver and driven sections contain gases at different pressures.

So, this device produces high speed flows with high temperature through traversing of normal shock waves. So, as I say that how in my previous lecture I told that how normal shock creates supersonic flow at one end and subsonic flow at other end. So, it drives the slug of mass to a very high velocity by instantaneous rupture of diaphragm that separates the high pressure gas from the low pressure gas.

So, you have a driver sections, these driver section is called as high pressure driver and it contains gases which are typically air, nitrogen and helium. Driven section is a low pressure region and it is mostly contain a test gas you normally call this is as a driven gas. And in this section, all measurement diagnostics are kept such as pressure transducer, temperature probes to do certain measurements in the downstream locations.

So, ideal choice to have a driver gas with lower molecular weight than the driven gas. That means, if you use helium because helium has a lower molecular weight it will have give a higher shock Mach number. And the diaphragm that separates between driver and driven is a thin membrane, like soft metal like aluminium, that divides driver and driven sections.

(Refer Slide Time: 34:57)



So, this is how it operates. We can say that there is a driver; driver contains helium gas and driven gas contains air, and initially the both the ends are closed or separated by a diaphragm. Now, when the diaphragm ruptures instantly what we see at one locations. So, when in the beginning state, the driver gas which is air it is at condition 1, and helium gas is at condition 4, whereas, after the rapture we see that one time instant the shock wave is sitting at this locations. We call this as a incident shock or we call this as a primary shock.

When the shock wave is moving in this primary zone, it allows the slug of mass which is air that gets compressed. So, we say that this is what the driven gas that or test gas that gets compressed. And the blue color that shows that air in this zone is undisturbed, where air in the yellow zone is disturbed.

Now, between this yellow zone and this driver gas, what happens? There is a contact surface. Contact surface means it is a kind of a region in which the driver gas and driven gases are separated. That means, when the diaphragm ruptures instantly shock wave is generated the shock wave moves towards right, side by side we have expansion fan, we have expansion wave which moves towards left.

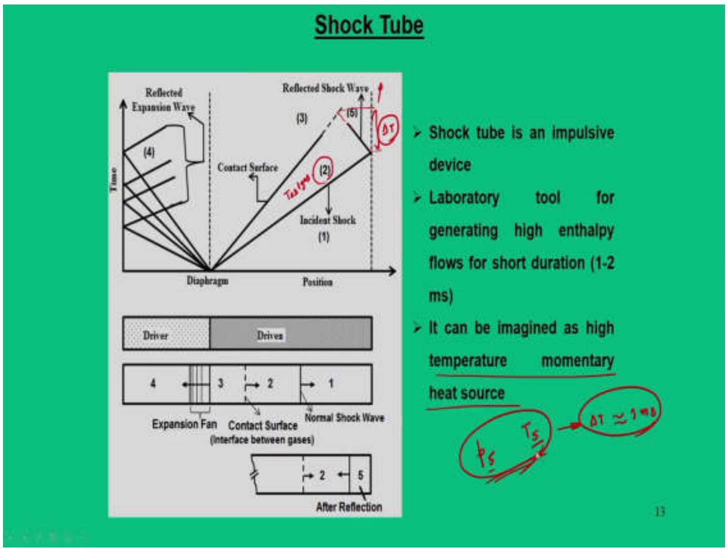
Now, between the shock wave and expansion wave, they tried to spread. So, there is a partition in which we see that, in this contact surface zone we may have the driver gas as well as the driven gas. But, the partition that separates has two lines, one we say in the shock region other is in this expansion region. So, what we see here? Shock wave is moving. Behind that there is a contact surface. And between these shock wave and contact surface the slug of mass which is the test gas gets compressed. This is the second instant.

And similarly towards the left hand side we have expansion wave moving towards the left. And now, in another time instant what see that the shockwaves gets and reflected from the end wall. When it gets reflected from the end wall entire slug of mass becomes yellow; that means, they have already exposed to the primary shock for which temperature and pressure gets elevated and then it is moving towards reflected mode.

Now, when it is moving reflected mode, the further rise in pressure and temperature happens. So, because of this reason you can see that now we have a red color; this red color means it has already exposed to primary shock as well as the reflected shock.

Now, similar situation happens in the expansion wave also. We can see that the color of green becomes little bit of fading. So, this expansion wave goes and hits in the end wall. So, this process keeps on happening within this tube.

(Refer Slide Time: 39:24)



But how to quantify it? Means, which is shock wave, which is expansion wave? So, to do that a simple diagram what we call as x-t diagram is plotted; it is a kind of a distance timing diagram for a given shock tube.

Now, considering the conditions region 1, 2, 3 and 4; that means, 1 is primary undisturbed gas, 2 is the region in which the gas is exposed by primary shock, 3 is the contact surface region and 4 is the undisturbed region. And after reflection we get region 5. So, what we see is that after the rupture of diaphragm we say that primary shock path is given in this manner and finally, it goes and hits the end wall and it tries to reflect.

Now, since the shock wave speed is higher and following to this shock wave we have a contact surface that path is given by the second line. Now, what happens? So, since this speed of contact surface is obviously less, so it is moving at lower speed. Now, side by side we see here the expansion fans that generated at the location of diaphragm.

There are lot of because expansion fans, they always try to diverge, they never converge. So, we say they sprayed; that means, we have the head of the expansion fan and we have tail of the expansion wave, then it goes and every fan they try to reflect.

So, this is what we say reflected expansion wave. This is primary expansion waves and this phenomena happens. Now, what you see here? when the region one is there, in this region the shock wave condition is undisturbed gas, region 2 it is exposed to primary shock, region 3 is contact surface, region 4 is undisturbed expansion wave, and region 5 that is reflected shock and in that means, in this region the gas which is exposed to both primary as well as the reflected shock.

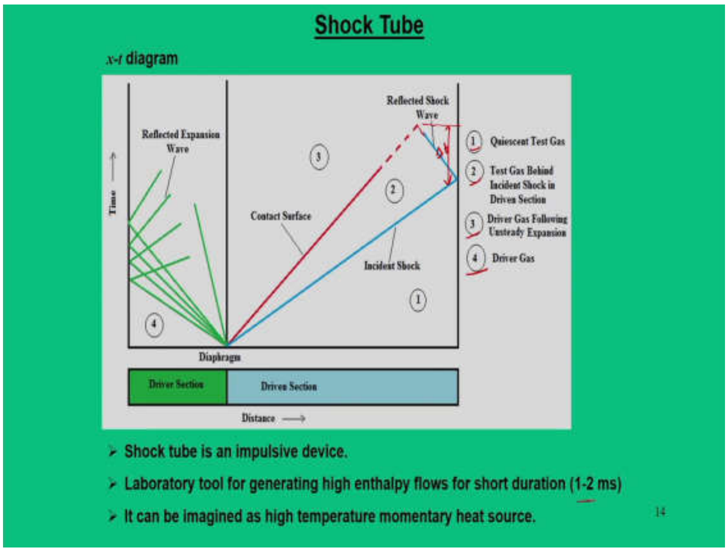
So, what may happen is that this reflected shock and goes and meets this contact surface. So, in this zone 2, we say we have test gas and if we plot a vertical line, so this is the time, ΔT. So, for this ΔT time, what we can see here that this test gas is exposed to both primary as well as reflected shock and its temperature becomes very high, pressure becomes very high and we call this a momentary reservoir or heat source.

Since, this pressure becomes p_5 that is 5 stands for region 5, temperature 5 stands for T_5, but this p_5 and T_5 conditions is attained for the time ΔT. And this is typically in our shock wave facilities is 1 milliseconds. So, what I can say that for 1 millisecond time, I can generate a momentary heat source using a shock tube.

Now, why this is 1ms time, because if you look at here beyond this time the test gas will be exposed to contact surface and that means, it gets diluted with the driver gas. So, test gas is no longer as whatever they are in the driven gas.

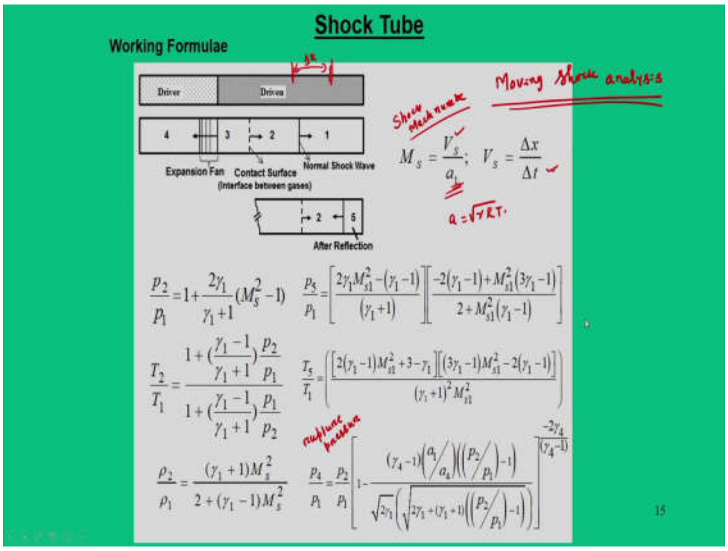
So, that is the reason we say this momentary heat source for a very short time. So, this is the basic philosophy that tells since time is involved here, so we say its impulsive facility and we say that it is a reservoir because the shockwave has made its pressure and temperature very high.

(Refer Slide Time: 44:01)



So, likewise I have explained here that shock tube it is a laboratory tool for generating high enthalpy flows for deviation of 1 to 2 milliseconds. So, it can be imagined to be high temperature momentary heat source. Here also another version of the diagram that explains about different regimes 1, 2, 3, 4 and it is the ΔT which is this.

(Refer Slide Time: 44:38)



Now, there are certain working formula. So, in fact, these working formula need not have to remember. So, what it says is that previously we have discussed about this moving shock analysis in one of the module, where we say that shock wave is moving and we are looking at in a laboratory frame. Since, it is a moving shock situation we define a term called as shock Mach number that is M_s that can be calculated from the speed at which the shock wave is traveling and speed of sound. Typically speed of sound is controlled by $\sqrt{\gamma RT}$. Here 1 stands for region 1.

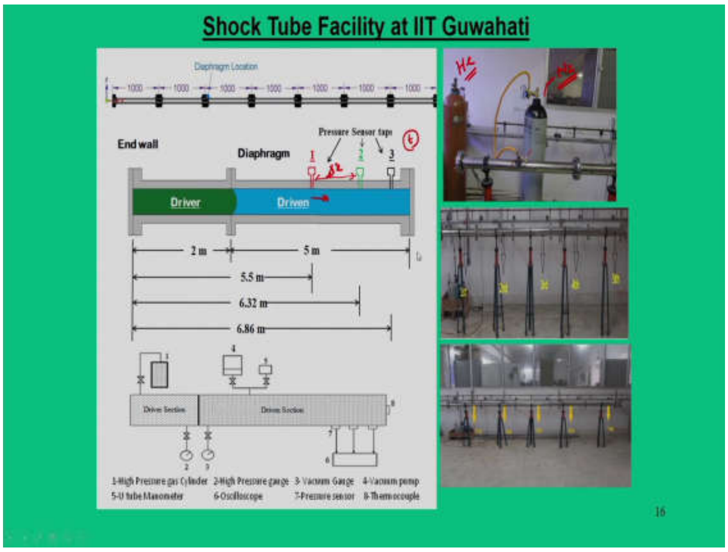
So, here one thing to be noted that whenever 2 is given, this 2 stands for this region, if I say 5 stands for this region, and likewise we can say the pressure ratio after the primary shock $\frac{p_2}{p_1}$, pressure ratios after the reflected shock $\frac{p_5}{p_1}$, temperature ratio after the primary shock, temperature ratios after the reflected shock, density ratios across primary shock and this is the pressure ratio of say $\frac{p_4}{p_1}$ that is normally called as rupture pressure.

What it says that all these ratios are obtained through moving shock analysis and we consider this as a working formula and no need to remember. Because all these parameters are derived parameters from this relation, but what measurement you require is that shock spee.

Now, to calculate this shock speed, normally we define since it is a one dimensional tubes we define two locations in a shock tube, where you mount the pressure sensors; once we know the two locations and you can get this Δx. So, this is the Δx. I can put two sensors that will give you time; that means, we can say that we can obtain the time by mounting some sensors which can let us know that when the shock wave is passing through that location.

So, Δt is known. So, we know Vs then we can find out shock Mach number. When you say shock Mach number, all the other derived parameters can be calculated.

(Refer Slide Time: 47:52)

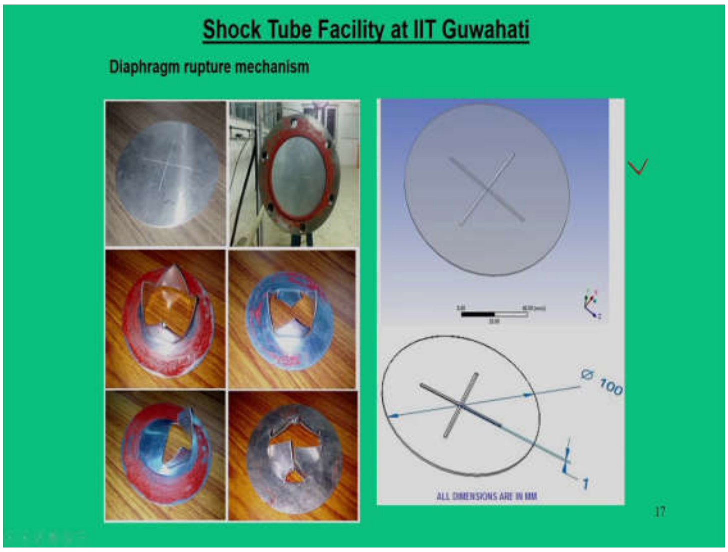


So, likewise we have a shock tube facilities at IIT Guwahati. And this is a 7 meter shock tube driver and driven, we have mounted 3 pressure sensors. You can see that the driver gas is filled with high pressure gas. In this photograph here, this particular cylinder refers to helium; this particular refers to nitrogen; that means the driver gas can be helium or nitrogen.

And in the downstream side we have vacuum pressure. We can see here in this figure, we have driven section is vacuum pump, where driven section is maintained at low pressure region. So, we have a high pressure regions, we have low pressure regions, and in the driven section there are 3 taps, 1, 2, 3.

We call this as a pressure taps where we mount our pressure sensors. So, because the prior to this we know these locations we call this as a Δx, and this pressure sensor will give the time at which the shock wave is passing through that sensor. So, having said this, we can get the shock Mach number.

(Refer Slide Time: 49:15)



Now, another important aspect of this shock tube that when we are talking about a shock tube whether really a shock wave is generated or not. So, this is ensured through a visual inspection and we put this diaphragm into picture. So, we have a very well designed diaphragm that is a circular diaphragm, and it has a kind of a groove which is triangular grooves, something of this sorts along this depth.

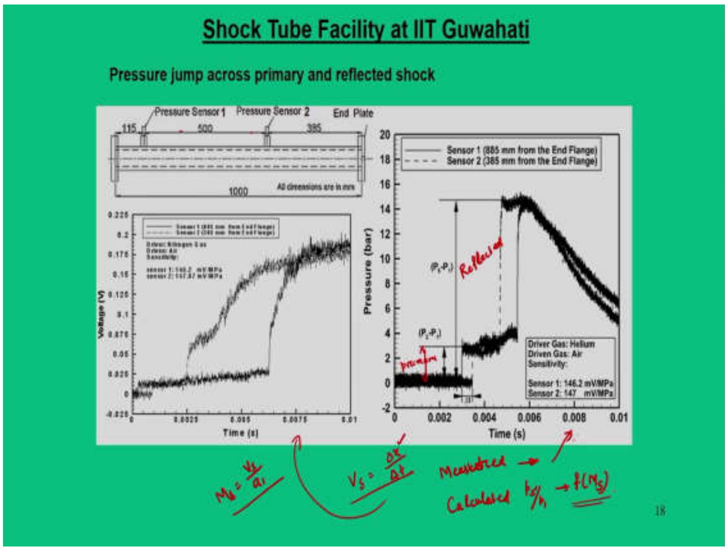
Why we made this groove? Because we want to rupture this diaphragm in a controlled manner, so that instead of getting it ruptured haphazardly it will rupture at one particular place and the rupture should be very instant because we say that the shock wave is the merger of all compression waves instantly. So, that means our ruptures should happen in this instantly.

Now, the original diaphragm with well-designed grooves and it is fixed between the driver section and driven section in this manner. Now, after we pressurize it ruptures. Now, when it ruptures, I have shown here 4 photographs of different rupture phenomena. So, if you look at that we have one situation where it is like a petal like rupture, just like a flower structure petals; all 4 petals that comes out uniformly.

But, whereas in another situation, this rupture is non-uniform. So, although we say it is a rupture, but this rupture is not due to shock wave, it is due to compression waves. And since we have not used a right kind of groove or right kind of logistics, so we are unable to rupture.

So, for this situation I can say although diaphragm ruptures we get the measurements, but those ruptures concept is not due to shock waves, but it may be due to compression waves. That means, all shock waves are compression waves, but all compression waves are not shock waves. It is a one particular instant. So, instantaneous rupture is shown like this petal like rupture.

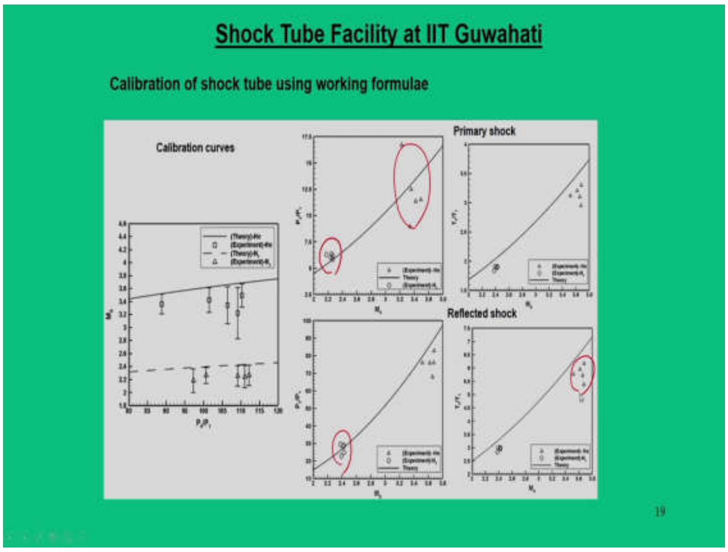
(Refer Slide Time: 51:59)



Now, once you say that we have ruptured uniformly then we can take the measurements. This is the typical voltage data. Voltage means we have pressure sensors here, we know the distance. So, these voltage data will give us the time, from the distance and time, so we say $V_s = \frac{\Delta x}{\Delta t}$. Δt we can get from this time axis and delta x is fixed by the pressure sensor location. So, we know the velocity of the shock wave.

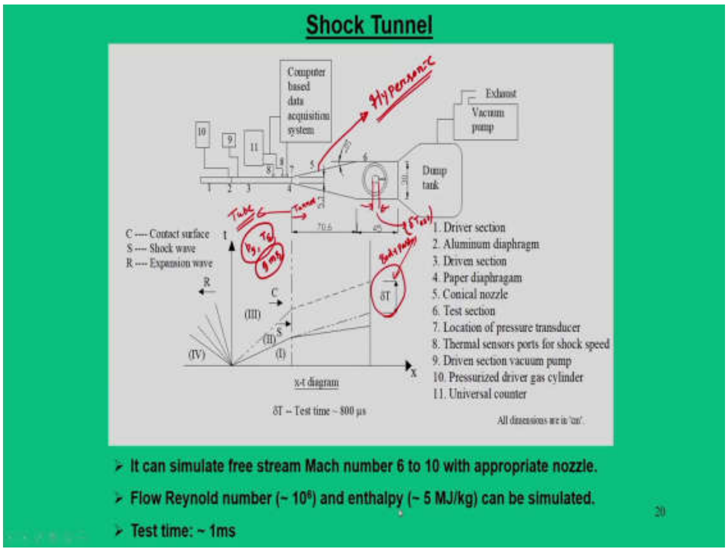
And these pressure sensors also measure the jump in pressure. So, we say $\frac{p_2}{p_1}$ that is due to primary shock, this is $\frac{p_5}{p_1}$ that is reflected shock. Now, we have two parameters, one measured parameter that is through experiment and we have calculated parameter. We can say $\frac{p_5}{p_1}$ is a function of Mach number. This Mach number we can calculate through shock speed and speed of sound. So, we have two data, one through experimental measure other is calculated measure. Then, you prepare the calibration curves.

(Refer Slide Time: 53:39)



There are variety ways that we can plot the calibration curves of Mach number versus rupture pressure ratio, we can have primary shock, $\frac{p_2}{p_1}$, $\frac{T_2}{T_1}$, we have reflected shock $\frac{p_5}{p_1}$ and $\frac{T_5}{T_1}$. And if you see that the solid lines indicates the theoretical curve and the the points that we are looking at, these are the experimentally measured points. So, in some cases our predictions are under predicted, it all depends on the accuracy in the experiments.

(Refer Slide Time: 54:23)



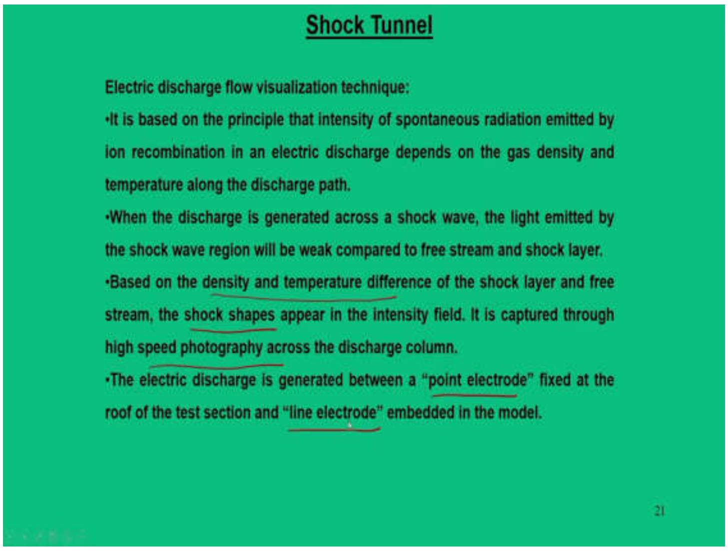
Now, I will move further to give some introduction to a shock tunnel. So, we discussed about the shock tube exhaustively. Now, a shock tunnel is nothing but we attach a nozzle and test section. So, we have two parts here, one is tube part like we have a shock tube part and we have tunnel part.

So, as I mentioned, this tube part will give me a momentary reservoir conditions as p_5 and T_5 for 1 millisecond durations. Now, what I do? This reservoir conditions, I try to use a nozzle to expand the flow. Now, when I use this conditions to expand the flow and put a model here, then I can get desired Mach number. So, by using this nozzle we can get hypersonic Mach number because shock tunnels are referred as impulsive facilities and for hypersonic Mach number applications. We can put the model and do our testings.

So, likewise we say this is the test time which is available to us that is ΔT, and we can say this is the length of the model which we are using and we say it is ΔT flow establishment time. And a definite ratio between these two is the body pass that I have explained.

Apart from this, there are other ancillary requirement that we need to have a vacuum pump, we need a very high end vacuum pump to evacuate this, to keep this conditions alike. And we call this particular facilities as high enthalpy facilities.

(Refer Slide Time: 56:42)



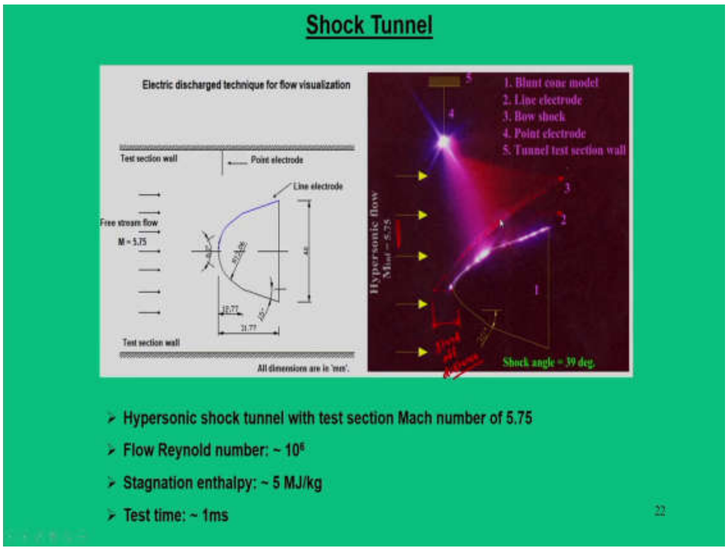
Now, I will just conclude this shock tunnel topic with one particular technique which is a kind of a electric flow visualization technique, that whether really a shock wave appears or not. So, one such visual experiment we did with a flow visualization technique, and this method we call it as electric discharge method.

It works on the principle that intensity of spontaneous radiation emitted by ion recombination in an electric discharge depends on the gas density and temperature along the discharge path. I will explain it how it happens.

Then, this discharge is occurred across a shock wave, and we know that across a shock wave there is a density and temperature difference. Now, when there is a density and temperature difference, and we create a discharge, we use high speed photography to capture that flow path. So, this capturing flow path we get the shock shapes in this intensity field.

Now, to create the discharge we need two metallic electrodes, one we call this as a point electrode, other is called as a line electrode; line electrode is embedded in a model.

(Refer Slide Time: 58:15)



So, what we see here is that a model which is mounted in the test section. So, this entire domain is the test section wall, on the test section wall there is a point electrode, and matching to this a line electrode is embedded on the model surface.

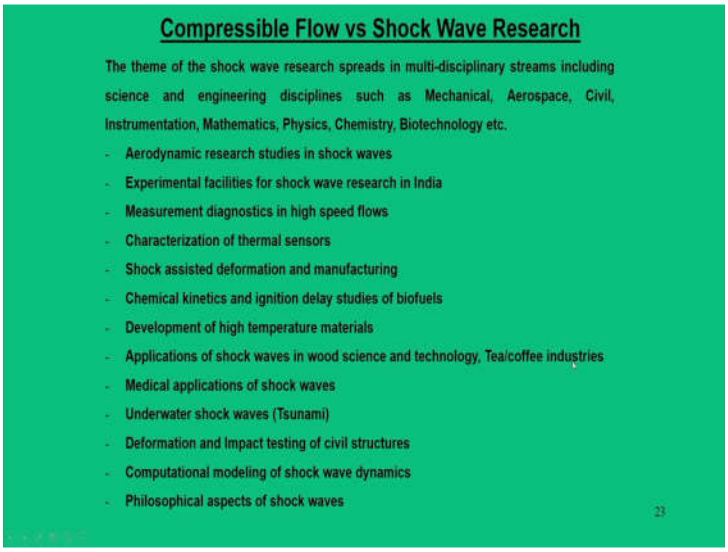
Now, between this line electrode and point electrode, we create a very high electric discharge or you give a high voltage source and when the flow is exposed to hypersonic flow and simultaneously we create a discharge, this appears as a glow and when there is glow appears, we can capture that as a image in a photograph through high speed photograph.

So, as I can see that there are glows that is appearing and we can see a structure of a shock wave pattern and typically we call this as a bow shock for this model. And with this philosophy it gives a visual indication that really shock waves appears in a supersonic flow and in fact this Mach number here is about 5.75.

So, for 5.75 Mach number, we can see a bow shock that is appearing from this point and it goes along this body part. And we say this shock is a detached shock. It is quite obvious and this is what we call as standoff distance. Why we say it is a detached shock? Because the body is blunt, and for which the oblique shock solution is not possible, so we will have a detach shocks. So, this gives a visual indication about the formation of shock wave on a blunt body.

In fact, I started this lecture with this photograph and gave my introduction lecture that we can visualize a flow path. Now, I am closing this lecture with same figure about explaining that through using appropriate flow visualization technique one can capture the shock waves. And nowadays, there are many advanced equipments or instruments available such as Schlieren method, shadowgraph methods to have a continuous mode of evaluating the shock wave path.

(Refer Slide Time: 61:08)



So, with this I will conclude this lecture as well as this module and as well as the complete course. And finally, my overall remark would be that we have discussed about the compressible flow fundamentals and all aerodynamics principal work on this compressible flow phenomenon, but in turn one particular aspect is shock wave which is a very critical phenomenon in a compressible flow research.

But, however, the area of shock wave research is not limited to mechanical or aerospace streams, but it is spreads in variety of multidisciplinary area, as far as shock wave research application is concerned. And, more or less I can say that only mechanical and aerospace streams they are get exposed to all fundamentals subjects on compressible flow. But people working in the shock wave research in the area of instrumentation mathematics, physics, chemistry, and they are not aware of the fundamental side of the compressible flow.

In this regard, this course is very beneficial and hope in addition to the parent's streams of mechanical aerospace this course is also very useful for those people who are people of civil, instrumentation, mathematics, physics, chemistry, biotechnology, those who are working in the shock wave research.

Now, what are the particular topics in the shock wave research that can be attempted? First few things are only based on aerodynamic measurements, where we say aerodynamic research, experimental facilities for stimulating high altitude conditions, measurement diagnostics in high speed flows, characterization of thermal sensor. Here you introduce another topic shock assisted deformation and manufacturing; that means, shock wave research has entered into the manufacturing area.

There are chemical kinetics and ignition delay studies for fuels. So, here we are chemistries and people in the area of alternative fuels, they are also part of it. Then, there are situation like that shock wave give instantaneous rise in the temperatures. So, people are talking about high entropy or high temperature materials. So, materials area also is a part of it.

And many people they work in bioscience and bioengineering, so in this case that shock waves in the wood science and technology, tea and coffee industries, very potential applications. People working in medical area we call this as a medical application of shock waves, like using shock waves as a injection mode to the human bodies.

There are civil people who can work on the area of underwater shock waves; that means, tsunami behavior if can be also modeled. Then, we have deformation and impact testing of civil structures. Apart from this in the end we have computational modeling and there are some psychological aspects of shock waves where human minds are also controlled.

So, the areas research areas are many, disciplines are multidisciplinary, but the course is start only in for the people of mechanical and aerospace in their parent syllabus. So, with this philosophy, I hope the compressible flow in this particular module is very vital to get the fundamentals of the shock wave research.

With this I will conclude my module as well as the topic and the course. I hope I have attempted all your queries or answers in this course.

Thank you, and best wishes.