Gasdynamics: Fundamentals and Applications
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Lecture 37
Experimental facilities

So, we have discussed about nozzles and diffusers these are various varying area ducts. And one application where this is extensively used is in the design and operation of experimental test facilities aerodynamic facilities. So, even one designs any aircraft or objects moving in air having very high velocities then one has to understand the various forces or the flows around these bodies.

And the way it is done experimentally is by designing wind tunnels that can create such flows.
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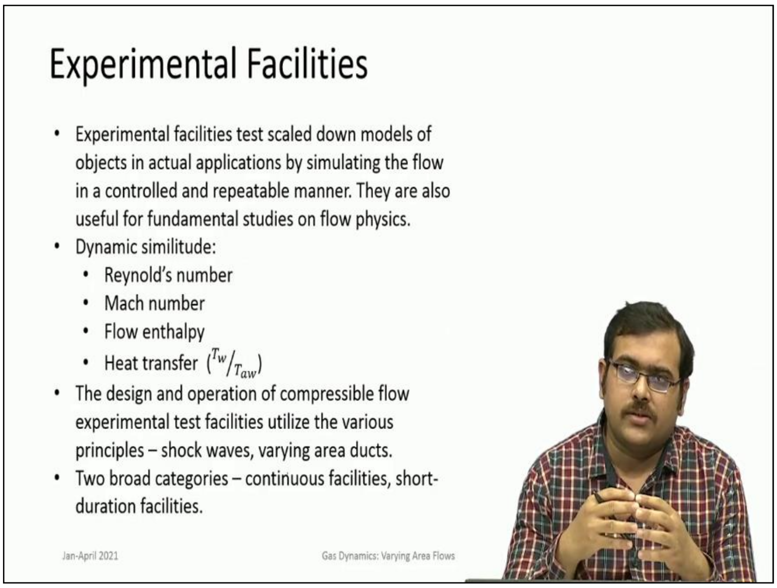

So, ideally what is done what happens in practice is that you have a body moving in air maybe an aircraft it can be if maybe a rocket may be a launch vehicle or it can also be aircraft transport aircraft or military aircraft they can go on various Mach number ranges. So, but they are all very big. So, you cannot test them directly in wind tunnels very difficult because of their size.

So, usually what is done is their size is kill down and we also use the approach that instead of having the body moving at a particular velocity we keep the body stationary and allow the flow to happen at the same Mach numbers that the body is flying. And then in steady flows. we should be able to get when everything is steady then we should be able to get the forces and moments from these tests.

And that can be used as data towards designing these kinds of objects. So, here we produce the flow in a very controlled and repeatable manner. And these are also useful to study in a fundamental way what is happening to compressible flows. But when you look at simulating such i mean trying to put objects which are there in real flight you want to put it inside the wind tunnel you obviously have to bring down the scale.

So, they are scaled down models then in order to see that the results from the wind tunnel do hold good even in actual scenarios. There is certain sort of care that should be taken and these are done through what are known as dynamic similitude you have by scaling the model you have maintained the geometry in a scaled fashion. But that is not sufficient you should ensure that the forces are also scaled in a certain way commensurate way.

And this is done by a Buckingham Pi analysis that would have been covered in fluid dynamic classes. So, we talk about various non dimensional numbers Reynolds number, Mach number. But in compressible flows both Reynolds number and Mach number are important we should be getting same Reynolds number and Mach number. Besides that there are other issues like flow enthalpy.

So, when you take certain objects which are flying at very high speeds say Mach 6, Mach 7 or there are objects which are re-entering the Earth's atmosphere then these objects fly at very high speeds. And when flow comes on to these bodies then the kinetic energy of the flow gets converted to enthalpy or internal energy then temperatures can go really very high. So, then at that point some things change in the flow because of certain high temperature effects.

So, while maintaining Reynolds number and Mach number the same is important. So, that there is dynamic similitude we need to simulate the flow enthalpy also, so that effects like high temperature effects can also be simulated. Then if you want to see that heat transfer is also being simulated especially in high temperature flows. Then you are also requiring certain temperature ratios that fluid at the wall and of the wall itself.

So, these ratios are maintained in a certain fashion. So, it is not just that we have a particular facility and we can do a certain tests it is that we have to maintain all these parameters. So, that results obtained in the test facilities are useful and they can be transferred to the real flights also. So, there are challenges involved here. So, when designing such compressible flow wind tunnels then obviously we use a lot of principles of varying area ducts shock waves and how they interact.

So, now we will see a few sorts of principles first principles of about these wind tunnels. Generally they are categorized as continuous flow facilities and short duration facilities.

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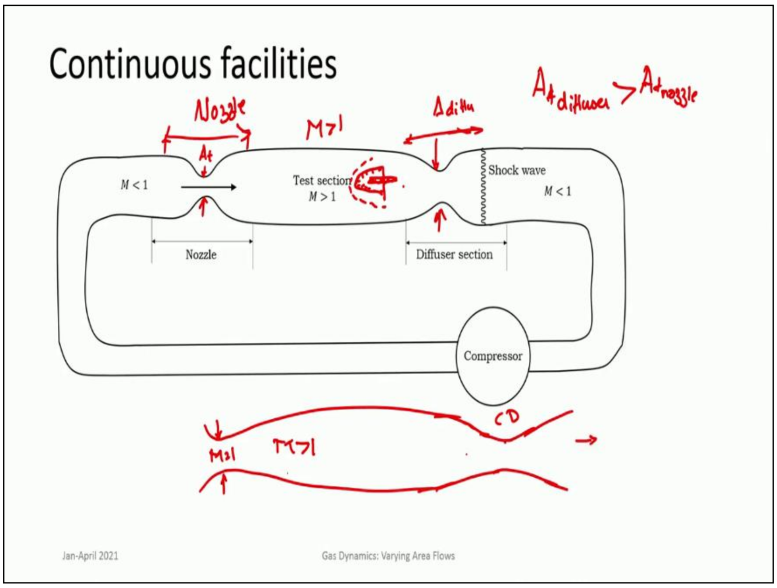

So, for example this is a schematic of a continuous flow facility we know now that to produce a Mach number which is greater than 1 you need to provide significantly higher pressure. So, pressure ratios across the nozzle. So, this is a nozzle nozzle block. So, you have nozzle. So, nozzle converts the a subsonic flow to a supersonic flow which can be maintained in the test section.

So, this is a test section where you can place a model for example some model like this can be placed and you can have instrumentation to do various measurements on this model if this is supersonic you will have a shock wave around it and you will observe all these flow phenomena you can measure pressures you can measure temperatures measure forces and. So, on and after the flow passes over the model it is diffused it is pressure is recovered in a diffuser section and the velocity is brought down this is done.

So, that we can save some amount of energy because to operate these kind of facilities you need huge amounts of energy to produce the pressure ratios which are very high some of the examples we were seeing say Mach 2, Mach 3 the pressure ratio required increased very quickly. So, to provide the pressure ratio in a continuous facility like what is shown here you will have a compressor which operates continuously.

This a bare bone schematic it is like a skeletal structure there are lot more intricacies to these wind tunnels but the essential features are a nozzle and a diffuser and the test section. So, diffuser converts this supersonic flow to subsonic flow. And now here you should make note of this difference in the throat of the nozzle see this is A throat of the nozzle and you look at the throat of the diffuser this is A throat of the diffuser.

But you can observe that a throat of diffuser is greater than A throat root of nozzle you should ask the question that why is it. So, if I take this duct I have Mach number becoming greater than 1 here and then again I have to convert when I have to convert back its another CD duct and here Mach number is 1 at the throat Mach number is equal to 1. Mach number becomes greater than 1 then while coming back it should again go back to one and then further diffuse.

So, then if that is the case these two area ratios should be the same but that is not the case and we discussed this that the problem with diffusers is that you should handle the starting problem. When the spin tunnel is about to start then you always do not have the exact operating conditions. So, we know the nozzle of starting operation characteristics initially it will be fully subsonic thereafter you get shock waves and then they move out into the test section.

So, this problem where you get shock waves in the test section is what decides how the diffuser should be designed. So, it is not always that the throat area of the diffuser will be equal to the throat area of the nozzle.

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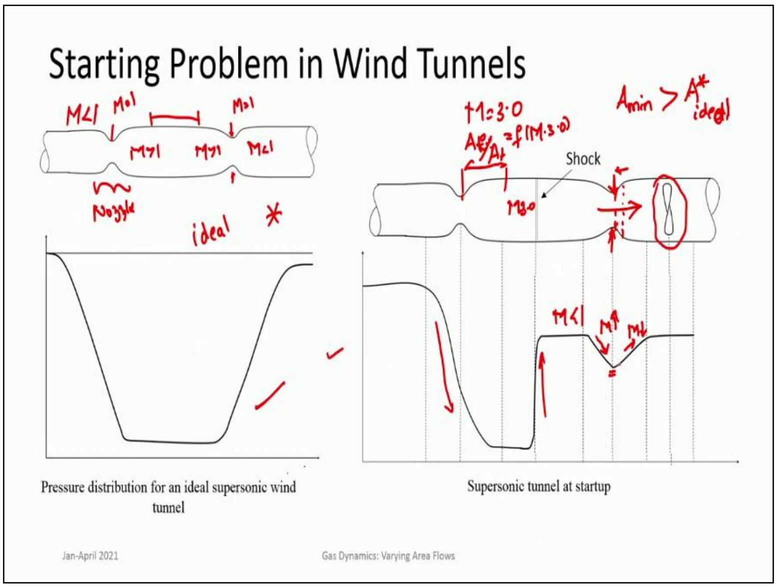

Now the amount of energy required to, run such continuous facilities for long times is very huge. So, as a consequence most of the places what they have is usually an intermittent type of wind tunnel where they have large high pressure tanks. A compressor is used to fill these high pressure tanks over a longer duration of time this ensures that you can do this compression effectively and store it in large tanks.

It is very similar to having a rechargeable battery and then when required this flow is passed through a nozzle and into the test section. But the point is that this, whatever high pressure that you had stored in such pressure vessels in such reservoirs is limited. So, this cannot be run continuously it will be for a smaller duration of time but still the duration of time that we talk about in such blow down type wind tunnels will be in the matters of tens of seconds or few minutes.

So, it is of that kind but it will not be hours or long duration like that of the continuous facility. They are of three kinds one is you can have a high pressure storage and then pass it through a nozzle and then you have a test section and then this is exhausted right into the atmosphere or ambient after properly reducing its velocity by a diffuser. That kind of wind tunnel where only high pressure systems are used they are known as blow down type wind tunnels.

Since pressure ratio is important you can now understand that is for area for varying area duct is the pressure ratio that is important to produce a certain Mach number and really not the absolute pressure. So, you could provide the pressure ratio by giving a higher pressure upstream. So, you can give a higher pressure upstream here that is P_0 is very high or you can also do the same thing by maintaining low pressure downstream that is what is done here P_b back is reduced.

These types of internals are known as in draft maintenance they take atmospheric air draw in atmospheric air. So, $P_0 = P_{atm}$ but they have very low vacuums in large vacuum tanks and then a nozzle is used to produce the required flow in the test section. Why do we need different kinds of facilities we need to get different Reynolds numbers and Mach numbers Reynolds number is $\frac{\rho V D}{\mu}$.

So, in a compressible flow both $\mu, \rho\ and\ V$ all of them are variables and D is a typical dimension. So, in certain kind of facilities you get certain Reynolds numbers in some other kinds you get a different Reynolds numbers. So, you can combine the benefits of both of them and have a pressure vacuum driven wind tunnel where you have both high pressure and vacuum on either sides. So, this is also possible.

So, if you look at the operating characteristics of these wind tunnels. So, this here we come into variable area ducts and shocks and how they interact as we had said before an ideal case of an internal operation is when you have the flow that is $M < 1$ this is the nozzle block. So, flow is less than Mach number is less than 1. So, in nozzle then it accelerates, pressure reduces you have Mach number 1 at the throat.

And then you have the test section here in this region and after the test section the flow diffuses from Mach number greater than 1. So, here Mach number > 1 , to Mach number less than 1 if this diffusion is ideally carried out without any shock then Mach number here should be 1. . This is the ideal case if you think about it this is the ideal case.

But the problem here is that during starting of these wind tunnels shocks are developed at the nozzle because nozzle starts and the pressure ratio is not always ideal. So, as it is starting it will develop shocks within the nozzle and ultimately these shocks come into the test section. So, the strongest possible shock that can come in is for the designed operation. So, for example if this Mach number in this section is Mach number equal to 3 the area ratio to be provided across the nozzle will be corresponding to that is a test section area or $\frac{A_{exit}}{A_{throat}}$ will be corresponding to Mach number 3.

So, corresponding to that you will have this area ratio. And but if a shock the strongest possible shock that would exist will be if it exists at the test section then Mach number is 3 Mach number is three exactly 3 and then you have the strongest shock this shock can come within the duct. If the diffuser was designed such that it would support only ideal operation then we have already discussed that a shock that stands at the entry of the of a converging divergent diffuser if it has to be pulled inside then the area ratio at the throat or at the throat of the diffuser cannot be that for an ideal operation.

The area ratio has to be or the throat area or minimum area of a diffuser will be greater than the ideal operation A^* . So this is the main criteria by which such design of wind tunnels is done design of diffusers of internals is done. So, that you get what appropriate Mach number is required within the test section you get that Mach number inside the test section. So, that way this shock is able to be pulled out of this test section.

It can either stand somewhere in the diverging passage or at the throat the maximum possible upstream direction that the shock can take is at the throat, so, during startup if you look at the; pressure. So, this is pressure distribution for ideal case where there are no shocks now this is during startup you can have a shock at the test section. So, across the nozzle there is a smooth decrease of pressure but there is a shock at the test section.

So pressure increases this is subsonic. So, Mach number is less than 1. So, then it sees a varying area duct CD duct first it decreases the Mach number increases it reaches the minimum area but then it will not reach Mach number 1. So, therefore further diffusion happens. So, Mach number reduces here and pressure will increase diffuser is useful.

So, that the various systems that you are providing say high pressures or there is a fan or compressor you can keep the work done minimum by ensuring there is a pressure recovery otherwise it is the amount of energy required will be much higher. So, this is during startup at the startup this will be the case.

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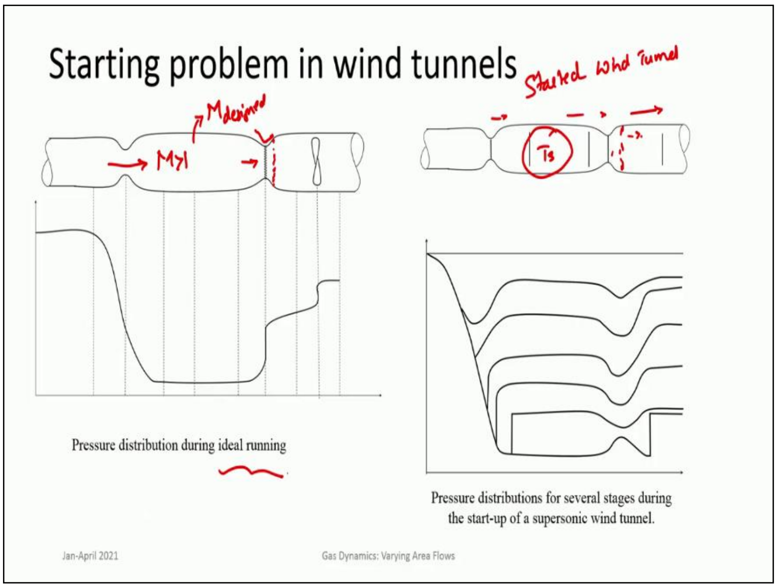

And during ideal running the operation then what is expected is that you have a shock free flow that is Mach number is greater than 1 after the nozzle it has achieved design Mach number. So, been designed and when diffusion happens in the diffuser the minimum possible shock because shock now that we cannot do away with the shock in the diffuser. But what we can do is reduce the strength of the shock.

So, because shock is entropy generating it reduces the efficiency of the device. So, if you have minimum possible shock strength then the device is more efficient and that is possible at the minimum area because there the supersonic Mach number is minimum. If the shock stands in a diverging passage at some other point here then it would have decelerated to the minimum Mach number.

But again accelerated to much higher Mach numbers and the shock standing in the divergent portion will be much stronger. So, ideal running condition is when the shock is at the minimum area of the wind tunnel so, diffuser of the wind tunnel a CD diffuser. So, putting all these ideas together you can see the various ways in which the operation of internal takes place from startup.

The shock actually progresses all the way from the nozzle to the diffuser and then it is stationed either at the throat or station the way in the divergent passage. So, to ensure that this shock does not stand in the test section, so, this is known as starting of wind tunnel or started wind tunnel to ensure that we have to see that this area of the diffuser is higher than that of the nozzle but the exact conditions can be calculated. So, this is a very important point in this operation of wind tunnels.

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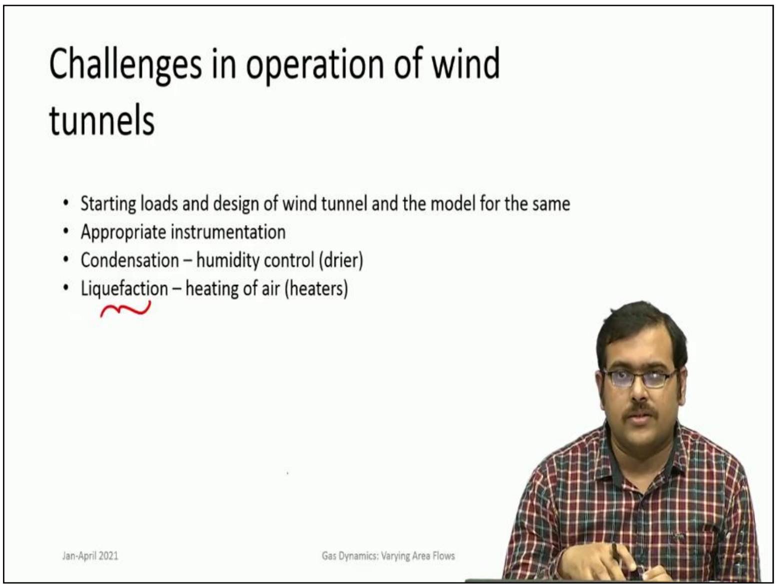

So, guiding principle we have discussed it is $P_{01}A_1^* = P_{02}A_2^*$ where $\frac{P_{02}}{P_{01}}$ is the stagnation pressure ratio across the normal shock. Besides these points there are other challenges also in wind tunnels one is. So, now we know that you have to design for starting that means initially you have to give much higher pressure. So, that the nozzle starts the diffuser starts and the internal operates.

So, that is known as a starting load. Starting load that you have to give or starting pressures that you have to give the wind tunnel. So, that it achieves starting is quite high. So, if you are putting some models inside and you want to test them then you have to design them for much higher pressures than their operating ideal running pressures of the wind tunnel. So, these are certain challenges.

Similarly the challenges are there for instrumentation not only that. these supersonic wind tunnels you see that when Mach numbers become high not only does pressure drop temperature also decreases rapidly. So, you have other challenges coming in if there is any humidity in the air that you are using that will condense. So, that can cause problems in the internal whatever test that you are doing. So, humidity control becomes important you need dryers.

If Mach numbers become higher then it is also possible that pressure temperatures reduce. So, low that air itself may liquefy. So, those problems also occur. So, they are liquefaction that time you need to heat the air. So, having an operational wind tunnel involves not only aspects about nozzles diffusers but also various other accessories to see that the wind tunnel operates correctly.

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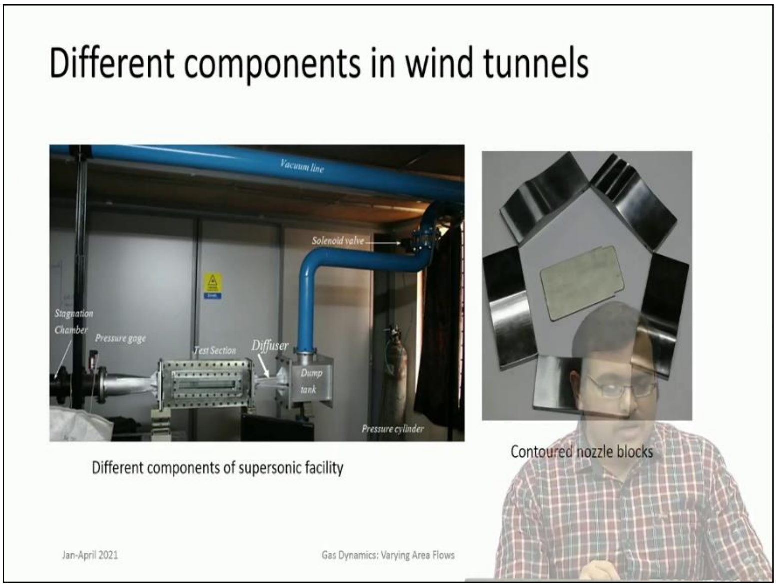

So, here are some images of wind a very small wind tunnel in Indian Institute of Science. So, you can see the test section here before the test section there is a nozzle block which is internal we cannot see it. And before that there is a stagnation chamber and this is the diffuser section going into the dump tank and then from there it goes all the way outside to the vacuum line.

And these are nozzle blocks they are specially designed. So, that the flow is uniform within the internal they are known as contoured nozzle blocks and we can do this design using certain special tools which we learn in later classes.

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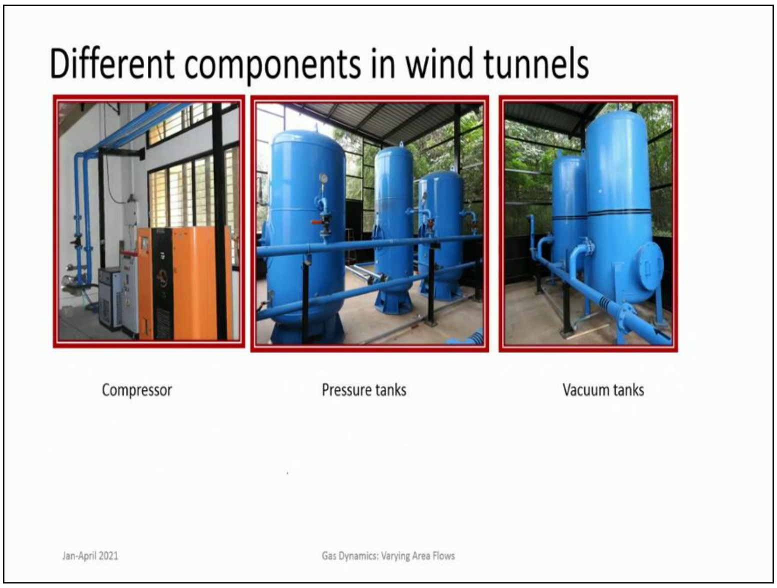

So, these are the high pressure tanks compressors, dryers, high pressure tanks and vacuum tanks. So, you need good amount of storage to run even for a few seconds.

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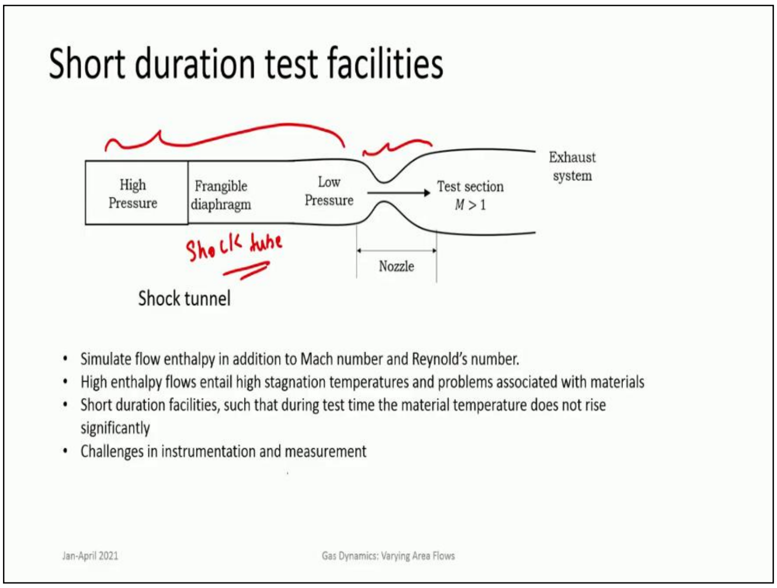

Now the we come to short duration test facilities. These test facilities are required because when we go to very high Mach numbers then we need to simulate not just Reynolds number Mach number but also flow enthalpy that means temperatures are high stagnation temperatures. But when stagnation temperature becomes very high then you have a problem of the materials becoming heated of the wind tunnel it becomes very hot and they may not be able to withstand the high temperatures.

So, the way to go about such a problem is to reduce test time to very small values. And this is achieved by combining a shock tunnel which can produce a shock tube which can produce very high pressures and temperatures to a wind tunnel by means of a nozzle. So, this is a shock tube we discussed this shock tube in early parts of this course, and this is a nozzle attached to the shock tube and finally the exit part is the test section.

So, here the problem is that the test times become very small in the ranges of milliseconds not in seconds. So, there is challenge in instrumentation and measurements at very small times. But with adequate sort of advanced facilities it can be done very well. So, that is possible.

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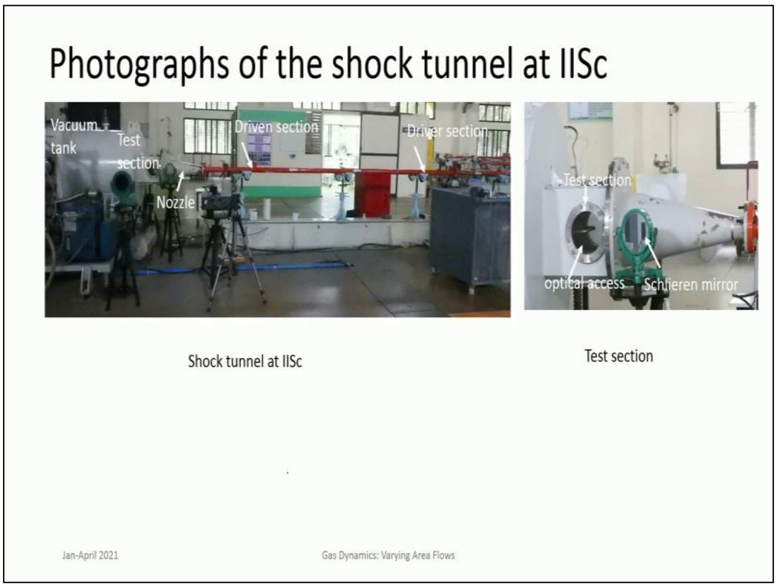

So, here you have the photograph of a shock tunnel at Indian Institute of Science and there is a driver section which is filled with high pressure and a driven section which is at lower pressure and a diaphragm is situated between these two. And when appropriate pressure ratio is achieved across the driver and driven this diaphragm bursts a shock is produces travels in the driven section compressing the gas.

And then further that high pressure high temperature gas is expanded through a nozzle into the test section. So, this is the expanded view of the test section of such a typical tunnel. So, with this an introduction about various test facilities for compressible flows high speed flows is given. And also, some photographs of such facilities in Indian Institute of science have been explained.

So, now let us look at some simple problems on diffuser starting because that is very important to understand about supersonic diffusers. In next class we will do a few problems on diffuser starting, thank you.