Gasdynamics: Fundamentals.. And Applications
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Lecture 55
Hypersonic Flows – I

So, we have covered Compressible flows in fair detail, the basics of them and applications of them. We have gone through both integral or control volume kind of approaches and then differential equation kind of approaches. We had fair amount of understanding of Compressible flows. We know what shocks are. What are Expansion fans, and so on. So, but now we can look at some specific topics.

Some special topics where few things go beyond what we have learnt in a normal course of Gas dynamics and introduce you to such topics which are also topics of research and then if further on you are interested in those topics you can learn more. So, the first topic that would like to look at is Hypersonic flows. So, we know what is Subsonic flow? The definition is Mach number should be less than 1.

We know what is Supersonic flow definition for that is Mach number should be greater than 1, what is Hypersonic flow? What is so, special about Hypersonic flow? Hypersonic flows are also flows with high Mach numbers that is Mach number is greater than 1 but they are of much, much higher Mach numbers than moderate Mach numbers like 1, 2, or 3. Generally what is considered is Mach numbers > 5, that is a general description that Mach number greater than 5 can be considered as Hypersonic flow.

But really there is no hard and fast rule that this is the exact demarcation between Supersonic flow and Hypersonic flow.

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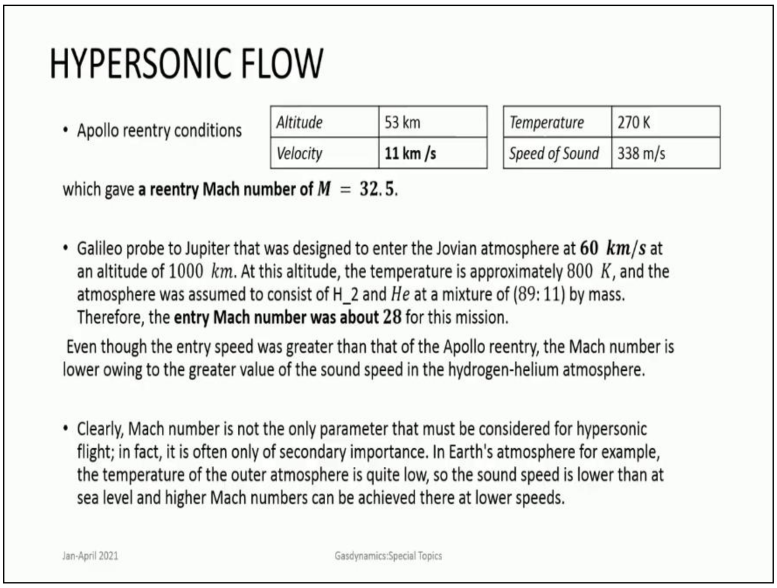

Hypersonic flows are important in several cases especially for cases involving travel to space and return and so on. But even nowadays people are also looking at Hypersonic flows at lower altitudes. Usually when a spacecraft goes into orbit, or for example, we had many such missions where they go into orbit and come back, the orbital velocity is approximately 8 km/sec, and you return.

An example is given here of the Apollo missions, that the US had carried out there at an altitude of 53 kilometres, the velocity was 11 km/sec. Speed of sound at that altitude is 338 m/sec. So, if you calculate Mach number it is a very large number 32.5. The Mach numbers of this nature are often encountered during re-entry. But we also must ask the proper questions whether we can actually define what a proper Mach number is at these particular conditions because there are many things that happen in a Hypersonic flow.

So, similarly if you consider other planetary atmospheres for example the Galileo probe to Jupiter that also the entry Mach number was around 28. So, that is in a different planet. So, in general if you consider these kinds of missions, they will have very, very high Mach number. Now can we then describe things only based on Mach number is something that we have to understand.

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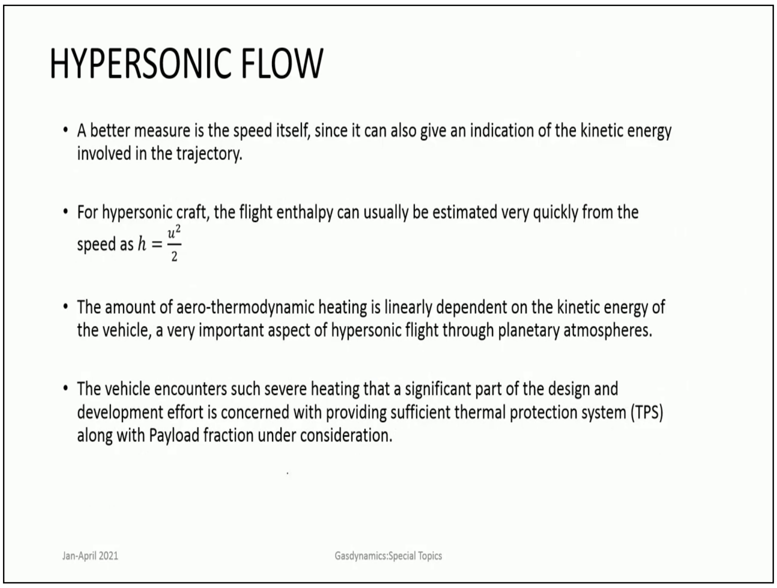

Mach number in general, it relates how the kinetic energy of the flow is related to the internal energy of the flow itself. So, as Mach numbers increase very quickly, we find that the kinetic energy contained in the flow can be as high as the enthalpy of the flow itself. Now in that case if such a flow which has very high kinetic energy been made to slow down, which happens when a body enters atmosphere, at very high Mach numbers.

Then on the surface of the body, the flow must match the body's velocities, or it must come to a relative stop at the body or it has to come to stagnation. Then all that kinetic energy will be converted into heat energy, then the amount of heat that it produced is very high, the temperatures can become extremely high something of the orders 5000 K or 10000 K. So, it can be very, very high and that means that such bodies at their noses can face very high temperatures and significant heating.

So, what we find then is that what we call as Hypersonic flow is not only just about Mach numbers. There are some things which happen different in Hypersonic flow there are some physical flow features or some flow physics that enter that we generally do not consider in a supersonic flow. Though there is heating in supersonic floors that heating is relatively insignificant when you compare it to cases where Mach number is very high, like 38 25 and so on.

In such Hypersonic flow cases always, we must protect the vehicle thermal protection system is important and it plays a dominant role in deciding what is the weight of the vehicle how much payload it can carry and all such things.

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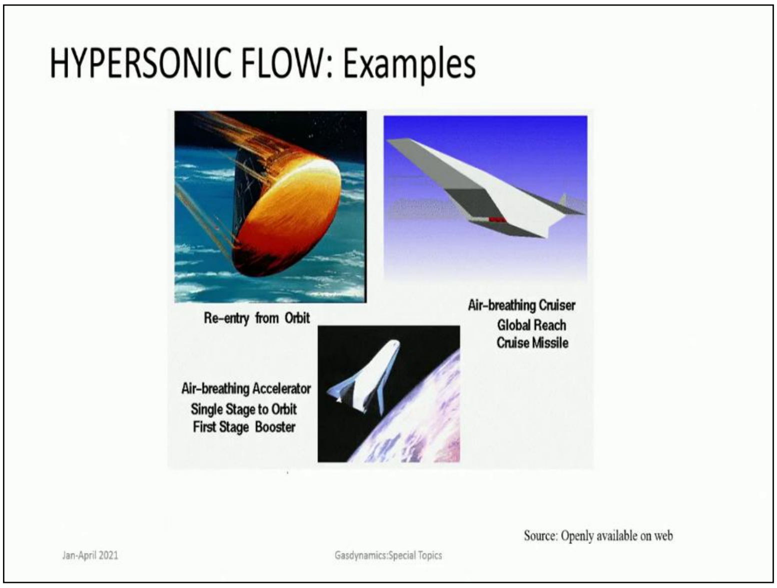

So, examples of such these are taken from what is available in websites or on the open web. So, one is case of some re-entry of some capsule it can be containing humans or some experimental capsules as they enter the Earth's atmosphere, they undergo significant heating which is also shown over here. The other case is that of different novel applications that people are looking at one is looking at very high-speed cruise vehicles that can be looking at travelling across the globe in short durations.

Or the other one can be using single now normally if you consider any rockets, they carry both the oxygen and fuel within themselves and they go up and usually it is consumed the rocket is also not readily recovered. Though nowadays there are technologies to recover the launch vehicles. But people have been thinking of situations where they can develop vehicles which can be reused again and again in that case such vehicles will go through Hypersonic flows as they go out into space and come back.

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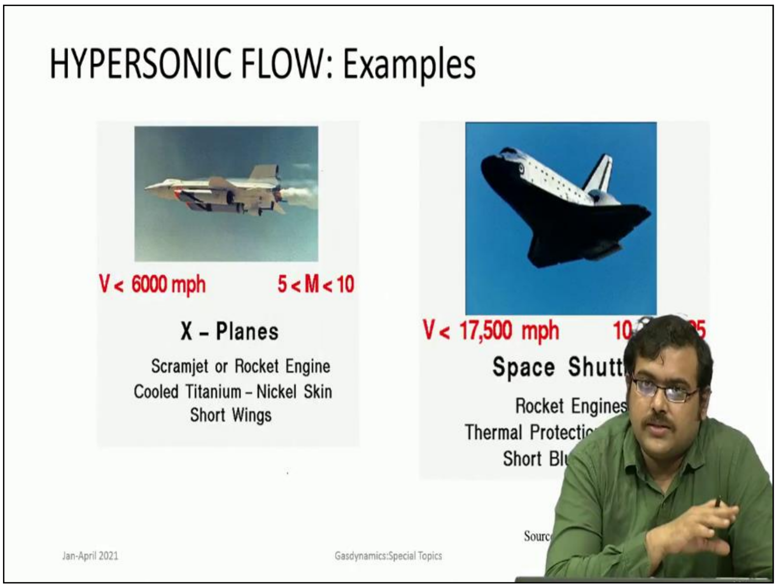

Now if you just look at how these vehicles are. For example, here you have a typical research vehicle which is supersonic in nature its Mach numbers are significant but not very high. If you look at the way they are designed they all have sharp surfaces they have good materials but still made of titanium and such high temperature materials. But essentially sleek body with thin wings.

But if you look at another example, which is many of you would be familiar it is the space shuttle this is also this has similar structures to the previous example, but you look at the shapes they are all rounded they are all blunt. And there is a significant black portion underneath which is all thermal protection this goes through severe heating as it re-enters the Earth's atmosphere.

Also significant is that most of the sections are blunt it is not sharp. So, just the design of vehicles that fly in Hypersonic regime and supersonic regime they are completely different.

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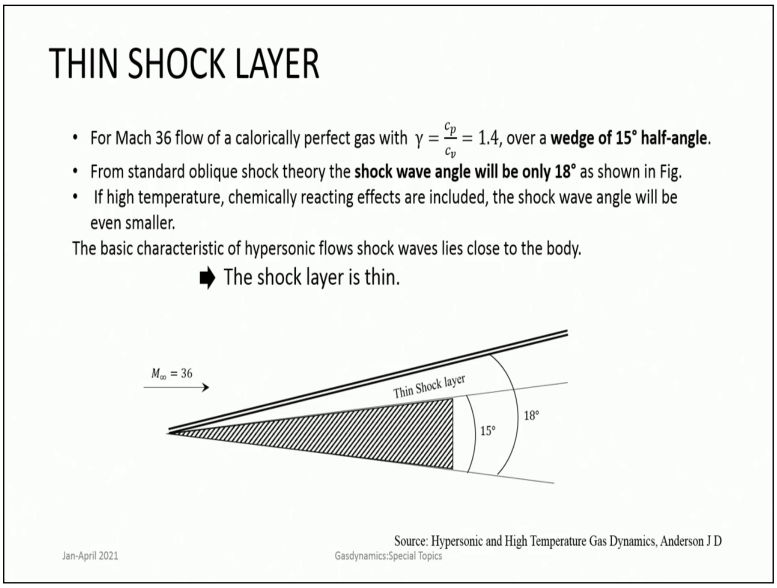

So, what are these additional flow features that come into picture in Hypersonic flow? So, just by saying that Mach number is greater than five it is not enough to describe Hypersonic flows and most of these descriptions is described very well in the textbook by Anderson on Hypersonic and high temperature gas dynamics and these descriptions are mainly taken from that textbook.

So, if you consider for example a very thin wedge of angle 15^o and very high Mach number say max 36, what we were considering earlier just consider for the sake that the gas is a perfect gas and gamma is 1.4. We find that the angle of the Oblique shock that this wedge makes is 18^o. Now the angle of the wedge itself is 15 ^{o} and the shock wave is at 18 ^{o} that is not very far away from the body.

So, that means that the shock is very, very close the body and across the shock there is a sudden jump in pressure temperature density and so on. Very high temperatures can be encountered in this small region between the shock and the body. If temperatures go very high then high temperature effects come into picture, where the air that we know as a mixture of Nitrogen, Oxygen mainly and other species like CO_2, Argon and so on.

But mainly Nitrogen and Oxygen as molecules it does not remain as this mixture anymore rather it undergoes several chemical reactions at higher and higher temperatures. So, you find that there are high temperature effects that come into a picture at these high speeds and that happens very close to the wall that means now heat transfer into the wall becomes very important. So, one basic character of Hypersonic flows is that shocks are located very close to the body and sometimes it is called as a shock layer, thin shock layer. So, shock located very close to the body is 1 characteristic of Hypersonic flows.

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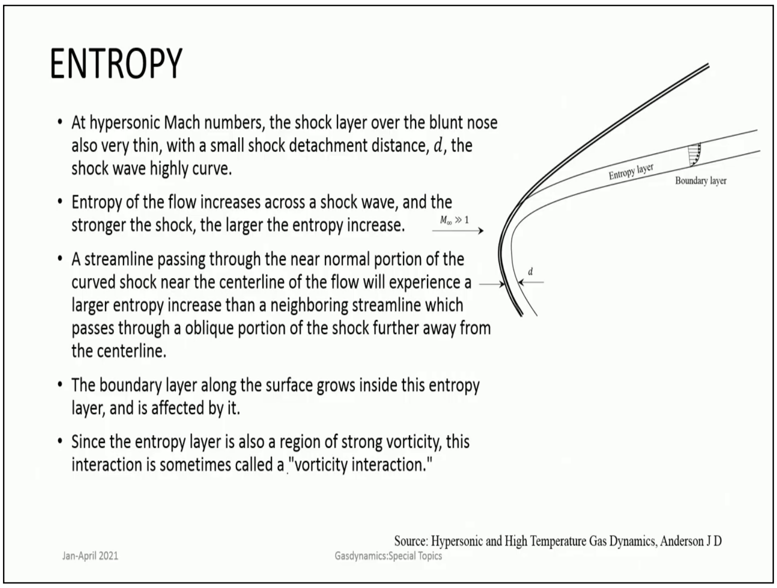

The other characteristic is that generally the Hypersonic vehicles they are they have blunt shapes their noses are made rounded they are not at all sharp. Consequently, the shock that develops around such bodies is also it is a detached shock a bow shock. We had discussed this kind of a shock in the context of Croco's theorem much earlier where we said that the bow shock is a region where there is lot of gradients of entropy.

Therefore, the flow that occurs around the bow shock is not irrotational it is rotational because of entropy gradients. This because you have a curved shock and as the shock curvature is different at different points it has different strengths at those points therefore different entropies for streamlines that pass through the shock therefore an entropy gradient develops.

Now a normal approach that is done usually that is carried out for the analysis of these kind of vehicles or any aerodynamic analysis is to split the flow field into parts where we do not have to consider viscous effects the inviscid part and the part very close to the body. Where we say that viscous effects are important which is the boundary layer. So, that is the boundary layer. So, here you have the boundary layer this is the boundary layer where viscous effects are important.

The general understanding is that in the inviscid region you have, and the flow is irrotational. But if you consider such kind of blunt bodies then you have a layer which comes from the curved shock where there are entropy gradients and consequently there is rotational flow and this washes over the body. Therefore, now it becomes difficult to say where, is that rotational flows where are the boundary layer and so on.

Doing this calculation becomes very difficult and therefore this layer where there is significant entropy is known as the entropy layer. So, these become significant in Hypersonic flows. So, doing the traditional analytical approach a traditional analysis approach of a rotational flow then a boundary layer must be revisited carefully.

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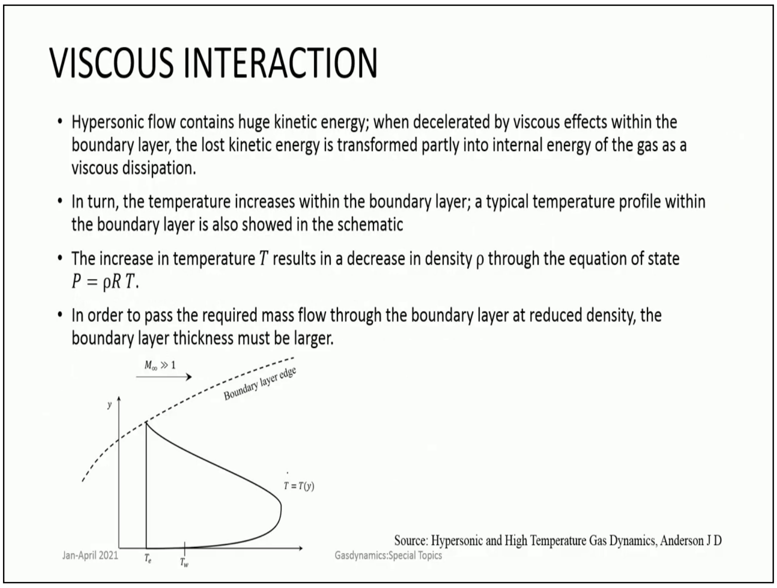

The other problem that occurs or the other thing that occurs in Hypersonic flow is that now the huge kinetic energy it gets transformed into internal energy close to the walls that is at due to viscous dissipation also. So, when that means the temperature near the ball will increase significantly. When temperature increases correspondingly density decreases and therefore what you get is that to pass the same mass flow rate you need much higher thickness or thickness is required it becomes much higher.

So, we are talking of flows very close the wall. So, we are talking about viscous effects and the boundary layer that means this boundary layer thickness must be quite large in Hypersonic flows is significantly larger than at moderate Mach numbers.

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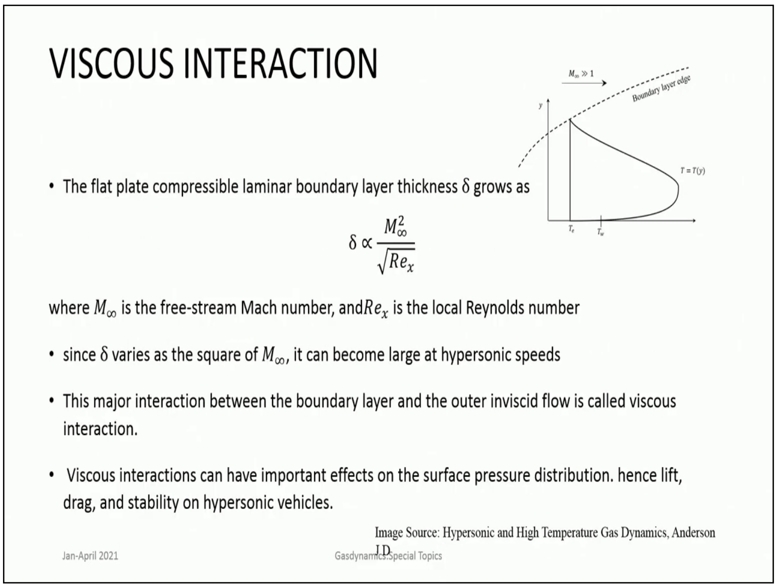

It goes as Mach number square by square root of nodes number. So, when Mach number significantly increases boundary layer thicknesses increase significantly. Now what is the consequence now for the flow what it really sees is if there is certain body here and the flow sees a body and there is a small very thin boundary layer around the body, and we say that the flow outside the boundary layer is message inviscid.

So, if we can solve the inviscid part for the outer flow then that imposes a pressure field over the body due to which we can calculate the pressure forces on the body. But in Hypersonic flow the same case the boundary layers become very thick they become very thick. Therefore, the inviscid flow outside gets deflected by much larger margins than what is normally found in thin boundary layers.

So, this affects the invisible flow and consequently the pressure distribution gets affected. So, this means that a viscous effect on the boundary is affecting the inviscid flow also and it affects the surface pressure distribution. Hence calculating lift and drag they must be done very carefully.

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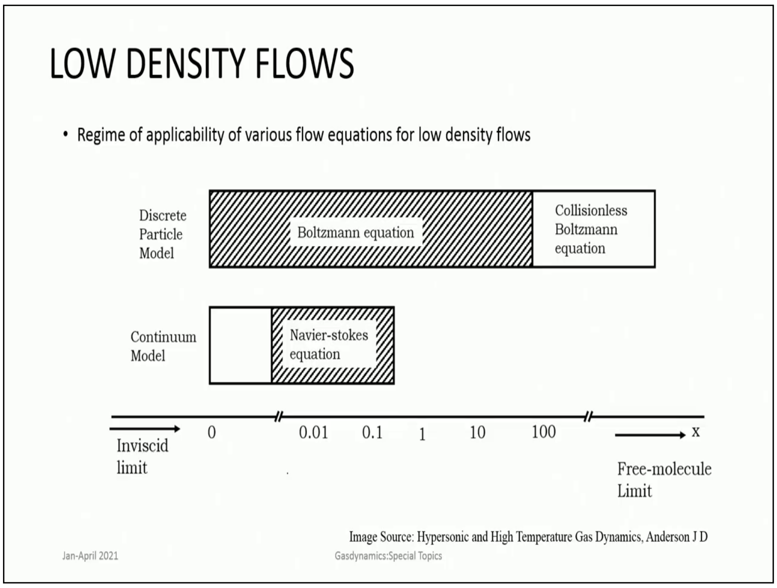

Usually, these Hypersonic flows occur at very high altitudes as we have seen like 50 kilometres 60 kilometres at such high altitudes' density is also very low. Then one must carefully consider this part about continuum is something that we had discussed very early on when we were discussing the thermodynamics in the context of gas dynamics. Now we really see where those topics come into picture.

The weather continuum applies or not has to be evaluated by looking at Knudsen number carefully. So, when we do analysis of Hypersonic flows always its good practice to calculate Knudsen number first and then can find out whether we can continue with compressible Navier stokes equation or have to use other equations like the Boltzmann's equation and so on. So, those are also a part of looking at Hypersonic flows.

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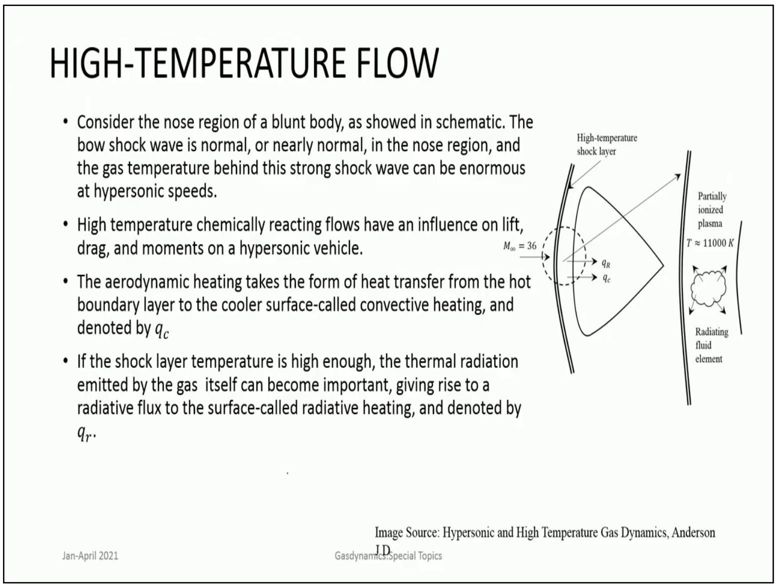

As has been now sort of mentioned often the Hypersonic flow is a flow where temperatures become very high due to conversion of kinetic energy to the internal energy of the gas. So, when temperatures become very high then the nature of the gas itself can change. So, when temperatures are as high as 11000 K taken by considering a calorically perfect gas it can be bizarre numbers like 11000 K or 20000 K and so on.

But one must carefully consider at this point because calorically perfect gas assumption no longer holds good it may be chemically reacting flow it may be ionized flow therefore energy interactions will be very important. The energy equation itself must be reconsidered there may be additional modes of heat transfer that may become important like radiation. So not only just convective heat transfer convective heat transfer itself is quite large.

This convective heat transfer is inversely proportional to the radius that is if you have blunt bodies with large radii of curvature, they have lower convective heat transfer. That is why sharp corners are not preferred in Hypersonic flows otherwise they can simply melt away always rounded or blunt corners are preferred. So, this is the reason why space shuttle is very rounded compared to any supersonic flights. So, high temperature effects become important in Hypersonic flow.

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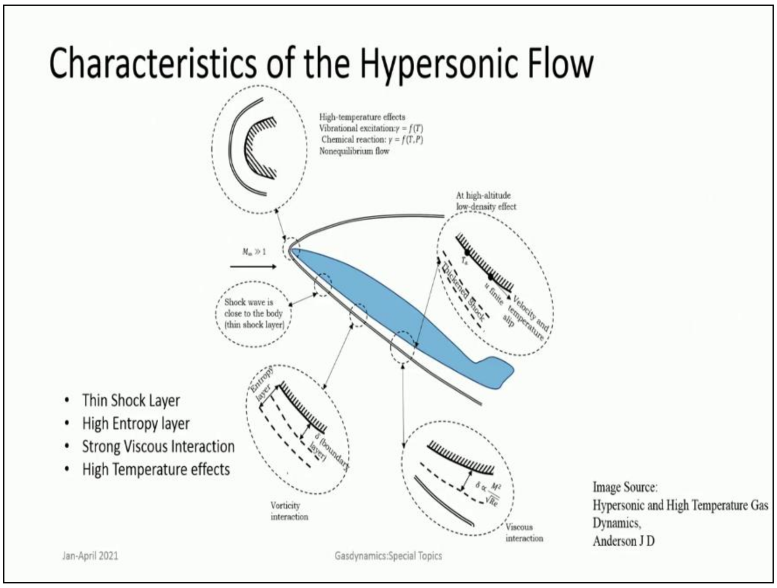

So, in all if you consider a body in Hypersonic flow then there are several aspects to it one thing is shocks become very close to the body. Then the other 1 is that you have very high temperatures. So, high temperature effects like chemical reactions non-equilibrium flow and so, on become important. You have a very strong interaction of the viscous effects with the invisible flow and the entropy layers become important.

So, all in all if you look at the Hypersonic flow there are several physical features of this kind which is important which we normally do not consider in supersonic flow. So, when such effects become start dominating the flow field then it is termed as Hypersonic flow. Generally, a Mach number greater than 5 is a good ballpark point to say that the flow has become Hypersonic, and you can start considering these effects.

But even at lower Mach numbers if there are chemical reactions and so on happening then some of the aspects of Hypersonic flow may become important even at lower Mach numbers. So, this gives a very general introduction to Hypersonic flow what physical flow features become important in Hypersonic flow. And we see that there are lot more complexities involved in Hypersonic flows than supersonic flows. But Hypersonic flows also provide simplification which you cannot do in supersonic flows precisely because of thin shock layers and so on.

They provide approaches like there are the coefficients or non-dimensional numbers become independent of Mach number which is known as Mach number independence and this can be demonstrated just by looking at the oblique shock equations. And another useful way of analysing Hypersonic flows or forces in Hypersonic flows is by considering what Isaac Newton had remarked much, much earlier before all these became important about forces on bodies over which flows impact.

So, that is an impact method, and it is also called Newtonian method. And surprisingly in Hypersonic flows these techniques work well which are quite simple they are based on only the local inclination of the surface and nothing else. So, we will see some of these sorts of simple methods to look at Hypersonic flow in the next class. So, what we really need to understand in Hypersonic flows is that there are several flow features which are become dominant, and they become different compared to supersonic flows.

Therefore, if you are looking at Hypersonic bodies in Hypersonic flow their shapes the way they are designed are completely different from the way bodies in supersonic flows are designed. So, we will close this class now, thank you.