Combustion in Air Breathing Aero Engines
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Lecture – 23
Laminar Premixed Flames II

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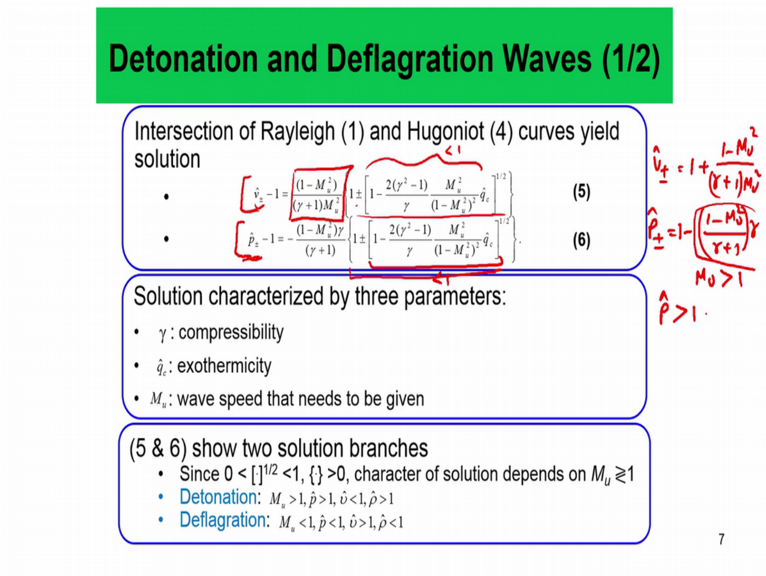

Then we can of course solve and when we solve we find these things that this V cap and P cap are given by this formulas. So, now you see that before we go into this, so here these are the points basically where the Rayleigh lines and the Hugoniot curves are intersect and these are the P cap and V cap solutions; plus minus 1; as you will see what these we will come into what these actually represents.

So, first things is that the first thing is that you see these part; this for this equation to be true; this equation, this part should be less than 1 because it is a 2 to the power of half for it to be real this part has to be less than 1. If this part is less than 1; this is 1 minus this part this whole thing has to be less than 1.

So, because it is 1 minus something, so when it is 1 plus minus 1; this part is essentially always even if it is minus we have this sign then this part is always positive because this part is always less than 1. So, then it means that the sign of this guy that is V cap minus 1 is essentially only given by this part that is 1 minus M u square; this is very very important because now you see that then you can write to just to determine the sign or to do the full thing; that is V cap plus minus 1 is equal to 1 plus; essentially 1 minus M u square times gamma plus 1 times; M u square.

So, you see now we have that and also for this part similarly for P cap, you see this now P cap is given by that is only the sign part is given by 1 minus; 1 minus M u square divided by gamma plus 1 times gamma. It was also by the same argument this part has to be less than 1; only this part because otherwise 1 minus this thing should be negative, then it can be imaginary just because of this square root. So, this whole part is always less than 1.

So, when this whole part is less than 1; then this 1 minus this part should also be less than 1, but then it means that it is always positive. So, the sign of this thing that is P cap plus minus 1 is equal to then sign is only determined by this part; that is 1 minus, if you take this 1 to this thing; 1 minus 1 minus M u square divided by gamma plus 1 by gamma; minus 1 times gamma.

Now, let us consider the situation when M u is greater than 1, so when M u is greater than 1; what you see here is that this is 1 minus M u square. Then this thing is inherently negative, so when this thing is of course, you have these things that is you have also this parts, but now you see when you have M u; to be M u essentially is greater than 1, then these thing whole this thing is essentially negative and you have essentially P cap essentially is greater than 1 and also you have and similarly for the other situation; you have let us arrive at this just 1 second.

So, what we were discussing is that we will consider this part of the equation. So, when we consider this part of the equation; that is equation 6; we will just go back a little bit that is when we have; there we see so many exponents here which is to the power of half.

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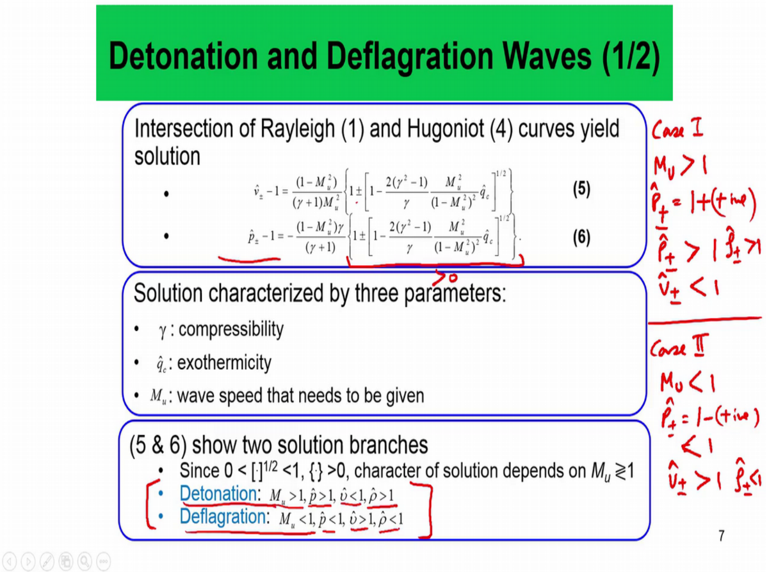

So, this essentially a square root, so for the insight of the square root to be real, for the square root the solution of the square root to be real; the inside of the square root must be greater than 0. So, then it means that this 1 minus this whatever you have; this part should be less than 1. Now, for this part to be less than 1; if this is less than 1, then this is 1 minus this then this whole thing is less than 1. After you get the square root, this whole thing is less than 1; now this is 1 minus; 1 plus minus this; when it is plus then 1 plus say let us say this is 0.5 or 0.6.

So, then 1 plus 1.5 is of course it is positive number, but whenever you have the negative sign this is 1 minus say 0.6; then also it is positive. So under all circumstances, you see these quantity is positive; we do not have to determine what M u is to know that this quantity is positive. Similarly, for this we have also; now then what I want to say is that then the sign of this guy is only determined by 1 plus 1 minus this or only is purely determined by this part.

Now, say what happens when your M u will consider 2 cases M u to be greater than 1 and M u to be less than 1. So, when M u is greater than 1, then this is 1 minus M u square; M u is greater than 1 say means 1.2. So, M u squared is 1.44; so, 1 minus 1.44 is invariably negative; so, then this part is minus and this is also minus. So minus 0.44 or something so then becomes plus; so, then in that case P u plus minus 1 cap becomes is equal to 1 plus some more positive quantity.

So, then it means that p q P cap plus p plus minus 1 cap is inherently greater than 1 and because if you go back to the Rayleigh lines, but when P cap is greater than 1 V cap has to be less than 1. So, then it automatically means that v plus minus 1 because this is obtained by the intersection between the Rayleigh and the hugoniot lines is less than 1.

So, similarly let us consider case two; we will come back to what this case calls. So, similarly we come back to case two, so now M u is less than 1. So, when M u is less than 1; this is 1 minus M u square, this part then it becomes 1 minus M u square is inherently then positive. So, then this minus and a positive quantity then it retains a minus sign, then it becomes P cap plus minus 1 is essentially 1 minus a positive quantity; which is less than 1 of course, so it becomes less than 1.

So, when M u is less than 1; P cap plus minus is less than 1 and also V cap plus minus becomes greater than 1. So, and as a consequence of this here your rho cap plus minus if you have is greater than 1; is less than 1 for M u less than 1 and for rho cap plus minus is greater than 1. So, for case one; if you have M u greater than 1; your p cap, so far in the Rayleigh lines did not tell us that it just told us that when P cap is greater than 1, V cap is less than 1 or when P cap is greater than 1, rho cap is also greater than 1 or vice versa when P cap is greater less than 1, your rho cap is also less than 1.

But did not tell us in what regime this happened, so by considering the intersection of the Rayleigh and the hugoniot lines; we just find out that when M u is greater than 1 that is on coming if your wave is stationary and your flow is coming the reactant or the reactant flow is coming at a speed which is supersonic M u greater than 1, then the pressure; if the chemical wave is consuming the reactants at a supersonic speed; then the pressure lines will be greater than 1 and the density rise will also be greater than 1 and that will account to be a detonation state.

So, here basically the wave because it is restrained by free continuous feeding of the reactions, if we make the wave free that is if feed can propagate by having a fixed; having a coercion mixture, which is not flowing. If we have a mixture which is just present just static, which is not flowing then the speed at which it will propagate, if it is supersonic; then the pressure will rise downstream of the wave and now similarly that is called a detonation state.

So, and then consequently or similarly from this it arrives also that if the wave speed is subsonic; that is if the speed of the reactants at which it is being fed to the chemical wave; if it is sub sonic or if the chemical wave is propagating at a subsonic speed, then essentially your P cap will be less than 1 and your V cap will be greater than 1, but your density ratio should be less than 1.

So, this is then the very important concept of the difference between deflagration and detonation; this is one of the most important central concepts in combustion of what is the difference between deflagration detonation and that arrives that arrives by considering of this intersection of the Rayleigh and Hugoniot lines as you see. Then the difference is nothing, but the fact that when M u is greater than 1, P cap is greater than 1 V cap is less than 1, rho cap is greater than 1 and that is called detonation.

And for deflagration your M u is less than 1, your P cap is greater than 1, your V cap is greater than 1 and your rho cap is less than 1. So, in a detonation pressure arises density arises in the deflagration pressure drops density drops and that comes from configuration of fuel mass from momentum in energy relations and of course, this P cap and rho cap are nothing, but the density ratios and the pressure ratios that is P v by P u rho V by rho u.

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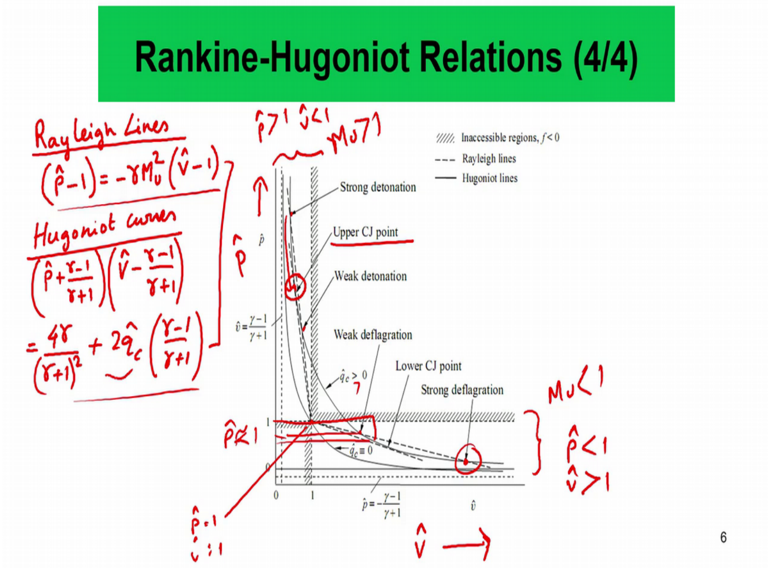

So, this is then that is why then this branch is essentially a supersonic branch going back to this thing and this branch is essentially a sub sonic branch; M u greater than less than 1.

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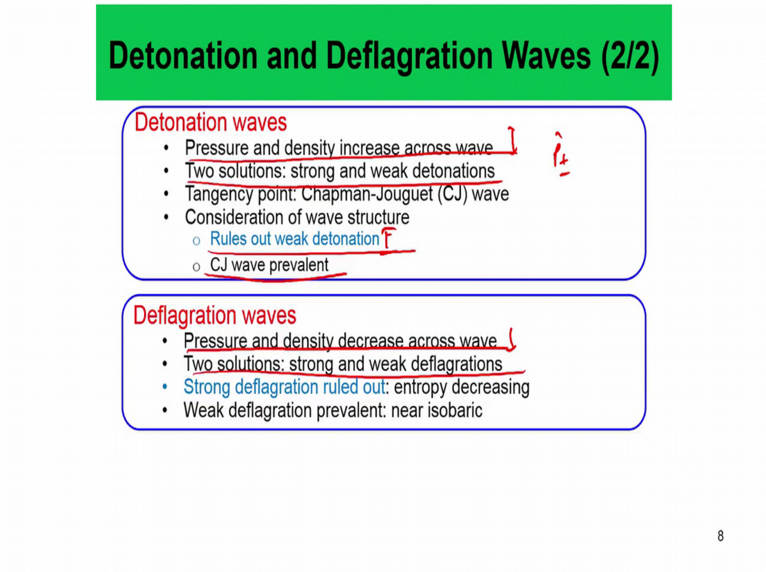

So, then this is the point that we were making; now there are some more interesting features that comes associated with it that yes we will just summarise them what are the properties of the detonation and the deflagration waves along with the interesting properties, so in a detonation wave, as you see the pressure and the density increase across the waves and we will get 2 solutions because you see that it came like P cap plus minus.

So, plus minus corresponds to this things that when you consider this to be plus; when you consider this plus sign your V cap, you consider the V cap plus or when you consider this plus sign, you consider the P cap plus. When you consider the minus sign, you consider V cap minus and when you consider this minus sign; you consider the P cap minus. So, that is when there are 2 solutions and then there is also an interesting point that is a tangency point that is this is a point tangency point. So, you can have a state that instead of the Rayleigh lines directly crossing through or interesting through the Hugoniot lines, you can have a state where the Rayleigh lines essential is a tangent to the Hugoniot lines.

So what does a tangent mean; tangent means that the slope is same. Slope of these 2 lines are same and also another thing is that the strong and weak detonation that we are talking is that the upper point. So, if you have a Hugoniot line like; this is your Hugoniot line; for a given q c and this is you Rayleigh line for a given m u. So, this upper intersection point is called the strong detonation point; strong why because your pressure rises around higher.

So, you will see this pressure rises hard and this is another point that is where the plus minus sign comes and this point is essentially the weak detonation point. So, this is the strong detonation point and this is the weak detonation point and this is the tangency point which is Chapman-Jouguet to the point; the upper Chapman-Jouguet point. So, and it would be seen that there is nothing called a weak detonation that does not exists because you will see that essentially what happens is that; it can be shown by pure by setting q c to be 0, there is actually then you will see that this point does not exists and definitely within (Refer Time: 13:37) and physical solution because you will see that by entropy consolations you will see that this does not permit this weak detonation point to be satisfied.

And this is also comes from the wave structure basically that there is no weak detonation and also the C J detonation wave is prevalent. Whereas, for the deflagration waves sorry there is not entropy consolation for this, this is just comes from the wave structure that there is no weak detonation. So, this point does not exists because of the wave structure of this thing.

Whereas, as we will see later that this point is also not very common whereas, the detonation typically propagates that this speed which is the upper C J point of the Chapman-Jouguet point; which is essentially the tangency between the Rayleigh lines and the Hugoniot curves. Now, we will find that out and then going to the deflagration waves; that is the M u to be less than 1, we will find that the pressure and the density actually decrease across this wave.

So, that is the most important deflagration difference between the deflagration and detonation; I mean this is our central point that almost always a combustion engineer must always know that; what is the difference between deflagration and detonation waves. Apart from the many things that the fact that the deflagration waves propagate a sub sonic speed, when unrestrained or here we are considering in a wave stationary frame that is; so, everything is coming in.

So, the from the rate of the speed of the incoming mixture is essentially supersonic or sub sonic, but if you were if we could our place our observe around the bond gas of the on bond gas, we will see the flame or the chemical wave to be approaching us and in that case we will see that its approaching us either supersonic or sub sonic speed. If it is approaching on a subsonic speed; then it is a deflagration, if it is approaching as a supersonic speed then it is a detonation.

And then the other properties are the most important properties of that; the pressure and the density decrease across the deflagration wave. Whereas, the pressure on the density increase across the detonation wave and this also gives you the true solutions that strong and the weak solution and the strong solution which is the large pressure drop that is this point P cap is much less than 1; that is the ruled out and that comes from the entropy consolation because I will see that the entropy decreases by crossing such a wave. So, it does not (Refer Time: 15:56) does not is the second (Refer Time: 15:57) does not allow and whereas, this is the weak deflagration and this is the thing.

Also interesting to notice that this is you see that this point is very close to this P cap is very close to 1. So, this we can go back again to our previous consideration that when the Mach number is small; if you remember that we arrive at this thing. So, that is we arrived at the fact that for order one change in u d u, d x you need order Mach number square change in pressure this were normalised; pressure if you remember from the previous classes in the governing equation.

So, we see that when the Mach number is small which is the case here from thermodynamics or from the governing equations you again arrive at the fact that your pressure drop is small. Whereas, in the case where pressure drop could have been large in the strong deflagration state that does not exists, so that is why you see in this region your pressure drop is small and that is your weak deflagration case; that is a common flame, a premixed flame that you see in the black gas, burners, in the aero engine, in the power generation engine, in gas turbine engine, in a ramgen engine, in a ASR engine typically as and when there is no (Refer Time: 17:09) till that that you see this essentially this deflagration.

Deflagration is diffusion control whereas, detonation is essentially a shock control phenomena is obtained by shock heating. So, whereas in the deflagration you see that the pressure rise can be huge; you see this is large very P cap is much much greater than 1 whereas, as the here is P cap is slightly less than 1.

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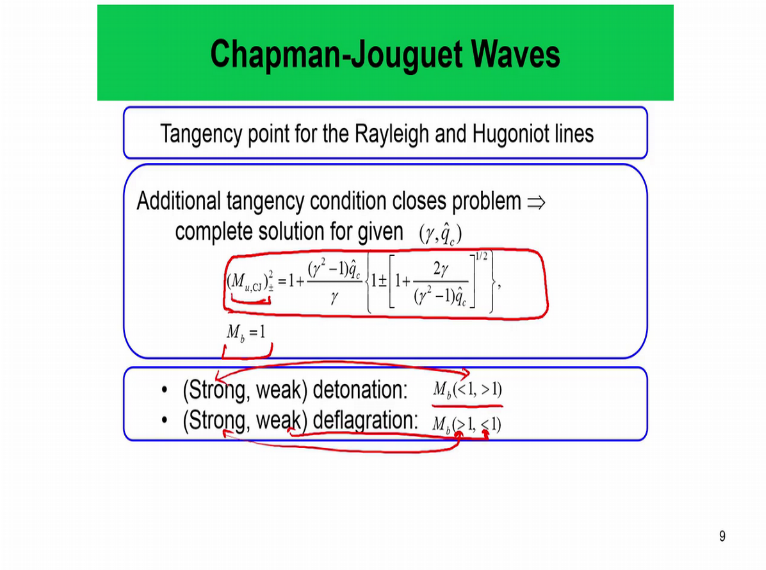

So, there is a small pressure drop, but not huge; so, this is the point. So, this gives very very important ideas about the combustion structure and about what happens and the characteristics of the deflagration and the detonation waves and as you have said that the deflagration wave is prevalent and this is isobaric. It is very difficult to stabilise a detonation wave; what you see that the advantage is that in a crossing a detonation wave you have launch pressurize.

So, can that be utilised someday? Can we have combustion pressurize? Whereas, in a gas turbine engine one of the parameters engine designer looks at is a pressure drop. There is obvious because if you have a previous combustion happening inside a gas turbine engine; what I have known previous as such, you will have actually in a gas turbine engine since it is a some mixed or premixed, non-premixed, non-partially premixed combustion, but for the sake of argument you have a premixed flame inside a aero engine combustion.

So, in variably what you have is you have a pressure drop, so in a thermodynamic diagram; in the previous diagram if you do, this pressure drop will actually result in loss of efficiency. Whereas in the detonation you see that that gives a rise to a huge pressure, so it is of interest to understand how basically the detonation can be stabilised, but because detonation is a very very fast as you will see that it will as propagates about kilometres per second almost. So, we need to understand and others mechanisms well and we are also another important (Refer Time: 18:55) of problem in combustion science is essentially how does how can we even transition a deflagration to a detonation. Well that is an open problem; that is still a very much of a research issue this deflagration to detonation transition.

So, now then the Chapman-Jouguet detonation points we will see that and that is the tangency point. So, we have basically 2 tan Chapman-Jouguet detonation points just using these things. So, these are the 2 Chapman-Jouguet detonation points this and this, so this is upper C J point and the lower C J point; the upper C J point which happens when M u is greater than 1, that is of very high interest for the detonation because it typically the detonation propagates on this C J point and there you can at this point a very interesting thing emerges that here you can essentially; from those relations you can find out this tangency problem because it means that your d p d v cap; d p cap, d v cap obtained from the Rayleigh lines is equal to d P cap d V cap obtained from the rankine from the hugoniot lines.

So, this from the combine solutions you can obtain the M u C J actually; that is the very beautiful thing that comes out and so instead of even specifying the wave structure, you can find out this Chapman-Jouguet velocity and this is the velocity with which a detonation actually or Chapman-Jouguet deflagration propagates and of course, the M b is equal to 1; that is the bond gas number should be equal to 1 and this is once again that strong and detonation; your m b is actually less than 1, greater than 1 and strong and weak deflagration your M b; whether it is a mass bond M b is actually greater than 1 or less than 1 or so.

From here also you can understand that; for a strong deflagration M b becomes greater than 1, which is not physically possible and so the only the thing that is possible is essentially is essentially a weak detonation and similarly you will see that your only also strong detonation for your M b’s less than 1; which is physically possible.

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So, with that we will close this class and then we will go into the deflagration wave; the details of the deflagration waves. In this class, in this course we will not go into detonation because that is a very very specialised topic; lots need to be known. So, when we say flames or when you do combustion, we will essentially implicitly mean that we will do deflagration and that we will cover in the next course thank you; next class.

Thank you.