Introduction to Airbreathing Propulsion

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Lecture – 37
Stationary Components: Combustors

Okay, so we have looked at the intake components now, like different kind of intake, subsonic, supersonic or helicopter and what is their configuration, I mean obviously there are certain analysis pattern of the intake, so one of the important things for the intake is that one need to take into account the losses in the intake and mostly those losses are to some extent the aerodynamic losses that takes place because of the geometry.

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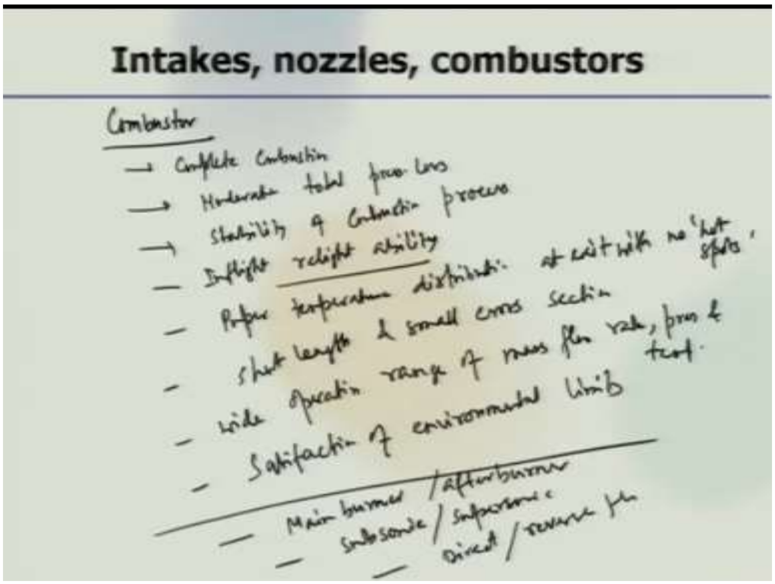

Now, we are going to the next component which is combustor, now combustor which actually sits in the system, any gas turbine engine it is after compressor. So, I mean some of the basic important feature for a combustor which one would expect from a like a designer point of view, it should provide like complete combustion, then it should have moderate total pressure loss, so then stability of combustion process like then inflight relight ability.

This is very, very important, then proper temperature distribution at exit with no hot spots, then short length and small cross section; we should have wide operating range of mass flow rate, pressure and temperature, then obviously satisfying or satisfaction of environmental limits which is terms of emission. So, types of combustion chamber there could be main burner or the afterburner like one can have main burner or afterburner or there could be subsonic or supersonic types depending on the speed of the airflow, which could be subsonic or supersonic type or direct or reverse flow.

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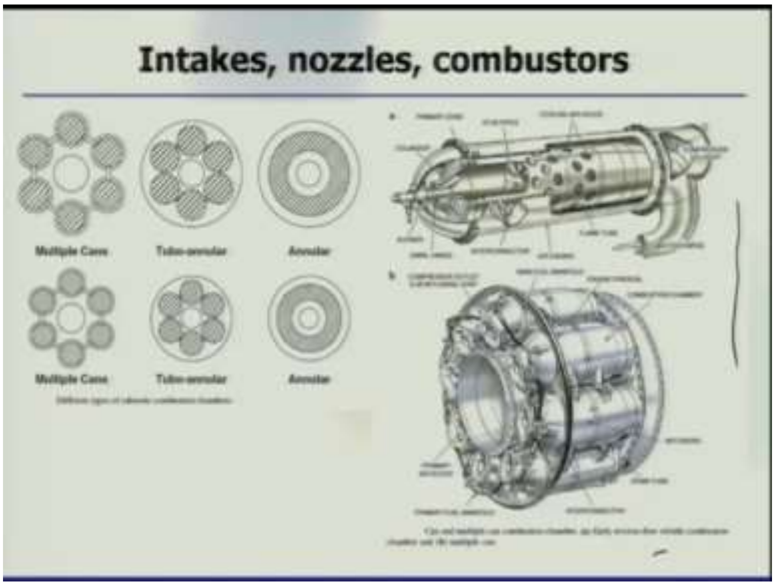

Now, subsonic combustion chamber may be further classified into 3 different types like multi cans, tubo-annular, and annular ones, like one can see one here, this is different types of subsonic combustion chambers like you have multiple can sitting there, then you have annular sitting there, you have annular there, multiple cans, so sometimes these are as tubular or can type combustion chamber.

It is used on centrifugal compressor engine like Rolls-Royce, Pratt and Whitney PT6 or now the number of combustion chamber is varying from 16 to 17 per stage, so the advantage of the tubular type are the following mechanically robust, so tubular annular combustion mechanically robust, fuel flow and air flow patterns are easily matched, Ring testing initiates only small fraction, easy replacement and maintenance.

So, now this is another one which was developed by Whittle W2B, this is a reverse flow kind of combustion chamber, you can see how they look like actually and there are so many components which are associated with this combustor geometry because these are very, very I mean, this is the one in any jet engine that imparts that energy which is going to finally expand through the thing.

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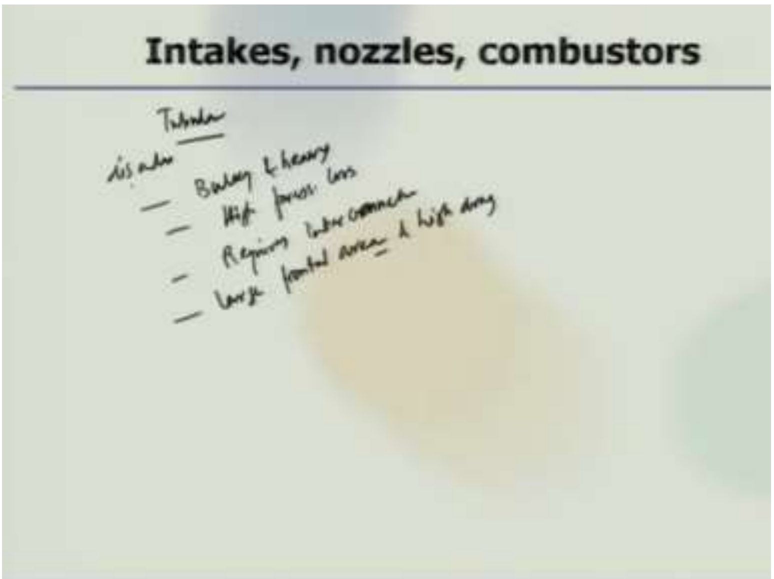

Now, when you talk about this tubular, there are some disadvantage also, the tubular; the disadvantage which comes are that it is bulky and heavy that is one thing, high pressure loss that is another thing, then it requires interconnector that then large frontal area, so and high drag. So, these are some of the problem like nowadays, tubular can type is used in jet engines, incorporating centrifugal compressor, axial power units and automotives.

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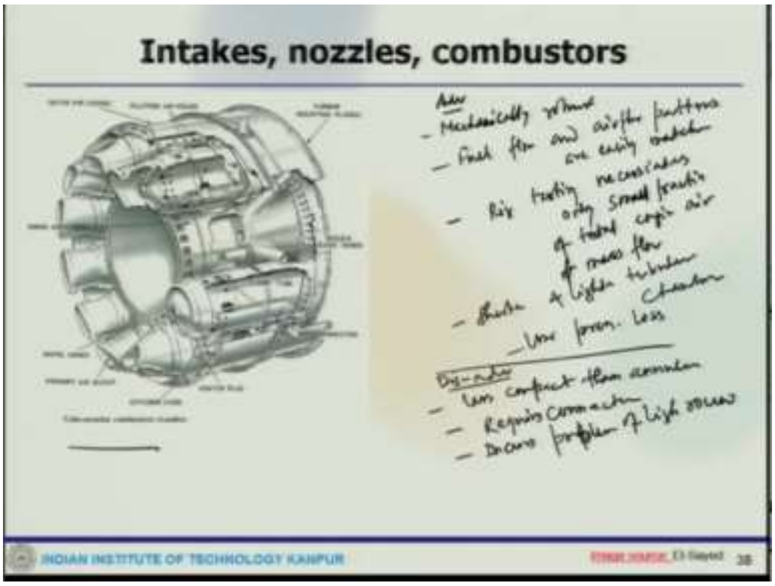

Now, you can see this is another tubular annular kind of combustor where you have this annular casing and then you have tube kind of combustor.

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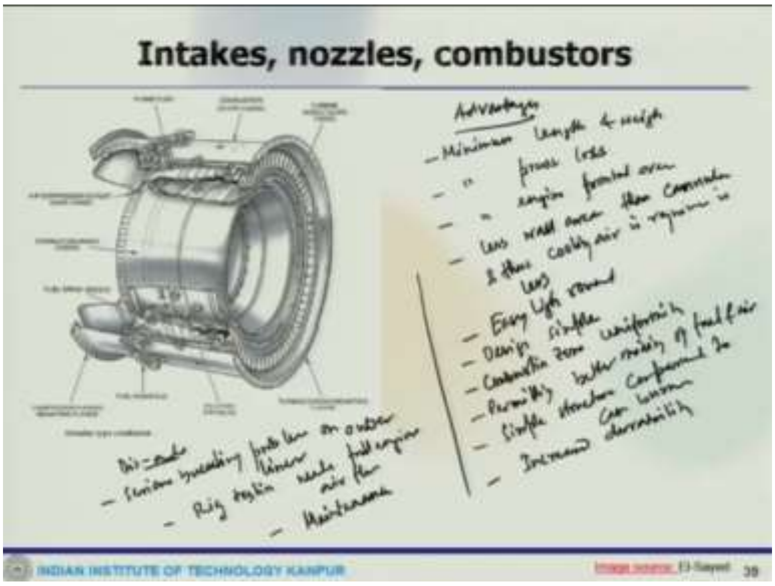

So, tubular annular combustor type, one of the cross section area would be like this, so it also has now the, this type can be identified as the can annular or annular which is called can annular or annular type. It consists of series of cylindrical burners arranged within common single things, so there are some of the advantages; mechanically robust, so they are quite robust, then fuel flow and air flow patterns are easily matched, Ri g testing which necessiates, so the fuel flow and air flow, air flow patterns are easily matched.

Then, you have Rig testing necessiates only small fraction of total engine air mass flow, then you can have shorter and lighter tubular chambers, low pressure loss, so these are the advantage but obviously when there are some advantages, there could be some disadvantages too and one is the less compact than annular, so less compact than annular, then requires connectors, then incurs problem of light round.

Now, then we can see like this is we can now going to see some annular combustion chamber, so this is an annular type combustion chamber which is a single flame type and chamber were completely annular in form which is contain like in inner and outer casing, so this actually normally, this type is used, many engines using axial flow compressor and also other in incorporating dual type compressor.

So, it has a history since 1940s but till I mean, now the annular combustors are fitted in GE CF 6, GE 90, PWD 4000, RR Rb211, Trent series, V2 500 series, so there are obviously quite a bit of advantages which are associated with that like it has minimum length and weight, minimum pressure loss, then you have minimum engine frontal area, less wall area than cannular and thus cooling air is required is less.

So, the combustion efficiency also increases, unburned fuel is reduced, oxidizes the carbon and carbon monoxide or nitric oxide, easy light round, design simple or design combustion zone uniformity, permitting better mixing of the fuel and air, simple structure compared to can burner, so simple structure compared to can burner, then increase durability, obviously these are listed advantage.

Then, always one can have some disadvantage also like serious bucking problem on outer liner, so this is a bucking problem, Rig testing needs full engine air flow, then must remove the engine from the aircraft to dissemble for maintenance and overhaul, so maintenance is also not that easy, so maintenance, so it has to be; now one can see there are components of the combustion chamber there are different components.

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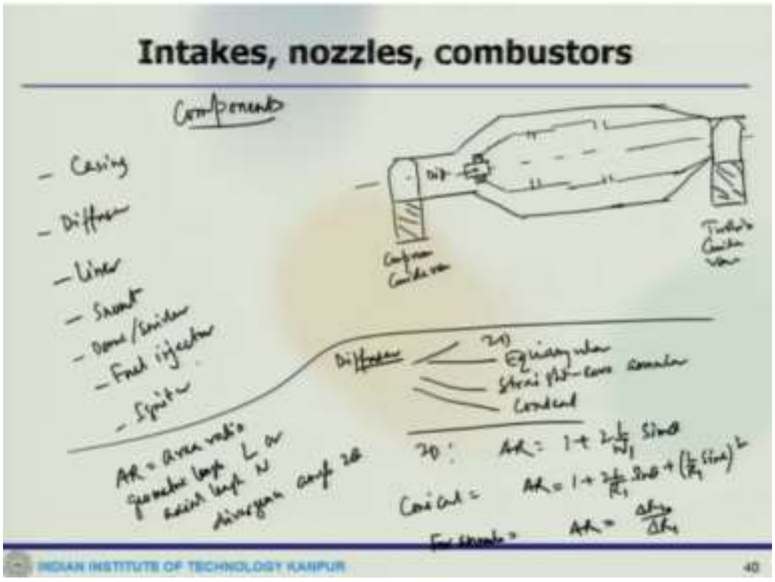

So, you can have like casing or the case, so just in schematic if I draw, let us say this goes like this okay, so that is how it goes that is the center line, then we have another casing comes here, then we have this, this, this, this, then let us say, this is an just in schematic of that, so there could be hole, then so essentially you have these are swirler, there we can have, so this is compressor guide vane, this is turbine guide vane.

Then you have diffuser here, this is fuel nozzle, this is swirl, then there are cooling slot along these, these are secondary hole, there could be secondary holes here, then dilution holes, so there are multiple, just in schematic of that, so it has an one of the important is casing, so the casing is the outer cell of the combustor which is fairly simple structure and need little maintenance but it is protected from thermal load by air flowing on it.

So, the mechanical load is driving the design, so then diffuser, so the purpose of this diffuser is to slow high speed, highly compressed air from the compressor to a velocity which is probably optimal for the combustion chamber to avoid any losses, total pressure loss and also the avoid any combustion flame stability. So, diffuser must be designed to limit the flow distortion as much as possible.

Then one could have liner, the liner contains the combustion process and introduces various inflows, so these are very important component because the thermal load on the liners are quite, then you can have snout which is the extension of the dome, then one can have dome or swirler, these are used for the better fuel air mixing, so it imported the tangential component or velocity.

Then you have fuel injector, so this is another important component where the fuel is injected because the injector it plays a very, very critical role because how good the injector is that find the fuel spray can be produced and then that would have a lot of impact on the flame structure and obviously, the other aspect. Then igniter; so most igniters in gas turbine application are electrical spark igniters similar to that automotive spark plugs.

The igniter needs to be in the combustion zone where the now if you look at the aerodynamics of the combustion chamber, so the important part of this is the diffuser. So, the diffuser could be of different type like it could be 2D, could be equiangular, this could be straight core annular, then this is conical. The straight valued diffusion may be defined in terms of 3 geometric parameters like AR which is area ratio, geometric length L or axial length N divergence angle 2θ.

So, for 2D diffuser, AR would be

$$AR = 1 + \frac{2L}{W_1} sin\theta$$

for conical AR is

$$AR = 1 + \frac{2L}{R_1} sin\theta + \left(\frac{L}{R_1} sin\theta\right)^2$$

for annular

$$AR = \frac{\Delta R_2}{\Delta R_1}$$

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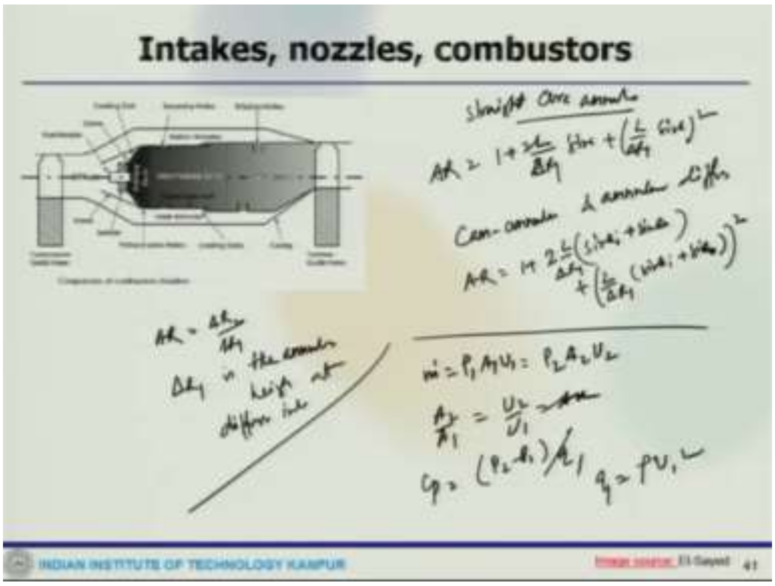

So, where; so this is what the schematic that I was trying to draw and here is $\frac{\Delta R_2}{\Delta R_1}$, where ΔR_1 is the annulus height at diffuser inlet, so now then straight core annular, the area ratio is

$$AR = 1 + \frac{2L}{R_1} sin\theta + \left(\frac{L}{R_1} sin\theta\right)^2$$

and then if it is can annular and annular diffuser, then Area ratio could be

$$AR = 1 + \frac{2L}{\Delta R_1}(sin\theta_i + sin\theta_0) + \left(\frac{L}{\Delta R_1}(sin\theta_i + sin\theta_0)\right)^2$$

So, you can just see there, there is a diffuser, nozzle, dome, cooling slots, so there will be different combustion zone primary intermediate dilution, you have dilutions hole where the again, air is injected, you have cooling slots or lever holes, 2 valve, then you have primary zone. So, now one dimensional incompressible flow analysis what we can write that

$$\dot{m} = \rho_1 V_1 A_1 = \rho_2 V_2 A_2$$

so

$$\frac{A_2}{A_1} = \frac{U_2}{U_1} = AR$$

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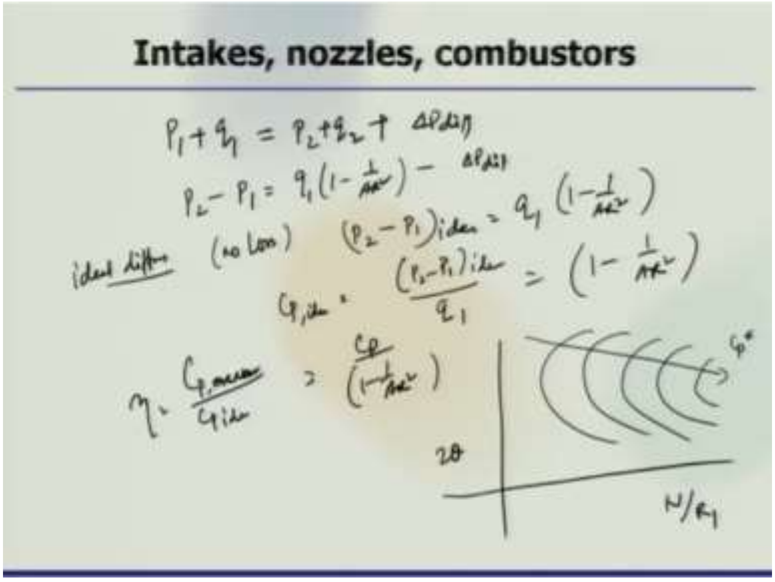

$$C_p = \frac{p_2 - p_1}{q_1}$$

where

$$q_1 = \rho U_1^2$$

so we can static pressure rise in the diffuser, we can write

$$p_1 + q_1 = p_2 + q_2 + \Delta p_{diffuser}$$

where

$$p_2 - p_1 = q_1\left(1 - \frac{1}{AR^2}\right) - \Delta p_{diffuser}$$

Now, in an ideal diffuser, so there are no losses, no loss, so we can write

$$(p_2 - p_1)_{ideal} = q_1\left(1 - \frac{1}{AR^2}\right)$$

so

$$C_{p_{ideal}} = \frac{(p_2 - p_1)_{ideal}}{q_1} = \left(1 - \frac{1}{AR^2}\right)$$

So, overall effectiveness of the diffuser which could be estimated as

$$\eta = \frac{C_{p_{measure}}}{C_{p_{ideal}}} = \frac{C_p}{1 - \frac{1}{AR^2}}$$

so that is how basically, I mean one can draw this just this is non-dimensional length N by R_1 by diffuser angle 2θ, so the curve goes like this, so this is varying or rather increasing trend of the C_p^*. So, C_p^* is the locus points and the that define the diffuser diverges angle producing the maximum pressure recovery in a prescribed non-dimensional length.

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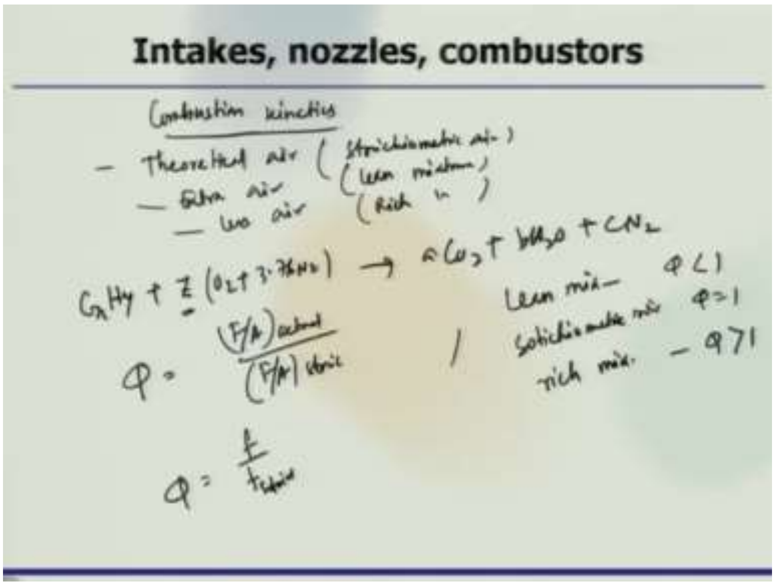

So, this is a qualitative curve that one can look at it, now the other thing that is important is the combustion kinetics, so though we are using different, different fuels so the kinetics is going to play a role because this is what is going to tell us whether you will have; so the important parameters when one has to know that theoretical air or stoichiometric air, then extra air, less air, so which is lean mixture, rich mixture like that.

And any for in general, if you burn

$$C_xH_y + O_2 + N_2 \rightarrow CO_2 + H_2O + N_2$$

and but if you have incomplete combustion that time you start producing CO and all these and this is the stoichiometric coefficient for all this. Now, when you define an equivalence ratio that is like fuel by air actual by fuel by air stoichiometric, so lean condition, fuel lean condition, lean mixture is ϕ less than 1, stoichiometric mixture that is ϕ equals to 1 and rich mixture which is ϕ greater than 1.

And fuel air ratio, so in the other way fuel to air ratio f and f stoichiometric, so we can write is

$$\phi = \frac{f}{f_{stoichiometric}}$$

so to prevent excessive temperature at the exit of the main burner or the afterburner to protect its wall and the overall fuel air ratio must be less than stoichiometric, so that is but this is what going to play an important role because what kind of combustion that we do because of the reactions and all these, there could be productions of the product.

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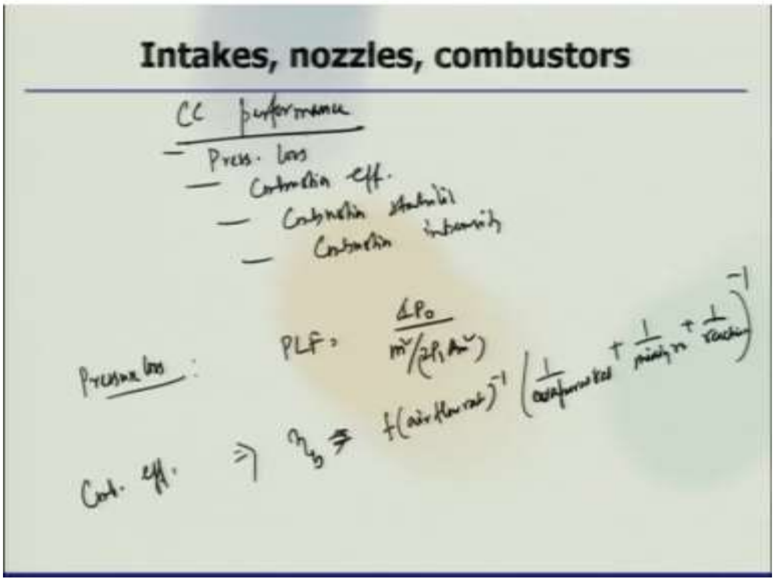

So, now the performance or combustion chamber; performance what we can see here, pressure loss, combustion efficiency, combustion stability, combustion intensity, so these are the important parameter, so pressure loss factor can be calculated like if someone wants to calculate the pressure loss factor like

$$PLF = \frac{\Delta p_0}{m^2/(2\rho_1 A_m^2)}$$

where m is the air flow rate, A_m is the maximum cross sectional air; ρ_1 is the inlet density like this.

Now, similarly combustion efficiency, so that is

$$\eta_b = f(air\ flow\ rate)^{-1}\left(\frac{1}{evaporation\ rate} + \frac{1}{mixing\ rate} + \frac{1}{reaction\ rate}\right)^{-1}$$

so that is how one can define the burner efficiency. Then combustion stability which means smooth burning and ability of the flame to remain alight over a wide operating range.

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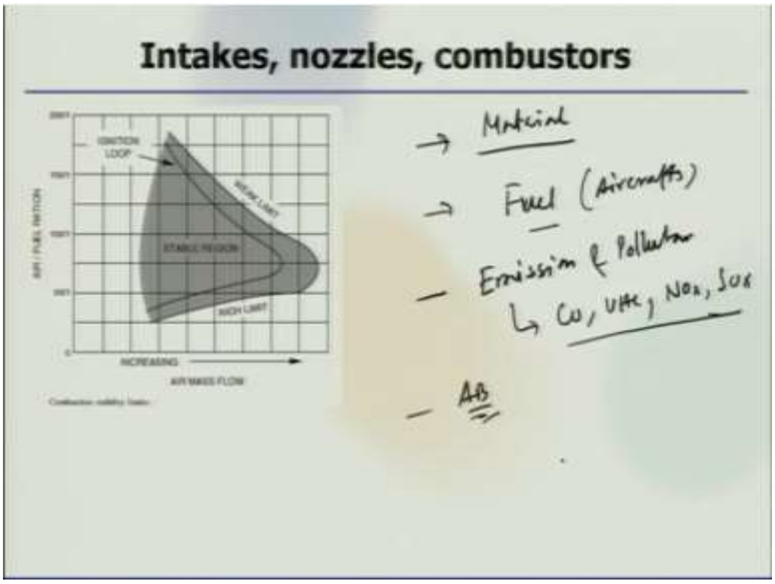

And for any particular type of combustion chamber, there are both rich and weak limit for the fuel beyond which, so one can see that limit here, this is how one can define that beyond the limit, the combustion could be stable or it could be unstable, so this is what is going to be important, then obviously there are other stuff like material what kind of material is used because combustion chamber has to withstand high temperature.

So, different kind of, so you need proper material to withstand that temperature especially, one is the chamber material, then you have a liner materials and all these, then fuels or aircraft fuel, there are different kind of fuels which are used, so that is also an important type because every fuel has its different burning capability. Then, another important aspect of the combustion chamber design is the emission or pollutants.

So, the design should be such that like emission like CO, unburned hydrocarbon, NOx, SOx, these are should be as reduced as possible but again, if you look at it these components are all connected with the kind of fuel you are doing and then kind of mixing that takes place and then the kind of combustion you have, then finally you can have after burner where it is a different kind of fuel injector or fuel like kind of different flame holders.

Because again this is the; this use in the military applications where you are going to use extra or second round of burning, so these are the kind of important things that one has to need to take into account while design the combustion chamber. So, we will stop here and continue the discussion on the nozzle and the other things in the next class.