Course Name: Combustion of Solid Fuels and Propellants
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Lecture: 12 Tutorial Problems

Hello everyone. So, we continue our discussion on the solid propellants. And if you recall in the last few lectures, we have ah covered various topics ah under this module like we started with the general discussion on solid propellants, then we talked about the propellant ingredients, the basic propellant ingredients, then we talked about the selection criteria for propellants like what are the major ah characteristics of propellants, which are considered while selecting solid propellants and in general actually for other propellants as well. So, the the general selection criteria for propellants were discussed. We ah discussed the propellant ingredients in details like starting from fuels, oxidizer, ah binder, the curing agent, plasticizer, burn rate modifiers and so on. There may be like numbers of ah many ah many ah propellant ingredients have been tried, but we have talked about the major ingredients.

And then we talked about the classification of solid propellants like in terms of their ah you know homogeneity, we have talked about like if the fuel and oxidizers are ah mixed intermediate intimately, then we ah told that that type of propellants are homogeneous propellants. For example, like double base propellants are the homogeneous propellants, where the major ingredients are nitrocellulose and nitroglycerin. And then we talked about the heterogeneous propellants like composite propellants, where ah polymeric binder is used to bind the solid fuels and solid oxidizers. For example, like the common composite propellants is ammonium perchlorate as oxidizers as oxidizer, HTPB as binder and aluminum particles as fuel.

Now, if we modify the ah double base propellant by adding some amount of ammonium perchlorate as oxidizer or even organic oxidizers such as HMX or RDX, then we can improve some of the properties in terms of like either physical properties and ballistic properties. So, once we modify the double base propellant, it is called composite modified double base propellant. So, we have discussed about that. Then we talked about the nitramine propellants like it is containing ah HMX or RDX as oxidizers. We also talked about like for certain tactical missile tactical missile applications, where the smoke trail is a problem.

So, there the low smoke or medium smoke or even reduced smoke propellants are required. So, generally the propellant containing ah aluminum ah fuel, it creates some white smoke in the trail. So, because it converts to aluminum oxides, which creates this white smoke. There are other ingredients like example of other ingredients such as ah burn rate modifiers, certain oxide catalyst, certain metal catalyst may also create some smoke ah in the exhaust. So, in order to have like low smoke or minimum smoke propellants, we need to make sure that it does not contain any metal particles.

On the other hand, it it should not produce any kind of ah you know chlorinated substance as well. Ammonium perchlorate as an oxidizer is also kind of you know going to give some kind of a you know trail of ah HCL. And you know sometime hydro you know water also can condense in a low temperature air and that can also give some whitey ah color in the exhaust. We also talked about the other categories of propellant like gas generator propellants. So, in case of gas generator propellants, the main motive is not to produce thrust rather the motivation is to provide like moderate temperature gas.

So, there are various application of gas generator propellants like you know ah I can talk about like different type of applications, where gas generator propellants are used like pilot emergency escape. There will be like push missiles from somewhere in launch tubes or land mobile canisters. There will be different actuators and valves, where the gas generator propellants are used. ah One very common example of gas generator propellants is in the automotive airbags. And then we have talked about the igniter propellants, where the major ah objective of this propellant is to provide like fast heat release.

So, that it can provide the hot plume onto the propellant surface and it will provide the sustainable ignition. And then we ah ended up the chapter with these discussions. So, today we will look at ah some of the you know tutorial problems just to understand like ah different you know solid loading, the fuel rich propellant or oxidizer rich propellants what we have already learnt. One parameter we have learnt there is called mixture ratio or MR, which was defined as the mass of oxidizer by mass of fuel. So, applying those you know understanding, we will try to solve some numerical problems so, that we can you know very much familiar with what we have covered in this chapter ok.

So, before moving into the tutorial problems, let us look at one ah parameter is called like solid loading ratio. Now, if you recall the very common oxidizer used in composite ah propellant is the AP or ammonium perchlorate. Now, AP has you know different particle sizes and based on the particle size ranges, they are categorized like either it is a coarse particle. So, it may be like varies from 400 to 600 micrometer or micron. So, 1 micron you can know you know 1 micron is 10 to the power minus 6 meter.

Now, another category can be like medium, which is in the range of like 50 to 200 micron. Another category can be fine, which is 5 to 15 micron and there is ultra fine ultra fine which is you know submicron to submicron to 5 sorry 5 micron ok. So, you know it is not always ah required that only the coarse or only the medium ah ranges particles are used. Generally to improve the loading fraction or the sorry to improve the packing fraction, packing fraction means to minimize the volume of the solid particles. Somehow we have to improve the packing of the solid particles within the rocket motor.

So, this fraction is the volume of the propellant or rather I would say like the volume of the solids when packed to its minimum volume. That is a theoretical condition. So, you want we want it to be like packed within the propellant grain considering a very minimum volume as much as solid particles are packed together. So, that will take a very small amount of volume within the propellant grain. So, that is the packing fraction.

So, you we want to improve the packing fractions by compacting as many as solid particles within the ah propellant grain or considering the minimum solid ah minimum volume for the solid particles like solid particle means we are talking about the aluminum as a fuel or boron as fuel and the ammonium perchlorate as the oxidizers. Now, there are difficulties while we put too much of solid fractions within the propellant grain because ah if you look at the uncured propellant when we put too much of ammonium perchlorate as a crystals solid oxidizers we put aluminum particles there. So, processing complexity will increase if we add too much of you know solid particles within the propellant matrix. So, that part we must need to take care in order to like maintain the proper you know physical property or the mechanical property of the grain as well as the ballistic property of the propellant. So, that there is a tradeoff between that accordingly the solid fraction ah is chosen.

So, if we look at the solid you know ah loading ratio. So, by definition of solid loading ratio is the mass of the mass of solid ingredients divided by the total mass of the propellant total propellant mass. Now, this is very true for composite propellant because composite propellant consisting of the ammonium perchlorate as a crystal ah crystal crystalline oxidizer aluminum particles as fuel and the rubbery polymer as the binder ok. So, this is essentially the binder this is the fuel and this is essentially the crystalline oxidizer. So, once we say the solid loading ratio that means, we are talking about the mass of ammonium perchlorate plus mass of aluminum divided by the total propellant mass.

So, if we are asked to find out what is the solid loading ratio we must need to add up the mass of ammonium perchlorate and mass of aluminum particles and then divide by the total propellant mass ok. So, it is the mass of solid ingredients divided by total propellant mass is the solid loading ratio. So, I will try to see ah through some example problems like how we calculate the solid loading ratio and how that are how that are going to influence the you know the ratio of oxidizer to fuel whether it is becoming oxidizer rich or whether it is becoming fuel rich. So, we will look at ah those things through some through one example problem. Now, solid loading can be as high as 90 percent because to improve the you know performance we may want like solid loading as high as 90 percent in some composite propellant.

But of course, the high solid loadings as desired for high performance, but that will you know introduce some additional complexities as well as the cost enhancement or cost increase. So, there must be a tradeoff between you know the ballistic performance and the physical properties the the process ability the manufacturing capability all those things should be you know taken care of while choosing the solid loading ratio ok. So, with that I think it is pretty much ok with our theoretical stuff. So, now let us look at some ah typical you know tutorial problems where we will try to brush up some of the basic stuff what we have just learned in these ah few lectures. So, let us look at one ah tutorial problem.

If you look at the problem statement it says a composite solid propellant consists of the following ingredients. So, it has like AP as oxidizer HTPB as binder. So, it is typical composite propellant we already know that typical composite propellant contains AP as oxidizer and hydroxyl terminated poly butadiene as binder. Now they are mixed in stoichiometric proportion. Let us assume the molecular weight of HTPB is 2734 kilo joule per kilo mole.

Now it is asking us to find out the mixture ratio and the solid loading in the problem ok ah sorry solid loading in the propellant. So, it is basically it is asking about how much solid loading ratio is there. So, this is an example problem taken from one book by professor Ramamurthy. So, we just look at how we understand the theory part. So, we will just simply proceed with that.

So, you know as it is given to us the stoichiometric proportion of the AP and HTPB. So, they are mixed in stoichiometric proportion. It is given in the problem statement ok. So, it is basically solid loading in the propellant that will be the correct I think word ok. What about the chemical formula for HTPB? We have earlier learn this that it is like a you know hydroxyl terminated polybutadiene.

So, it will have like butadiene many butadiene chain structure connected together. So, it will be like this N and it will have hydroxyl radical at the N. So, this is the typical formula of HTPB. Now we can we can write this we can write this in a little simplified form we can write this as C4H6NOH2 there are hydroxyl radicals at both the ends. Now since the molecular weight is given as 2734 kg per kilo mole.

Let us try to write from there. What you can write from there that how many you know we can we can get like how many carbon, how many hydrogens, how many oxygens are present there and accordingly we can find out the number N. So, let us try to do that we can write 4 carbon. So, it is like 4 into 12 plus 6 into 1. So, that is 6 that is times N plus we have like 6 plus 1 into 2 that is going to be equal to 2734. So, if you solve it I think we will get solving this one we will get N equal to 50.

So, that will essentially give us the chemical formula of HTPB if we put this in this equation. So, this will become sorry. So, this will become we have like C4H6 into NOH2.

So, we can multiply that one. So, the chemical formula will become based on this molecular weight we can get C200 sorry H we can put it inside.

So, H we have like 2 here and 6 times 50. So, that will become like 302. So, we can have H 302 and O2. So, that that is this is the chemical formula of HTPB we get after solving. Now since the chemical reactions between the HTPB and AP is given as stoichiometric combustion since it is given as the stoichiometric combustion of AP and HTPB.

What you can write that all carbon atoms will become like carbon dioxide or hydrogen atom will become combined with oxygen will become water. So, what we can write is and the of course, the whatever the nitrogen will present will be there nitrogen present in the AP molecule. So, if you write down the formula for HTPB here. So, it is basically C200 H 302 O2 plus AP you already knowing no AP is NH4 CLO4. Now let us we do not know how much how many molecules are going to be you know reacted with HTPB to have the complete combustion reaction.

So, let us write that as A and we can just simply write CO2 plus HCL is going to form HCL plus you know water plus nitrogen. So, we can easily write nitrogen molecule. So, this will become A by 2 easily write because here is A N. So, we can write A by 2 and let us say carbon dioxide we know because there is only carbon atom here. So, we can correct directly write 200 in CO2 HCL we do not know.

So, we can write HA we have H here the other can be like let us write this as B H2O. So, from the balance of you know balancing this reaction after balancing we need to solve for it. If you solve it I think we will end up getting you know 2 B equal to 302 plus 2 A. So, B equal to like 4 A minus 398 if you solve for it I mean this is not a very difficult task for you people. So, you may easily do it and you can find out the value of A as 219.6 and B as 480.4 you can check these answers you can do yourself and check this answer that you are getting this. Now, you can immediately write the stoichiometric equation after getting the value of A and B.

So, we can write this stoichiometric equation and this stoichiometric equation will become C 200 H 3 0 2 O 2 plus 219.6 NH 4 Cl O 4 that will become 200 CO 2 plus 219.6 HCl plus 4 8 80.4 H 2 O plus 109.2 N 2. So, this this is the complete combustion equation or the stoichiometric equation. So, we are asked to find out the mixture ratio as per the definition of mixture ratio we have already learned that mixture ratio is the mass of oxidizer mass of oxidizer divided by the mass of fuel mass of fuel. Now, in this case since there is no aluminum particles are present as fuel here the binder is acting as a fuel.

So, we have the mass of HTPB and mass of AP. So, we can simply write what is the mass of oxidizer here mass of oxidizer is this one. So, we can simply get the 219.6 into the molecular weight of NH 4 Cl O 4. So, we can write for N it is 14 4 into 1 that is for hydrogen for taurine it is 35.5 for oxygen it is 16 into 4 divided by we have fuel here. So, 200 into 12 for carbon 300 into 302 into 1 for hydrogen plus 2 into 16.

If you solve this you will get 9.44. So, that is essentially the mixture ratio. Now the second question so, this is the answer for question number A. Now in the second part of the problem we are asked to find out the solid loading. So, what is the solid loading or the solid loading ratio? You see the solid loading in the propellant is the fractional mass of solids present in the propellant. Since this is not an aluminized propellant there is no aluminum particles present.

So, in our case the solid loadings will be simply the mass of you know oxidizer divided by the mass of propellant as per our definition. So, here mass of oxidizer means mass of AP, mass of AP plus mass of HTPB. Now if you divide this mass of AP by mass of HTPB we can have mass of AP divided by mass of HTPB in the numerator and in the denominator we can write mass of AP by mass of HTPB plus 1. So, what is mass of AP by mass of HTPB? It is nothing, but the mass of oxidizer by mass of fuel which is mixture ratio MR divided by MR plus 1. So, if you just put the value there you will get MR we have just found out 9.44. So, it is 9.44 divided by 9.44 plus 1. One can actually calculate this it will come something around you know 0.9 or 90 percent or 90 percent. So, you can see it is very high you know solid loading in the propellant. Now you know considering the percentage of binder. So, here it is like 90 percent AP and 10 percent binder or 10 percent polymeric fuel you this is the combination now what we found out just.

So, because you know this is a high mixture ratio the mix mixture ratio is you see it is 9.44 and from there we can found out the solid loading is like 90 percent is solid loading. So, it is kind of difficult to you know such a large value of solid loading because in order to bind them the requirement of polymer will be slightly higher. So, it is very difficult to bind these you know oxidizer with a such of huge percentage. So, this is one such you know problem you can you can solve you can do the similar type of problems you know this will help you to understand the you know theory part of this portion better.

In fact, this will help you to you know solve some assignments as well. Now let us look at the other type of propellants where you can actually find out if the solid loading ratio is given to us and instead of just only like HTPB plus AP as oxidizer let us add aluminum particles also because aluminum particles act as fuel in the composite propellant. So, we can take the example of a solid composite propellant where aluminum particle will be there as a fuel HTPB will be there as a binder and ammonium perchlorate will be present as oxidizer and from there we will try to see that whether is becoming fuel rich or oxidizer rich we will try to calculate and understand. So, let us look at the second problem. So, look at the problem statement first it is saying a composite solid propellant has a solid loading of 90 percent and it contains 10 percent aluminum the fuel binder is HTPB and the oxidizer is AP.

So, fuel or binder we are saying that HTPB because HTPB will act as fuel as well because it is hydrocarbon fuel, but here it is a it has proper fuel as aluminum and binder is HTPB and oxidizer is AP. Now it is asking the question that what is the mixture ratio and molar composition of the propellant and also it is asked it is asking us to find out the composition whether it is a fuel rich or oxidizer rich ok. This problem also taken from the same book, but we will try to understand the you know we just brush up our understanding what we have learned in the theory course because this will help us to you know do the assignments as well. So, let us look at the problem statement and write what is given. So, what we can write from here as per the problem statement solid loading is given.

So, solid loading is given as 90 percent. So, you can immediately write that solid loading as per our understanding it is the mass of ammonium perchlorate plus mass of aluminum divided by the total mass of the propellant which is mass of AP plus mass of aluminum plus mass of you know HTPB that is given as 90 percent which is 0.90 ok. And also it is given if you look at here it is given like 10 percent aluminum. So, we can write that mass of aluminum divided by mass of AP plus mass of aluminum plus mass of HTPB this is given as 10 percent which is 0.1. So, this is equation 1 let us say this is equation 2 ok. So, combining this we can easily find out that mass of AP plus mass of aluminum divided by mass of aluminum will simply become 9 because we are dividing equation 1 by equation 2. So, we can get this or from here we can easily get like mass of AP plus mass of AP by mass of aluminum mass of aluminum plus 1 is equal to 9 or from here we can get mass of ammonium perchlorate by mass of aluminum will be 8 ok. So, this is another you know finding. So, from here what we can say that the oxidizer to aluminum mass ratio is 8. So, from there we can actually get the ratio of binder to the aluminum particles we can see how much is present in the propellant.

So, let us say if we want to find out like mass of aluminum plus we can get from the equation 1. So, from equation 1 we can easily write. So, or even equation 2 also same thing. So, let us say we write from the equation 2 because we are writing mass of aluminum. So, mass of aluminum and mass of AP plus mass of aluminum will simply become 9 time mass of aluminum because 8 times is the mass of ammonium perchlorate with respect to mass of aluminum.

So, we are adding the we are just writing in terms of mass of aluminum plus mass of HTPB which is given as 0.1 from equation 1. If you now do this thing you will end up getting mass of HTPB by mass of aluminum will be equal to 1. So, what does that mean? There is a equal proportion of the polymeric binder and the ah the metallic fuel.

So, it is like 10 percent aluminum and 10 percent HTPB. So, typical if you write down the mass ratio it will become like mass of ah AP is to mass of aluminum is to mass of HTPB will simply become 8 is to 1 is to 1 ok. So, it is like 80 percent ammonium perchlorate 10 percent aluminum and 10 percent HTPB. So, now if you are if you are if you try to find out the mixture ratio what will be the mixture ratio? Mixture ratio will be simply the mass of oxidizer divided by mass of fuel. Remember this time the mass of fuel will be the mass of binder plus mass of aluminum particles.

So, it will be like 8 by 1 plus 1 which is like 4. So, this is the answer for question number A. Now, molar composition I think one can easily do it. If you try to find out the molar composition, molar composition can be found out by you just ah try to do it like number of mole for AP is to number of mole for aluminum particles is to number of mole for ah HTPB. Since we know the mass we can simply write like mass of AP by molecular weight of AP is to mass of you know sorry mass of aluminum is to molecular weight of aluminum is to mass of HTPB by molecular weight of HTPB ok. So, if you write down this mass you already know that was like ah we can do it the mass of this one was 8 by molecular weight of one can find out the molecular weight of this NH_4ClO_4.

So, if you do this I think you will get 117.5 ah kg per kilo mole. So, you just put the values there I am not solving fully I am just writing how to do it. So, just simply write and mass of ok molecular weight of aluminum is 27 molecular weight of HTPB we can take from the previous example problem, but it must be given there otherwise is difficult to say because molecular weight of HTPB varies. So, you can easily find out ah the ratio from this and from there you can actually find out the combination of the you know the molar composition you can actually get the molar composition.

So, it is coming something around you know 0.672 is to 0.325 is to 0.003 I mean the participants are requested to verify the calculations once ok. So, eventually if you write down the equation sorry the molar composition of the propellant you can get like it is containing 0.003 of HTPB.

So, HTPB was the formula was C 200 H 302 O 2 plus 0.672 of NH_4ClO_4 plus 0.325 aluminum ok. Now, in the second question if you remember it was asking us to find out whether it the composition is fuel rich or oxidizer rich. Now, how do you find out that thing that whether it is a oxidizer rich or fuel rich we can actually find out that how many number of hydrogen is present there because you see the the complete ox oxidation product or the complete combustion products will contain if you consider like stoichiometric reaction the complete combustion products will have HCl then we have H_2O you have CO_2 and for aluminum you will have aluminum oxide ok.

So, we have how many number of hydrogen. So, we can add up like 302 into 0.003. So, it is like for hydrogen if you calculate it is like 0.003 into 302 plus here we have 4 into 4 into 0.672 that will give us like 3.594 hydrogen atoms. Now, out of this 0.672 will be oxidized to form HCl because you remember there is 0.672 chlorine atom is there. So, 0.672 hydrogen will actually become like HCl it is going to form like HCl.

The remaining hydrogen so, it is like 3 point remaining hydrogen atoms is like 3.594 minus 0.672 that will is going to take you know oxygen and will become water. So, like 2.922 hydrogen atoms will oxidize and let us go back. So, it is 2.922. So, how much oxygen atom requires to oxidize hydrogen to H_2O. So, it will be simply like 2.922 divided by 2. So, that much of oxygen atoms required for converting hydrogen atoms to water.

So, this will become like 1.461. Now, what about the carbon atoms? So, the carbon atoms will have like 200 into 0.003. So, carbon atom is like 200 into 0.003. So, we can have 0.6. So, the oxygen atoms required you know for converting for converting C to CO_2 will be like 0.6 by 2 0.6 into 2 because CO_2 requires like 2 oxygen atoms. So, it is like 0.6 into 2 which is 1.2. Similarly, for oxidizing the aluminum we have like 0.325 aluminum which will convert to Al_2O_3. So, the oxygen atoms required for this purpose will be like oxygen atoms required will be like 0.325 into 3 by 2 because Al_2O_3. So, it is 3 by 2. So, that will become like 0.4875. So, the total you know moles of O_2 required will be this like 1.461 plus 1.2 plus 0.4875 divided by 2 that will becoming 1.745.

Now, you see the number of moles available in the reactants, number of moles of O_2 available in the reactants because that will determine whether it is a fuel rich or oxidizer rich. You can get what is the availability of oxygen molecule? It was like 0.003 plus 2 into 0.672 which is coming as about 1.347. So, this is the available and the required is this one. So, what you can see it is fuel rich. Is not it? Because the availability is actually less than the required for the stoichiometry reactions. So, it is fuel rich. So, similar way one can actually try to you know find out the ratios and one can actually understand that whether it is a fuel rich and oxidizer rich like this based on the you know composition of the reactants.

One can actually do the solid loadings ratios just by calculating the amount of solid mass present in the propellant and divided by the total mass of the propellant. And similarly if the solid ratio is given one can actually find out the composition as well. So, these three total problems actually help to you know solve some of the assignment problems later on given to you. So, I think with that we close this you know module on solid propellants.

Next week sorry the next class we will continue with a new topic. Till then you can revise this stuff. Thank you.