Fundamentals of Combustion (Part 2)
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Lecture – 65
Introduction to Droplet Combustion

Let us start this lecture with a thought process from Albert Einstein.

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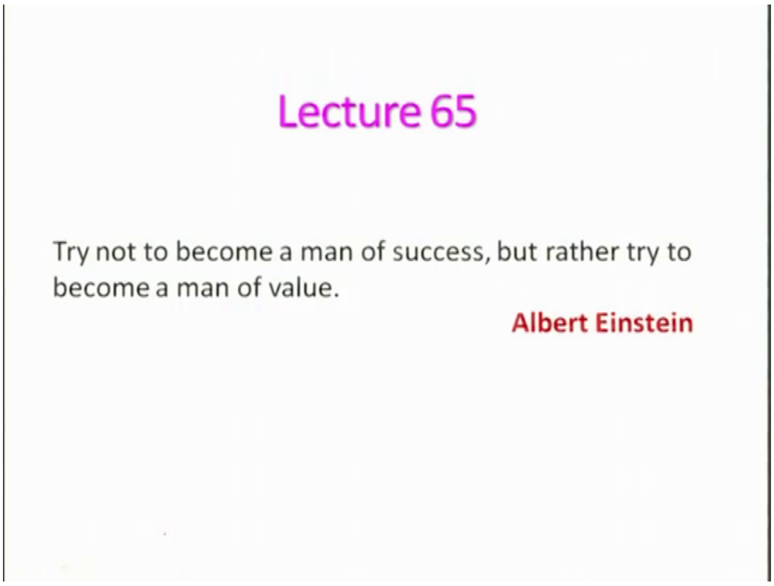

He says try not to became a man of success, but rather try to become a man of value of course, in today's world people do not look at his statement, but which is eternal. So, in the last lecture basically we looked at the suit mechanism of the jet diffusion flame and also the diffusion flame general. And, later on we moved into the initiation of discussion on the liquid fuel combustion right and we will continue that discussion on that. And, let me just tell you that we need to basically convert the bulk liquid into spray.

In other words arrays of spray is basically arrays of droplet size of various kind and such that it will be helpful for the high rate of combustion. Why? I will just give an example, 3 mm diameter of droplet right if I want to convert into of course, hypothetically 30 micron. What will be the 30 micron diameter? Like let us say there is a big droplet 3 mm, I will convert to a 30 micron and it will be like something 1 million right and the if you look at the surface area will be increase by tremendously.

So, therefore I can enhance the heat release rate per unit volume for the same amount of fuel being burned or for burning the same amount of fuel. So, that is the beauty of this thing, but however, it is quite complex in nature and not only atomization, but also the combustion process involved. I will just try to give you overall picture of a the liquid oxygen and gaseous hydrogen will combustion in a rocket engine, this is a very simplified one.

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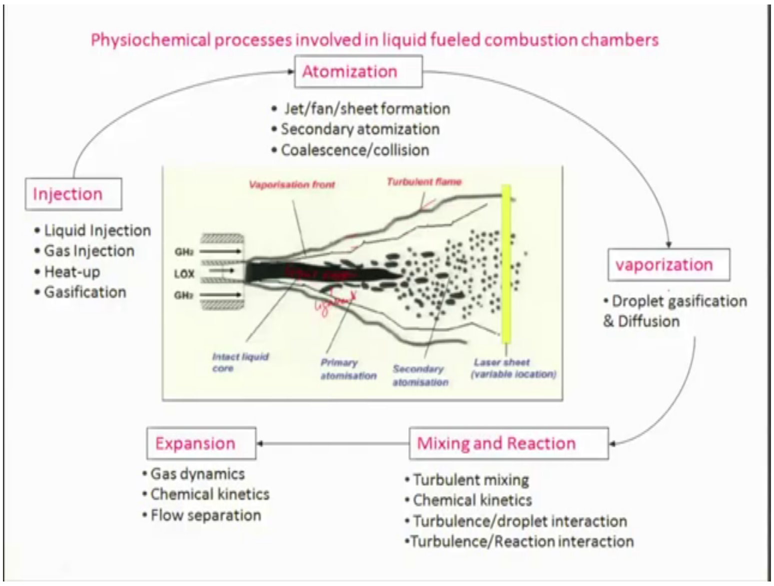

If you look at this I have shown here and it is having a liquid oxygen jet which is a liquid itself, this is the liquid right liquid oxygen. And, this is remaining intact; however, when the hydrogen is moving around it is trying to smear out the some of the larger ligaments. These are ligaments you know which will be coming out of that and then this of course, will be interacting with the gaseous hydrogen and other things, they may collide each other. Then the, they will be subjected to decrease in their diameter and this keep in mind that these are not spherical in sub ligaments maybe may not be, but generally no.

This entanglement of ligament from the bulk liquid is known as a primary atomization and later on these ligaments will be converted into droplets and then it will be interacting with a cell sometimes. The droplet may coalescence, but not near this place, but may be far aware momentum will be very much reduced not that they may coalescence also. That means, small droplet can you know combine two small droplets are many droplets will combine to bigger droplets. So, that will occur only when the momentum in the this thing is not there and combustion has not taken place.

So, this is if you look at it is a quite complex process. Let me just start with the liquid injection, injection is the isolate problem, the gas injection other problem. One has to of course, the if there is a flame if you look at this a flame is here of course, you will have to unite and then there will be some gasification, vaporization of the like front. These are the vaporizing front right, I have shown and then of course, the liquid will be heated off. And, then the atomization there can be a jet or there may be seed formation. Of course, here is not being shown, but that is a fan also depending on the type of injectors whatever.

I am not discussing about type of injector that will be another all together very different subject. So, secondary atomizer, I have told coalescence and collision can occur right in this case and there will be a vaporization, droplet vaporization, gasification. Some flame will be formed I will be showing something how it will be going on and beside this there will be turbulent mixing, chemical kinetics like which will be governing the reaction rate. Turbulence and droplet interaction and turbulence and reaction interactions you know all those things will be coming to picture in actual systems. Beside, these as there will be heat release there will be expansion of the gases and of course, the flow may separate.

Because, we want to enhance the mixing in the real system then there will be flow separations. And, all those things has to be model and understood it is not that easy it is quite complex process. So, I have just given you the birds eye view of the fluid fuel combustion. Unlike gaseous fuel combustion, liquid fuel combustion is quite involved to understand and to model right. And, it is a two phase flow so, turbulent and then you know heat transfer, mass transfer, chemical it is quite complex. And, also the droplet size, the distribution will be changing right. How will take and all a random in nature keep in mind, the droplet atomization process is random in nature.

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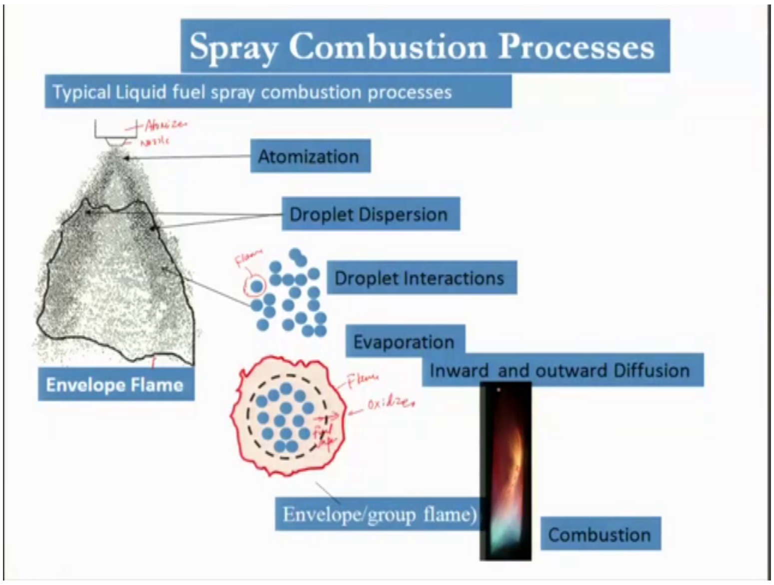

So, I will just give you some idea about that is let us say this is a atomizer right and a jet is coming through this nozzle right. This is your nozzle and there is a atomization is taking place, there might be droplet this dispersion right and there might be droplet interaction. The droplet will be interacting with each other, there will be evaporation and this is of course, the envelope flame I have shown here kind of things.

If you look at there might be a situation where there is a several of droplets and they are very close each other right. And, they may together will be giving some vaporization of the, this thing and then oxidizer will be coming over here, oxidizer right. And, this is coming fuel vapor and this is a flame will be formed right and this is known as a group combustion or group flame. There might be a situation where a single droplet flame might be there right and there might be situation two you know droplets burning droplet having flame together a little far away. So, there is a all permutation combination one can occur of course, this I have shown a flame in my lab itself, the liquid fuel combustion.

You can see this is again a jet liquid fuel combustion that is this a blue color, it is well mixed and here of course, that droplets are and these are the path line where the droplet will be moving you know that source. So, it is not a very good image. However, if it is the high speed image, you can get track the droplet provided it is a bigger one. If it is small it will be very difficult to track exactly right and bigger one you need not to you should not have that you know right.

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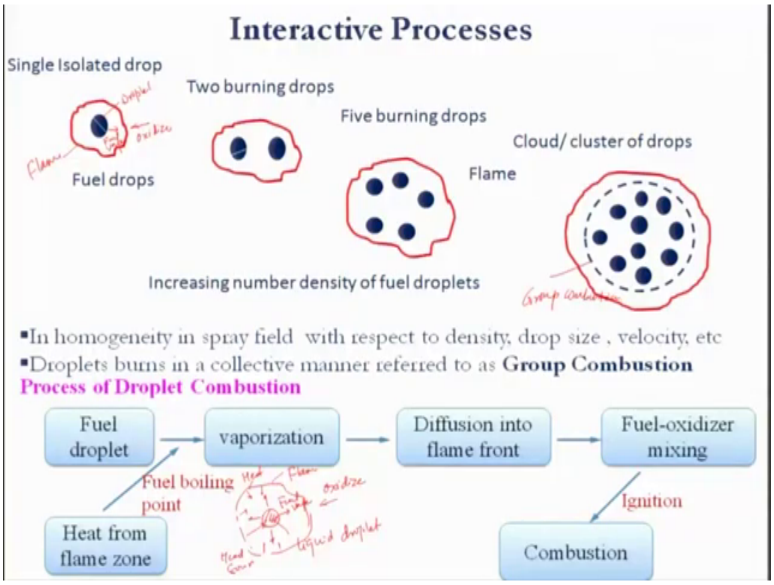

So, let us look at what will be happening? Happening is that there is a one situation is a single isolated droplet right, one single droplet this is your droplet right. Of course, generally it will be spherical nature right and there might be as I told that there will be a evaporation from the surface of the droplet right. This is a vapor well vapor and this will be oxidizer which will be coming and then this is the flame which is forming right. And, there might be two droplet, which are together having one flame, there might be some maybe five burning droplets which are together right. And of course, if there is a number then they call it a cluster or a cloud of the droplets and there is known as a Group Combustion.

Generally, in the homogeneity the spray field with respect to density, drop size and velocity, you know it is very difficult to get right. And, droplet is burns in a collective manner refer to as a Group Combustion. You can say this has a basically group combustion or you can also call this as a five, but generally two burning droplet, three burning droplet it is very rare you know like a ribbon. When it will be occurring? Where there are number density; that means, number of droplets per unit volume is very high. That means, they are very close to each other, although I have magnified it and shown but they are very close to each other each droplets.

So, therefore the group combustion will be taking place and it can all permutation combination can take place. Like you can have a fuel droplet single isolated droplet combustion, two burning droplets and five burning maybe seven, nine, you know eight, six whatever it may be it may be also together. So, anything can happen and on all together. So, let us look at what is happening the process of droplet combustion. Once this fuel droplet is there what you need to have is basically heat from the flame surface right. If there is a droplet here right there should be some ignition source you will have to give.

So, that the heat will be coming out right it will be getting into this droplet like let us say this is the heat, heat source you know heat source. So, some heat has to get into. Why it is required? Because, it has to evaporate right it has to vaporize the liquid droplet right and then fuel of course, will be start boiling vaporizing rather. And, there will be vaporization which will be occurring right and this vapor you know fuel vapors will be moving. Of course, this will be moving towards all the sides right and similarly this is the quiescent atmosphere. So, therefore oxidizer will be coming toward that also.

And, whenever they will meet right so, some kind of this flame I can say this is your flame will be formal. So, and fuel and oxidizer will be mixing at the surface of the flame; that means, in this case the and this is occurring because of diffusions and this is diffusion control. And, reaction will be very fast right as compared to the time required for mixing. And, then of course, we will have to ignite and if there is a flame already, there is no ignition in the flame will be giving you heat into the surface. This is heat, heat will be getting into the surface of the droplet and it will evaporating heat you know.

So, the droplets will be getting evaporated due to the heat received from the flame once the flame is established. So, what will be doing? We will be basically looking at a single droplet combustion in our class because, it is very difficult to tackle the problems of the spray combustion. Later on we will be using this how we will be using those results for analyzing the spray combustion, again within the limitation of 1-dimensional flow right.

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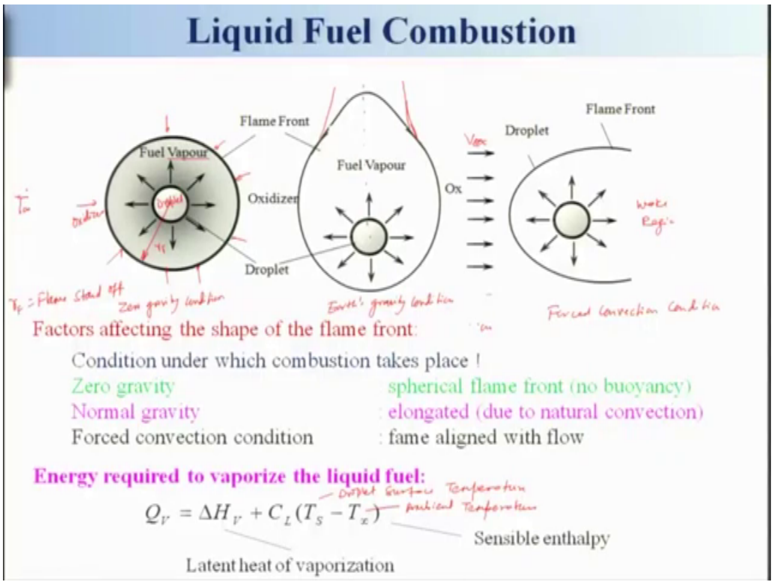

So, let us look at the single isolated droplet and in the first is the situation where droplet is there, this is your droplet having certain diameter, fuel vapor is going out and then this quiescent atmosphere. Therefore, oxidizer will be coming in right from atmosphere right. Now, I will get a flame like this right and there is another situation where the droplet; this is a droplet and I am getting a flame like that. I have shown you earlier a flame in my lab itself. But, under what condition I should get? This is will be corresponding to the zero gravity condition gravity condition right and, this is earth gravity condition.

Of course, one can conduct experiment also the high energy as well and keep in mind that generally the this will be problem which is complex as compared to the zero gravity condition, is not it? Because, here the flame is symmetric in nature whereas, here also it is symmetric but, it is symmetric with what will be along with this not with this right, along the vertical direction in this diagram, but not in a horizontal right and, beside this the, this elongated flame is coming because of buoyancy. Now, buoyancy effect has to be also taken care and there is another situation which is a practical one that where the flow will be there right or I can say this is oxidizer velocity which is moving.

And, then I will get a flame here and this is your wake region right and this is your boundary of the flame, there will be boundary layer, hydrodynamic and also thermal alright. So, this will be there and this is also a quite a complex in nature. What will be doing? We will be basically trying to look at the droplet burning under the zero gravity condition, trying to analyze it and use the data for the convective flow. Because, this is basically force convection right condition and this is natural convection right condition. And, this is the zero gravity, there will be some convection, but however, it is some bulk fluid will be moving, but that will be radially it is going on.

So, this is known as normal g what you call zero g, right this is zero g and keep in mind that this distance if I take from the center or maybe I can take from center here. So, these distance what I call this is the flame stand of distance r F is the flame standoff distance. If you look at that is very important and that will affect basically the how first the droplet will be receding means getting consumed right. So, what are the factors that affect the shape of the flame front? Is basically as we have already discussed condition under which combustion takes place, for the 0 g this will be spherical flame front no buoyancy effect this is a spherical and symmetric also. Normal gravity is elongated due to natural convection and force convection condition flame aligned with the flow.

Because, this is the flow which is taking place it is aligned and energy required to vaporize this liquid fuel is a very important because, that will be governing how much you know fuel is vaporized and how it is moving out and then coming in contact with the oxidizer for forming a flame. So, Q V is equal to delta H V plus C L T S minus T infinity. If you look at the first term is basically latent heat of vaporization and the second term is the sensible enthalpy. And, T S is the what the surface temperature droplet or surface temperature.

And, T infinity is the ambient temperature. If you look at the let us say of course, here it will be very high, but you will have to look at when you started what will be the ambient. For example, far away from here this will be T infinity very far away from the droplet, nearby it will be it will be flame temperature right, a near the flame, flame temperature after that it will be residing.

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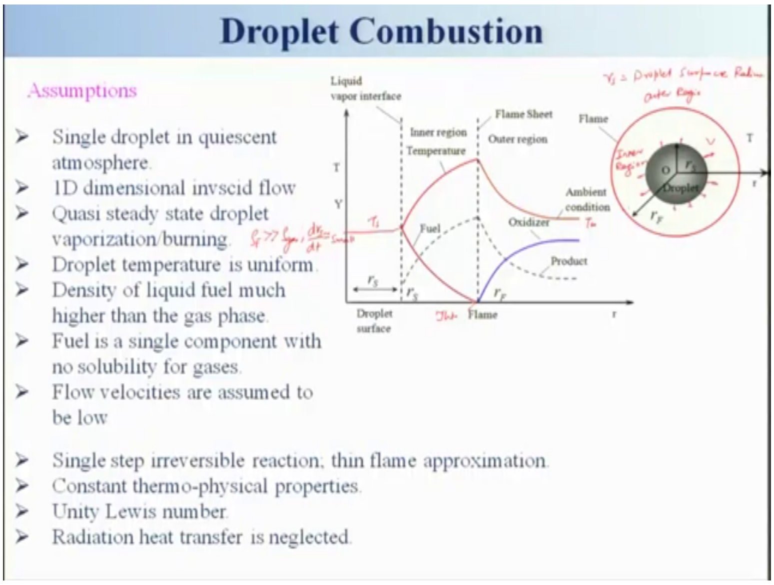

So, we will be analyzing these thing and for that what we will say let us look at a single droplet. We are considering the zero g condition, force convection condition if you look at any practical combustor will be force convection because, the flow will be coming and the droplet will be there and then it will been right. But, single droplet certainly no you will have to conduct an experiment to understand the process. The array of droplet will be there and it will be moving and each may be droplet will be moving with their own velocities.

But, you know also the velocity will be changing across the cross section of the combustors and as it moves it will also changing it quite complex. Generally, force convection means is a practical situations and these single droplet what we are discussing, do you think that it will be anyway practical? No, right it is only for our understanding or in experiment for research purposes we do. So, if you look at the droplet is here and this is a symmetric, in the sense along the phi direction because, this is spherical in nature droplet. And, the phi direction and then the phi direction that will be the symmetric and it will be varying only along the r direction right.

So, if you look at this distance is basically from here to this, this is the r S, r S is the droplet surface radius right. This is basically I can say r S it is the droplet surface right and this is your as I told r F is your flame stand up distance. Because, flame will be located at certain region that will be dictated by basically how fast this fuel is diffusing into the flames and also the oxidizer being diffuse and mixed. So, that will be dictated by that and if you look at the region wise and there will be inner region right in this portion. This is your inner region right and outer region will be here I mean like outer region.

So, in a region what will be happening? If you look at temperature of course, from the surface temperature this is your surface temperature right. This will be surface temperature T S and it will be increasing to the flame temperature and then after that it will be decreasing. And, this will be something T infinity right ambient conditions and similarly if you look at the fuel mass fraction is decreasing. It will be maximum at the flame surface sorry under droplet surface and it will goes on decreasing and then it becomes 0 at this location. And, similarly the oxidizer also will be mass fraction of the oxidizer will be decreasing and it becomes 0 as the flame surface and this is the flame sheet.

And product of course, will have peak value at the flame surface because product is one and keep in mind that this is the approximation what we are doing thin flame approximation. So, if you look at this is basically the single droplet in a quiescent atmosphere. There is no you know disturbances there is no flow, it is just you know quiescent atmosphere. So, if it is quiescent atmosphere then and also it is under zero g condition right and I can as I told earlier that it is we can consider it as a 1-dimensional invscid flow right. There is no viscous effect we are considered and the we can assume that quasi steady state droplet vaporization or the bonding is taking place.

Keep in mind that this vapor which will be moving right that depends upon whether it is steady state or not because, of fact that what is happening the rho F of the fuel density of the fuel right will be far greater than the row of the vapor right or the gas whatever being; you know this gas the fuel get gets vaporized on the surface of the droplet and then it moves right.

So, that density is very very higher. So, if it is higher so, what you can say that d r S right I can write down d r S by dt will be very very small right; as compared to the velocity the bulk velocity which it will be gas will be moving. Because, the gas will be moving outwardly right with certain velocity because it says you know due to the diffuse right which will be taking place and also right. So, therefore this will be quasi steady state, this is not changing you know it will be something few mm or a not mm even it will be micron per seconds.

So, it is almost you know changing, but whereas, this velocity will be higher order. So, therefore, it will be almost steady quasi steady, we cannot say it is a steady process because, the droplet size is decreasing as the burning is taking place ok. That decrease of the droplet size is quite small with respect to time as compared to the with which velocity will be moving. So, the droplet temperature is uniform, but which is not true right because, at the centre temperature will be different, at the surface it will be different. But, we are assuming otherwise you will have to solve the equation for the liquid or the droplet inside that we will have to solve.

But, we are assume need to be the uniform which is not the case even if you conduct experiment it is not possible ok. But however, simplicity we have done and density of liquid feel much higher than the gas phase, I have already told you. Fuel is a single component with no solubility of gases. Because let us say diesel, diesel is a multi component fuel right. So, there might be multi components fuel like nowadays people there is gasoline, there adding some alcohol. So, then it is not that way it is the only single component fuel. There is no other gases which are being there in that and otherwise there will be a lot of problems in that like; what x will be formed there is a quite complex phenomena.

And, flow velocities are assumed to be low right and single step irreversible reaction rate will be using which is basically, as I have told this is the thin flame approximation. This is the thin flame or you can say this is a thin flame right approximation will be doing and constant thermophysical properties as usual we do Unity Lewis number right and radiation heat transfer is neglected.

So, these are the things we are making this assumption and no other phase is formed in the liquid fuel droplet right. Because, in the droplet there might be two phase think there might be solid particle or some other things so, that is not there. So, with this we will stop over and we will be discussing in the next lecture how to carry out this analysis ok.

Thank you very much.