Spray Theory and Applications
Prof. Mahesh V. Panchagnula
Department of Applied Mechanics
Indian Institute of Technology, Madras

Lecture – 41
Spray combustion

Welcome back. We are going to continue our discussion of Spray Combustion. We started our discussion with single droplet evaporation. And we showed how the surface area or d squared, where d is the diameter of the drop decreases linearly with time in the context of a single drop evaporating in an infinite quiescent ambient atmosphere; that is unsaturated with the vapour of the liquid that is evaporating. Then we showed how this d squared law seems to hold true in many other situations, where the assumptions that I just described may not be rigorously valid.

Like for an example, if I have a small adjective current of air flowing pass the drop, the surface area still seems to decrease linearly. The turbulent if the flow also happens to be turbulent. There is a contribution of the turbulence to the mass transfer of the vapour away from the liquid vapour interface, but the surface areas still seems to decrease linearly. So, again the last two conclusions that I am describing are essentially, empirical observations there is probably little theoretical basis to conclude that the d squared low should be valid just so happens to be valid.

We already seen one such instance in the context of sprays where we did whole bunch of linear instability analysis which are only rigorously valid in the infinitesimally perturbation limit. So, I take a flow I perturb it infinitesimally and watch the fastest growing mode and there is empirical evidence to show that whatever is the fastest growing mode in that context seems to also dominate the breakup which is at the finite amplitude disturbance level and far away from this infinite perturbation limit. So, one could imagine the d squared law also to fall in that sought of class of models.

So, we started with d squared law and then will showed how the same can be apply to the context of a drop evaporating in a flame. Flame is nothing but a hot a region. Essentially, some of your properties seem to change, but the process is still diffusion limited. The drop evaporating in an infinite ambient atmosphere is mass diffusion limited, that is; it is limited by the rate at which vapour that is produced at this liquid vapour interface is diffused is transported away from this liquid vapour interface towards the unsaturated ambient atmosphere. In the context of a drop evaporating in a hot atmosphere or a flame it is limited by the rated which heat can be diffused, heat can be transported to the drop which is essentially, thermal diffusion limited process.

So, we made the assumption of a unity Louise number where the thermal diffusivity divided by the mass diffusivity is one which means, that in the context of unity Louise number evaporation situation the a drop still evaporates following the d squared law. But the rate constant in the d squared law would now depend on the heat release due to combustion, thermal diffusivity, and other properties, and the un-saturation in between the drop, and the far away ambient in terms of the temperatures.

And then we showed how this can be extended to a spray combustion situation and in extending to extending these single droplet evaporation models to spray evaporation first, we said there are four possible modes and which this can happen. And really speaking we started to talk of combustion, primarily because in the case of liquid fuel combustion the process is entirely evaporation limited. The rate of evaporation is much slower than the rate of combustion itself. The time scale associated with let us say, gasoline vapour reacting with oxygen to form carbon dioxide and water vapour is very fast in comparison to the time scale over which a gasoline drop, liquid gasoline drop releases vapor.

So, the simplest assumption to make when you have this kind of disparity in times scales is to say that if, as soon as the evaporation process happens and vapour is created the vapour is instantaneously reacted and form, and the reaction speeds or almost instantaneous in comparison to the evaporation speeds; in evaporation time scales. So, this spray combustion in that sense offerses this one simplification that you can assume that evaporated vapour reacts much faster than evaporation process itself. And therefore, you can only in look at one modeling one process and replace the other process with all most in algebraic model which is essentially like a very fast process.

And we said all the reaction happens only in the vapour phase which means that if I know how the evaporation process happens I almost have completed my understanding of spray combustion itself.

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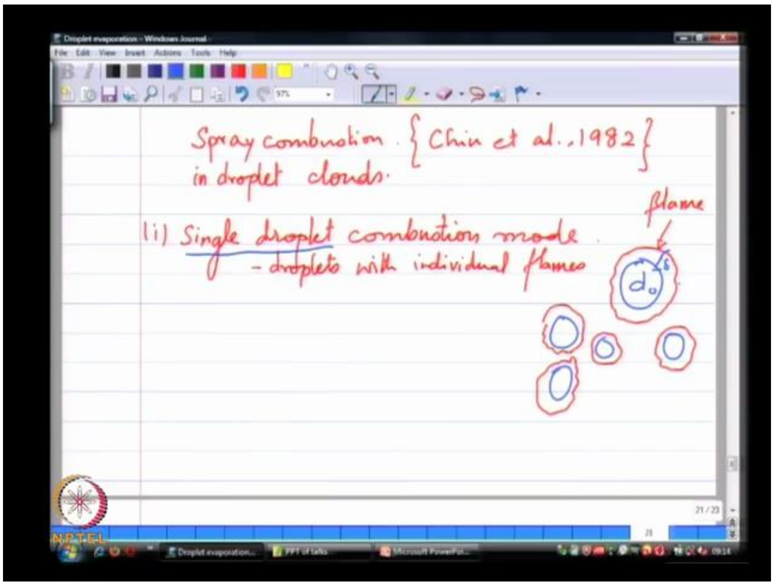

Spray combustion in droplet clouds. {Chin et al., 1982}

(i) Single droplet combustion mode.
- droplets with individual flames

So, we said as far as evaporating clouds of droplets, there are four possibilities and we started to talk of those four possibilities. The simplest of the four is, where you have single droplets single droplet combustion mode where I have drops, each drop is encompassed or engulfed in a flame surrounding it. Now we said that, this distance delta the flame stand of distance essentially depends upon the point at which you have near one or near stoichiometric here it to fuel ratio.

Which sort of a simplistic assumption but let us just say, that very close to the droplet interface you have too much the fuel air mixer is too rich to sustain combustion and very far away from the droplet interface you have if the mixer is to lean to sustain combustor again. So, somewhere in the middle there is a point at which you have flame would be sustain. And this flame is essentially transporting heat back to the drop either in the form of radiation or some other process and that process is further accelerator is vapour release.

So this flame is going to be sustains as long as you have a source of fuel, as long as the fuel is not completely exhausted. The moment the fuel is completely exhausted we are not going to be able to use this model.

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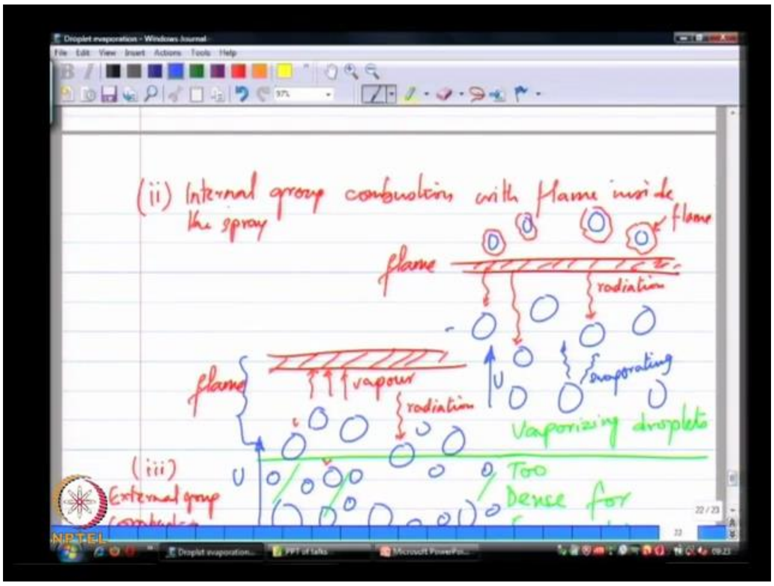

(ii) Internal group combustion with flame inside the spray

Then the next model that we talked about in the context of droplet combustion is internal group combustion where I have a flame; so the flame is given by this red hash line, I have drops that are generated from some nozzle and this nozzle is essentially producing a poly disperse spray. So, I have all the drops that are been transported towards the flame U at some velocity U and these transported droplets are coming in to the flame zone, are receiving heat from the hot gases that are that comprise the flame zone and realizing vapor.

But this process, let us take a very simple situation where; if this process was such that the time scale associated with the droplets coming in to the flame zone is fast in comparison to the rate of transport of heat to the droplets. It is conceivable that the droplets would not be completely evaporated. When the droplets are not completely evaporated you have a flame sustain by whatever vapour is released from the droplets, but you still have and intact all those small and intact liquid droplet that escapes the flame zone and the way this process can escape is if you have each drop still engulfed by a small flame. So, if they droplets escape the flame zone intact then they I am going to be angles by a small droplet flame just like the single droplet evaporation case, that we described earlier.

Now, if I continue this time scale analysis all though we are not doing it in a very rigors sense. If the density droplet number density which is based on the spacing between the droplets, the ratio of the spacing between the droplets in the time scale over which the concentration gradient happens in the ambient atmosphere. If that is too high then you actually have a region which is indicated by this sort of a green hash zone where there is no evaporation possible. So, essentially you have the evaporation process is completely suppressed. And so, I mean we are not really looking at the green line in a spray where below which there is no evaporation and above which there is evaporation, sought of a schematic for as to understand how this process happens.

So, you could have a region very close to the nozzle where the droplet number density is so high that the ambient interstitial air is completely saturated at that given temperature. And heat is not being transported to that zone, because let us say radiation essentially is aptitude by the drops that are in between the flame and this den-spray region or some of or through some other process. Essentially you have a region where there is all most know evaporation followed by a spatial region where you do have droplet evaporating and supplying fuel to the flame. So between these part is like our internal group combustion except that the flame is now completely supplied only by vapor. So, you do not have any droplets reaching the flame at all or the only source of energy to the flame itself or the flame zone is vapour fuel alone.

So, this would be the primary mode of combustion that is, primary desirable mode of combustion the most applications, because every time you have a burning droplet escape the flame zone that could become a source of suit. Because you cannot ensure well mix sadness, you cannot ensure the appropriate equivalence ratio in situations where individual droplets are burning. Whereas, if I ensure vapour face reaction homogeneous vapour face reaction, then you are desires stoichiometric is better control you are desire for even stoichiometric is achievable.

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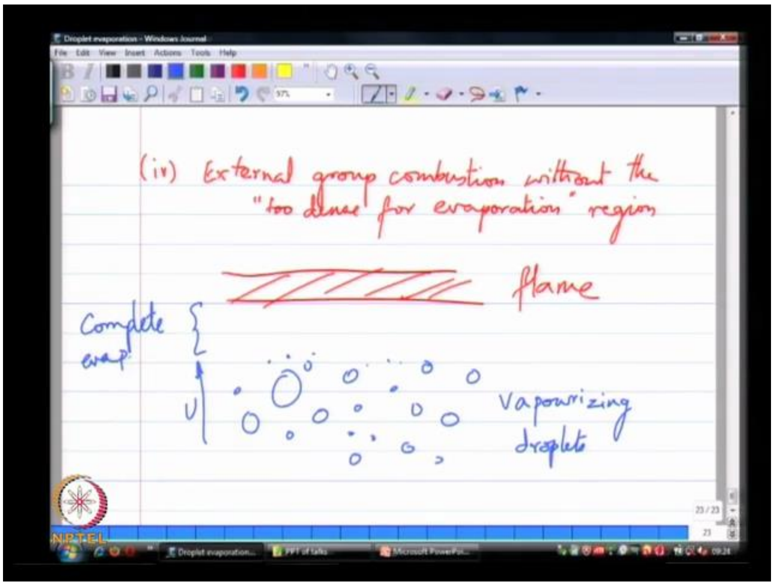

(iv) External group combustion without the "too dense for evaporation" region

The last possibility is external group combustion without the two dense for evaporation region. So, essentially it is very similar to the last example we saw that I will have a flame zone, which with droplets that are being transported towards the flame, but all the droplets are vaporizing and the droplets themselves are completely evaporated prior to the flame zone. This is our fourth mode of combustion. So, this is also in fact, a very desirable regime of operation, primarily because your flame is entirely sustained by a homogeneous mixer of vapour and air.

So, you have more likely to eliminate rich and lean spots or you are more likely to eliminate mixer ratio or equivalents ratio fluctuations in the spatial fluctuations in the equivalents ratio. So, you have the third and the fourth modes that are similar and, but are only distinguishable by the density number density of the droplets. So, the same the name the number three mode if the droplet number density was a little low then you would essentially result the situation would look like number four, where you have external group combustion without the two dense evaporation region.

So, essentially you would have heat being transported all the way to the nozzle which creates a spray that is evaporating right from the outset. Now whether you have number three or four is usually, not in our control primarily because the droplet number density is determined by the flow rates that you may require and atomization characteristics of the nozzle itself. If I desire a certain power from my spray combustor heating power that also, determines the liquid fuel flow rate which intern determines the droplets number density. So, if my power requirement is low then I may, I have a low number density creating a vaporizing droplet stream right from the nozzle outlet itself.

Whereas, if my power density power density which is sort of the power expected per unit volume of the combustor itself, that has a role to play in whether you are operating in regime number three or regime number four. So, these are still schematics of what happens when I have a cloud of droplets that are feeding energy or feeding fuel vapour in to a flame zone. Now the flame itself is trying to burn back burn back towards the nozzle and this fuel supply towards the flame is what is sustaining or stabilizing the flame at a in a zone that is far away from the nozzle itself.

So, very close to the nozzle I may not have in a fuel vapour supply to sustain a flame and the flame is there stabilize in a general spatial region where the equivalents ratios are appropriate for combustion to happen. Now in a typical gaseous fuel flame the flame itself is very very thin and the flame thickness has to do with the laminar flame speeds where not going to go in to a discussion here on that part, but in a typical spray flame is much more diffuse for two reasons. One the laminar flame speeds of fuel vapors like even gasoline which is among the faster burning fuels is fairly slow in comparison to other gaseous fuel like methane or hydrogen.

Secondly we have in the case of liquid fuel flames all most always your flame itself is non-premixed that is your oxidizers source and the fuel source are spatially separated and. So, they would have to mix. So, there is like a described in the schematic in the last class there are three possibilities.

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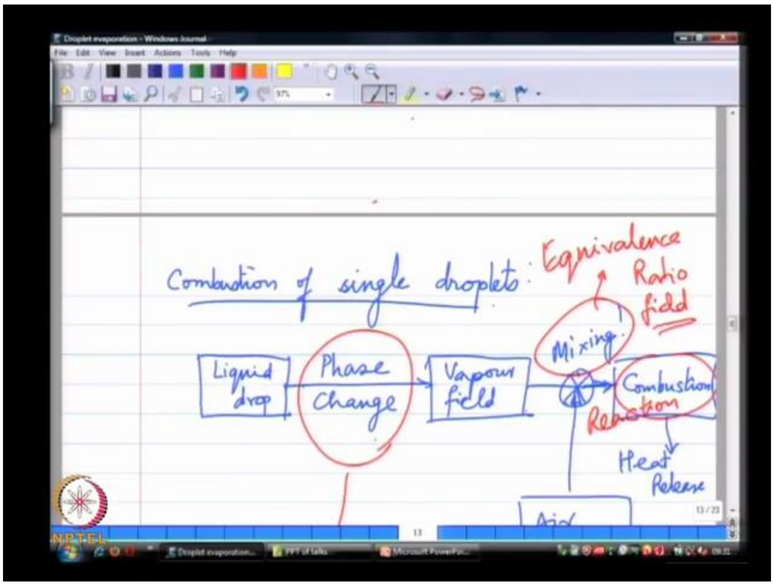

So, I have, in the case of combustion of single droplets or I can now extend this to combustion of a cloud of droplets I have a liquid droplet cloud, that has to undergoes some kind of a phase change process to give me a vapour field, that is I have a distribution of vapour concentration in a certain spatial region.

That vapour generated from the evaporation process has to now mix with the air around. So, as to give me this mixing process creates and equivalence ratio field this equivalence ratio field is essentially now limited by the rate of mixing. I have a source of vapour which is my cloud of liquid droplets the source of oxide the oxidizer source is spatially separated. So, in let us say a swirl stabilized burner I may have the air coming through some kind of a swirler and that air source from the swirler, would have to now mix with the vapour generated from the droplets stream, and that intern has to give me an equivalence ratio field that would than undergo reaction which we call combustion and releases heat.

So, this process of first of all phase change we said it is diffusion limited that is essentially the rate of transport of the vapour away from this cloud of droplets. Even if I was able to do that, the next limiting step is mixing the rate at which oxidizer in the vapour can be mixed and after that, in relation to these two time scales the rate of reaction itself is so fast, that you can assume that as soon as they become mixed they burned. If I am able to achieve either if my rate of evaporation is poor or if my rate of mixing is sort of non-homogeneous then I am likely to create fluctuations in equivalence ratio. So, I am able I am likely to be create rich and lean spots in my in the spatial region.

And this generally is not desirable because the rich spots are nucleation regions for suit and the lean spots are generally not, are going to be hotter and may not talking very very lean, but liner than let us say equivalence ratio one are generally regions where you are likely to create nox, nitrogen oxides. So, this fluctuations even though you are mean equivalence ratio is still you whatever your designed requires it to be these fluctuations are what are responsible for pollutants being form then a typical spray combustion application.

So, the physical steps that we have to rapper around some mathematical models are one phase change, which we did using extensions of our d squared law to mixing which requires and understanding of turbulent transport. And then reaction, which requires some knowledge of the chemical kinetics that you know in the vapour phase itself. The whole process of heat release from spray to reaction is limited by the slowest of these three steps which is usually, never the reaction process which is either the fixing process or the rate of evaporation process. So, one of these to determine the rate of it is release in a typical spray combustion application.

So, we talked a little bit about spray combustion I think starting with spray formation which is essentially the process by which bulk liquid is broken up in to blobs of liquid like a large or small does not matter is governed by the growth of some kind of instabilities on this liquid, on the bulk liquid that is emanating from nozzle. The process by which these liquid drops might for the break down is what we called as secondary atomization. So, you have flow inside the nozzle followed by primary atomization, followed by secondary atomization, which is then followed by evaporation, which is then followed by mixing which is where the vapour is mixed with the oxidizer strain and then you are reaction.

Now I said followed by and followed by, but it is that does not denote either that they are spatially separate or that they are temporally separate, you could potentially have one process involving all these physical steps occurring simultaneously and that is a big challenge for modular’s today. To take a model that involves all this physical process is to come up with a modal that involves all these physical process is happening simultaneously is where most of the research is being focused on in this area of spray combustion.

Because you have process is that happen over many many different times scales the reaction process is a very very fast process in comparison to say evaporation process. Say if I just to give you a feel for actual times if I take let us say 50 micron or a 100 micron drop gasoline vapour drop in an internal combustion engine, its evaporation happens in about you know few milliseconds. Whereas, the rate of reaction of gasoline vapour with the oxygen present inside the cylinder is a few microseconds. So, usually at least 100 to a 1000 times faster whereas, the rate of mixing is in a typical IC engine it is the rate of mixing that seems to limit the rate of heat release. So, you create this very rich and very leans spots to which have to be higher and out to give you a fully burnt mixer and the rate of mixing is what is what becomes the rate limiting step in that kind of a process.

Now spray combustion is one of the most important applications of sprays, but there are other process is like spray drying. We talked about that earlier on, spray drying is essentially all of this except your creating vapour field without the reaction process happening. So, it is essentially everything that we discussed today without the last step. So, you would have, you would still have cloud evaporation and it is again in a drop single droplet level evaporation models that are driven by our old d squared law, and the precipitation process of the of the constituency of these liquid drops is what a typical spray drying process is after, that is you have a suspension of say a detergent particle in some liquid that is volatile and the volatile liquid evaporates out giving me the detergent particles that precipitated in a typical spray dryer. So, this process is essentially governed by the rate of decrease of the diameter of the drops following some kind of d squared law and then the complete evaporation process giving me a precipitated stream of particles.

So, this completes our discussion of a Spray Theory and Applications. I think we will look at some applications as some other applications as part of the course notes accompanying these videos. And that would give you sort of a more holistic picture of sprays nozzles as devices that are employed in engineering systems.

Thank you.