Heat Transfer And Combustion in Multiphase Systems
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Lecture 37
Regimes in spray combustion

Welcome to this Lecture! So, in this lecture, we are going to finish off this Droplet combustion related studies. So, one other phenomena that was interesting in the case of a droplet and one should mention is that multicore; if a droplet actually come is composed of two components, they basically many of the fuels are actually two component fuels, right.

So, and these components can have a wide range of volatility. That means they are saturation vapour pressure may be very different, right. So, for example, your ethanol with some other fuel so, for ethanol is a high vapour pressure fuel. Others will like dodecane may be a very low vapour pressures well, right.

So, once you operate with a mixture of two or more fuels, okay there can be volatility, disparity between the two fuels concerned, right.

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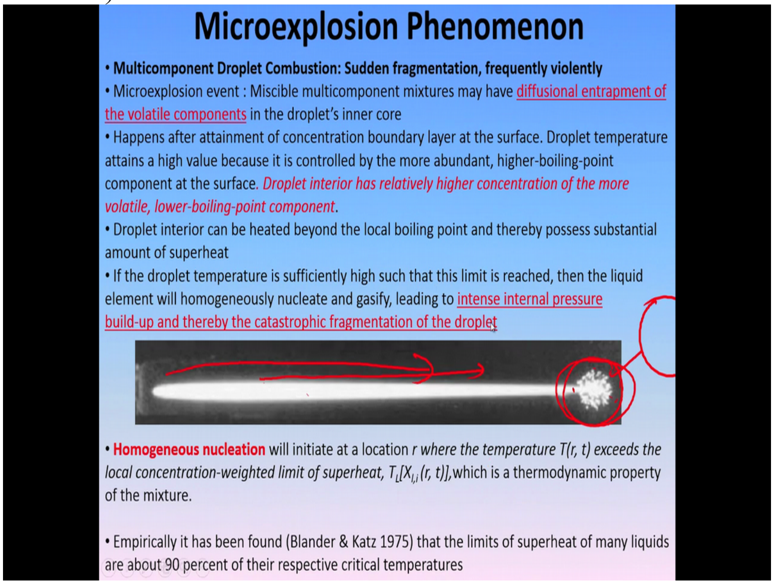

Microexplosion Phenomenon

- **Multicomponent Droplet Combustion: Sudden fragmentation, frequently violently**
- Microexplosion event : Miscible multicomponent mixtures may have diffusional entrapment of the volatile components in the droplet's inner core
- Happens after attainment of concentration boundary layer at the surface. Droplet temperature attains a high value because it is controlled by the more abundant, higher-boiling-point component at the surface. *Droplet interior has relatively higher concentration of the more volatile, lower-boiling-point component.*
- Droplet interior can be heated beyond the local boiling point and thereby possess substantial amount of superheat
- If the droplet temperature is sufficiently high such that this limit is reached, then the liquid element will homogeneously nucleate and gasify, leading to intense internal pressure build-up and thereby the catastrophic fragmentation of the droplet

- **Homogeneous nucleation** will initiate at a location *r where the temperature T(r, t) exceeds the local concentration-weighted limit of superheat,* $T_L[X_{l,i}(r, t)]$,which is a thermodynamic property of the mixture.

- Empirically it has been found (Blander & Katz 1975) that the limits of superheat of many liquids are about 90 percent of their respective critical temperatures

In those cases, what happens is that and this observation work comes from Sikala's work. Is that you see, that the droplet basically undergoes a shattering.This is not the kind of shattering that you see in the case of your droplet atomization studies. This is very different, right. You see a droplet burning. They actually let the droplet fall from a drop tower essentially.

And they saw that this is the streak, this means the droplet is our, is just burning nicely, okay. But at the end, it had kind of shattered and forms this all this nice, it is like, like almost like a Diwali firework, right. Why does this thing actually happen, okay? So, this happens is because the multi-component droplets exhibit something which is called Diffusional entrapment.

What does Diffusional entrapment exactly means, okay? Say, once Diffusional entrapment happens, the droplet is actually prone to this kind of catastrophic breakup which is called micro explosion, okay. So, what is Diffusional Entrapment? Diffusional entrapment is very simple. When you actually have two component to component fuels like, for example, you have a droplet over here.

Let me draw it properly. Let me go to the journal and then that may be useful.

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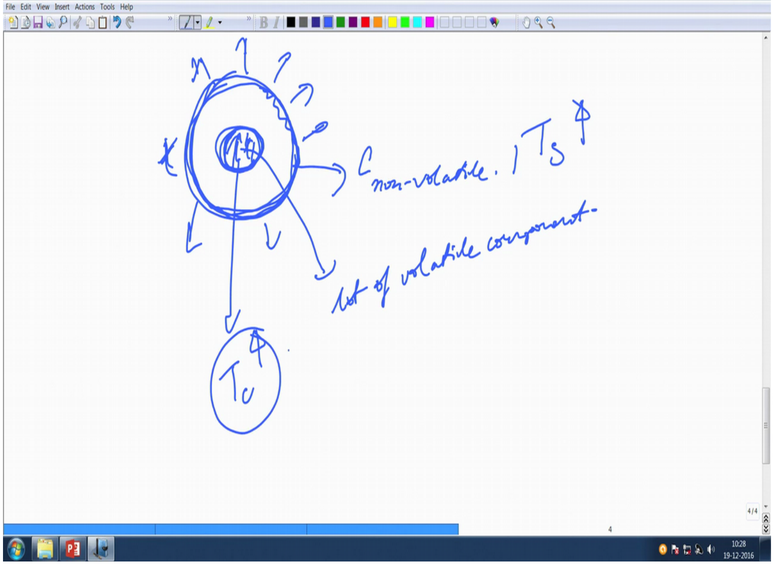

So, if you have a droplet like this over here and it is composed of two components, so what happens is that after some time, there is an accumulation. So, what happens is that the more volatile component actually escapes, right. More volatile component it escapes, okay. So, the surface be very near to the droplet surface, okay.

There is an increase in the concentration of the non volatile component is not that so, right. There is a increase in the concentration of the non volatile component. But, for what it does is that, but in the center of the droplet, you still have a lot of volatile components now, present, right okay.

But because of the presence of this non volatile component of the surface in increased amount, what it happens is that it leads to an increase in the surface temperature, right because the volatility is low. So, the surface temperature goes up as the surface temperature goes up, okay, these volatile components which are trapped in the interior of the droplet their temperature also goes up;

The surface temperature goes up that Tc should also grow up, right okay because of that as the surface temperature goes up, this might exceed the boiling point of the, of the polar tile component which is basically shown over here, okay. So, the droplet temperature attains a higher value because it is controlled by the more abundant, more higher boiling point, low volatile component.

The droplet temperature is heated beyond the local boiling point and provides a substantial amount of superheat. That means the center which still contains that volatile component now is raised above its boiling point, right. If that is sufficiently high then the liquid will homogeneously nucleate. This is homogeneous nucleation.

This is not heterogeneous nucleation which you will see what boiling is and what nucleation are. So, homogeneous nucleation essential means that it does not require a surface, it happens at the molecular level, right. So, you can homogeneous nucleate and gasify leading to, so, it forms those bubbles, it starts to form those bubbles inside the droplet.

You now have this small, small bubble within the droplet, right and these bubbles grow. They create a pressure surge and cause's this catastrophic breakup. It is almost like bubbling inside a droplet, right which grows and shatters the whole droplet right, because of the pressure expansion, right. So, what happens over here is very simple. You need a non-volatile, in need of a high degree of volatility difference.

When there is a high degree of volatility difference, the more volatile component starts to preferentially evaporate at the surface leaving the less volatile component on the surface, right. As a result of that there is a temperature search on the surface, right. As there is a temperature search on the surface the high volatile component which is now trapped in the droplet core also experiences a temperature search.

And if this temperature search crosses the boiling point and the superheat limit, okay some of these this high volatile component within the droplet core may actually form bubbles. And these bubbles will grow leading to intense internal pressure build up and lead to catastrophic fragmentation, right. So, homogeneous nucleation will initiate at a location where the temperature exceeds the local concentration weighted superheat, right.

When the superheat limit is exceeded, this is what happens. It has been found in many cases that that limit for the superheat is about 90 percent of their critical temperature. So, this value can be really high, right. It is just not the boiling point. It is very close to the critical point sometimes. For example, the critical point for water is quite high, okay.

So, it can be like that as well, okay. But this is the mechanism. This is called what we call diffusional entrapment. This does not require a surface. This is normal. The process is very normal, okay.

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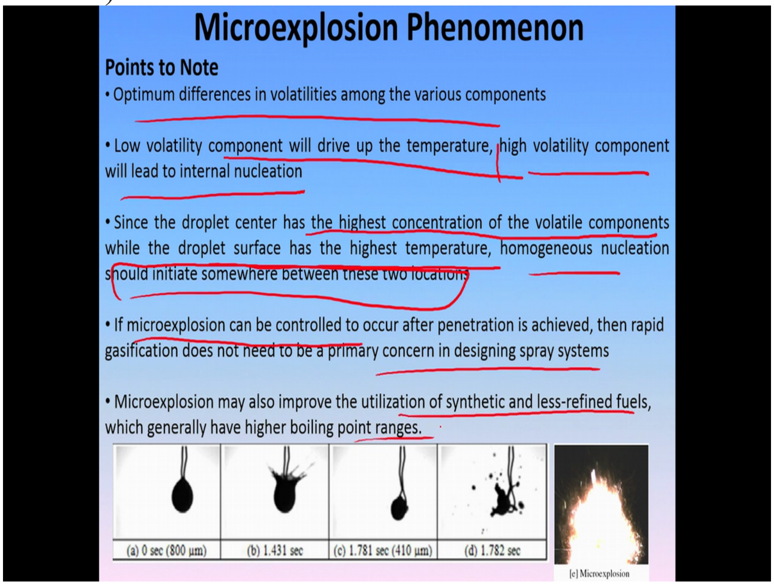

Microexplosion Phenomenon

Points to Note

- Optimum differences in volatilities among the various components
- Low volatility component will drive up the temperature, high volatility component will lead to internal nucleation
- Since the droplet center has the highest concentration of the volatile components while the droplet surface has the highest temperature, homogeneous nucleation should initiate somewhere between these two locations
- If microexplosion can be controlled to occur after penetration is achieved, then rapid gasification does not need to be a primary concern in designing spray systems
- Microexplosion may also improve the utilization of synthetic and less-refined fuels, which generally have higher boiling point ranges.

So, Microexplosion happens. So, there has to be an optimum difference. The low volatility component will drive up the temperature. The high volatility component will lead to internal nucleation. So, both the components have got their own role to play, okay. So, the droplet Center has got the highest concentration of the volatile component while the droplet surface is the highest temperature.

So, homogeneous nucleation occurs somewhere in between these two locations. Microexplosion, can this lead's to microexplosions, what we already said, okay. It also can improve the utilization because through Microexplosion, you generate these very small dotted droplets, right which actually is like a secondary source of atomization, so to say, right.

So, even when the droplet is burning. See, we talked about atomization which was purely driven by aerodynamics or it was driven by other things, right not by heat per se. Here it is driven by heat. So, basically through these bubbles and boiling and other things, we are able to get this, this microexplosion thing to happen, you got it.

So, it may improve the secondary atomization behaviour. And so, but for this to happen, you need a lot of difference in the volatility, okay.

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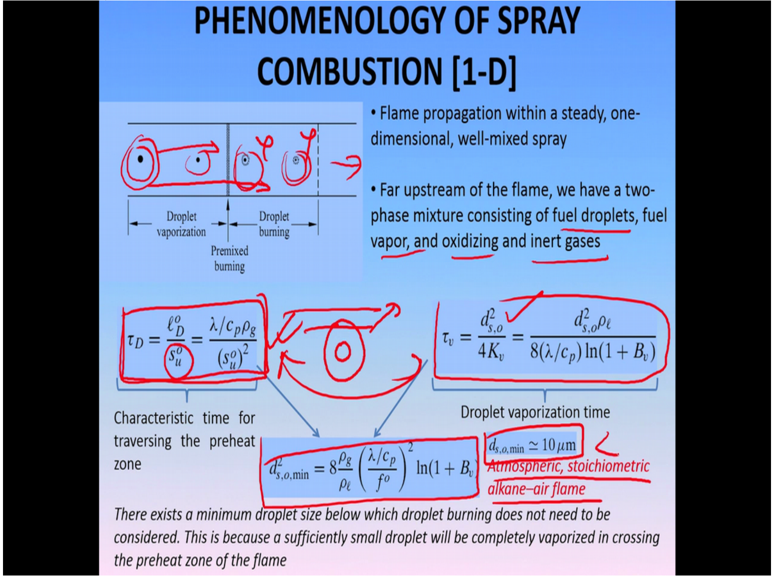

PHENOMENOLOGY OF SPRAY COMBUSTION [1-D]

- Flame propagation within a steady, one-dimensional, well-mixed spray
- Far upstream of the flame, we have a two-phase mixture consisting of fuel droplets, fuel vapor, and oxidizing and inert gases

$$\tau_D = \frac{\ell_D^o}{s_u^o} = \frac{\lambda / c_p \rho_g}{(s_u^o)^2}$$

Characteristic time for traversing the preheat zone

$$\tau_v = \frac{d_{s,o}^2}{4K_v} = \frac{d_{s,o}^2 \rho_\ell}{8(\lambda/c_p)\ln(1+B_v)}$$

Droplet vaporization time

$$d_{s,o,\min}^2 = 8\frac{\rho_g}{\rho_\ell}\left(\frac{\lambda/c_p}{f^o}\right)^2 \ln(1+B_v)$$

$d_{s,o,\min} \simeq 10\,\mu m$

Atmospheric, stoichiometric alkane–air flame

There exists a minimum droplet size below which droplet burning does not need to be considered. This is because a sufficiently small droplet will be completely vaporized in crossing the preheat zone of the flame

So, one other thing, in the case of a phenomenology of a droplet combustion or a spray combustion is that, okay, so, what we have considered so far is how a droplet burns how the droplet and explodes, okay what are the differences in the burning modes etcetera, etcetera. Now, one may be really concerned about that how we can actually say, do the droplet really burn, right?

Because you have a flame, if you look at it, so, what we are saying is that there is a flame that surrounds the droplet, right like that. Of course, this can be a little egg-shaped also depending on the flow and other situations. Does it happen like that or does the droplet completely vaporize before it actually, before the flame is actually initiated, got it. So, if look at this particular diagram what happens is that there is a droplet which approaches a pre-mixed burning zone.

And this is basically the droplet flame that is actually burning. And then, ultimately it becomes gas. So, far upstream what we have, we have fuel droplets, fuel vapour and oxidizer and inert gases like here. As it approaches the droplet high slowly becomes smaller because it evaporates because of the heat that is released, okay. And after that the droplet starts to burn.

Now, if the characteristic time for penetration of the droplet through this preheat zone. If we consider this as the preheat zone, that is given by this particular parameter. This is basically called the flame speed, okay. We let us not consider, let us not dwell a lot on the flame speed, okay. Flame speed, you can read up your Stephen terms or other types of books to find out what is Flame speed is, right.

Then, there is also something called the droplet vaporization time which we already know it is r square by Kv. Kv was the burning rate of the droplet, right okay. Now, if we compare these two, these two numbers if these two time scales are the same, that means the droplet vaporization time and the droplet reversing time, if they are both the same, that means the droplet turns into vapours by the time it crosses the preheat zone, right.

So, a droplet takes say X seconds to pass a preheat zone, right. The droplet vaporization time which is the time that is required to completely vaporize the droplet is also X second, right all lower than that. What will happen? The droplet will actually completely evaporate, correct okay before it actually gets into the preheat zone. Now, that is an important consideration over here, that this is what happens when the droplet.

So, when these two ratios are the same, okay we get a minimum droplet diameter, okay below which the droplet burning does not happen at all. The droplet completely evaporate in crossing the preheat zone of the, got it. The droplet completely evaporates in, in the preheat zone. So, there is nothing called droplet fling and that is something like 10 micron for atmospheric stoichiometric alkane air flames, got it.

So, any droplet which is below this basically evaporates completely before it actually burns, got it.

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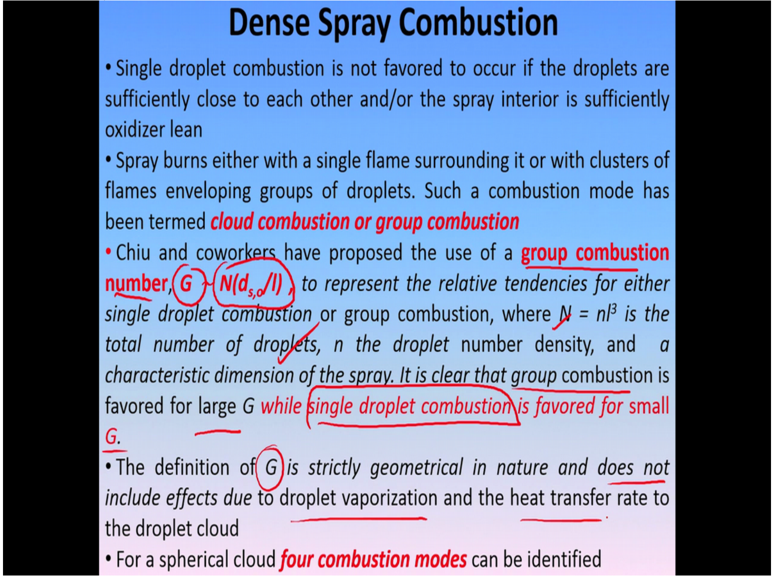

Dense Spray Combustion

- Single droplet combustion is not favored to occur if the droplets are sufficiently close to each other and/or the spray interior is sufficiently oxidizer lean
- Spray burns either with a single flame surrounding it or with clusters of flames enveloping groups of droplets. Such a combustion mode has been termed ***cloud combustion or group combustion***
- Chiu and coworkers have proposed the use of a **group combustion number**, $G \sim N(d_{s,o}/l)$, *to represent the relative tendencies for either single droplet combustion* or group combustion, where $N = nl^3$ *is the total number of droplets, n the droplet* number density, and *a characteristic dimension of the spray. It is clear that group* combustion is favored for large *G while single droplet combustion is favored for* small *G.*
- The definition of *G is strictly geometrical in nature and does not include effects due* to droplet vaporization and the heat transfer rate to the droplet cloud
- For a spherical cloud ***four combustion modes*** can be identified

So, so that is the one of the phenomenology, okay. One other thing that we are going to consider as a part of this lecture is basically what is called the dense spray combustion. As we said, we have considered single droplet combustion. We have considered single component, multi-component, droplets looked into micro explosion but as we know in most of the space that droplet comes in clusters, right.

There are many droplets. Too many, right. So, the droplets are very close to each other. And in some cases the spray interior can become sufficiently oxidizer lean. So, spray flame actually burns either as a single flame which surrounds clusters of droplets, right. In that case, what we call it as group combustion or cloud combustion.

So, you cannot isolate these nice little flames, okay. So, most of the Chiu and co-workers have proposed the use of something called a group combustion number which is called G. It is basically given by n into this particular quantity where n is basically the total number of droplets, okay. And so, large G essentially means that there are a lot of droplets, right.

And largely actually favours group combustion; where a single combustion single droplet combustion is favoured for small g. So, it is basically a geometric definition that the definition of G. And so, it does not include the effect like of droplet vaporization and heat transfer to the droplet cloud etcetera etcetera.

It is just a number that we are proposing to isolate that, what are the different combustion modes that are available for a spherical droplet cloud.

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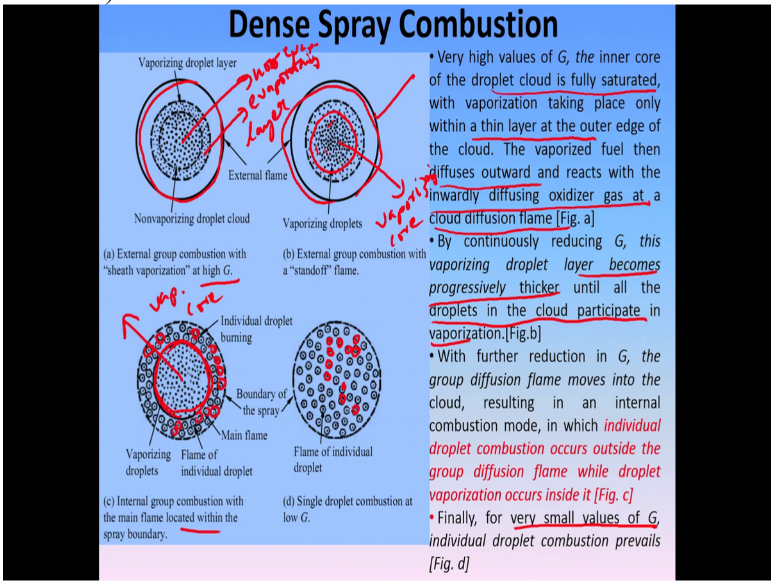

Dense Spray Combustion

(a) External group combustion with "sheath vaporization" at high *G*.

(b) External group combustion with a "standoff" flame.

(c) Internal group combustion with the main flame located within the spray boundary.

(d) Single droplet combustion at low *G*.

- Very high values of *G, the* inner core of the droplet cloud is fully saturated, with vaporization taking place only within a thin layer at the outer edge of the cloud. The vaporized fuel then diffuses outward and reacts with the inwardly diffusing oxidizer gas at a cloud diffusion flame [Fig. a]
- By continuously reducing *G, this vaporizing droplet layer becomes progressively* thicker until all the droplets in the cloud participate in vaporization.[Fig.b]
- With further reduction in *G, the group diffusion flame moves into the* cloud, resulting in an internal combustion mode, in which *individual droplet combustion occurs outside the group diffusion flame while droplet vaporization occurs inside it [Fig. c]*
- Finally, for very small values of *G, individual droplet combustion prevails [Fig. d]*

So, this is an in what and figure if you look at this very carefully, what you will find is that this is for very high G, the first one; very high value of G, okay. You can see it clearly three regions, okay. There is an external flame, so, there is a single flame, right which surrounds this droplet cloud, okay. There is an evaporating core, okay. This is an evaporating droplet layer or an evaporating layer.

What do you mean by evaporating layer? That there is a cloud of droplet that actually evaporate. Center, there is no evaporation, no evap, as you can see over there. That means the center of the droplet does not even see, right the flame. It does not experience anything, okay. So, if what happens is?

The inner core of the droplet crowd is fully saturated vaporization takes place, only within a thin layer and the vaporized fuel diffusive outward and reacts with the inward moving oxidizer and forms this cloud diffusion flame, got it, okay. Now, if we move to a slightly lower g, that means you are continuously reducing this G, what happens is that the core now starts to participate in the evaporation.

Now, it is a vaporizing core. The entire core vaporizes, right. The flame is still a common flame for everybody, right. It is not distinct you cannot distinguish that which droplet is contributing to the flame, right. This vaporizing layer now has become very thick and it encompasses all the droplets in the cloud.

So, all the droplets are actually evaporated. They are interacting and evaporating, right. And but, the flame is established outside this droplet cloud. Now, if you reduce the g even further, that is the third mode, okay what you will have is that you will have a main flame like this. And you will have this individual droplet flames. So, this is fascinating, right.

So, you have a flame of individual droplets; you have a main flame, which is the common player and then there is a vaporizing core, right, okay. So, the diffusion flame has moved inward now. It was here, right. It has moved inward inside this droplet cloud, right. Some of the droplets are actually burning as individual pieces, okay. And but the majority of the droplet are burning as a whole in this diffusion cloud right okay.

The individual droplet combustion is happening outside this, this main flame, right. Further, for very small values of G, you get actually individual flames. There is no main flame; all the droplets are burning as individual pieces, right. So, these are the four modes of combustion, right. You are clear about this. So, these are the four modes of combustion that you see over here, okay.

One is, there is a non vaporizing core, there is an outer vaporizing layer; then there is a flame Then, in the next case, you have a vaporizing core and an outer flame. Then, you have a main flame of vaporizing core and individual droplets which are burning outside the main flame. And then you have a case of individual droplets which are burning as flames, got it, okay.
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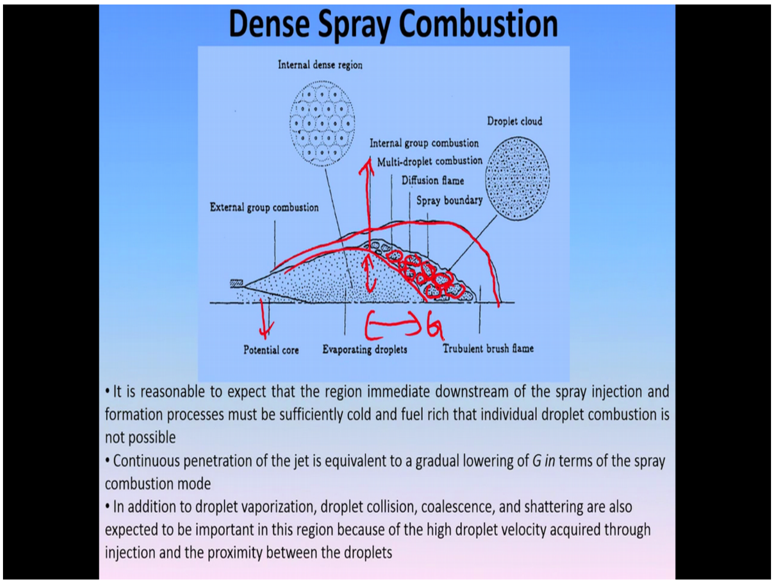

Dense Spray Combustion

- It is reasonable to expect that the region immediate downstream of the spray injection and formation processes must be sufficiently cold and fuel rich that individual droplet combustion is not possible
- Continuous penetration of the jet is equivalent to a gradual lowering of *G in* terms of the spray combustion mode
- In addition to droplet vaporization, droplet collision, coalescence, and shattering are also expected to be important in this region because of the high droplet velocity acquired through injection and the proximity between the droplets

There are in the case of jet flame, you have a little bit more suggestive thing. For example, there is an external group combustion behaviour, as you can see. So, this is the group combustion, okay. So, there are multiple flames present. So, this is for example, the individual droplet clouds.

So, there can be pockets of such clouds. And remember there is a flow droplet interaction also in these cases, right. So, there is now, there is internal group combustion over here, okay. And this is basically the potential core okay where the droplets do not feel anything, okay. So, in a flame like this, okay you can have this kind of non-homogeneous distributional droplet and non homogeneous distribution of the flame front.

So, there may not be one single flame there can be multiple flames, right. There can be individual droplets burning; there can be external sheet combustion; there can be internal sheet combustion also, right. Further and so there can be a lot of variation of G. So, it is not just a one value of G the G varies in a spatial manner, okay.

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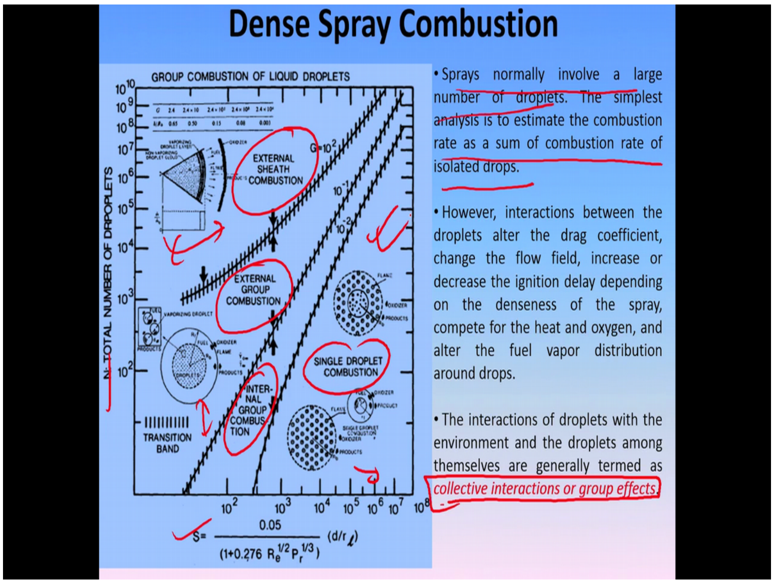

Dense Spray Combustion

- Sprays normally involve a large number of droplets. The simplest analysis is to estimate the combustion rate as a sum of combustion rate of isolated drops.
- However, interactions between the droplets alter the drag coefficient, change the flow field, increase or decrease the ignition delay depending on the denseness of the spray, compete for the heat and oxygen, and alter the fuel vapor distribution around drops.
- The interactions of droplets with the environment and the droplets among themselves are generally termed as *collective interactions or group effects.*

In this particular case, So, this is a very famous diagram which was proposed by Chiu and co-workers, right where they actually said for the total number of droplets divided by the plotted against s, okay. So, this is the group combustion behaviour or a regime maps, so to say. So, in this regime maps what you have, you have this internal group combustion line here, single droplet combustion lying there, right okay.

And then external group combustion here, external sheet combustion here, you can see what each of those symbols means by these small cartoons over here. There are transition bands also. So, it involves as you know that the spray involves a lot of droplets. The simplest analysis is to estimate the combustion rate as a sum of the individual combustion behaviours. But it is not the case.

As we already saw that interactions can change the gasification, it can change the ignition; it can change a whole lot of things, right. The interactions of the droplet within that environment are given by this collective interactions or what we call the group effects. And this is still a hot field of research, because nothing is concretely known how to model these kind of systems.

How to know the dynamics of this kind of systems, right when you actually have say a flame, that is established in a gas turbine. Say, for example, where it has got strong swirl, strong turbulence, multiple ranges of droplets, okay it is very difficult to isolate and know about each of the flame, right.

And what kind of a flame is established, in what kind of a range that is still a pending question that we have.

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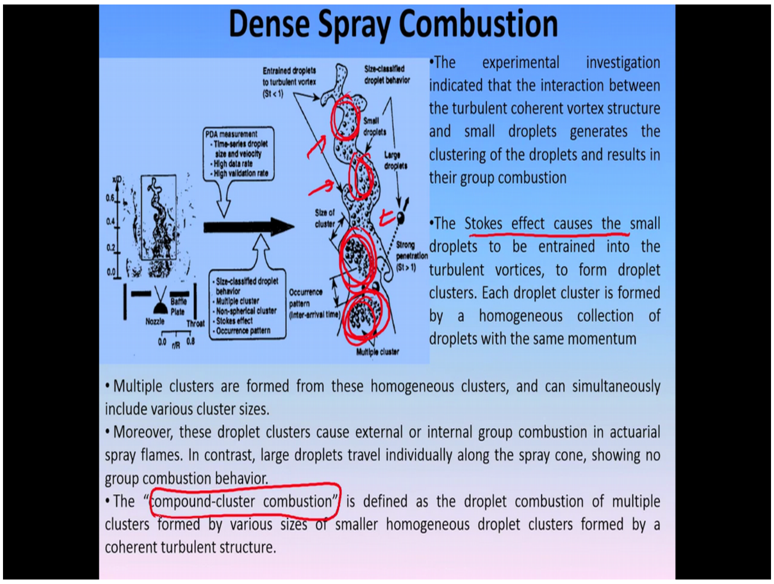

Dense Spray Combustion

- The experimental investigation indicated that the interaction between the turbulent coherent vortex structure and small droplets generates the clustering of the droplets and results in their group combustion
- The Stokes effect causes the small droplets to be entrained into the turbulent vortices, to form droplet clusters. Each droplet cluster is formed by a homogeneous collection of droplets with the same momentum

- Multiple clusters are formed from these homogeneous clusters, and can simultaneously include various cluster sizes.
- Moreover, these droplet clusters cause external or internal group combustion in actuarial spray flames. In contrast, large droplets travel individually along the spray cone, showing no group combustion behavior.
- The "compound-cluster combustion" is defined as the droplet combustion of multiple clusters formed by various sizes of smaller homogeneous droplet clusters formed by a coherent turbulent structure.

In addition, the area, there are other types of things say, for example, as we know already, that droplet in homogenisation happens almost because of the flow conditions, okay. And that is given by something like a Stokes number, right if you do not know stocks number, stocks, then, you just read it up, okay.

So, it essentially means that smaller droplets are actually entrained better, okay. And these droplets forms is homogeneous clusters; multiple such clusters can be formed inside of flow situation as you can see, from this little cartoon over here, okay. So, when you try to ignite a flame like this, okay it burns at different ways, the different group combustion behaviour at different spatial locations essentially, right okay.

So, unlike gas diffusion, of the gas phase combustion, right this is a very complicated Beast, so to say, because of this multitude of droplet sizes and multitude of flame the group combustion compound, cluster combustion that is what we call it. It is not a simple cluster anymore. It is a compound cluster that you actually see over here, okay. So, these are the kind of things that one should know, okay.

One's one tries to look at the combustion behaviour of droplets as such, okay. So, this part is still a subject of very active research, okay. And people have not been able to come to a very concrete, you know, theoretical framework for this. There have been a lot of these things that has been kind of attempted, okay. You know a lot of studies like this, okay. So, this part I want you to just know that there are four such stages.

This is the most important thing, right depending on something called a group combustion number, okay.

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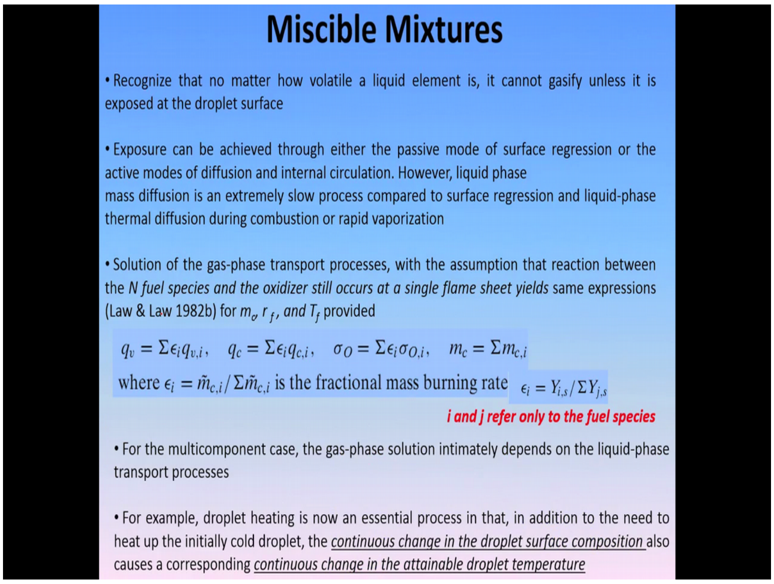

Miscible Mixtures

- Recognize that no matter how volatile a liquid element is, it cannot gasify unless it is exposed at the droplet surface

- Exposure can be achieved through either the passive mode of surface regression or the active modes of diffusion and internal circulation. However, liquid phase mass diffusion is an extremely slow process compared to surface regression and liquid-phase thermal diffusion during combustion or rapid vaporization

- Solution of the gas-phase transport processes, with the assumption that reaction between the *N fuel species and the oxidizer still occurs at a single flame sheet yields* same expressions (Law & Law 1982b) for m_o, r_f, *and* T_f provided

$$q_v = \Sigma\epsilon_i q_{v,i}, \quad q_c = \Sigma\epsilon_i q_{c,i}, \quad \sigma_O = \Sigma\epsilon_i\sigma_{O,i}, \quad m_c = \Sigma m_{c,i}$$

where $\epsilon_i = \tilde{m}_{c,i}/\Sigma\tilde{m}_{c,i}$ is the fractional mass burning rate $\epsilon_i = Y_{i,s}/\Sigma Y_{j,s}$

i and j refer only to the fuel species

- For the multicomponent case, the gas-phase solution intimately depends on the liquid-phase transport processes

- For example, droplet heating is now an essential process in that, in addition to the need to heat up the initially cold droplet, the *continuous change in the droplet surface composition* also causes a corresponding *continuous change in the attainable droplet temperature*

And we have, so, we have covered they almost the entirety of your droplet combustion. We have skipped a few like Miscible mixtures, okay.

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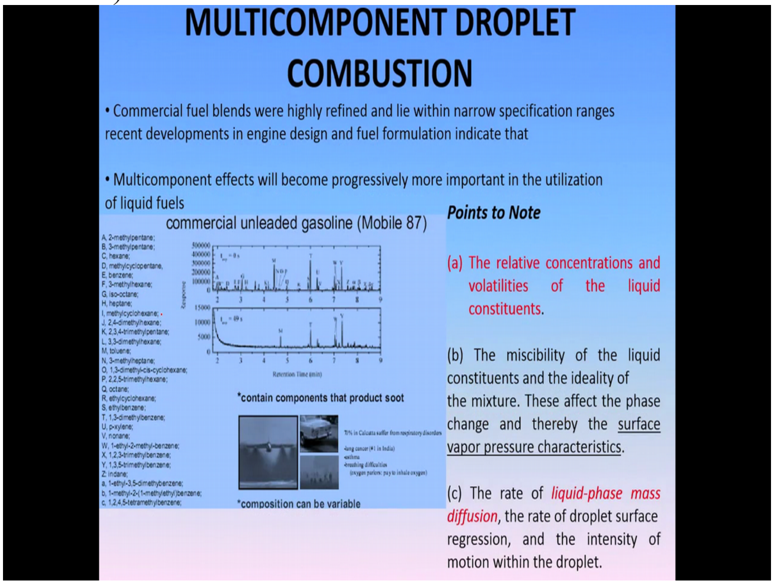

MULTICOMPONENT DROPLET COMBUSTION

- Commercial fuel blends were highly refined and lie within narrow specification ranges recent developments in engine design and fuel formulation indicate that

- Multicomponent effects will become progressively more important in the utilization of liquid fuels

commercial unleaded gasoline (Mobile 87)

A, 2-methylpentane;
B, 3-methylpentane;
C, hexane;
D, methylcyclopentane,
E, benzene;
F, 3-methylhexane;
G, iso-octane;
H, heptane;
I, methylcyclohexane;
J, 2,4-dimethylhexane;
K, 2,3,4-trimethylpentane;
L, 3,3-dimethylhexane;
M, toluene;
N, 3-methylheptane;
O, 1,3-dimethyl-cis-cyclohexane;
P, 2,2,5-trimethylhexane;
Q, octane;
R, ethylcyclohexane;
S, ethylbenzene;
T, 1,3-dimethylbenzene;
U, p-xylene;
V, nonane;
W, 1-ethyl-2-methyl-benzene;
X, 1,2,3-trimethylbenzene;
Y, 1,3,5-trimethylbenzene;
Z indane;
a, 1-ethyl-3,5-dimethybenzene;
b, 1-methyl-2-(1-methylethyl)benzene;
c, 1,2,4,5-tetramethylbenzene;

*contain components that product soot

70% in Calcutta suffer from respiratory disorders
-lung cancer (#1 in India)
-asthma
-breathing difficulties
(oxygen parlors: pay to inhale oxygen)

*composition can be variable

Points to Note

(a) The relative concentrations and volatilities of the liquid constituents.

(b) The miscibility of the liquid constituents and the ideality of the mixture. These affect the phase change and thereby the surface vapor pressure characteristics.

(c) The rate of *liquid-phase mass diffusion*, the rate of droplet surface regression, and the intensity of motion within the droplet.

Multi-component droplet combustion

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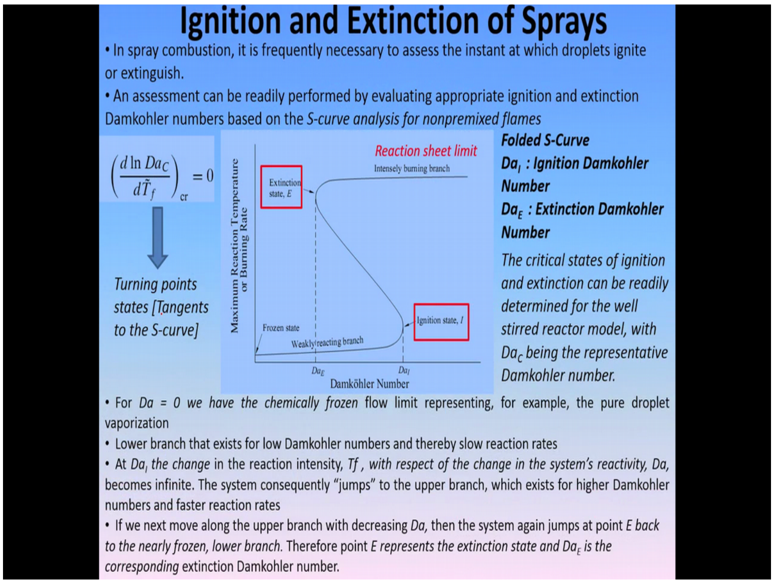

Ignition and Extinction of Sprays

- In spray combustion, it is frequently necessary to assess the instant at which droplets ignite or extinguish.
- An assessment can be readily performed by evaluating appropriate ignition and extinction Damkohler numbers based on the *S-curve analysis for nonpremixed flames*

$$\left(\frac{d\ln Da_C}{d\tilde{T}_f}\right)_{cr} = 0$$

Turning points states [Tangents to the S-curve]

Folded S-Curve

Da_I : Ignition Damkohler Number

Da_E : Extinction Damkohler Number

The critical states of ignition and extinction can be readily determined for the well stirred reactor model, with Da_C being the representative Damkohler number.

- For *Da = 0 we have the chemically frozen* flow limit representing, for example, the pure droplet vaporization
- Lower branch that exists for low Damkohler numbers and thereby slow reaction rates
- At Da_I *the change* in the reaction intensity, *Tf , with respect of the change in the system's reactivity, Da,* becomes infinite. The system consequently "jumps" to the upper branch, which exists for higher Damkohler numbers and faster reaction rates
- If we next move along the upper branch with decreasing *Da*, then the system again jumps at point *E back to the nearly frozen, lower branch. Therefore point E represents the extinction state and Da_E is the corresponding* extinction Damkohler number.

And Ignition and extinction of sprays, okay so that you can read up, if you want in your spare time. So, these are given as, like, kind of reading materials. We also know how the droplet interacts with each other, right, and when the interaction approaches the single droplet burning regime.

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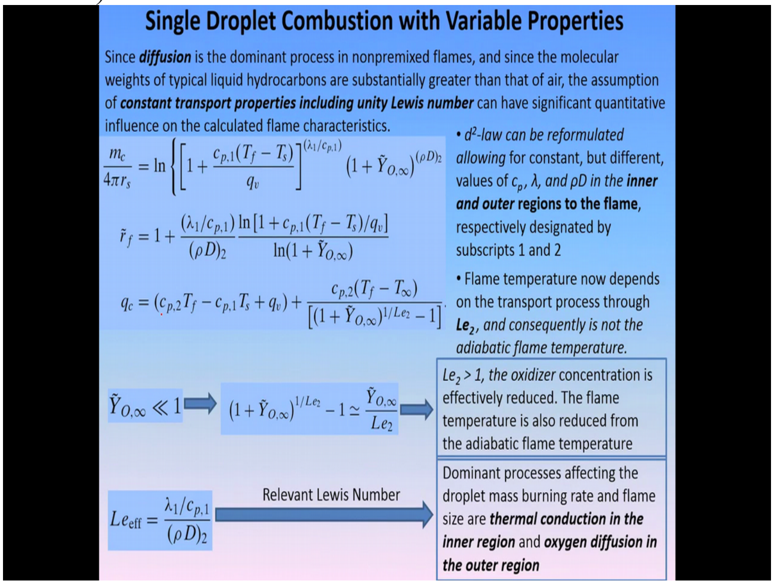

Single Droplet Combustion with Variable Properties

Since ***diffusion*** is the dominant process in nonpremixed flames, and since the molecular weights of typical liquid hydrocarbons are substantially greater than that of air, the assumption of ***constant transport properties including unity Lewis number*** can have significant quantitative influence on the calculated flame characteristics.

$$\frac{m_c}{4\pi r_s} = \ln\left\{\left[1+\frac{c_{p,1}(T_f-T_s)}{q_v}\right]^{(\lambda_1/c_{p,1})}(1+\tilde{Y}_{O,\infty})^{(\rho D)_2}\right.$$

$$\tilde{r}_f = 1+\frac{(\lambda_1/c_{p,1})}{(\rho D)_2}\frac{\ln[1+c_{p,1}(T_f-T_s)/q_v]}{\ln(1+\tilde{Y}_{O,\infty})}$$

$$q_c = (c_{p,2}T_f - c_{p,1}T_s + q_v) + \frac{c_{p,2}(T_f-T_\infty)}{[(1+\tilde{Y}_{O,\infty})^{1/Le_2}-1]}$$

- *d^2-law can be reformulated allowing* for constant, but different, values of c_p, *λ, and ρD in the* ***inner and outer*** **regions to the flame,** respectively designated by subscripts 1 and 2
- Flame temperature now depends on the transport process through **Le_2**, *and consequently is not the adiabatic flame temperature.*

$$\tilde{Y}_{O,\infty} \ll 1 \Rightarrow (1+\tilde{Y}_{O,\infty})^{1/Le_2} - 1 \simeq \frac{\tilde{Y}_{O,\infty}}{Le_2} \Rightarrow$$

$Le_2 > 1$, the oxidizer concentration is effectively reduced. The flame temperature is also reduced from the adiabatic flame temperature

$$Le_{\text{eff}} = \frac{\lambda_1/c_{p,1}}{(\rho D)_2}$$

Relevant Lewis Number

Dominant processes affecting the droplet mass burning rate and flame size are ***thermal conduction in the inner region*** and ***oxygen diffusion in the outer region***

We also know what external convection does to the burning behaviour. We also know about the single the variable properties part we also skipped. But you can read this up, okay. It is not going to be difficult. You just read it up and see that what you understand out of it is given as a reading material.

Then, internal recirculation droplet with internal recirculation is also covered in kind of very details in this particular section. And we say that Hill Spherical Vortex is once again used, okay for this setup.Then, we talked about Fuel accumulation. How the Fuel actually accumulates, because normally, the d square law assumes that consumption and the evaporation of fuels are the same, okay.

We also said that the droplet heating time active heating time is only about ten percent of the total lifetime of the droplet, okay. And we also showed the two limits of droplet vaporization, when you actually have a flame surrounding it, okay. And lastly, we also said, we discussed in depth about the single component droplet combustion behaviour.

And the d square law that we already did in the, let us go to the journal and the D square law that we that we did over here. We also explained what is called diffusional this is diffusional entrapment. So, this you should know the degree of superheat that is required, okay. And we also covered a lot on the spatial uniform but temperature varying profile the concept of peclet number over there.

And lastly, lastly we also did the D square, where, this is the D square law, okay. And we showed that the gas phase quasi-steadiness also holds over here. Remember, of course, the flame temperature is the adiabatic flame temperature for the stoichiometric ratio that is given, okay.

And the reaction standoff distance ratio remains constant, okay. So, with what we do is, that we are going to finish this droplet combustion related studies, okay. And what we are going to do in the course of the next couple of lectures, that we have left is: We are going to look into another important aspect of multi-phase flow which is basically the bubbles. Or in other words it is called boiling, right.

So, let us introduce in the next two minutes about what boiling is, okay. And before we move on and explain it in more details, right. So, boiling is not evaporation.
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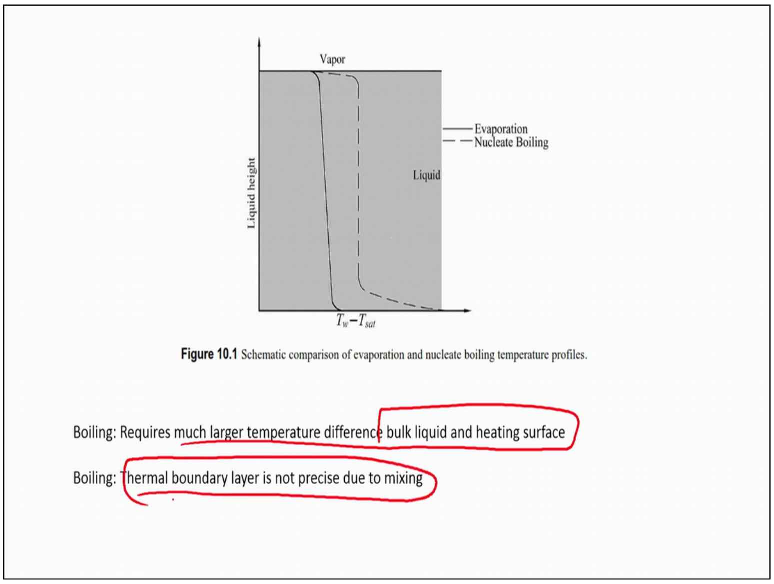

Figure 10.1 Schematic comparison of evaporation and nucleate boiling temperature profiles.

Boiling: Requires much larger temperature difference bulk liquid and heating surface

Boiling: Thermal boundary layer is not precise due to mixing

If you look at this particular little slide over here, boiling is not evaporation okay; once again, we are going back to Amir Faghri and Yuwen Zhang book, okay. So, boiling requires much larger temperature between the bulk liquid and the heating surface than evaporation, right. So, you can have evaporation and you can have boiling as you can literally see, if the evaporation curve is this.

So, the difference in temperature between the wall and the liquid is very low, right. Well, in the case of boiling, okay there is a much larger temperature difference that exists, okay. And evaporation is a surface phenomena. Boiling is not a surface phenomena anymore. The thermal boundary layer that you actually have in the case of evaporation, okay is not very precise in boiling because of the large scale motions, okay that are created within the liquid, the churning that are created within the liquid.

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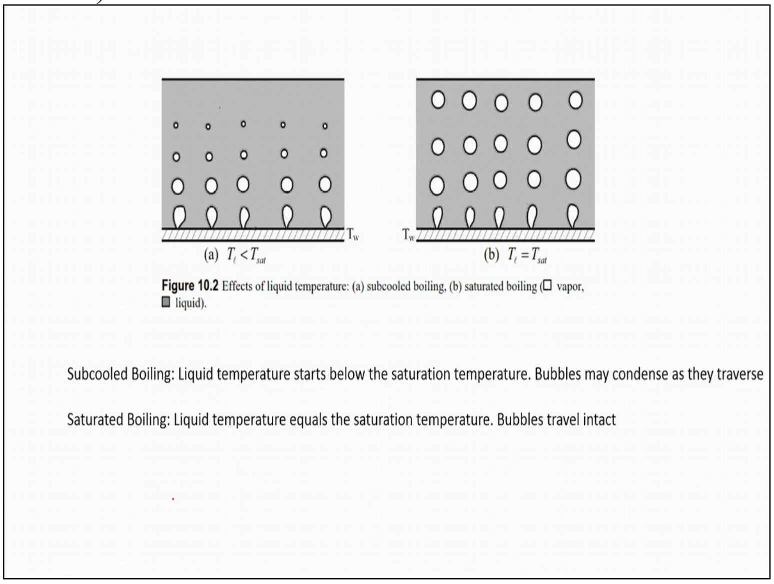

Figure 10.2 Effects of liquid temperature: (a) subcooled boiling, (b) saturated boiling (☐ vapor, ▨ liquid).

Subcooled Boiling: Liquid temperature starts below the saturation temperature. Bubbles may condense as they traverse

Saturated Boiling: Liquid temperature equals the saturation temperature. Bubbles travel intact

So, we will there are different types of boiling and there are different types of other things which we are going to do in the in the following lecture where we are going to see that boiling is bubbles essentially, the story of bubbles like we had the story of droplets, it is the story of bubbles. This boiling can be of different types homogeneous, heterogeneous, nucleate, there are different core classes of boiling, okay.

And not only that boiling and evaporation are very different. Evaporation is a slow process. Boiling is not a slow process anymore, right. We just briefly saw how boiling can enter into the picture in that micro explosion of drop here. We are going to formally give you an idea. We are not going to go into too much depth because of the lack of time.

We are going to just emphasize that: what boiling is? What are the different types of boiling; some equations which represents in the boiling, okay. But these are the two main differences. Evaporation requires a much lower temperature difference. In fact, any small temperature difference can drive evaporation. If you leave a saucer of water out in the open, it actually evaporates out, right okay.

But it does not boil, obviously. So, boiling requires a much larger temperature difference and the thermal boundary layer is very imprecise in the case of boiling. So, we will see in the next lecture that how we can actually analyze this boiling in more details, thank you.