Spray Theory and Applications

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Lecture – 09
Introduction to Atomizers and their design-1

Towards the end of the last lecture, we started to draw some conclusion about where the energy that is input into a spray going or input into a spray nozzle going. So, we started to say that there is two forms of energy in this spray itself, the bulk kinetic energy available in a each and every drop that is moving added over all the drops that are moving is a substantial amount of the total energy in the spray. The second aspects is this increased interfacial area of the drops themselves from their parent configuration where I had imagine all the liquid in one drop and I had some mechanical greater, that grated this big drop into bunch of smaller drops.

As it turns out that grating process will call it atomizing process, cannot happen without increasing the kinetic energy of the dotted drops themselves; which means that there is some amount of energy that is stored in the half m v squared of every drop and then on top of that there is an increase in the interfacial area, and therefore the interfacial energy. As it turns out while we set out to increase the interfacial energy that was or interfacial area, and we said that in order for me to increase the interfacial area there is an cost associated with that interfacial energy, but that cost was very very small in comparison to the actual energy that we typically put into a spray, and the reason for that is the kinetic energy of all the drops moving is very high in comparison to the increased interfacial area.

This increase in kinetic energy is the reason why is basically the biggest reservoir of all the energy that we input into the spray nozzle itself.

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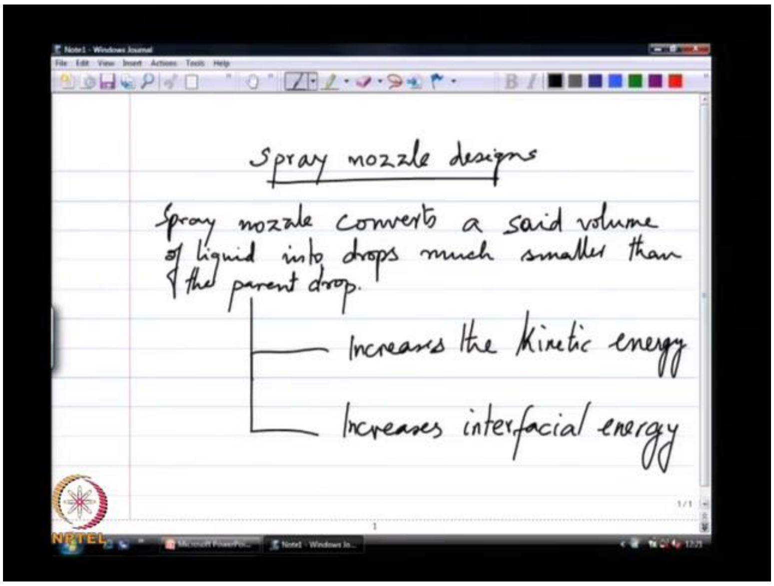

So, essentially we started to look will start to look at some spray nozzle designs and look at this underline principle of kinetic energy versus interfacial energy. So, a spray nozzle we started to say converts sort of a crude definition, but as it turns out it increases, a spray nozzle does both of these in differing magnitudes. So, we need to understand why it does this and what is the reason why the increased in kinetic energy is usually much higher than the increase in the interfacial energy, we will look at these two reasons today.

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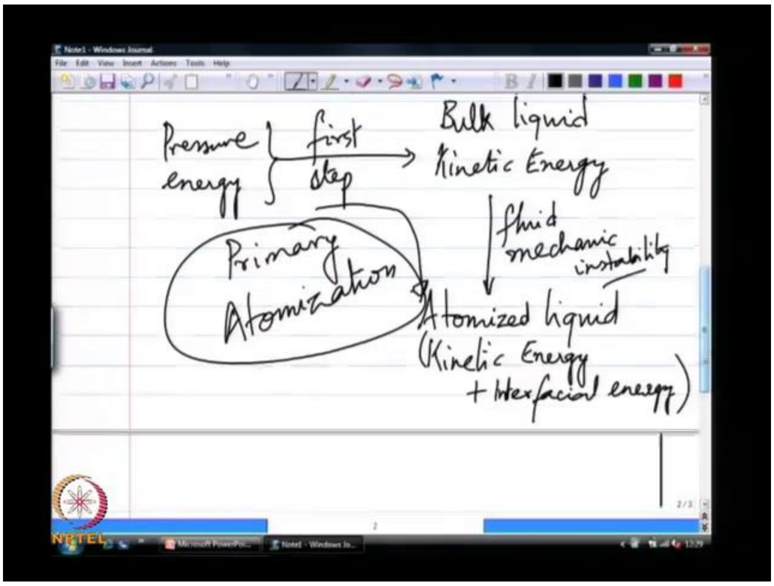

In a typical spray; so we are now looking at the mechanics of a typical spray nozzle. The first step is to convert; the first step in any in most spray nozzles is to take a pressurized source of liquid, if it is not already pressurized it is then pressurized. This is our initial source of energy. The plunger pushing like before I push the plunger chances are the perfume inside is atmospheric pressure the act of pushing the plunger down causes the pressure to go up slightly. So, the first thing is I have this pressure energy. We look at that in some quantitative terms later on, but essentially there is the idea that fluid at higher pressure has some capacity to do work which is nothing but energy.

That pressure energy is converted into kinetic energy, inside the nozzle we are not yet where we have atomized it just bulk liquid inside the spray nozzle is moving faster than it is then of course rest condition where it is just sitting at the bottom of a reservoir. That increase kinetic energy is a first step in this spray process. And then that increased liquid kinetic energy I will call this bulk kinetic energy of the bulk liquid; let me actually do it like little more precise with this. So, essentially the pressure energy is converted into bulk liquid kinetic energy. So, it is still bulk liquid I use the word bulk the phrase bulk liquid to denote non-atomized liquid. So, it is still in the form of a contiguous medium basically.

This bulk liquid then goes through some other process to give rise to atomized liquid. So, now, this is in the form of drops the kinetic energy of the bulk liquid inside if I have to go to my real ideal spray that we started to describe that I use an a input energy that energy is goes to increased interfacial area. So, I have put in 10 power minus 6 joules of energy I get ten microns fragments of liquid, that is my dream atomizer. But if I go through this route, this mechanistic route, I have already accelerated the bulk liquid to some kinetic energy that kinetic energy cannot go back into the liquid as interfacial energy, because that is also going again this idea of quality of energy.

Moving liquid is like a very, very refined highest form of energy interfacial energy is also not is a lower quality energy source than mechanical moving parts, moving entities. So, this kinetic energy cannot go back into interfacial energy alone with 100 percent efficiency. It cannot spontaneously go back to interfacial into interfacial energy. Is everybody with me on this? That I have mechanical energy which for it, it cannot spontaneously go back to become interfacial energy. It is sort of like saying heat spontaneously becoming work or heat spontaneously becoming a mechanical shaft. It cannot happen at 100 percent efficiency, it could happen, but surely not at 100 percent efficiency. Therefore, you are always going to be left with some kinetic energy of this drops plus interfacial energy.

So, well actually I cannot say that it cannot happen at 100 percent efficiency although it can, thermo dynamically there is no reason to believe that process cannot be 100 percent efficient because this is not a cyclic process, because all of our ideas of second law are only valid for cyclic process is this is not a cyclic; at least I have drops in motion let us say some fast motion. Can I get stationary tiny fragments out of it? No reason to believe that cannot happen but unlikely we will see in the moment in most instances you get some ruminant kinetic energy in the drops. And that kinetic energy is still substantial in comparison to this increased interfacial energy.

So, this is the route in which most mechanical atomizers work, I will give you just a simple thought example of a non mechanical atomizer. If I take a drop of liquid and imagine I have embedded a tiny amount of some power in it some explosive at a center of the blob of liquid and I explode it. So, there was a chemical energy in that explosive, at the end of it if I can create stationary blobs without any dissipation then all of the chemical in the energy in the explosive is completely converted into interfacial energy. If I can do it through that route, but as it turns out fluid mechanically the only route to creating an atomized spray is through increasing the bulk kinetic energy and then using that kinetic energy and some sort of an instability in that flow field to give rise to tiny drops. We will look at this in grade detail later on.

So, essentially this route is what is called Primary Atomization. This route of taking pressurize liquid increasing the kinetic energy of that bulk liquid and some fluid mechanic process in the middle, typically some sort of an instability in the fluid mechanic flow fields will see this later on gives rise to atomized liquid that has kinetic energy and some increase interfacial energy. This is process of breaking up contiguous liquid into fragments is called Primary Atomization.

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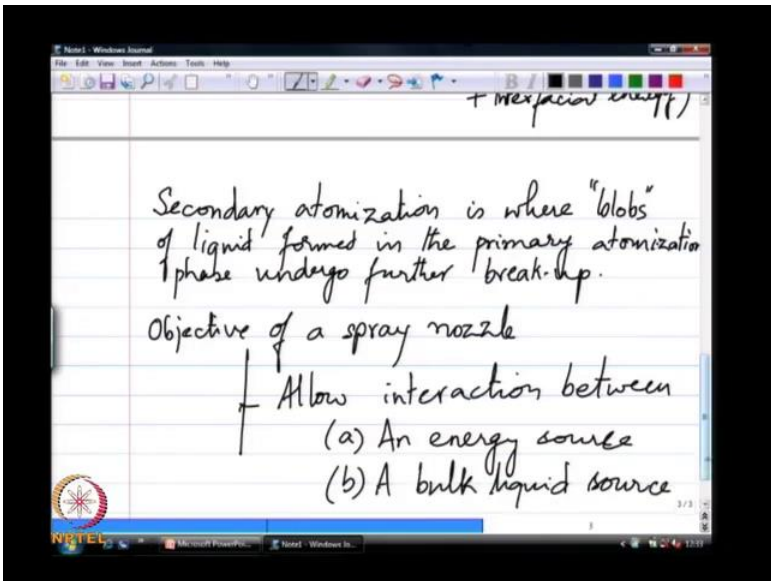

To distinguish this from, obviously if I called this Primary Atomization a better define a secondary atomization otherwise the word primary has no meaning, I will use the word “blobs”. The blobs form from the second primary atomization phase undergo for the break up.

So, somehow these blobs of liquid are themselves not stable and therefore, are likely to break up, this process is what we call secondary atomization. So, from nozzle to nozzle we look at in just moment, we look at about does not different designs of these spray nozzles. The common theme is going to be I need a source of energy I need a source of liquid I need a process by which that energy source interact with the liquid source and causes the liquid to break up that is primary break up after the break up has happened the primary break up has happened these blobs of liquid that are formed, blobs could be tiny drops or big blobs you know I just use a word interchangeably these blobs of liquid could be more unstable could be unstable still and break up to smaller drops or blobs later on, that later on process we will come to later the later on process is relatively insensitive to these nozzle designs.

So, In other words the blob a blob of liquid breaking up sort of depends on the local flow field around that blob of liquid and it has in some sense forgotten the design of the nozzle through which it has come because it now only depends on its local environment versus the primary break up process where I have an energy source I have a source of bulk liquid I bring these two together inside my nozzle and cause them to exchange energy to the point where the bulk liquid breaks up that is my primary objective in the primary instability process and I am going to facilitate that through this nozzle design that is the objective of trying to actively engineer a design in a spray nozzle as suppose to just sort of let them come together. So, the objective of a spray nozzle is to allow interaction between a, an energy source and b, a bulk liquid source different atomizer designs do this differently, different atomizer designs work with different energy sources, different atomizer designs are intended to work with different kinds of bulk liquids.

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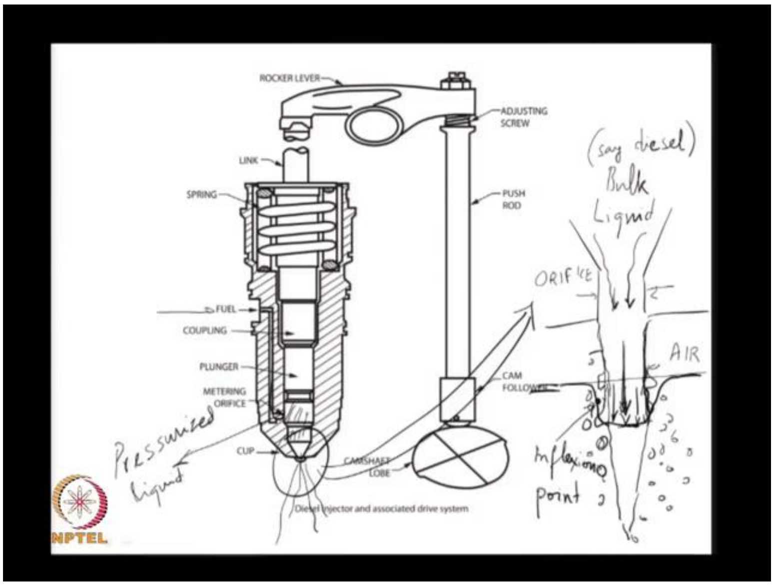

So, therefore, so, many different choices for a and b as many different designs for spray nozzles. So, will now look at starting with some fairly simple designs we look at a few different designs here, this is sort of a its actually a diesel injector that is shown in this schematic the diesel injector has a source of fuel as you can see the fuel flows through this passage and is and usually fills this gap here or this area, this volume and there is a rocker mechanism the that is released by storing energy into a spring and this imagine it just abruptly comes pushes this liquid out of this injector.

So, this is like a pulse of liquid that comes out and a the morphology of the liquid coming out if I zoom out on this side here what does that look like, this whole thing is still bulk liquid, this bulk liquid is now accelerated through this orifice it is just this a through hole just a drilled hole basically, what comes out is a jet, this jet is moving at some velocity. So, I have taken the spring energy converted first into pressure energy in the liquid and that pressure is act that pressurized liquid is accelerated through this converging passage to give me a fast moving source of liquid, this fast moving sources of bulk fast moving bulk liquid has some kinetic energy unit now what is the source of, I need some source of energy to break this up, as it turns out in this case it is the air around that is that rest.

So, imagine you can think of it in many ways, but the way I think is sort of the most intuitive ways the liquid is moving very fast, but if you are moving with the air, with the liquid it is the air that is moving back very fast in relative frame of reference. So, it is as though I have taken as stationary column of liquid and I moving air back in this direction at a very high velocity and that is if you want to imagine is source of energy the air is a the kinetic energy of the air is the source of energy that source of energy destabilizes this interface and intern strips of drops.

So, I am creating some drops stripping off from the side and as these drops are strips from the side this core diameter decreases and essentially I get. So, if you imagine this meniscus is now unstable because one part of if I take a profile across some section like that this part is moving at high velocity this part is relatively at rest. So, this is a shear layer here that develops that shear layer in some classical fluid mechanic sense has an inflection point and inflection point in a velocity profile is sufficient to call that velocity to ensure that the velocity profile is unstable and because of that you create an you create a growth of that instability essentially shading these drops.

So, what is the area over which the fluid which is in this case the bulk liquid let say diesel and air which is around interact it is the area of that interfacial area of the cylinder. So, if I want to increase that interfacial area essentially to facilitate this interaction in a more intimate passion for the same volume of that liquid column I should increase the surface area of interaction.

So, as it turns out, a circle has the list parameter for a given area a cylindrical column has the list surface area for a given height of the cylinder of liquid per unit volume. So, it is going the other way around. So, ideally I should make the hole like a star shape or something that would increase the interfacial area for this energy in the air stream to interact with the liquid now, I post the problem as though the air is atomizing the liquid which is. In fact, the correct way to think of it, but really speaking even if this liquid was injected into vacuum the liquid by virtue of it shown inertia also breaks up.

But in a in a specific design that we are looking at here which is a diesel injector it is essentially a shear driven instability that causes this drops to be sheared from the surface area of the cylinder where I get tiny drops and sort of an experimental evidence that you can use as testament to my argument is that. That the drops formed a typically much smaller than the diameter of the whole itself, we will see a example where there on the order of the diameter of the hole.

In fact, the simplest example of a spray is a dripping faucet if I take a tie my bathroom faucet and allow it to just drip volume goes into the atomizer or my nozzle or the faucet itself comes out in the form of a drip inside the nozzle water is in a contiguous form it is a one continuum once it comes out is now discrete set of drops there is an increase in interfacial energy in this process that is facilitated by gravity in that particular instance. So, that is the source of energy they faucet which is my atomizer is bringing it to bringing them together there is some sense although it is a very trivial case to think of, but even in this in this instance the atomizer is introducing the liquid in a way that the air can destabilize the liquid now and break up break the liquid up into drops.

So, this is the simplest form of an atomizer that I have taken pressure energy in the liquid. So, it is in the energy here is, in the form of a pressurized liquid that pressurized liquid allows some of the pressure energy to the converted into kinetic energy in the liquid through when it accelerate through this passage. And that kinetic energy in the liquid when is it comes in contact with the air around which is now at rest creates this inflection point in the velocity profile between stagnant air and fast moving liquid air and that inflection point is sufficient to cause this flow field to the unstable and cause drops to be sheared from this side.

So, I have cylindrical column it breaks up this is the basic principle of operation of a diesel injector now if I want to increase the interfacial area between the liquid and the air like I have to go to some veered shape like a star as it turns out the star is not as veered the way people engineer a star into a diesel injector is by having multiple holes. That is the reason for having multiple holes in a diesel injector instead of having one star shaped hole I can take 6 holes of 5 holes as many different designs have different designs ways of looking at it essentially I have taken volume florid going into each of these orifices is one is one over n is the number of holes in relation to having all florid go through orifice. So, you can clearly see that the interfacial area available for the air to destabilize the liquid is now higher. In some sense the efficiency of atomization is better with multiple holes, how far do I take this arguments can I go to a 100 holes on a diesel injector sure you can except the hole size then become extremely small.

So, manufacturability is the bottom line constraint in all of this actually not completely the constraint manufacturability is one of two constraints the other constraint is the fuel quality itself, diesel as clean as I can get from a gas station has tiny particles in it. So, if I make the hole, if I have a way of drilling 1 micron holes a 100 them at the bottom of a diesel injected step, I will clock it up a no time. So, that is the other side of this the whether you get the clocking process to be initiated from the cumbersense side some should particles coming and clocking at a or from the fuel side particles in the fuel that come and get themselves and a embedded in this little orifice one way or the other it is not good for the atomizer. So vowing to these two, I can increase in a number of holes to the points where to some judicious point where I still, I am not encountering clocking as a problem and manufacturability is not the issue.

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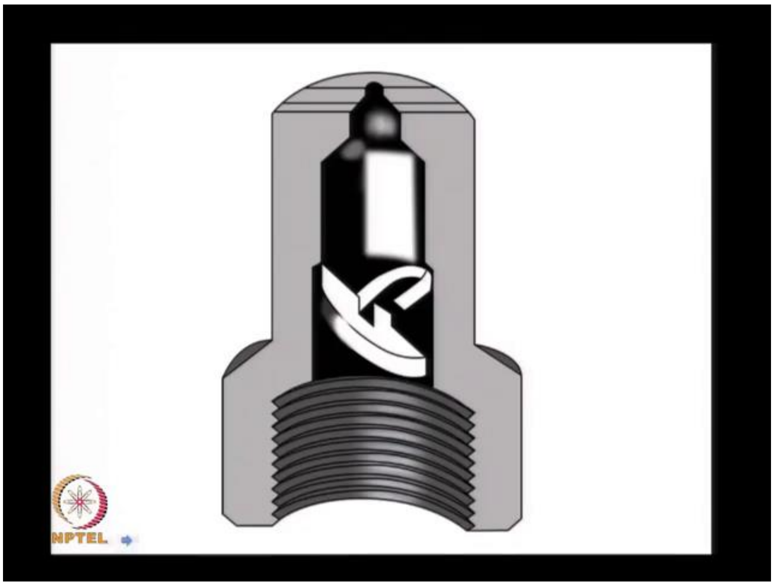

Let us how a diesel injector works the simplex of the kind as it turns out, it is very inefficient at creating interfacial area.

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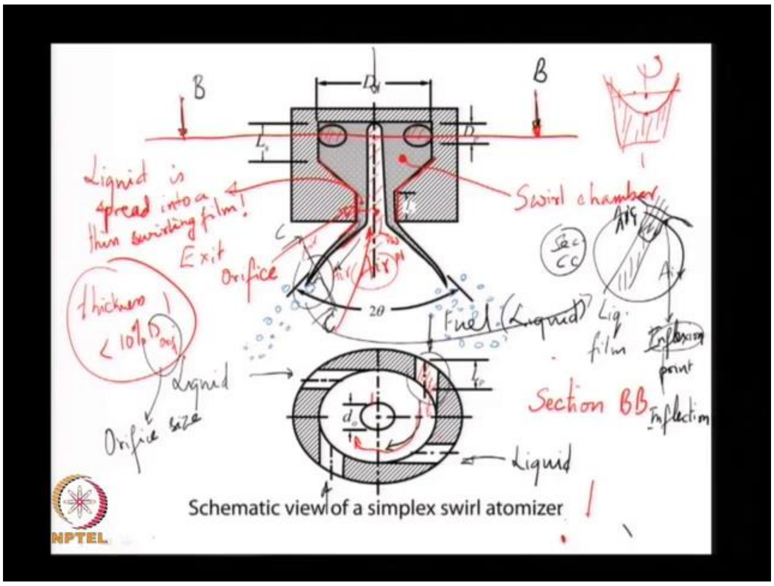

So, will go to the one that is actually most widely used which is called a Simplex Swirl Atomizer, simplex swirl atomizer is by far the most commonly used of any spray nozzle design the basic principle of operation is this. So, imagine this is my nozzle instead of injecting the liquid straight through from the top and allowing it to accelerate through a converging passage what is done is it is the fluid is a injected through a set of tangential slots I will call this fuel or liquid, liquid is injected through a set of tangential slots and what I have essentially done now, this is the cross section at some.

At this section BB, this is sort of the view shown here. So, essentially you can see the orifice is shown as circles here really speaking they are sort of just shown there to give you the idea that that they are tangential orifices is they are better shown. So, this is the tangential injection passage and what I, does is I create a swirl inside here. So, this chamber is very often called a Swirl Chamber and the liquid is swirling in this particular instance the way I have shown the view when I look some top the swirl is clockwise.

So, they the fluid is swirling inside and when the swirling fluid goes through this converging passage I accelerate the swirl just like simply using the principle of conservation of angular momentum just like; a ice skater with the hands wide apart spins when the hands are drawn in the angular velocity of the ice skater goes up. So, in a very analogues manner the angular velocity of the fluid goes up and that increased angular velocity also has in a increased centrifugal force of the liquid.

So, all of the liquid because of this very high swirl velocity is now sticking to the walls of this exit orifice. So, this part called the Exit Orifice, It is just a straight hole except if I look at if this hole orifice was filled with liquid and a liquid is swirling. Essentially, it is just like a spinning bucket you know I create a void in the middle because of that all of this is essentially air, it is exactly like a spinning bucket, the liquid is spinning it is also moving in the downward direction the way I have shown in the picture because the volume of the swirl chamber is constant and I am introducing more liquid from the tangential slots.

So, the liquid inside the swirl chamber has no choice but to come out, the point the reason I am going through this gory explanation of this is because it has nothing to do with gravity this can be oriented anyway it is the incompressibility of the liquid that is causing the fuel to flow in the axial direction. So, this in compressibility of the fuel causes the small axial velocity, but a very high swirl velocity notice how I can. Well, we come to the ratio of the two velocities in the moment, but essentially I have created a very high swirl velocity of this liquid and those high swirl velocity causes low pressure region in the center line causing this air to be drawn in so, this is a low pressure there.

And that just like a spinning bucket you know how I take a bucket, I start with the meniscus if I spin it around the center line I spread this out into a parabola. So, that point is now come down so the water now occupies where the shape where the meniscus is the parabola, a part of a parabola, this decrease in the meniscus level is exactly analogues to where the meniscus should have been here. It is now back here because of this spin, now the what I have essentially done here is I have taken this liquid and spread it out into a thin swirling film.

So, this is my liquid, this schematic is not actually to scale the thickness is usually less than 10 percent of the actual diameter the diameter of the orifice. So, if D orifice is the diameter of the orifice is itself the thickness is very very small thickness of the liquid. So, most of the orifice is just interfacial is just air basically, see how this is fundamentally different from the diesel case. The diesel atomizer, the diesel injector was a situation where the orifice was completely flooded with liquid. The only interfacial area there was the surface area of that cylinder exiting the injector, here the interface is now 2 fold there is an interface on the inside here and a interface on the outside.

So, I get twice the benefit for the same orifice size and because I have spread it out into a very thin film, the will the film thickness is 1 of 2 determinant of the final drops size the film thickness is very small will see the benefits of this in a moment. But, the interfacial area of interaction between the air and the liquid is now twice has much as I had the chance to create in the diesel injector, in addition this is swirling. The swirling film is naturally going to expand outwards once it exists the atomizer that is what you see here which is depicted in the form of this cone.

So, I had wall inside which the swirling film was sticking as soon as the liquid exists from the other side, because the swirl creates a additional centrifugal force; that is now unbalance from the wall reaction it is going to further expand outwards and this further expansion outwards does two things. One, it increases the interfacial area between the air and the liquid even more and two, it is slows down the swirl of the liquid it just now the reverse of the ice skater problem.

The objective of the swirl was 2 fold a, to spread it out into a thin film spread the liquid out into a thin film and b increase a interfacial area of interaction and c because the actual kinetic energy. Remember, we said this kinetic energy thing is a bad thing, I do not want drops to the moving very fast or let us say if I have an a application where I am only interested in increasing the interfacial energy of the liquid. I really do not want a fast moving spray but, and like I said earlier like we said earlier that is the cost that we have to bear.

And I want to see if I can minimize it, here the way to minimize it, the axial velocity of this liquid is only determined by the flow rate. So, for the same flow rate I can increase the number of tangential orifice is through which I inject liquid into the swirl chamber causing a height tangential velocity, but low axial velocity, axial velocity the being the same I can increase the tangential velocity of the motion, the tangential velocity is what is responsible for this water to liquid to go and stick to the walls creating a very thin film.

So, I can create a as thin a film as I want for whatever be your flow rate by changing the design the diameter of the tangential orifice is the tangential injection orifice and the number of those orifice this is an added degree of freedom I did not have in the diesel injector. I can now control the axial motion which is said by my mass flow rate independent of the film thickness which like I am going to show you is going to be one of the main determinants of the droplet size a simplex design allows you to control droplet size relatively independent of the mass flow rate that you put in.

In the previous diesel injected design if I increase the mass flow rate for the same orifice diameter, I have essentially increase the velocity of the few of the liquid coming out which means I have increase the nature of the instability at the inflection point, I am likely to get smaller drops so over. In fact, going back from the other way in this injected design the only way to get smaller drops is to increase the velocity of the bulk liquid which if I do not change the orifices size means I am stuck with the same flow rate. So, one way to over commit is to have multiple orifices is injecting the fuel. So, the same mass flow rate while in this particular design you only have one degree of freedom which is your orifice size.

Here you have 2 degrees of freedom which is this tangential orifice diameter and their number as well as the orifice size both of these put together allow us independently control of the mass flow rate and the drop size to of over a very large operating reason and that is that is I think the main reason why this particular nozzle design is widely used. In fact, the real reason it is found wide commercial applicability is because I am not constraint by this orifice size you know this D orifice size which is my orifice size can be a fairly a large value I can have a fairly large sized hole that I drilled and I am fluid mechanically causing the cross sectional area through which the liquid flows out to become small I am using fluid mechanic process is to decrease the cross sectional area through which the fluid flows swale.

So, that is the reason I can create as tiny film as thin as a film I want to while having as relatively speaking again as big a hole as I can. So, from a manufacture ability perspective is always a good thing when I do not have to drill tiny holes in metal parts, is always a good thing when I have to go to plastic molded component it is an even better benefit that I do not want to work with tiny features molding tiny features in plastic is also a pain.

So, this is a simple design that provides 2 degrees of freedom now when the film that spills out of the film that spills out of the nozzle itself now is going to die is going to expand outwards and because you have a similar fluid mechanic in stability. So, this film is now moving in this direction with the air being relatively speaking stationary. So, I have essentially if I take a cross section here I have the same inflection point in velocity profile. So, if I zoom that out on the side here this is my film, this film is moving in this direction it may also have a small swirl component, but that would have died out by the section that I have drawn. So, if I take this section CC the air outside is at rest.

But, the liquid is moving some velocity again I have the same inflection point in the velocity profile I think that is spelt inflection sorry not within x this inflection point again is sufficient to assure us that that velocity profile is unstable because of which you get a certain kind of instability we will look at that in some detail later on.

So, this again causes this liquid film to further break up so downstream of here I will change my pen color just to show you drops in blue these drops in blue or formed from this film from the breakup of this film we will look at we look at in this some more detail in the next class, but there is some break up process is that are causing this film to break up into drops this is our primary break up process. Now some of these drops may be further unstable and later on they may break down into even smaller drops and that is our secondary process, but we are only going to focus on the primary process which is what the nozzle is responsible for.

Now, a problem with this is that I create drops; let us say if I take a further section downstream we still talking about the simplex nozzle design.

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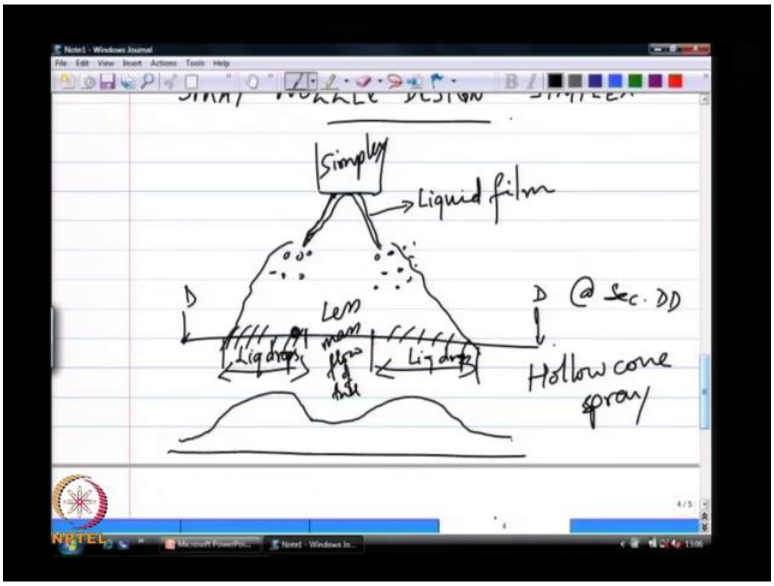

If I have let us say one of those simplex nozzle that I showed in the schematic and I create this film that is filling out this is the liquid film I am going to create this drops like assured in that same schematic here if I take a section down here call this I am going to have more drops. Let us say this is my spray now I am going to have more drops in this region and less drops here.

So, essentially that section DD if I was to take an image of the liquid itself liquid drops is going to be like a donut at like a vada with the hole in the middle, because this going to be less mass flow rate of the drops in the middle this going to be more mass flow rate through that cross sectional area. So it is really going to look like a diffuse vada in other words I cannot tell when the hole appear, but it suddenly appears it is because just like this spray edge, it is not sharply defined edge it is not like the edge of a pen. We discuss this, it is a relatively speaking a defuse region over which you had a spray and now there is no spray similarly on the inside you had a spray here and in the middle you have less density of drops. So, this is called a Hollow Cone spray.

So, a simplex nozzle by design delivers a hollow cone spray. So, In other words all the drops are distributed into a nice hollow cone there are applications where it is actually good to have a hollow cone spray there are other applications where I would rather not have a hollow cone spray, but more of a spray where I have a nice uniform distribution of drops, unfortunately a simplex nozzle is a bad choice when I want a nice uniform distribution of drops we look at how to solve that problem a little later on.

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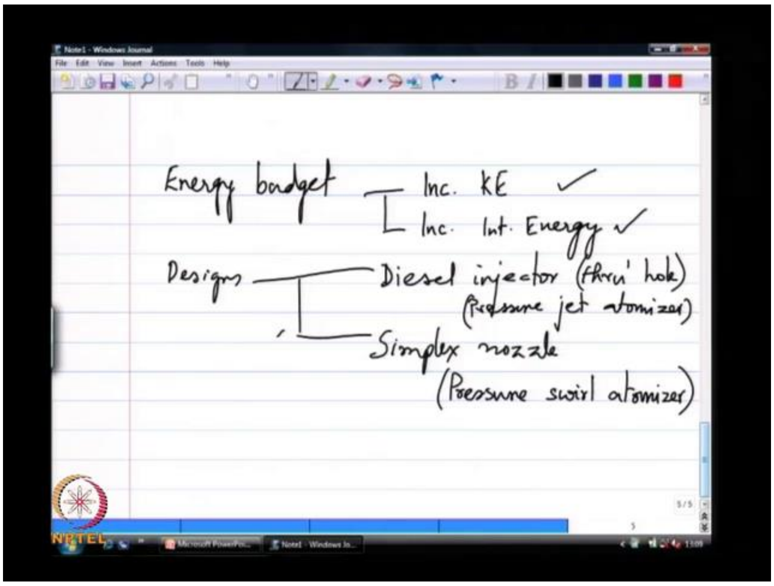

So, let is quickly recap what we have done today, we looked at the energy budget for a spray nozzle and said it does two things set increases a kinetic energy it increases the interfacial energy while this is my objective I cannot do without this as you saw from the case of the diesel injector where I am increasing the kinetic energy. In order to facilitate the inflection point, in order to cause the break ups to happened. So, this is the as suppose to let us say a mechanical carrot greater where I control the break up process by the frequency at which the greater approaches the carrot and the flow rate is how fast I move they can be unrelated, but in this case they are they are coupled.

So, with that we said simple design we looked at two separate designs -one, is diesel injector which is essentially also called a Through Hole Atomizer it is like a pressure jet atomizer the other example is just simplex design so also called a Pressure Swirl Atomizer. We looked at these designs, we have at least other ten such nozzle designs to look at depending on.

Remember we said there is an energy source, there is a bulk liquid source, the objective of a nozzle is to introduce the two to each other, and the cause the liquid to break up here are two ways of doing it we will find; and other at a few different ways in the next class.