Spray Theory and Applications

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Lecture - 10
Introduction to Atomizers and their design-2

Good Morning. We are going to continue our discussion on various spray nozzle designs. Towards the end of the class, we had looked at the 2 sorts of designs of spray nozzles; one that is just a through hole through which you squared a liquid that is pressurized a design that is commonly used in diesel injectors.

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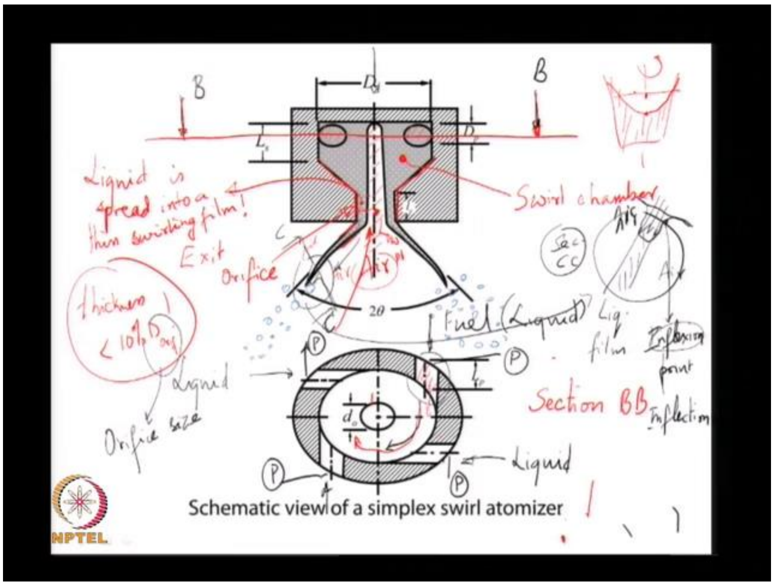

And another which is more widely used design called the simplex swirl atomizer. This simplex swirl atomizer is very simple in its construction, essentially a set of tangential passages bring the fluid into a chamber called the swirl chamber and that swirl chamber has a converging passage in which the swirl action is accelerated. The swirl velocity is accelerated and the acceleration causes the liquid to exit the spray nozzle by just forming into a thin film that is sticking to the walls of the orifice. And the big advantage of this design as we discussed in that class, is that the size of the film that is formed is what is going to determine the drop size later on not the size of the orifice.

I have now sought of decoupled machining practices from fluid mechanic performance of the spray nozzle which is always a good thing.

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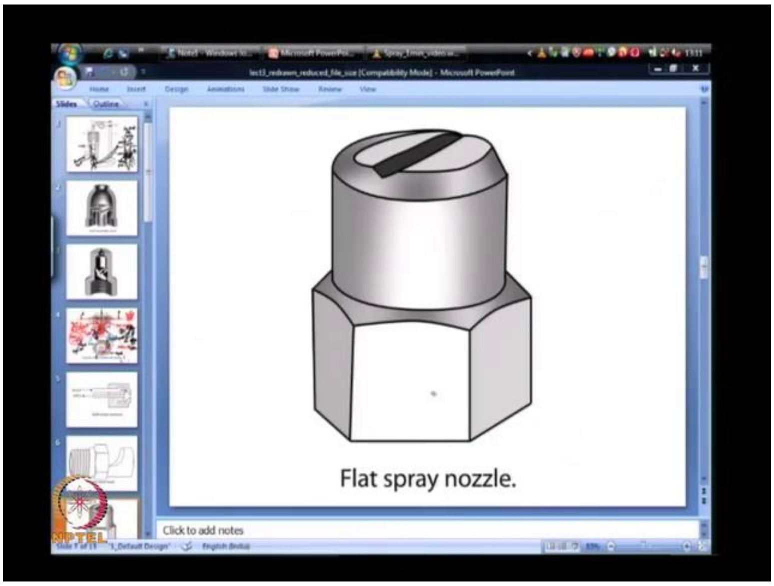

What we are going to do, just briefly is to look at one of these spray nozzles in action. We are going to look at a video of a fairly common spray simplex swirl nozzle from a water spray container. We will see in just a moment. Let me start to play the video. This was captured at 10000 frames seconds and is being played back at 30 frames a second.

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Let me pause the video here. Now, what you see over here is the tip of the spray container. What you see coming out is a conical sheet of water and a conical sheet of water, when I play this you will see is not just a steady cone, it is sort of flapping; it is got a temporal oscillation to it, it is flapping and is undergoing let me pause the video, is undergoing as certain kind of breakup process.

So this flapping liquid sheet exiting the swirl spray nozzle is what is responsible for its breakup. And as you can see the sheet is breaking up right around the region where my mouse is pointing. And for the downstream you essentially have drops that are moving down stream. This is an instance where you know the sheet thickness is not very obvious in this film, but the sheet thickness is much smaller than the orifice through which the sheet is exiting. And that sheet because of its unsteadiness is response for the sheet itself breaking up into what looks like rings, you can see the oscillatory motion of the sheet.

Now, we will go back to make some observations. Now if you look at this, there is the conical sheet exit in the nozzle is not steady and it is flapping and this flapping motion is due to the swirl action which is causing the liquid sheet expand out words and the very fact that fluid mechanically. This kind of a velocity profile is unstable. We will look at that as we go long as well. Now this flapping liquid sheet causes the liquid sheet, in this particular instance you can see evidence that it is sort of breaking up into rings and the rings themselves are further breaking up into drops for the downstream.

If you will imagine for a moment, a sheet like this breaking up into rings, the ring diameter or if you will, it is like a toroidal ring, the torus diameter is now going to be determined by the film thickness. It is going to be on the order of the film thickness. And that film thickness being small by accelerated swirl is naturally going to be responsible for smaller drop down stream. That is the mechanism by which drop size is controlled in a design like this. Another feature to observe here is that well again it is not very obvious here, but the fact that I have spread the liquid out into a swirling liquid sheet is going to naturally cause all the drops to be concentrated in a donut of sort weather hole in the middle where there is no concentration of fluid.

Now, there may be applications where that is good where I want all of the drops to be only on the periphery I do not want anything in the middle, but in instance is where I want a uniform distribution of drops. For example a paint spray, when I paint a wall, I want to have a relatively uniform coating all over. I do not want a thick edge on top and bottom of the spray and a sort of less than coating in the middle, I do not want that.

I would rather prefer a full a sort of a more uniform coating of the spray paint. And for that, there are designs that have evolved which are sort of evolutions from the simplex nozzle. The simplex atomizer is like a swirl. It is one of the most widely used and many of the other designs, we will see today are all based on the basics simplex concept. One variant of the simple concept is what I have, what we are seeing here in this schematic.

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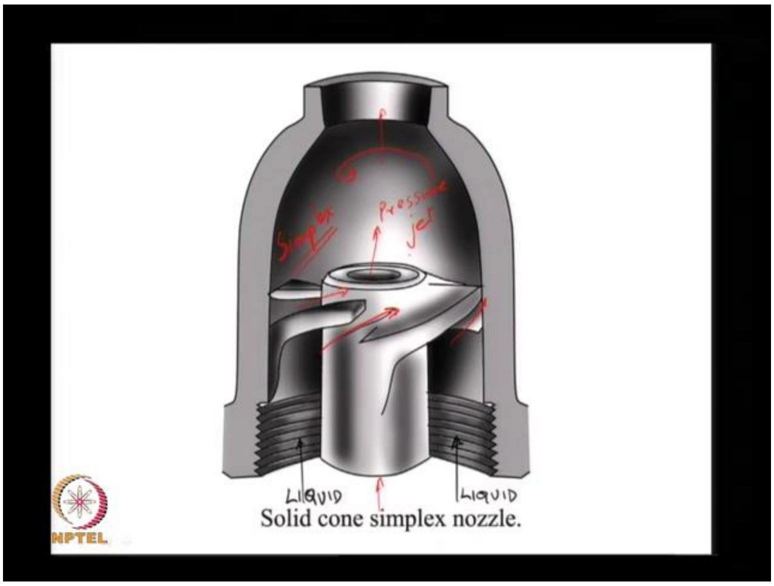

The liquid comes through this sort of an annular passage, and because of these vanes cause the liquid to be introduced into this region with a certain kind of a swirl action. So, you create a natural swirl inside this chamber that is going to be oriented in that direction; except you are also introducing some liquid directly through the middle through a center orifice of kind.

Not only is this going to create a swirl action, but it also going to create some liquid coming straight through this way. The resulting spray is going to be a combination of a pressure swirl and the pressure jet atomizer. Therefore, this is essentially to control the spray pattern coming out of the nozzle pattern is a indication of whether the drops in the spray are distributed in a hollow cone or in a solid disk like distribution.

In this particular design, it is more likely that you are going to have drops in the middle. Now because of the way the simplex part of this nozzle works in relation to the pressure jet part of the nozzle. This is more like a pressure jet spray and this part is more like a simplex spray because of a combination of these two. The drop size is coming out to the pressure jet are going to be generally larger than the drop sizes in the simplex spray. While I have ensured that there is sort of a more uniform volume drop volume distribution that drop volume in the middle of this spray near the center line of this spray is going to be distributed in to larger drops in comparison with the drops on the periphery of this spray. So, this is sort of a by result of this kind of a design, there is really no way around it as far as this design is concerned. But we at least overcome the problem of having nothing in the middle, no fuel or no liquid in the middle.

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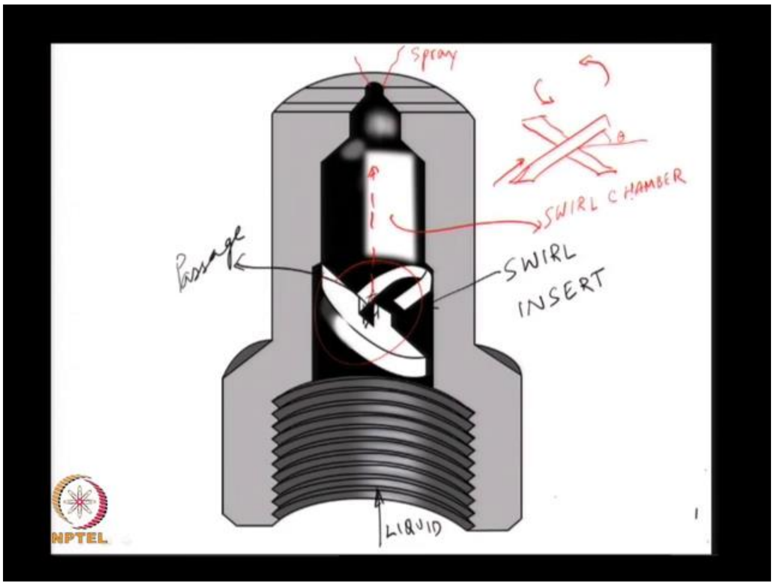

The next kind of design is again offshoot of this simplex nozzle and this particular design is, it simplifies a few different aspects of this simplex nozzle by making the passages fairly large. This is again a schematic, where the liquid is injected through the middle through this, what we are seeing here is sort of a cut section of the nozzle itself. And there is an insert this is typically called as swirl insert.

That is responsible; it is sort of like 2 fans, 2 vanes in that are oriented as an x. The liquid that comes up, the first vane is going to cause a swirling action in this direction. The liquid that comes up this vane is going to cause a swirling action this way. And by engineering a small passage here, we can cause some fluid to come directly down the middle as well.

That column of fluid that comes down the middle is also going to be in the vicinity of this swirl vortex that is formed inside the simplex nozzle. As a result it is also going to be a swirl in column of liquid that is going to come out in the form of a spray. Again you are, this is solid cone design, but by taking this y, I am going to try and draw a schematic of this, the fluid that comes of this way is going to cause it swirl, this way the fluid that comes up the other way is going to cause it swirl. This way and that causes swirling action in this swirl chamber.

The drop size in this case is again determined by the angle of this swirl, insert in some sense that angle is going to determine the magnitude of the swirl velocity in relation to the axial velocity and that essentially determines like the swirl momentum flux like swirl momentum flux is, what is responsible for the degree to which the film is sticking to the wall.

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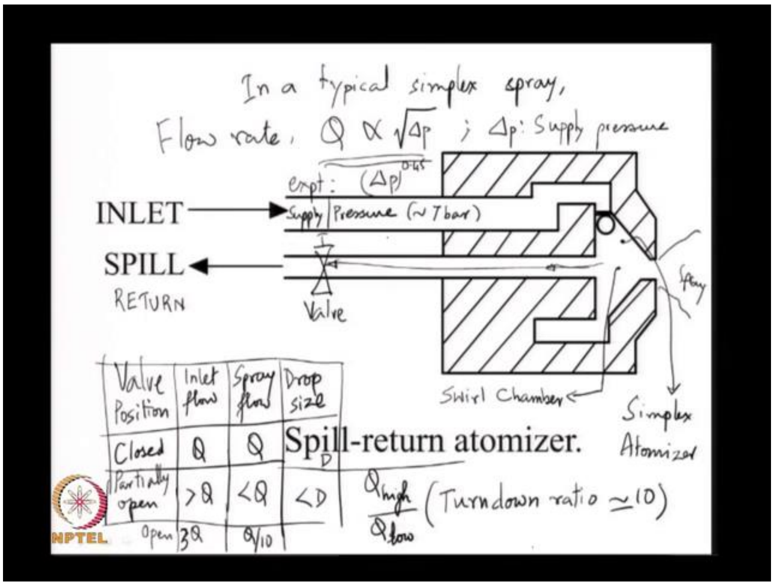

One of the features of all of these nozzles is that I have one fluid inlet that brings fluid into the nozzle and all the fluid that enters the nozzle is spread now as I increase the supply pressure.

If you go back to the simplex design for a moment as we increase the supply pressure at this point which is a same at all the 4 inlets, as we increase that supply pressure, you likely to see that the flow rate through this nozzle goes up. Because the geometry of the passages remains the same as the pressure goes up the flow rate through the nozzle goes up, as the flow rate goes up because of the nature of the geometry the swirl velocity also goes up. There is a range of operation where increase in the pressure increases the flow rate without adversely affecting the drop size in the spray that is usually the range where simplex nozzles are employed.

But, because of the nature of this feature; essentially if you will imagine, these are like restrictions they are like fluid mechanic restrictions, people are found over many, many kinds of designs that in a typical simplex spray Q goes as this square root of delta p. I use the symbol delta p for supply pressure. It is essentially that difference in the pressure between the actual absolute pressure at which the liquid is supplied and the pressure into which the spray enters. Assume for a moment that the spray enters pure ambient condition. So delta p is the same as the gauge pressure that at the entry to the nozzle.

And this relation that the flow rate goes as square root of delta p is sort of empirically observed in many, many different kinds of nozzles, actual data shows that this is the exponent is not exactly 0.5, but close to 0.45. Q goes as delta p raise to the power 0.45 that is again over a wide class of simplex nozzle. There is a problem with this square root kind of dependence that if I increase the supply pressure by a factor of 4, I only get a factor of two changes in the flow rate.

If I want to double the flow rate conversely, I have to increase the supply pressure 4 times which is usually quite difficult to do. Just too again gets some order of magnitude, estimates most simplex spray nozzles operated pressures between about 2 bar 2 about 7 bar. Like for example, your spray water can that we saw just a moment ago is probably the nozzle part itself is operating at a pressure about 2 to 3 bar. To go up from about 2 bar if i have to double the flow rate coming out, I have to go up to 8 bar which is prohibitive in many application.

But, on the other hand I want to be able to modulate the fuel output coming out in the form of a spray. I want to be able to control what comes out, the mass flow rate of the let us just say fuel that comes out of this spray nozzle, because for one simple example, is let us take a process furnace. I have a boiler in which, there is an oil fired burner. We are spraying some kind of petroleum based oil into it into a combustion chamber to create heat for use in a process heating application. Now when I start off this process cold on a Monday morning, I require a high through put of this of heat and consequently a high oil flow rate. But, after I have heated off the contents of this, let us just say boiler or the process heater up to a certain temperature, I will only want to maintain it that temperature I do not, I only want to add as much heat as required to overcome losses around the losses to the ambient environment.

The startup requires a very high flow rate the maintenance of that temperature only requires, what is often called trickle heating. So, what sort of a spray nozzle can I use that will give me certain flow rate for startup conditions and something like a 10th of the flow rate during normal operating conditions. This kind of a problem is also encountered in an aircraft, where at the take of point the pilot is running an aircraft a full thrust which is when all the atomizers are firing at their highest flow rate. But, when the pilot is only cruising at some high altitude, you do not require full thrust. And so the spray nozzles have to now scale back and operate that a much at a much lower flow rate condition.

But at the same time produce a good spray quality; spray quality in terms of drop size. Here is a design that does that, this is called as spill return atomizer. If you will consider this essentially, there is an inlet. The inlet is at some pressure at some supply pressure typically let us say 7 bar; 7 bar is about 100 p s i, 10 bar is about 150 pounds per square inch, say these are all units that are used commonly in the spray industry.

Let us just say the supply is at 7 bar and this is supply going in to your conventional simplex nozzle. This part here is a regular simplex atomizer. It would be I, it would exactly be a simplex atomizer, but for this one hole that brings the fuel back out of this swirl chamber, call this spill return. Now let us see what this does. Let us say, I will take a situation where I have a valve on this line. If that valve is completely closed then whatever supply goes into the swirl chamber has to come out in the form of a spray. If I partially crack the valve open, then a part of the flow rate is now allowed to come back to a supply tank of sorts and by controlling the opening on this valve, I can control the actual flow rate of the spray coming out of just of the nozzle the flow rate of this spray coming out in the form of graphs.

Now, typically again from observations, what we find is that between the 2 extreme cases, where the values completely closed and completely open, the actual flow rate of the fuel going into the swirl chamber does change when the valve is completely open, there is actually more fuel going in. Even those you have less spray coming out in the situation, where the valve is completely open, there is more fuel going in through the inlet line, but most of it is returning back to the through the spill line in to the tank case of by opening the valve completely we increase the flow rate coming in to nozzle, but decrease the flow rate coming out in the form of a spray. Little counter intuitive, but it is a very elegant design to get, what to get ratio of highest to lowest flow rates by all most a factor of 100 a factor of 10 is not to difficult to achieve in a design like this.

If I take the situation where the value is completely closed, it this just a regular simplex spray nozzle when the value is completely open you have a high flow rate coming in to the swirl chamber because of that you have a high inertia associated with a swirl. Actually as the valve is opened, the flow rate coming out of the swirl nozzle goes down, but since the angular momentum flux is higher than when the valve is completely closed the drop size is lower. We just write this down. If I take a reference situation where the valves position is completely closed inlet flow is let us say Q is spray flow is also equal to Q when the valve is partially open the inlet flow rate is greater than Q and the spray flow rate is less than Q and if d is the drop size this is less than d. As you d as you open the valve, the spray flow rate decreases and because you have putting in a higher angular momentum through the higher flow rate because the inlet flow rate is greater than Q and all of this inlet flow rate is coming in through tangential passages, but the flow going out is not taking back any of that angular momentum it is only taking out linear momentum.

You introduce the flow which some angular momentum, but what is coming out through the spill line is only in some sense linear momentum flux. All of the angular momentum flux that came in with the higher flow rate is now entirely with the spray alone that causes a lower film thickness and smaller drops. Very nice design to actually get many different design objectives achieved now like I said a factor of ten ratio between the highest and the lowest flow rate is quite possible not difficult at all.

Now what I mean, nothing in life comes for free the reason over head in that let us say if Q is my completely co closed condition flow rate and if I take the fully open condition. Let us just say, I have the inlet flow rate is some is now greater than Q and this spray flow rate is a 10th of q. This is assuming a turn down ratio on the order of 10 turn down ratio is defined as the highest flow rate possible in that nozzle divided by divided by the lowest flow rate. If when I have a factor of ten lower flow rate coming through there this inlet flow rate is let us say is typically about 3 times is a factor of 3 higher.

So, I am putting in 3 times the flow rate to get a 10th of the flow rate as appose to this if I had a simplex nozzle that was designed spray Q by 10 at a with a supply pressure of 7 bar that would use much lower energy. Essentially the amount of energy that I am in putting now at this fully open condition is 3 Q flow rate at a supply pressure of 7 bars that energy is clearly greater than putting in Q by 10 flow rate at a supply pressure of 7 bars. It is like the pumping power required is much higher in this case, but then in return for that you gain the flexibility of being able to control what the spray flow rate is on the fly without leading to do enacting to the pump and the pumping system by opening and closing a valve we can control the through put coming out again just to sort of complete this discussion since the angular momentum flux is higher in the fully open condition the cone angle is now bigger because you have a higher swirl velocity per unit flow rate the cone that is that comes out of the liquids spray nozzle is now going to be of a wider angle.

Typically, this spray angle increases as you go through this process of opening the control valve. These are all designs where our intention is to create as you see axis symmetric sprays all of these designs does far our only intended to create sprays which have a general axis over about which you expect this spray to be symmetric.

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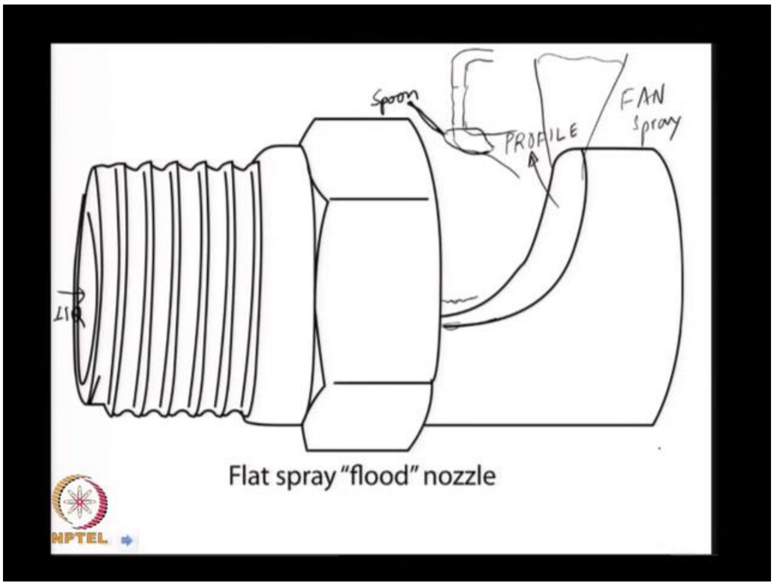

Now, there may be many applications where I do not want a symmetric spray. I want something that is more like a flat spray. Typically if I am in the business of washing the sides of a building let us say I do not want an axis symmetric spray as much as I would like a fan spray. What I want is a flat spray that I can use to just clean dirt on the side of the wall. This is one such design, now the simplest way to imagine this is that again your liquid coming in on one side the liquid goes through comes out in the form of a jet here and this is basically a profile to spread this jet coming out on this side in to a film

The simplest instance that you can imagine is let us say I take a faucet water jet coming down and I hold a spoon regular hold kitchen spoon and I allow. So, as this liquid jet falls on the spoon you can easily see how it is spreads out in to a fan and the fan breaks up just like the conical you essentially create a high speed fluttering fan of liquid sheet. It is essentially liquid sheet that is fluttering and this fluttering liquid sheet is going to breakup further into drops that are the design for obvious flat spray. So called flood nozzle, it is called a flood nozzle because it is one of the nozzle that gives you a very high flow rate with reasonably good drop size.

Reasonably good is the few 100 microns very achievable, you know design like this and the basic principle is exactly the same as water falling on top of a kitchen or on top of a spoon in a kitchen faucet and what you create is a spray that sort of like a fan the next design is also intended to create a flat spray, except it is slightly different then the flood nozzle design the outside looks something like this. I am going to try and see if I can draw a cut section through here.

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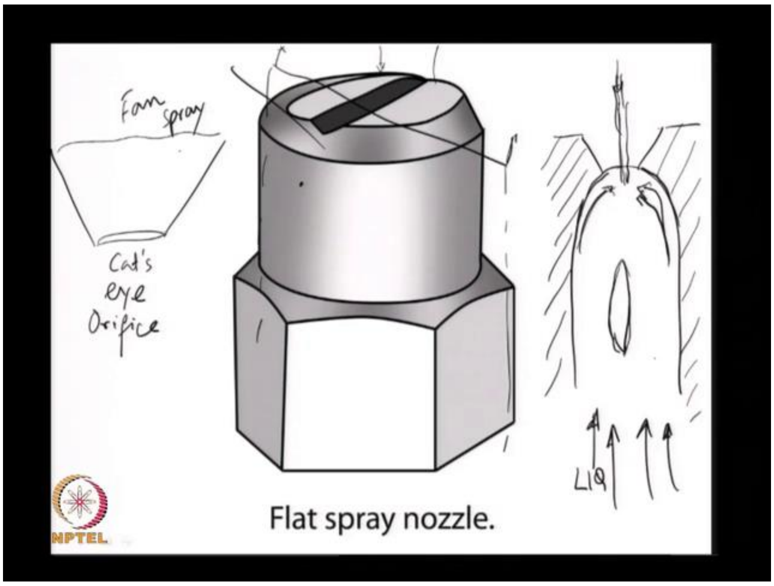

When I take a cut section through this section, here this is what it looks like. What you essentially have happening here is that the liquid goes through this central part and is make to converge at this section somewhere on the inside over here. If you will imagine the liquid sort of converging from 2 sides and on top, here if you look at this view from top that is essentially like an eye of a cat. This view is going to create an orifice that looks sort of like the eye of a cat it is oriented in and out of this of the plane of this board.

These two liquid jets, if you will converging on near the cat’s eye, orifice essentially causes this liquid to be spread into thin film and that thin film is now going to breakup and create a fan spray in this direction. In the other plane if this is my cat’s eye, end up creating a fans spray, most pressure washes that you see, you know that I used that use high pressure water for cleaning is a design like this. Anywhere that you require flat fan like spray with reasonable reasonably lower drop size, you do not want something that is completely atomize because the intention of these application is to actually have drops impact in the sub strain and cleaning dirt or cleaning grime, I do not want to create a missed that just diffuses in to the air.

I in fact, in an application like this; I do not want very good atomization. I just want drops to be distributed in to a fan where the drops themselves a large enough to ballistically carry their momentum all the wear to the sub strain. Some of these designs are intended to show you that good spray quality does not always mean extremely fine atomized spray. A classic example is a fire fighter, when a fire fighter uses a fire holes nozzle and shoots a cylindrical jet of liquid, let us say toward the second floor of a building, you do not want any you do not. In fact, want any atomization for all practical purposes it is your pressure jet, but I want the liquid to remain in tag and be carried all the way in to the target which could be on a second floor now this requires a certain kind of nozzle design that keeps it from getting atomized.

Typically, you will see fire holes nozzles are extremely stream line to prevent the introduction of any kind of disturbance to the cylindrical liquid jet and you create even at a relatively higher Reynolds number of fairly laminar looking jet. The surface is dividing of many perturbations and that is the starting point for this jet to remain in tag all the way to the sub all the way to your target in the process. If this jet were to break down and give you atomized quality jet. If you create drops you are more likely to not reach the target sub strain because these drops the same volume of liquid distributed in to a collection of drops is going to have a higher drag force on it which is going to prevent it from reaching the target.

These next few examples are intended to show you that there are many in some instances competing design interests that is achieved through these designs. This is again another instance of a non axis symmetric geometry where you want some atomization because you want the liquid to be distributed, but you do not want a extremely fine spray you do not want an extremely fine spray, let us come to this in a little bit. I want to first talk about typical air mixing atomizers.

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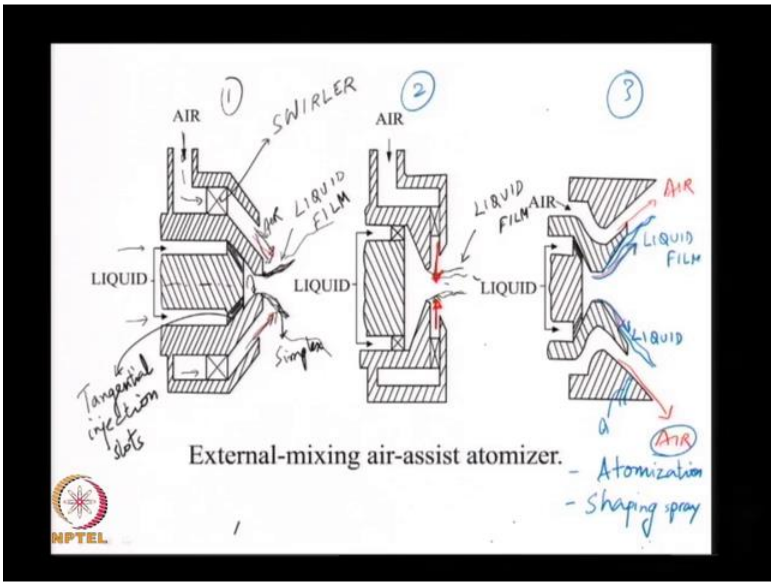

Up and till now, the source of energy remember we said that there are two things that this spray nozzle does; one it brings the liquid in contact with the source of energy that is essentially the objective of a spray nozzle.

The source of energy in all of the previous designs was the liquid inertia itself. The liquid moving fast in a stagnate environment of air, what is the source of energy that we are now going to look at some designs where air in some compressed form is used as a source of energy. We will start to look at the first design where if you will imagine liquid entering through this annular gaps and coming out. This part here, there are tangential injectors injection slots.

This part here is just like a simplex nozzle. I have liquid be injected through a pair or sum number of tangential slots and these tangential cause slots cause a little swirling action in this region. I have some sort of a spillover of this liquid sheet on the outside we have air coming in again remember; this is sort of an axis symmetric design. This air is also being spread in through here and this indicates a swirler. Typically a swirler is used to decrease axial momentum flux and I mean you do not know want to dissipate momentum you do not want to. Essentially it is there to decrease the axial momentum flux and increase the swirl momentum flux.

This air swirler causes the air coming out of these passages to take on a swirling velocity field and is now allowed to come directly impact this spilling film. So, if you will this is a liquid film this spilling this liquid film that is spilling over from this point here is impacted by this high speed air this impacting by high speeder is primarily responsible for atomization. So, it is typically a design like this will operate at the liquid supply pressures on the order of less than fifty one tenth of a bar. So, it is very low liquid supply pressures the liquid supply pressure is only intended to sort of push the liquid through it is not a source of energy for the atomization itself the atomization is entirely being control by the air stream.

And this is the region where the air coming out of this swirler the swirling air and the liquid film that is spilling over from the tip come in contact and. So, this is where you start to form a spray here this is one design of what is called an external mix air assist atomizer the second is where it is sort of similar except the air pass air is now more directly injected directly on to the liquid film itself. So, if this is the liquid film, it is going to be spilling over the air coming out is more directly impact in the liquid sheet its give you different kind of a, a spray now as you can probably imagine this is going to give you a much more narrow spray than in the previous instants where i have swirling air that is coming in its some angle like that the third design is where the air and the liquid film.

This is the air part and this is the liquid film that is now spilling over the relationship between the air and the liquid film is much more congenial there they co exists for a little while and it is only by the sharing action that the atomization takes place. So, the objective of a design like this is also. So, the air here is serving 2 purposes unlike the previous 2 instances it is serving for it is serving the purpose of atomization, but it is also shaping the spray we will see what this means in just a moment because you have this the air outside by controlling this angle I can control the spray angle itself the angle over which all the drops are going to be distributed.

This gives me an independent control parameter in this in these 2 designs. It is hard to do that in the first in the first second in the first and the second design it is hard to control the spray angle using the air usually there is another source of air that may be required. These are all configurations called air assist atomizer and specifically there called external mixing air assist atomizer because you have a simplex nozzle and outside this simplex nozzle you created an air passage that would cause further atomization and you are now using the simplex nozzle only to introduce fluid into a certain geographical region in to a certain spatial region.

In all these in the in these designs that use air like we said air is the source of the atomization energy and most specifically we will see later on that it is the relative velocity between the air and the liquid that controls the atomization quality. So, I would rather not have a high speed liquid flow I want to slow it down as much as possible I have, but increase the air velocity to where I am able to achieve the required atomization quality only problem with making a liquid flow rate the liquid flow rate is also independently control by the liquid velocity.

I cannot independently vary the liquid velocity without changing the liquid flow rate in this kind of a design. For a given flow rate i can choose an air velocity and therefore, an air flow rate that is sufficient to achieve a certain level of atomization. I first fix the liquid flow rate and based on that we choose the air flow rate that is required to completely atomize this fluid.

Now, in all the 3 previous designs that we saw where you look at a typical simplex nozzle or even a flood fans spray flood nozzle you are injecting in to stationery air and the spray angle as well as the drop size or fluid mechanically controlled by the inertia in the liquid itself. The level the number of the design parameters that you need to control; these 2 qualities are provided by the tangential offset.

This you know, how far away from the central line is the tangential orifice that is going to in some sense control the swirl momentum and the second is the size and number of those holes those are usually the 2 parameters that we can control to effect the flow rate and this spray quality independently.

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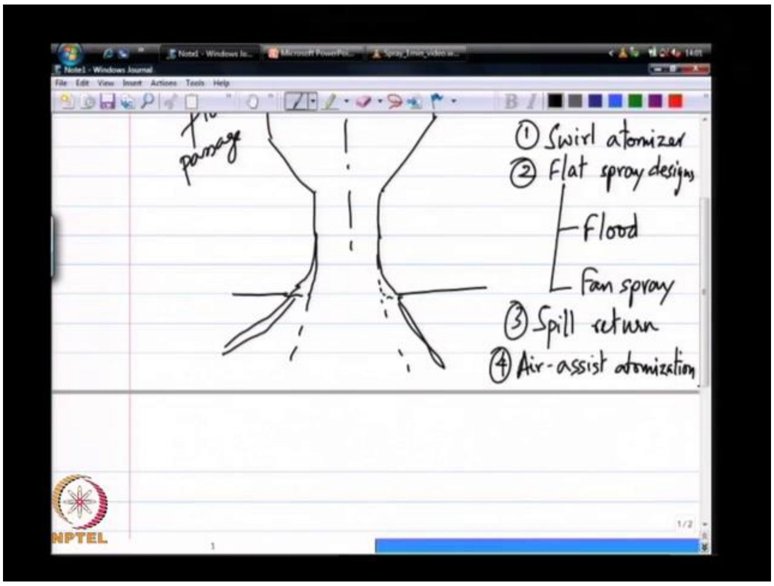

Now, as far as this spray angle is concerned there some interesting ways of being able to control the spray angle one of the simplest ways is where let us say I take a swirl nozzle that is got a set of tangential holes just like that I show this hole to show that it is a tangential hole. That creates a certain swirl action inside the spray nozzle and by shaping this exit passage appropriately I can control the angle over which the liquid film will depart. This verses if the spray was if the passages only sort of like that then I have get a spray that is slightly narrow over in this spray angle. By shaping the exit geometry of the simplex spray nozzle one can control the actual spray angle.

Quickly just to recap the different designs that we looked at today we looked at the swirl atomizer in some more detail and looked at a couple of different flat spray nozzle designs in terms of the flood nozzle, and the fans spray nozzle. We also looked at spill return. And then finally we started to look at air assist atomization.

We will continue this discussion in the class.