Design of Farm Machinery

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Lecture 45 : Droplet size determination

Hi everyone, this is Professor H. Raheman. I welcome you all to this SWAYAM NPTEL course on Design of Farm Machinery. Today is lecture 45, where I will discuss droplet size distribution or droplet size determination. The concepts which will be covered are droplet size, their measurement and size distribution, then how to find out mean, median, and percentile droplet diameters. Droplet size determination and its distribution are part of performance evaluation of a sprayer.

So, when liquid is atomized, droplets of various sizes are formed. The spray droplets are classified by their diameter. Typically, these diameters are measured in microns or micrometers – 10^{-6} meters. The performance and effectiveness of an atomizer depend on droplet size and size distribution. So, this is an important parameter while evaluating the performance of a sprayer.

So, there are different ways to represent droplet size distribution. One important plot is a histogram, where we try to plot the number of droplets in each size class and then join the midpoints. So, that will give you a curve represented by a function called a distribution function. Basically, you have to draw a bar graph, then join the midpoints, and from those midpoints, you will get a curve if you connect them. So, that represents the maxima of each size class,

So, the curve is represented by a function, which is commonly called a distribution function. If the distribution function is known explicitly, then only a few parameters, like mean diameter and standard deviation, are needed to define a given distribution. The minimum and maximum sizes are additional parameters; we can mention them, or we may not mention them. Then, another more convenient method of representing a particle size distribution is to plot the cumulative fraction of the total number smaller than a given size against that given size. So, that plot is called a cumulative frequency plot.

So, basically, you have to plot the droplet size on the x-axis and cumulative percentage on the y-axis, and then, wherever you need to find out - suppose you want to find out the median, then at 50 per cent cumulative percentage, you draw a horizontal line; wherever it touches the curve, there you draw a vertical line. So, this diameter refers to your median diameter - that means it will divide the spray into two halves. The plot could be on a probability paper - a probability plot - or it could be directly on a graph sheet, and it could be a cumulative number or it could be cumulative volume. So, both can be drawn. So, the x-axis you can say now you have taken cumulative percentage; y-axis droplet diameter. So, at 50 per cent, which will give you the median diameter, you just draw a vertical line. So, if this is representing volume, then this diameter will be the volume median diameter. Now, this line is showing the number - cumulative number percentage. So, if I show this point, it refers to the diameter - number median diameter. So, 50 per cent - wherever it touches - that point belongs to the - that point represents the droplet diameter size, which will divide the spray into two halves, either by number or by volume. Then, the question arises: how to draw this graph, which I have shown?

To draw this graph, you need to know the droplet diameters of the spray which you carried out. So, to determine the droplet diameter, you have several methods by which you can measure the droplet diameter. So, depending on the precision we required and the available equipment we have to select any one of them. So, the number one is laser diffraction, this is a technique which uses a laser to illuminate the droplets. The scattered light - basically the scattered light pattern is analyzed to determine the droplet size based on the angle of scattering. This is the concept.

Now, the second method is your image analysis. In image analysis, images of the spray are captured using a high speed camera, then using the image analysis software the diameter of droplets in the images are measured. This method is more effective for visualizing droplet size distribution.

Then microscopy method, if the droplets are of larger size, a microscope can be used to examine the sample of spray and hence the diameter is measured using the scale provided in the microscope. The sample has to be made. That means, you have to carry out spraying on a glass surface coated with vaseline, then carry out the spraying, spraying the desired liquid and this liquid has to be mixed with nigrosine so that when you take a photograph, a black spot will come. So, after spraying on the glass surface which is smeared with grease or vaseline then you again spray with paraffin. So that the paraffin being lighter it will enter into those droplets and it will not allow the droplets to shrink. So, after that you take the glass plate and put it in the microscope and then find out what will with the corresponding diameter of different droplets.

The other method is a micrometer or caliper. So, this is only possible for larger droplets, and a micrometer or caliper can be used to measure a few selected droplets directly. So, for distribution, this is not a good method to follow.

Then comes the laser spray measurement system. These are specialized systems used to measure droplet size and velocity in real time using laser technology. So, it will provide more precise and immediate results.

Then the last one is the Coulter counter. This device measures the change in electrical resistance as droplets pass through a small aperture, allowing for accurate size determination. So, these are some precise measurement techniques, but the most commonly used technique is your microscope or image analysis using the image analyzer. That means you have to carry out spraying, then you take the image, and with the help of the software, you can find out the distribution - the number of droplets in each class and then do some calculations to find out the mean diameter or median diameter. For carrying out droplet size determination in the field, we have to first randomly select the plants in the field and then put the water-sensitive papers at different positions. Positions mean at the top, at the top under, then middle, middle under, then bottom, bottom under, and ground. So, at different orientations, we have to place them, and at different plants. Those plants are to be selected randomly - and based on this, we have to take images. We have to carry out image analysis to find out the parameters like VMD (volume median diameter), number median diameter, uniformity coefficient, droplet density, and volume contributed by drops of all sizes. The thing is, when spraying is carried out after putting the water-sensitive papers, you can see the paper was yellow initially, but now it has turned to a purple color. So, the stains are visible. So, after carrying out spraying, these water-sensitive papers are to be taken, and then an image has to be taken. From the images, using the Fiji software, it will convert the image of the water-sensitive paper to binary images, just like this one. Then from the binary images, the software will give you the droplet diameter in micrometer in an Excel file. That means, the spots which the software will detect that will have different varieties of diameter - droplet diameter. So, it will indicate for each diameter how many times it is coming. So, that way we will be counting this number. So, suppose 52.82 we have to see that from 1 to 22. That means, 22 numbers of droplets are having diameter 52.82, in the same spot we have 60.21. So, it will have another 8 or 9 droplets of diameter 60.21. So, that way you have to first combine and find out what are the diameters you are getting, what are the corresponding numbers you are getting, then from there we can utilize this equation to find out what is the actual diameter. Though I have said actual diameter, I basically have calculated the actual diameter utilizing using this equation which is given by Sies et al., 2017. $D_a = 0.95 \times D_s^{0.91}$and D_s is what?

What is the image spot diameter? So, $D_s = \sqrt{\frac{A}{\pi}}$. That means, we have assumed that it is a sphere and area of that sphere will be $4\pi r^2$. Since you are calculating diameter. So, the $2\times r$ that will give you D_s. So, that is why I have written $\sqrt{\frac{A}{\pi}}$.. So, once we know the area then divided by π that will give you the actual diameter which is computed here.

Then you group the data like the diameter, then the numbers in each diameter, then you try to find out the percentage, percentage of the total whatever you observed, then percentage by number, then you try to find out volume, volume $\frac{\pi D^3}{6}$, then we try to find out cumulative volume percentage, then cumulative volume percentage, then we try to plot it on a graph sheet. The graph sheet what exactly we do is in the x axis we plot the cumulative percentage and the y axis we plot the NMD or VMD whatever. So, both are - if you are plotting both then you have to take NMD and VMD. Then, when we plot it then we will get. So, suppose this is your NMD - this blue curve is your NMD. So, that means, if you are interested to find out the volume median diameter sorry number median diameter then at 50 per cent you just draw a vertical.

So, it touches here and then draw a horizontal. So, that becomes your NMD. Similarly for volume, draw a line at 50 per cent wherever it touches the curve then there you draw a horizontal line. So, wherever it touches the y axis that becomes your VMD. Either you can draw a vertical line or you can best fit the curve with an equation and then from that equation you can put - that equation is nothing, but the NMD versus cumulative percentage and VMD versus cumulative percentage. So, now, if you put cumulative percentage as 0.5, then whatever value you are getting for y that becomes your NMD or VMD, depending on which equations you have used. So, either you draw a vertical line or you draw a or you develop the best fit equation and then from there you can calculate. So, this is the exercise which you did. You can do for the numbers, you can do for the volumes. So, both can be possible and then the steps are : for calculating the volume what you have to do is you have to assume the diameter and then assuming the droplet to be a sphere. So, utilizing the formula that is $\frac{\pi D^3}{6}$ and knowing the number of droplets, we can find out the total volume in each size. Then you take the summation of those, which becomes the total volume that is sprayed, and for finding out the percentage in each class. So, what we do is take the volume obtained in each size, divide it by the total, and multiply by 100. That will give you the percentage in each size - the percentage corresponding to each size. Then we also find out the cumulative percentage. So, you just go on adding.

So, that becomes the cumulative percentage, and then you have to go for plotting it. So, I will take up an exercise. So, what I have shown is whatever I just explained. Then I will take up an exercise where you can see how to find out the VMD and NMD from a given set of data obtained from software after image analysis. Then, once you find out VMD and NMD, the other two parameters, as I said, the uniformity coefficient, can be found out, which is nothing but the ratio of VMD to NMD. So, what does it exactly represent? The uniformity coefficient represents whether the droplet size is more uniform or not. So, if it is uniform, the uniformity coefficient becomes near to unity, meaning they are more uniformly distributed. Then the other parameter is droplet density. How do you obtain this? This is obtained by counting the number of drops in one square centimeter area of water-sensitive paper, along with the number of droplets of each size in that one square centimeter, because there could be different sizes of droplets. So, we have to find out the droplets of each size in that one square centimeter area and the spotted diameter of those droplets.

The area covered by droplets will be millimeter square per centimeter square, which is calculated by using this equation: $\frac{\pi D^2}{4}$ number of droplets. That will give you the area covered by droplets. With the number of droplets in a 1 square centimeter area and the actual droplet diameter, the volume of spray distribution - deposition contributed by each size can be found out. Because the diameter is known, $\frac{\pi D^3}{6} \times$ the number of droplets will give the volume. A similar method is to be used for the calculation of volume contributed by the droplets of other sizes, and then you have to take the sum of those volumes. That will give you the total volume of liquid which is sprayed. Then, in a 1 centimeter area of water-sensitive paper, that will be the volume of spray deposition. And you know the area. So, that will give you these many droplets per centimeter square.

So, there are other parameters which are associated with the spray distribution, like mean diameter, median diameter, and percentile diameter. So, mean diameter refers to - mean diameter could be arithmetic mean, it could be surface mean, it could be volumetric mean, or it could be Sauter mean. So, we represent as D_{10}, which represents arithmetic mean; D_{20} means it represents surface mean; D_{30} means it is volumetric mean; and D_{32} means it is Sauter mean diameter. These are mean diameters. Then, median diameters - median means it will divide the spray matter into two halves. The diameter which is represented will divide the spray into two halves. So, median means half. So, VMD we can call volume median diameter. If I write $D_{V\ 0.5}$, that means this will divide the spray into two halves. Similarly, number median diameter. So, $D_{N\ 0.5}$. Then we have percentile diameters like D_V

$_{0.9}$, $D_{V\,0.1}$, $D_{N\,0.9}$. D_N means number, D_V means volume. So, these are the different ways or different parameters which you can calculate.

So, for calculating the mean droplet diameters, this is the generalized equation which has to be used: $D_{pq}^{p-q} = [\frac{\sum_{i=1}^{n} N_i D_i^p}{\sum_{i=1}^{n} N_i D_i^q}]^{1/(p-q)}$. Here, p and q could be 1, 2, 3, or 4, and p is always greater than q. N_i means the number of droplets in each size. And Di is the corresponding diameter. That means, if i is 1, then what is the number of droplets in size class 1 and what is the representative diameter in that size class 1. Number, diameter - that way you have to calculate, and n is the total number of size classes. Now, when p is equal to 1 and q is equal to 0, this becomes your arithmetic mean. If p is equal to 2 and q is equal to 0, it becomes surface mean. If p is equal to 3 and q is equal to 0, it becomes volume mean. If p is equal to 3 and q is equal to 2, then it becomes Sauter mean. That means, the volume-to-surface area ratio of the spray - how much area it covers - is represented by the Sauter mean diameter. So, these are detailed explanations of how to calculate arithmetic mean diameter, surface mean diameter, and volume mean diameter. These are mean diameters.

Now, for calculating median diameters - volume median diameter or number median diameter. So, volume median diameter refers to the midpoint droplet size, where half of the volume is composed of droplets smaller and half of the volume is composed of droplets larger than the median diameter. So, it is calculated from the plot of actual droplet size and the cumulative portion that is important. Cumulative percentage plotting is important; otherwise, you cannot find out the volume median diameter or the number median diameter.

So, droplet size at which the cumulative percentage volume of droplets reaches 50 per cent is the VMD of spray droplets. So, suppose I get a value say 100 micrometer. So, what does it indicate? That means, the spray which is carried out, it has droplets 50 per cent droplets lesser than this diameter and 50 per cent droplets larger than the diameter.

When I said volumetric mean diameter is 100 micrometer that means, volume of that into number of droplets that will give the total volume of this discharge or the volume which is sprayed. Similarly, when I say surface mean diameter. So, we find out the area of each droplet then multiply with the number of droplets that will give you the total area covered by the spray which is carried out. Similar to volume median diameter there will be number median diameter it will divide the spray by numbers - divide the spray into 2 halves by numbers. So, again you have to calculate the numbers in each size class then we have to plot the actual droplet diameter versus the cumulative percentage. And then either you as I discussed before either you fit a best fit equation you develop or you draw a vertical line at 50 per cent cumulative percentage, then wherever it touches the graph there you draw a horizontal line to touch the y axis and that will give you the NMD value.

In addition to this volume median diameter there will be percentile diameters $D_{v\ 0.1}$, $D_{v\ 0.1}$ it indicates that 10 per cent of the volume of spray is having droplets smaller than this value and may contain a major part of the fine driftable droplets. So, the remaining 90 per cent of the total volume is having droplets larger than this diameter. This value is useful for understanding the fine end of the particle size distribution. So, what are the finest droplet we got that it will be indicated by this value.

Then $D_{v\ 0.9}$, this value indicates that 90 per cent of the volume of spray is having droplet smaller than this diameter and 10 per cent is larger than this diameter. So, it is often used to characterize the coarse end of the particle size distribution. So, one is fine end the other one is coarse end. Then $D_{N\ 0.1}$ this is the diameter below which 10 per cent of the particles fall. This means that 90 per cent of the particle in the sample are larger than this diameter.

Then $D_{N\ 0.9}$. The $D_{N\ 0.9}$ is the diameter where 90 per cent of the particles are smaller than this diameter and the remaining 10 perc ent of the particles are larger. So, this $D_{N\ 0.9}$ is useful when the distribution of particle size is being analyzed in terms of count of particles or any applications where the number of particles is more relevant than their volume. So, this measure helps in understanding the distribution of smaller particles in a sample providing insight into the finer particles that dominate the count even if they contribute less to the overall volume.

So, I will take up a problem and then whatever we discussed that will be - how you are going to find out those parameters that we will see. So, the data what you got is it is a class size in micron and into each class size what are the numbers we got that value is given. So, this is the output from the image analysis - the image analysis software whatever you got these are the values which we will get. Then after that what we have to do to find out the volume median, the arithmetic mean diameter etcetera etcetera.

So, in the first column this is the size class. So, number in each size class is given in the second column. Then midpoint of the size class we have calculated. Then a number N D number × diameter. So, that is calculated that means, N_iD_i, then NiD_i^2 square. So, assuming this to be sphere so, $4\pi r^2$. So, NiD_i^2 then assuming to be sphere you calculate the volume, volume is $\frac{\pi D^3}{6}$. So, $\frac{\pi D^3}{6}$ ×the number, here 450 that will give you this value.

So, now likewise you calculate for each class then you take the sum. So, that gives you the total. Now, when you try to find out the arithmetic mean diameter is nothing, but $\sum N_i D_i/N$. So, $\sum N_i D_i/N$, N here 1041 that will give you this value. Now, $\sum N_i D_i^2/\sum N_i$, so, that will give you this divided by 1041 that will give you the surface mean diameter and $\sum N_i D_i^3$, this value divided by this number $\sum N_i$, that will give you this value.

And the last one is Sauter mean diameter which is nothing, but $\sum N_i D_i^3 / \sum N_i D_i^2$. So, that way this divided by this that will be the this one, the last column and the last but one column. So, that will give you the Sauter mean diameter. So, the Sauter mean diameter basically represents two things : how much - what is the volume which is spread and corresponding to that volume what is the area which is covered. So, that is an important parameter in that way, but rest of the values they only represent either volume or either number or either area which is covered.

Now, coming to VMD. So, the same data which we discussed just now for arithmetic mean, the same data we have taken to calculate the volume median diameter or the number median diameter. So, what we did is we first try to calculate the - for the number median diameter we tried to calculate the number percentage that means, sum of these will be this much. 450/1041 that will give you the percentage in each class. Similarly, 286/1041 that will give you the number percentage in second row. Similarly, in the third row, 154/1041, that's how you calculate. So, the total will be your 100 per cent. Now, cumulative percentage by number means you just keep adding: the first one is 43.23, then you add this 2, which becomes this one or this 3. So, likewise, you have to do it. Then, for volume in each class, first, we try to calculate the volume of each particle, then multiply by the number, which will give you the volume in each size class. So, that exercise we have to do first, then we get the total here. Then, this divided by the total becomes this percentage, the volume percentage in this class. So, this divided by the total will give you 12.07. So, likewise, you have to do it. Then, the cumulative percent will be the summation: the first one is the same, the second one will be the summation of these 2, the third one will be the summation of these 3, the fourth one will be the summation of these 4, and so on.

So, this has to be plotted in an x-y plot. What will be on the x-axis? Cumulative percentage (this column and this column), and on the y-axis, it will be diameter. So, there are two graphs which will be obtained: one is the NMD, which is the orange one, and the blue one is the VMD. Now, to find out the VMD and NMD, you have to draw a vertical line at 50 per cent. So, if exact, it comes to 35.56 micrometers - NMD, number median diameter. Now, here also, it gives 95.5 microns.

So, this is the simplest way if you want to make it generalized; you best fit this curve by an equation. So, this equation represents the droplet diameter in terms of cumulative percentage. So, wherever you want, you can put that cumulative percentage value x and then find out the corresponding y. So, for finding out the volume median or number median, you take x as 0.5, then you can calculate the droplet diameter. So, this way, you have to find out the droplet diameter, and then you can plot with the help of a histogram the frequency distribution curve.

These are some of the references, and the conclusion is we discussed the determination of droplet size, how they are distributed, and how to find out the mean and median diameter.

Thank you.