Designing and Optimizing Gas/Liquid Reactions for:

Environmental processes
Chemical Reactions
Heat Transfer

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There are countless applications where spray nozzles are employed to create liquid surface area to provide interaction between the liquid and surrounding gas. That interaction can support chemical reactions, transfer heat, induce a phase change and generally equalize conditions between the liquid and gas.

Consider a droplet floating in space. What could be happening?

- Any difference in temperature will equalize as heat flows from the warmer to colder medium.
- Liquid will evaporate or condense depending on the surrounding humidity level.
- Gasses will dissolve into the liquid or diffuse out depending on the relative concentrations.
- If chemicals are present that would tend to react, they will react as they encounter each other through the boundary layer.

The question is, how can you create a situation where you provide the optimal conditions to make your desired outcome happen?

It's a matter of surface area

When a nozzle sprays a liquid, it forms a web or ligaments (strings of liquid) as it is extruded through the orifice. The interaction of air resistance and surface tension breaks these into individual droplets which are capable of holding themselves together at their velocity. Very large droplets will split further if the surrounding air resistance overcomes the surface tension. (Watching a Lava Lamp operating can teach a great deal about droplet formation.)

Chart 1: Volume and surface area for various droplet diameters

Droplet diam. microns (µm)	Surface area of 1 droplet sq. mm's	Volume of 1 droplet cu. mm's	Total droplet count per liter	Total surface area per liter sq. meters
2000	12.6	4.19	239,000	3.0
1000	3.14	0.524	1,910,000	6.0
500	0.785	0.0655	15,300,000	12.0
250	0.196	0.00819	122,000,000	24.0
125	0.0491	0.00102	977,000,000	48.0
60	0.0113	0.000113	8,840,000,000	100.
30	0.00283	0.0000141	70,700,000,000	200.
15	0.000707	0.00000177	565,000,000,000	400.

When broken into droplets, the liquid surface area increases dramatically. For purposes of analysis, we assume all droplets are spherical. Chart 1 shows the relationship of droplet size, surface area and droplet count. (Droplet sizes are listed in microns (µm). 1000 µm = 1 mm.)

For a given volume of liquid, cutting the droplet size in half will produce eight times as many droplets and double the total surface area. With more surface area, there is more room for everything to happen. Creating a controlled droplet size is the key to making everything work the way you want it to.

Typical gas/liquid reactions

Here are some examples of common applications and a sketch of the important considerations to optimize the process:

Evaporative Cooling—When the objective is to cool a hot gas, spraying a liquid into the gas stream uses the sensible heat of the gas to warm the droplets until they boil off or evaporate. This lowers the gas temperature as the liquid absorbs the heat energy during the phase change. The vapor then continues to absorb energy as it warms to the surrounding temperature. Since these processes take place in a confined space, the droplet size has to be small enough to make sure all the liquid evaporates before it has an opportunity to hit a wall surface and wet the interior. Knowing the largest sized droplets and their trajectory becomes paramount since these travel the greatest distance. The main tradeoff is the energy cost of creating the smallest possible droplets.

Liquid Cooling—When the object is to cool a hot liquid, spraying the liquid into cooler surrounding air transfers heat out of the liquid. Some of the liquid typically evaporates in the process which helps with the cooling. Small droplets cool faster, but also evaporate more quickly or can be carried away by air movement. The tradeoff is creating droplets small enough to shed the heat but large enough to minimize liquid loss.

Chemical Reactions—When a reaction between a chemical in the gas and another chemical in the liquid is the desired outcome, there are additional tradeoffs to consider, so let's look at those individually.

Chemical Injection—Here the desired effect is to have the liquid atomized, turn into a gas and react gas to gas. The liquid simply performs as a carrier to assist in handling and distribution. This is a case of producing droplets small enough to evaporate in the required amount of time and space much like evaporative cooling. In some cases where you need to control the reaction rate such as a powerful exothermic reaction, keeping the droplets large enough to slow the evaporation can be an important means of control to avoid dangerous heat concentrations.

Two Phase Reaction—Here the reaction occurs between the gas and liquid without the desire to evaporate the liquid. This could involve a chemical that has to be dissolved in a liquid to dissociate into ions for the reaction to occur. Once the liquid is evaporated, the reaction stops. Since surface area controls the reaction rate, more is normally better but premature evaporation is not desirable. In these cases the reaction has to happen in a big enough vessel to allow large droplets for minimal evaporation but enough residence time for a complete reaction.

Gas Separation—Here a liquid is injected into a gas stream with the purpose of absorbing a specific component of the stream. If the gas is easy to absorb it may not require very small droplets and they can simply be collected in the bottom of the vessel. When smaller droplets are necessary, a mist eliminator can help remove them from the gas stream. The key is to use as large a droplet as practical and still achieve the desired removal rate.

Humidification/Dehumidification—These are two sides of the same coin. Humidification requires atomizing liquid finely enough to achieve complete evaporation before hitting a critical surface. Depending on the ambient humidity and temperature, the same volume of liquid could require drastically different droplet sizes to make the process work. On the other hand, if the temperature of the liquid injected is below the dew point of the surrounding gas, the vapor will condense on the droplets and dehumidify the gas. The important point is to collect the water before it gets too warm and begins to evaporate itself.

Spray Drying—This is one of the many methods of dewatering a product by spraying a solution or suspension into a heated vessel so the liquid evaporates in mid air allowing a dry powder to reach the bottom. This is a very sensitive process where the droplet size and drying rates are carefully controlled to create an end product with a specific particle size and density. There are specialized nozzles designed for this application to generate a narrow droplet size distribution.

All of these reactions benefit from having a specific droplet size and resulting surface area to optimize the process in light of the tradeoffs. Learning to control the reaction in that way is a very valuable skill.

Controlling droplet size

Turning a volume of liquid into droplets requires energy. This can be pressure provided by gravity or a pump, or using a stream of compressed gas to pull the liquid apart. Either way, the amount of energy expended relates directly to the amount of surface area produced. Smaller droplets require more energy. (However in some cases you can generate smaller droplets using a more efficient atomizer without more energy. Spraying 10 liters of water through one large full cone hydraulic nozzle will produce much larger droplets than spraying the same total volume at the same pressure through a larger number of smaller nozzles. Smaller hydraulic nozzles are more efficient and produce smaller droplets with no increase in energy consumption.)

The liquid itself has a huge effect on spray performance. Elevated viscosity levels or surface tension make the job much harder or even impossible. If this is a factor, there is no point in working on the nozzles until this problem has been minimized.

There are many tradeoffs to consider when trying to achieve a specific droplet size. Most of the time people ask us how to generate finer droplets so here are some common suggestions balanced with the downside:

Use the existing nozzle or a smaller nozzle and run at higher pressure. This is probably the easiest answer, assuming you have the appropriate pump capacity. Running the same nozzle at 60 psi instead of 40 psi will increase the flow rate and reduce the droplet size. A double benefit when trying to increase available surface area. (See Chart 2.)

Take advantage of the efficiency of smaller nozzles and use a larger group. You will face more complex piping and increased clogging potential, but these can be overcome.

Use a nozzle design that gives intrinsically smaller droplets if this is still possible. A great idea since an equivalent capacity hollow cone gives smaller droplets than a full cone, assuming you don't need the full cone's spray distribution. (See Chart 3.)

When you've run out of ways to get smaller droplets from a hydraulic nozzle, the next step is to use an air atomizer. These can produce the finest mist, but compressed air is expensive. Increasing flow volume and reducing droplet size both require more air and higher pressures.

To create larger droplets, do the opposite of these.

Chart 2: Pressure vs. Droplet Size

Standard, 7 orifice cluster nozzle

Pressure Bar	Droplet Size µm, d32	Flow liters/min
1	398	20
2	264	28
6	191	49
10	172	63

Chart 3: Comparative Efficiency

Spraying 20 liters/min @ 3 bar
Standard, typical nozzle configurations

Spray Pattern	Droplet Size µm, d32
Full Cone	550
Flat Fan	470
Hollow Cone	420
Cluster (7 orifice)	240
Air Atomizer	120

Evaluating droplet information

If you need to know how a nozzle is performing to evaluate a process, you will probably have to depend on the nozzle manufacturers for droplet size information. Few companies outside the nozzle manufacturing community have the specialized equipment needed to get reliable measurements. There are several manufacturers who make droplet measuring devices each with different methods. Deciding which is best could be the topic for an entire conference and more than we can discuss here. Suffice it to say that you should know which of the two main techniques provides the basis for the data you are analyzing.

Spatial Distribution—Basically this technique takes a 'snapshot' of a region of the spray freezing the droplets in mid air. The computer measures the sizes and tabulates the data.

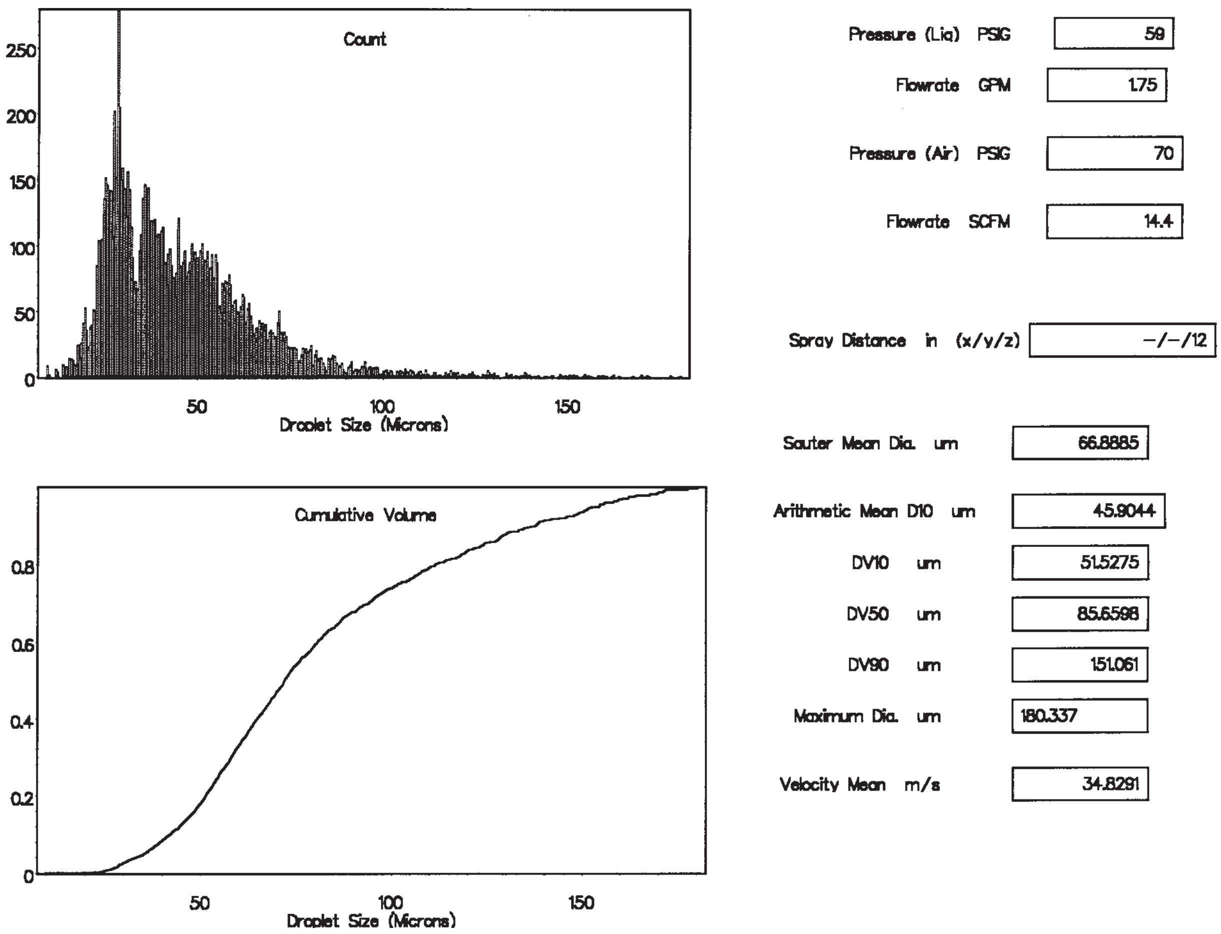
Temporal or Flux Distribution—Here the droplets pass a specific point and the device measures their diameter and velocity as they fly by. The computer tabulates the data and generates graphs.

If all droplets moved at the same velocity, these two methods would give identical results. However in reality, large droplets tend to sustain higher velocities since they are less subject to the drag of air resistance. A spatial measurement will not realize that the large droplets are moving faster than the small ones and that their count is in fact higher. Consequently, the spatial distribution techniques will report smaller droplet size averages than temporal.

In most cases, a temporal distribution would be preferred if available. If your main interest is simply seeing the largest and smallest droplet size across the range and not the specific counts for any given size, either will work.

Unfortunately, no nozzle generates only one size of droplets. They all create a range from smallest to largest, but some nozzles have a narrower spectrum than others. For certain applications, this can be a very critical point. Evaporative cooling applications are very sensitive to the largest droplet size, for example.

Normally you will find the droplet population shown as a graph with the droplet count on the vertical axis against the droplet size on the horizontal axis. The distribution forms a right skewed bell curve with a tail to the right. Frequently this is coupled with a second graph showing the accumulated volume. The horizontal axis is the same as the first graph, but the vertical axis is now the percentage of volume accumulated. The curve climbs to the right until it hits the 100% mark at the same point where the largest droplet is shown on the droplet count graph. Current droplet analysis software will also do the statistical calculations to generate the common averages and key points. Chart 4 (next page) gives a typical example.



Pressure (Liq) PSIG 59
Flowrate GPM 1.75
Pressure (Air) PSIG 70
Flowrate SCFM 14.4
Spray Distance in (x/y/z) –/–/12
Sauter Mean Dia. um 66.8885
Arithmetic Mean D10 um 45.9044
DV10 um 51.5275
DV50 um 85.6598
DV90 um 151.061
Maximum Dia. um 180.337
Velocity Mean m/s 34.8291

Chart 4: Output from an Aerometrics PDPA. The graphs give a detailed picture of the droplet distribution, while the program makes all the standard statistical calculations. This device uses the flux method of measurement.

This information can tell you a great deal about your specific nozzle and provide many tools for you to analyze the process as long as you understand what you are looking at.

Here are some strategic points to look for:

Nozzle operating conditions—Since these have a profound effect on the results, you need to know the operating pressure, point of measurement, distribution method, etc.

The statistical analysis tools can help if you understand what they signify:

Arithmetic Mean—The standard ‘average’ of the entire population. This is not a particularly useful measurement but it might be all you have to compare data from other manufacturers.

Sauter Mean—This is the critical number for calculating surface area. It represents the droplet that has the same volume to surface area ratio as the entire population of droplets. You can use this to calculate the amount of surface area produced for a volume of liquid, or find it on Chart 1.

DV10—The size at which the cumulative volume reaches 10% of the total. This can be of interest if you're concerned with droplets that could be carried away or will reach a mist eliminator.

DV50—Volume Median Diameter, or the droplet size at which the cumulative volume reaches 50% of the total. Half the volume is droplets smaller than this and the other half larger.

DV90—The size at which the cumulative volume reaches 90% of the total. Some people use this as the practical largest droplet size when doing evaporative cooling calculations. It can work but it is not the most conservative.

Maximum Diameter or DMAX—This is the largest droplet size found in the sample. This is the most reliable when doing critical evaporative cooling calculations since they take the longest to evaporate and travel the greatest distance risking contact with a surface.

You may find other values if you receive data from a variety of sources. Some are useful for arcane, specialized applications. If you need something specific, don't hesitate to ask.

There is one major caveat when dealing with droplet data: This is not an exact science. Droplet data can be influenced by the methods and equipment used, plus the skills of the operator. Experienced engineers know which part of the spray pattern is most likely to produce droplets of a specific size and can take the measurement there. ASTM has published **E799-92: Standard Practice for Determining Data Criteria and Processing for Liquid Drop Size Analysis** which is the method most companies use now. Beware of any that don't. Find out how old the information is. Most nozzle companies have been around for a long time and there may be data from the age of slide rules. Old measurement methods were crude and not the most reliable.

Ask for help

Any nozzle company worth working with will help you analyze your processes and use its collective experience to help you with your project or application. The more information you can provide related to the operating conditions and desired outcome, the better.