ULTRASONIC ATOMIZATION

Soft, Low-velocity Spray, Elimination of Overspray, Material Savings, and Precise Control

One feature that distinguishes pressureless, ultrasonic atomizing nozzles from most other spray nozzles is a soft, low-velocity spray, typically on the order of 3-5 inches per second. Other common atomization techniques, which use pressure in order to generate a spray, generally produce drops with velocities well over 100 times that generated by ultrasonic atomization. This velocity differential means that pressure sprays generate on the order of 10,000 as much kinetic energy as do ultrasonically atomized sprays. This striking contrast in spray energy has important, practical implications.

- In coating applications, the unpresssurized, low-velocity spray significantly reduces the amount of overspray since the drops tend to settle on the substrate, rather than bounce off it. This translates into substantial material savings and reduction in emissions into the environment.
- The spray can be controlled and shaped precisely by entraining the slow-moving spray in an ancillary air stream. Spray patterns from as small as 0.070 inches wide to as much as 1-2 feet wide can be generated using specialized types of spray-shaping equipment.

Ultra-low Flow Rate Capabilities

Since the ultrasonic atomization process does not rely on pressure, the amount of liquid atomized by a nozzle per unit time is primarily controlled by the liquid delivery system used in conjunction with a nozzle.

The flow rate range for ultrasonic nozzles is from as low as a few microliters per second to up to about 16 liters per hour.

Depending on the specific nozzle and the type of liquid delivery system employed (gear pump, syringe pump, pressurized reservoir, peristaltic pump, gravity feed, etc.), the technology is capable of providing a extraordinary variety of flow/spray possibilities.

Drop-size Range Selectivity

In general, the drops produced by ultrasonic atomization have a relatively narrow size distribution. Median drop sizes range from 18 to 68 microns, depending on the operating frequency of the specific type of nozzle. As an example, for a nozzle with a median drop size diameter of approximately 40 microns, 99.9% of the drops will fall in the 5 – 200 micron diameter range.

Ultrasonic Atomization

The phenomenon referred to as ultrasonic atomization has its roots in late 19th century acoustical physics, notably in the works of the ubiquitous Lord Kelvin.

Simply stated, when a liquid film is placed on a smooth surface that is set into vibrating motion such that the direction of vibration is perpendicular to the surface, the liquid absorbs some of the vibrational energy, which is transformed into standing waves. These waves, known as capillary waves, form a rectangular grid pattern in the liquid on the surface with regularly alternating crests and troughs extending in both directions.

When the amplitude of the underlying vibration is increased, the amplitude of the waves increases correspondingly; that is, the crest become taller and troughs deeper. A critical amplitude is ultimately reached at which the height of the capillary waves exceeds that require to maintain their stability. The result is that the waves collapse and tiny drops of liquid are ejected from the tops of the degenerating waves normal to the atomizing surface. A useful analogy that helps visualize this process comes from our everyday experience. Ocean waves coming into shore go through a transition from stability on the open water to instability as they approach shore. The instability is evident as the waves form foamy breakers.

The reason for instability in this type of wave is that as it approaches shore, the bottom of the wave contacts the ocean floor and is slowed down by frictional forces. The wave top, on the other hand, continues to move ahead unimpeded. The net result is that the wave topples over. In this process of breaking up, a spray of tiny drops is ejected from the wave surface. Although the mechanisms governing the creation of a spray from capillary and ocean waves differ, the results are similar.

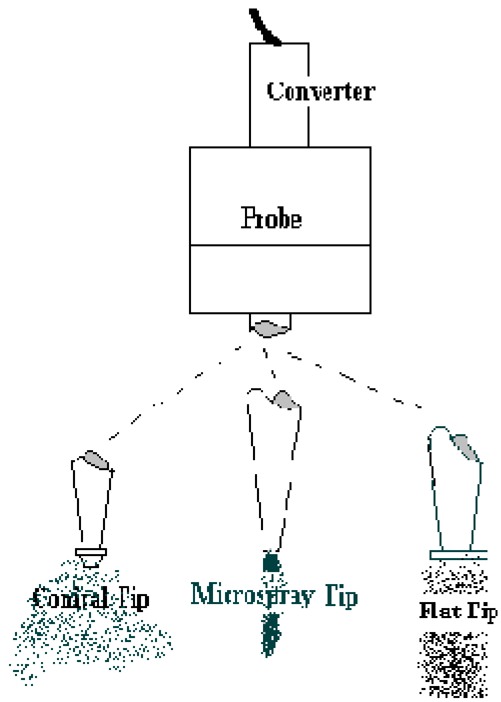
Ultrasonic Spray Nozzles

As their name implies, ultrasonic nozzles employ high frequency sound waves, those beyond the range of human hearing. Disc-shaped ceramic piezoelectric transducers convert electrical energy into mechanical energy. The transducers receive electrical input in the form of a high frequency signal from a power generator and convert that into mechanical energy at the same frequency.

The liquid is introduced to the atomizing probe with the use of a small pump or can be gravity feed. For the liquid to atomize, the vibrational amplitude of the atomizing surface must be carefully controlled. Below the so-called critical amplitude, the energy is insufficient to produce atomized drops. If the amplitude is excessively high, the liquid is literally ripped apart, and large “chunks” of fluid are ejected, a condition known as cavitation. Only within a narrow band of input power is the amplitude ideal for producing the nozzle’s characteristic fine, low velocity mist.

The fine control of input energy is what distinguishes ultrasonic atomizing nozzles from other ultrasonic devices such as welders, emulsifiers, and ultrasonic cleaners; these other devices rely on cavitation with input power of the order of hundreds to thousands of watts. For ultrasonic atomization, power levels are generally under 15 watts. Adjusting the output level on the power supply controls power.

Since the atomization mechanism relies only on liquid being introduced onto the atomizing surface, the rate at which liquid is atomized depends solely on the rate at which it is delivered to the surface. Therefore, every ultrasonic nozzle has an inherently wide flow rate range.



How Does it Work?

The ultrasonic power supply converts 50/60 Hz voltage to high frequency electrical energy. This electrical energy is transmitted to a piezoelectric transducer with the converter, where it is changed to mechanical vibrations. The ultrasonic vibrations are intensified by the probe and focused at the tip where the atomization takes place.

Every ultrasonic nozzle operates at a specific resonant frequency, which is determined primarily by the length of the nozzle. In order to produce standing, sinusoidal longitudinal waves, a necessity for the sustained vibration that produces atomization, the nozzle must be an integral number of half-wavelengths long. This requirement arises because bath free ends of a nozzle must be anti-nodes; that is, points of maximum vibrational amplitude. Open-ended organ pipes and chimes are other examples of this type of wave motion.

Sonics nozzles are manufactured in two different frequencies: 20 and 40 kHz. To give a sense of the physical size of these nozzles, one wavelength at 20kHz is approximately 5”. A 40kHz nozzle, one of the more common types in use, is approximately 2.5” long for the half-wavelength version.

There are several features worth noting. Probes / horns can only be mounted or clamped at the nodal point (point of no activity). For applications involving an interface to a vacuum chamber or another type of chemical reaction chamber, the probe can be machined with a mounting flange that bolts to an existing port on the reactor.

All probes are fabricated from high-strength titanium alloy (Ti-6Al-4V). This alloy also exhibits exceptional resistance to chemical attack.

The probes shown above features a cone-shaped atomizing surface. Its purpose is to spread out the spray. Some applications require that the spray be very narrow. In those cases, the atomizing surface is sculptured into a flat or nearly flat surface. Depending on the width requirements of the spray pattern and the required flow rate, the atomizing surface may have a very small diameter or an extended, flat section.

The configuration on the left shows the cone-shape spray pattern resulting from the conical shaped atomizing surface. Typically a spray diameter from 2-3 inches can be achieved. The one in the middle is characteristic of Sonics microspray line of nozzles. For this type of nozzle, the orifice size is from 0.015-0.040 inches. It is usually recommended for use in applications where very small amounts of material are to be delivered or where flow rates are very low. The one on the left depicts a cylindrical spray shape used in applications where the flow rate can be relatively high, but where the lateral extent of the spray pattern must be limited.

Operating Considerations

Input Power Range

The Ultrasonic Atomization process is confined to a relatively narrow input power range. Below the critical power level, there is insufficient energy to cause atomization. The power range in which atomization proceeds normally is generally confined to a narrow region, approximately 1-2 watts above the critical power level. At power levels above this range, the liquid is literally "ripped apart" by the excess energy provided, causing large chunks of material to be expelled, rather than the characteristics soft spray of fine drops. This condition is known as cavitation.

The exact magnitude of power required depends on several factors. These include:

- Nozzle type
- Liquid characteristics (e.g. viscosity, solids content)
- Flow rate

<u>Nozzle Type</u>

Each nozzle type, because of its specific geometry and other factors, will generally have a different critical power level for the same liquid. For example, the critical power level of a 40kHz nozzle, designed with a conical atomizing surface to deliver a wide spray pattern at substantial flow rates, will generally be in the neighbor of 3.5-4 watts of input power when atomizing water. Another nozzle, operating at the same frequency, but designed for microflow operation (a very small atomizing surface), may require only 2 watts to atomize water.

Liquid Characteristics
The type of liquid being atomized strongly influences the minimum power level. More viscous liquids or liquids with high solids content generally increase the minimum power requirement. For example, the 40kHz nozzle with a conical atomizing surface mentioned in the last paragraph, might require at least 8 watts of input power if the liquid being atomized were a 20% solid-content, isopropanol based material. See The Compatibility of Ultrasonic Atomization with Various Liquids below for further information on how the nature of a liquid determines whether or not a material is a good candidate for ultrasonic atomization.

Flow Rate
The flow also plays a role in determining minimum power level. For a given nozzle, the higher the flow rate, the higher will be the power required, since the nozzle is working harder at higher flow rates. See Flow Rate Ranges and Liquid Delivery Issues for further information on how flow rates bear on a nozzle's capabilities to atomize.

Temperature Limitations

The piezoelectric transducers that comprise the active elements of ultrasonic nozzles are limited as to maximum operating temperature. The limit is characterized by the Curie point, defined as the temperature at which the piezoelectric property of a material vanishes, as a result of the loss of its permanent polarization. For the lead zirconate-titanate transducers used in ultrasonic nozzles, the Curie point is just over 300 degrees C.

However, this does *not* mean that the transducers can be operated at temperatures anywhere near this limit, because the degradation in piezoelectric performance degrades gradually, not suddenly, with increasing operating temperature. A practical upper limit is approximately 150 degrees C. There is no lower temperature limit.

Therefore, the nozzle incorporating these transducers are likewise limited as to operating temperature, both in terms of the environment in which they can be placed and the temperature of the liquid running through them. Methods have been developed for air or gas cooling so that it is possible to operate nozzles at elevated temperatures under certain circumstances. Another factor that must be included in the thermal equation is that the nozzles themselves generate some heat. It is possible for a nozzle operating at a high power and at a 100% amplitude to experience a 30 degree C temperature rise. Although this represents an extreme case, this factor should be remembered in assessing what, if any, cooling is required.

Drop Size and Distribution

Drop size in an ultrasonically produced spray is governed by the frequency at which the nozzle vibrates and by the surface tension and density of the liquid being atomized. However, frequency is the predominant factor. Median drop size is inversely proportional to frequency to the 2/3 power. Thus, the higher the frequency the smaller the median drop size.

Various parameters can be used to characterize the mean and median drop size of a particular drop distribution. The number median diameter defines the 50% point in drop size – that is, one-half of the number of drops in the spray have diameters larger that this value while the other half have diameters smaller than this value. The number mean and weight mean diameters are average diameters. The number mean diameter is obtained by adding together the diameter of each drop in a spray sample and dividing that sum by the number of drops in the sample. The weight mean diameter is obtained by adding together the volume of each drop in a spray (volume is proportional to diameter cubed), taking the cube root of his sum, and finally dividing by the number of drops. The Sauter mean diameter is a specialized parameter used primarily in combustion applications. It measures the effective ratio of drop volume to surface area. The median drop size of a 20kHz atomizer is 90 microns were a 40kHz atomizer is 45 microns.

The Compatibility of Ultrasonic Atomization with Various Liquids

The physical nature of a liquid plays a central role in the ultimate success of any atomization process. Factors such as viscosity, solids content, miscibility of components, and the specific theological behavior of a liquid affect the outcome.

Pressure nozzles, both hydraulic and pneumatic, are generally unsatisfactory with materials that are abrasive or which tend to quickly solidify. In addition, it is usually necessary to operate such nozzles at high pressures, which produces overspray and consequent material loss.

Ultrasonic nozzles are even more "fussy". Although they offer many potential benefits, such as a soft, low-velocity spray, micro-flow capabilities, extensive spray shaping capabilities, and total freedom from clogging, the very nature of the technology presents restrictions on the types of liquids that can be successfully atomized.

Unfortunately, there are no hard-and-fast rules governing the atomizability of a liquid using ultrasonics. We have encountered cases where liquids that were seemingly easy to atomize, would not; and conversely, we have come upon situations where we felt that ultrasonic atomization would be impossible, but the liquid atomized perfectly well.

Although there is no specific set of rules to govern the ultimate success in atomizing a liquid ultrasonically, there are several guidelines, which have been developed through experience over a period of twenty years, that give a good indication of the probability for success.

To discuss these guidelines, we first categorize liquids as to type as follows:

1. Pure, single component liquids (water, alcohol, bromine, etc.)
2. True solutions (NaCI / water, alcohol / water, 10% KOH in water, etc.)
3. Mixtures with undissolved solids (coal slurries, polymer beads / water, silica / alcohol, etc.)

The only guideline that applies to most materials is that the higher the viscosity or solids-content of a liquid, the lower will be the maximum flow rate that can be atomized with a given nozzle. Even though the power delivered to a nozzle is user-adjustable in order to accommodate various liquids, the application higher power to hard-to-atomize liquids does not ensure that the nozzle will atomize at a flow rate near its rated capacity with water.

For (1), **pure liquids**, the only factor limiting the ability to atomize ultrasonically is viscosity. In general, the upper limit on viscosity is on the order of 50 cps. However, the maximum possible flow rate at 50 cps is severely limited, less than 0.25 ml/sec. As viscosity is reduce, the maximum flow rate correspondingly increases, eventually reaching the maximum flow rate for a given nozzle configuration at viscosities under 10 cps.

For (2), **true solutions**, the criteria for atomizability are, for the most part, the same as for pure liquids. An additional consideration arises when the solution contains very long-chained polymer molecules. In that case, the possibility exists that the polymer will interfere strongly with the atomization process because of the sheer magnitude of its linear extent. The molecule can inhibit the formation of discrete drops since there is an increased probability that it will span the region of the bulk liquid where two or more drops are about to be formed.

For (3), **mixtures with undissolved solids**, there are three primary factors that influence atomizability. These are particle size, concentration of solids, and the dynamic relationship between the solid(s) and carrier(s).

> Particle size is a critical parameter, in general we have observed that if the particle size covers an extent that is more than one-tenth the median drop diameter, the mixture will not atomize properly. This is clear on an intuitive level. For drops that contain one or more solid particles, their size must be significantly greater than the size of the solid particles(s) entrapped within. If not, there is a good chance that a majority of the drops will form will form without entrapping the solid component. The typical result is that the solid component and the carrier separate. The carrier atomizes nicely, but the solid component is left behind, accumulates on the atomizing surface and eventually drops off as an agglomerated mass.
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> The concentration of solids in a mixture is an important factor in its atomizability. Obviously, the particle size must be small enough to allow for any possibility of atomization. Even if the particle size is appropriate, other factors, such as the viscosity of the carrier and the ability of the solid component to remain suspended, play a role in the ultimate atomizability. As a result, there are no clear-cut guidelines to enable us to establish a relationship between atomizability and solids concentration.
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> From our experience, a practical upper limit on solids concentration is about 40%. This has been established for several materials, including solder fluxes and

various inorganic slurries. It must be stressed again that conditions must be just right in order to achieve atomization in this range of concentration.

Flow Rate Ranges

Sonics ultrasonic nozzles cover a wide range of flow rates, from 30ml / min to as much as 16 liters / hr. The flow rate range of a specific nozzle is governed by three factors:

- Orifice size
- Atomizing surface area
- Liquid characteristics

Orifice size plays a principle role in determining both maximum and minimum flow rates. The maximum flow rate is related to the velocity of the liquid stream as it emerges onto the atomizing surface. The atomization process relies on the liquid stream spreading out onto this surface and creating capillary eaves. At low stream velocity, surface forces are sufficiently strong to "attract" the liquid, and cause it to cling to the surface. As the velocity of the stream increases, a critical velocity is reached where the surface forces are overcome by the kinetic energy of the stream. Causing the stream to become totally detached from the surface. (The act of pouring water from a pitcher is a good analog from our everyday experience.)

In theory, there is *no* lower flow rate limit for any orifice size since the process is independent of pressure. However, in practical terms, lower limits do exist. As the flow is reduced, a point is reached where the velocity become so low that the liquid emerges onto the atomizing surface in a non-uniform circumferential manner, causing the atomization pattern to become distorted. In some applications, where stable spray patterns are unimportant (e.g. some chemical reaction chambers), this distortion may be tolerable. In other applications, where the integrity of the pattern is vital (e.g. surface coatings), the low-velocity stream distortions are unacceptable.

The amount of *atomizing surface* area available is the final factor influencing the maximum flow rate available from a given nozzle. This aspect of ultrasonic nozzle theory is somewhat involved so that we will not go into details here.

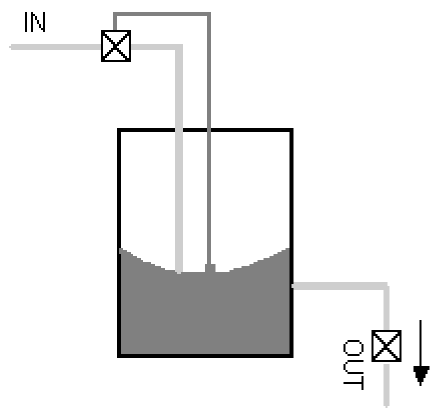
Studies performed at Sonics over the year's show that the maximum sustainable flow rate not only depends on the amount of real estate available, but also on the nozzle's operating frequency. Lower frequency nozzles can support greater flow rates than higher frequency nozzles having the same atomizing surface area.

In summary, there are three factors that can determine maximum flow rate for a given nozzle. However, in every instance, only one of these factors will set the limit. If we are dealing with a hard-to-atomize material, for example, it is likely that the maximum flow rate will not depend on neither orifice size nor available surface area, bur solely upon the atomizability of the liquid. Similarly, if we have a nozzle with an orifice whose capacity exceeds that of the available atomizing surface area, the surface area becomes the limiting factor. This interplay among the limiting factor is important in specifying a nozzle for a given application.

Liquid Delivery Issues

Since ultrasonic nozzles are basically passive devices, that is, they atomize whatever is delivered to the atomizing surface; the liquid delivery system becomes a dominant factor in making the process work properly. The following discussion of liquid delivery options is meant to serve as a brief guide to the subject.

<u>Gravity Systems</u>

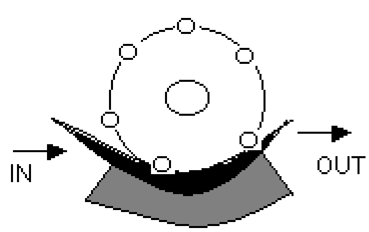


Principle of operation: Gravity feed with liquid entering a holding tank and regulated on the outlet; by valves; constant level maintained by level sensor and inlet valve.

Auxiliary requirements: Level sensor and control; flow control valve and cut-off valve on outlet; feed valve on inlet.

Primary benefits and limitations: Continuous or one-shot operation possible; tolerates solids-bearing materials; difficult to maintain reproducibility due to extreme sensitivity to pressure variations, line orientation, and entrapped air in lines.

<u>Peristaltic Pumps</u>



Principle of operation: Rotor with equally space cams (3 to 8 in number) squeezes flexible tubing, forces liquid to move through it.

Auxiliary requirements: Motor speed controller to regulate flow rate; pulse dampener; supply of spare tubing or tubing cartridges.

Primary benefits and limitations: Excellent with virtually any type of liquid; liquid on contacts tubing; for continuous flow only; multiple lines can be run from a single rotor; tubing has limited life; flow may vary as tubing distorts through usage; requires pulse dampener.

Spray Shaping

Since ultrasonics spray nozzles deliver such a soft, low-velocity spray, the spray envelope produced may not be suitable for a particular application without further shaping. In many applications, such as coating blood collection tubes, dispensing fragrances onto non-woven fabrics, and introducing chemicals into reaction chambers, the soft spray is perfectly suited "as is."

However, for other applications, such as coating wide substrates, focusing the pattern into a very narrow, well-defined line, or producing a pattern with precise outlines, auxiliary means for spray shaping must be employed.

To produce wide sprays from a single nozzle, the nozzle is mounted within a specially designed air-handler that uses low-velocity air to both shear the spray to desired width, and propel it in the desired direction in a uniform wedge-shaped pattern. Uniform spray patterns up to 20 inches wide can be produced with this type of equipment.

With the use of an air-handler, uniform patterns of spray can be generated, spanning a with range of 2 – 20". The spray can also be directed upwards, downwards, or horizontally with equally good results.