Basic Technical Considerations for Application of Spray Nozzles to Chemical Processing

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Abstract

Proper application of spray technology offers the potential for significant enhancement of end products and processes in the chemical processing industry. Final product quality, operating costs and maintenance down time are often materially effected by spray nozzle selection, use and application. Sprays, for example, are used in direct connection with the product manufacturing process, for packaging, for cleaning or disinfecting bulk processing equipment, and for environmental control.

Familiarity with basic spray functions, characteristics, classification and terminology is important to selecting the appropriate spray nozzle for a given spraying application. In addition to providing specific spray pattern coverage and liquid flow requirements, sprays are used to deliver specific liquid atomization characteristics, liquid spatial distributions, and impact (as in cleaning applications) and to cool and condition process gases.

Spray manifolds incorporating multiple nozzles can be optimized and properly applied to many conveyorized applications with the proper knowledge. Many end products and processing techniques that exist today are only possible through careful consideration of spraying applications.

A functional spray application requires periodic maintenance and replacement of spray nozzles to ensure continued good results. Like all mechanical components, spray nozzles are susceptible to erosion and corrosion, physical damage and degradation of important spray characteristics due to internal and external solid deposits. For any application sensitive to spray nozzle function, a quality program relating to the nozzle function should be developed. This may involve monitoring of the end product, the process, or the spray nozzles themselves.

This discussion provides a general working background on spray characteristics and terminology, with emphasis on impact delivery for cleaning applications, some specific considerations in selecting sprays for process applications, and spray nozzle/system maintenance.
The task of distributing liquids in controlled patterns with various defined characteristics can be accomplished by a wide variety of commercially available spray nozzles. In designing spray systems, there are often so many options available when specifying spray nozzles that the selection process itself can become somewhat complicated.

Nozzle type, pattern, size, design operating pressure, related drop size/velocity distribution and spray geometry all have demonstrated effects on the application capabilities of sprays. If multiple nozzles are used in a conveyorized application, the overlapping liquid distribution pattern of the nozzles needs to be considered because the process may depend strongly on the relative local volume flux of the spray.

Spray nozzles can be classified into several different categories depending on their method of operation. Hydraulic and pneumatic atomizing nozzle styles are common application choices. Pneumatic atomizers utilize compressed gas (not always air) which is mixed with a liquid. Mixing may be internal or external of the nozzle itself. Hydraulic atomizers depend on internal geometry and liquid pressure alone to produce a desired pattern. Hydraulic nozzles are usually further classified by pattern type. Hollow cone, full cone, flat spray and solid stream with associated sub-variations are the categories most used.

Hollow cone spray patterns can be formed in many ways. The most common method involves a single inlet orifice (“simplex” design) that exits tangential into a cylindrical swirl chamber that is open at one end with a circular orifice exit having a diameter substantially smaller than the swirl chamber at the other end (see Figure 1). Spray angle in this situation depends on the relative geometric proportions of the nozzle. This simple type of nozzle design has many desirable characteristics, including large free passages for a given nozzle size that results in a relatively high resistance to clogging. The same design concept is frequently applied by use of single or multiple inlets communicating with an exit orifice in an in-line configuration.

Another common hollow cone spray nozzle design involves the use of a radial deflector axially inserted into a straight orifice exit. Deflector type nozzles are somewhat prone to plugging and are susceptible to performance degradation due to erosion and damage to the deflector surface.

Hollow cone nozzles tend to provide the smallest drop size distributions obtainable among hydraulic spray styles. In addition, the relative span, or range, of drop sizes tend to be narrower than other hydraulic styles. The volume flux resulting from hollow cone sprays is concentrated, as one would expect, in an annular ring.

Full cone nozzle patterns can also be formed in a variety of ways. Most commonly, liquid is swirled within the nozzle and mixed with non-spinning liquid that bypasses the swirl element, or “vane” (see Figure 2). In some cases, the vane design provides for counter swirl. Liquid then exits through an orifice, forming a conical pattern. Spray angle and liquid distribution within the cone pattern depend on the vane design and location relative to the exit orifice as well as the exit orifice design and the relative geometric proportions of all of these elements.

Figure 1. Hollow Cone Nozzle

Figure 2. Full Cone Nozzle
The free passage through this type of nozzle is limited by the vane element. However, it is probably the best overall general-purpose full cone design style because the liquid distribution can be customized through proper design of the components. The characteristic drop size distribution for this design is larger than the hollow cone style and the range of drop sizes is the widest of the hydraulic types. Full cone hydraulic sprays are the most extensively used style in industry.

Hydraulic flat spray patterns are most commonly produced by spraying a solid stream onto a profiled deflector surface or by intersecting an angled or profiled external groove with a contoured internal cylindrical radius geometry (see Figure 3). The later style results in an elliptical (“cat’s eye”) orifice shape when viewed end-on. The elliptic orifice style flat spray nozzles can be designed to provide a wide variety of liquid distribution characteristics and have been successfully applied with or without spray overlap in many applications.

The use of internal elements such as pre-orifices can be incorporated into the basic elliptical orifice design to provide thicker sprays or to modify the drop size and velocity characteristics. Drop size response is between that of hollow cone and full cone hydraulic sprays for a given size nozzle.

Pneumatic, or air mist, atomizers are available in many styles and design configurations. Two basic distinctions in operating class are internal and external mixture. With internal mix designs, the gas and liquid are introduced into a mixing chamber inside the nozzle and later discharged through an exit orifice that is designed to provide a typically flat or round spray pattern. Air mist nozzles deliver spray droplets by means of self generated gas flow fields that can produce relatively high droplet transport velocities as compared to straight hydraulic systems.

External mix pneumatic nozzles function by impacting a stream of liquid with a series of strategically placed air jets that break up the liquid and form a spray pattern that is usually conical or flat (see Figure 4). External mix drop sizes and ranges are typically larger than internal mix styles, and they are most often used in situations where the material being sprayed is very thick or would otherwise clog the inside of an internal mix type nozzle. Liquid flow is not really affected by changes in gas pressure applied, which could allow for less complex process control systems. In this sense, external mix pneumatic nozzle function is much the same as hydraulic nozzles. The external mix styles are not often used in continuous caster applications.

Internal mix pneumatic atomizers (see Figure 5) are capable of producing fine drop sizes with a very narrow range of sizes. Drop size is generally much smaller than that produced by basic hydraulic atomizers at normal operating pressures. The liquid delivery rates and airflow consumption of internal mix nozzles can be quite sensitive to small changes in applied inlet pressures. Studies show that process rates for a given amount of liquid are far in excess of those attainable with simple hydraulic nozzles due to small, uniform drop sizes. The spray pattern is normally either flat or conical.
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The sensitivity of the liquid flow to changes in inlet pressures for internal mix pneumatic nozzles provides benefit in terms of the turndown ratios obtainable from these nozzles. This in turn allows for great flexibility. Turndown ratios for external mix and hydraulic nozzles are generally smaller than 3:1 while ratios of 8:1 or higher can be achieved with the internal mix pneumatics. This is of particular interest when designing a process system that responds to changes in process input variables.

Control systems for air atomizing systems are more complex than those of hydraulic systems. Operational costs are higher as well. Compressed gas that is used by the nozzles consumes energy at high rates and generally has a high capital cost associated with implementation. The nozzles are more expensive than simpler hydraulic types. Maintenance and implementation costs for a pneumatic system are typically higher than for hydraulic nozzle systems, as well.

FUNCTIONS/APPLICATIONS OF SPRAY TECHNOLOGY

General

Spray nozzle selection follows primarily from the function to be performed. In the simplest case, a single nozzle is employed to distribute liquid in a defined pattern to cover a surface or fill a spatial volume in a prescribed manner. In this sense, “spatial” refers to any case where the objective is not mainly intended to spray onto a surface.

Surfaces may be sprayed with any pattern shape. The result is fairly predictable based on the type of nozzle spray pattern. If the surface is stationary, the choice of spray pattern is usually some sort of full cone since this pattern will cover a larger area than the other styles in general. In conveyerized applications, where either the target or the spray nozzle is moving relative to the other, any spray pattern may be employed depending on the other desired characteristics. For example, if higher impact is desired, then a flat spray pattern would usually provide an advantage. If drop size uniformity at the target is needed, a simplex hollow cone spray or a pneumatic atomizing spray might be selected.

Spatial applications are much more likely to require more specialized spray characteristics. Often, success in these applications is completely dependent on factors such as drop size and spray velocity. Evaporation, cooling rates for gases and solids, process reaction rates and cleaning efficiency are examples of process characteristics that may depend largely on spray qualities.

A basic approach to selecting a spray based on the pattern and other spray characteristics needed generally yields good results. The spray selection should be considered early in the design of the system. Although spray nozzle manufacturers are capable of producing nozzles to suit virtually any requirement, it is good practice to select the sprays and set the spray parameters based on what is readily available. Special spray nozzle requirements will likely cause needless delay in a project, considering that the spectrum of standardized sprays currently in existence is so large.

Multiple Nozzle Installations

Nozzles are not always used singly but often are designed into spray manifolds. Manifolds may serve to accomplish spatial functions as in absorption in a gas exhaust stack. However, most manifold applications are related to spraying of surfaces in conveyerized applications such as process or production machinery. Conveyerized multiple nozzle applications merit special discussion. Generally, the goal is to provide uniform distribution of spray characteristics such as volume flux or spray impact transverse to the conveyor direction. In this sense, spray overlap analysis becomes important.

Overlap uniformity is judged by statistically analyzing the composite spray distribution produced by the header, boom or manifold. The spray overlap data is used to calculate Cv (coefficient of variation), which is simply put the standard deviation of the overlapping spray pattern divided by its average value and expressed in percent. Cv is an indicator that is used to characterize the overlap uniformity.
Two methods of determining Cv are commonly used. The direct approach is to set up a spray manifold on a patternator using multiple nozzles, collect actual spray overlap data, and statistically analyze it. An example of an overlap distribution is shown in Figure 6. The simulation approach involves collecting the spray distribution of a single spray nozzle (i.e., Figure 7), and using it as a “seed” distribution to conduct manifold simulations.

The results of an overlap simulation are usually conservative when compared with the results of an actual overlap test because the “seed” nozzle liquid distribution imperfections are accentuated when this distribution is overlapped with itself. In other words, the overlap uniformity of a simulation is usually worse than that of a real multiple nozzle overlap. If “oddball” nozzles exist in an installation or severe pressure drop from nozzle point to nozzle point exists, however, you should exercise some caution because the simulation may provide better results than the actual installation.
Functions/Applications of Spray Technology

Simulation is a valuable and powerful tool for analysis of spray manifold distributions. Predictions concerning many possibilities based on a limited amount of “real” distribution data can be made. Figure 8 shows a plot of $C_v$ as a function of nozzle spacing from a simulation calculation. This type of analysis quickly guides a user to the proper setup requirements if optimization of spray overlap is a system design criterion.

The $C_v$ is defined as the percentage of average trough volume collected which the standard deviation represents, i.e.,

$$C_v = \frac{S}{X_{avg}} \times 100\%$$

If the overlap distribution being analyzed were perfectly even, the $C_v$ would be 0. $C_v$ values of 15% or less are generally considered acceptable for most applications. A $C_v$ of less than 10% represents a high degree of uniformity.

Atomization Control

One of the more underutilized aspects of spray nozzle application is the control of atomization characteristics. Reaction rates, evaporation rates, gas cooling and humidity control are examples of applications that require specific drop size spectra parameters in addition to defined pattern and volume flux characteristics. A chemical or process engineer familiar with drop size terminology can calculate the specific atomization requirements for a specific application.

Information concerning the drop size response of various sprays under various conditions can generally be obtained from spray nozzle manufacturers. Spraying Systems Co., for example, has a fully equipped drop size measurement laboratory with a variety of commercially available instrumentation dedicated specifically to this purpose. Because drop size instrumentation is expensive to purchase and drop size testing and analysis requires a high level of training and skill, most nozzle users rely on the data provided by the manufacturers. For a basic discussion on drop size terminology and measurement, the reader is referred to ASTM E799-92 and 1296-92.
FUNCTIONS/APPLICATIONS OF SPRAY TECHNOLOGY

Cleaning Applications:

Spray nozzle applications that involve cleaning of surfaces have been well developed over the years. These systems vary in complexity depending on many specifics, but from the standpoint of the nozzle itself the goal is to deliver fluid with the force distribution needed to do the job. Because the nozzle is only one element, the overall process should be considered.

Cleaning systems are simply described by considering the soils and the steps required to remove them. “Soils” can be classified into three main groups. Those that are soluble in the liquid phase of the deterging system (i.e., sugar in water) constitute one group. Soils soluble or rendered dispersible by chemical action form a second group. A significant standing or soak time may be required to render these types of soils removable. A third class of soils requires some impact, agitation, and brushing or other means for removal.

To successfully clean something, the soil must be removed from the surface, dispersed and prevented from redepositing. All steps are equally important and should be given equal weighting in considering the process. Before this, it is necessary to consider how the soil is held to the surface to be cleaned. In conjunction with the surface characteristics and soil characteristics, this determines the possible removal methods.

Spray nozzles are naturally integrated into the cleaning process in every step. The deposition of detergent solutions for soil loosening, surface rinsing and mechanical force application through varying levels of impact pressure can be accomplished using various sprays. Rinse and detergent sprays are applied by considering the spray pattern geometry and spray volume flux requirements. Use and selection of nozzles for impact cleaning requires basic knowledge of energy transfer via spray impact. In spray cleaning, we are simply taking potential energy, supplied by a pump, and converting it to kinetic energy, as provided by the spray. Impact in this sense is the force and force distribution evidenced on a target surface due to the expenditure of kinetic energy.

Because the impingement of individual water droplets on a surface is generally considered to be inelastic, the total impact from a spray can be estimated with reasonable accuracy from a simple reaction force equation:

\[ F_t = \rho \times Q \times v \]

where \( F_t \) is the total force, \( \rho \) is the fluid density, \( Q \) is the total volume flux, and \( v \) is the exit velocity of the spray from the nozzle.

In English units, and with a little substitution, this works out to:

\[ F_t [\text{lb.}] = 0.0527 \times \text{gpm} \times \sqrt{\text{psig}} \]

\( \text{gpm} \) being the nozzle flow rate at \( \text{psig} \) operating pressure.

Although this formula is only technically correct when applied immediately outside the nozzle, there is a large body of empirical data showing that it applies at a target surface as well. Application of the formula usually involves the incorporation of a bulk efficiency factor that accounts for spray variables such as target distance, energy losses internal to the nozzle, drop size, spray angle, and spray type. Thus,

\[ F_t [\text{lb.}] = \eta \times 0.0527 \times \text{gpm} \times \sqrt{\text{psig}} \]

In practice, the efficiency may range from 0.55 for a simplex hollow cone nozzle to 0.99 or higher for solid stream nozzles under certain conditions. The situation may be further complicated by spray rebound, which increases the impulse and resulting impact force. Consider for example a solid stream spray impacting on a solid surface (see Figure 9). In case A, the spray hits the target surface and deflects horizontally. In case B, the spray strikes at an angle. Cases C and D are similar to A and B, except that the sprays splash upward somewhat. A real situation could be any combination of these situations.
Cases A and B would be the type of behavior expected when spraying at lower relative pressures onto smooth surfaces. Cases C and D represent higher pressures, rougher surfaces, and closer target distances. In case A, the impact force is the same as the reaction force formula predicts. In case B, the impact force is reduced because of the impingement angle. Total impact would be same as case A multiplied by the cosine of incident angle relative to “vertical”.

In case C, the total impact will be larger than the reaction force calculated from the equation. This is because impact results from a change in vector momentum. Since the liquid rebounds toward the nozzle, it imparts additional momentum to the target. If spray droplets collided in a perfect elastic manner with the target, the resulting impact could be as much as double that calculated from the simplified reaction force equation. Although the situation is a bit more complicated in case D, the same kind of effect is seen.

Splashback and the associated effect on total impulse is amplified by increased target surface roughness, increased spray pressure, higher liquid flows and closer target distances. All of these factors contribute to liquid “ramping” up over stationary or slowly moving liquid sitting on the target surface. While these effects may be interesting, the increased total impact resulting doesn’t necessarily help clean the target surface. The primary indicator of cleaning effectiveness from sprays is the maximum impact pressure on the target, or maximum specific impact.

Specific impact is simply the total impact divided by a unit coverage area. If this area is the entire spray pattern on the surface, then the result is termed **Average Specific Impact** \((I_a)\). The largest unit impact pressure on the target surface within the spray pattern is termed the **Maximum Specific Impact** \((I_m)\).

Because cleaning effectiveness relates directly to the specific impact level, “tighter” spray footprints tend to produce better results. The sharpness of a given spray is primarily influenced by the internal geometry of the spray nozzle and the nozzle’s ability to cope with varying levels of inlet turbulence. High performance spray nozzle designs that produce smaller pattern areas in comparison to other nozzle styles operating at equivalent conditions therefore provide an advantage (see Figure 10). In addition, proper design of spray manifolds and nozzle feed ports and the use of spray nozzle stabilizer components yields the highest possible \(I_m\) results for a given application.

In reviewing the total impact equation, it is possible to obtain the same total impact using two different size (and type) nozzles at different pressures. For example, a common solid stream pressure wash tip provides 8.3 pounds of force and 3.5 gpm at 2000 psig operating pressure, while a hand held “wash down” spray gun spraying 25 gpm at 40 psi provides nearly identical total impact force. Which would clean better?
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Though total impact pressure is similar, Im values will be much higher for the high-pressure combination. This is because the pattern footprint would be much smaller. Usually, then, this would be the preferred direction. A lower pressure system may be preferred, however, in bulk washing applications where large volumes of liquid are needed to transport the soil from the surface and to prevent redeposit.

Another consideration when comparing options is the energy consumption (operational cost) and the initial expenditure. High-pressure systems cost a lot more to implement. Power consumption from a nozzle can be predicted from a simple hydraulic horsepower function:

\[
(Hp) = \left[ \frac{\text{gpm} \times \text{psig}}{1714} \right]
\]

Based on this formula and the current example, it can be seen that high-pressure systems cost more to operate as well. The high-pressure nozzle is consuming about 4.1 Hp while the bulk washing spray gun is only using 0.6 Hp. The decision to go to higher pressures in cleaning applications is thus not always justified. On the other hand, the high volume system uses much more fluid (which may have to be treated). The best approach is to determine the required level of specific impact needed to do the job at hand and the associated spray nozzle requirements and to exceed this only as prudent to ensure cleaning process uniformity from a design standpoint.

Although changing spray nozzles to higher performance design styles for cleaning may cost more money up front; the specific impact results are substantially improved. Thus, if the existing system was performing properly, a possibility exists for reducing operating costs by using better spray nozzles. For example, it may be found that substitution of a smaller size high performance spray nozzle can be executed without effecting system performance. This reduces the power consumption of the system and the amount of liquid to be sprayed (and recirculated or treated) at the same time. Substitution of the same size nozzle in a high performance design may allow for a reduction in operating pressure, again reducing power consumption and sprayed liquid volume without effecting the system performance. System maintenance costs may also be reduced.

In chemical and process industries, a wide variety of cleaning applications exist, often on a single production line. If, by considering the basics of spray nozzle functions as described, the overall system requirements are properly balanced with the implementation, operational and maintenance costs, there are very few alternatives that can compete with a well designed spray system.

Spray Nozzle/System Maintenance Considerations

A system incorporating spray nozzles should be monitored as appropriate to ensure that proper performance is maintained. Some spray installations may work properly after thousands of hours of operation while others may require attention on every production shift. As with other manufacturing tools, the nozzles require periodic inspection to preserve product or process quality.

In early stages of deteriorating spray nozzle performance, the overall effect may not be easily discernible. In later stages, the result is likely obvious. Thus, some study is necessary so that the spray variables associated with the process or product quality and cost can be identified and, if necessary, tracked. Loss of product or process quality results in direct increased cost due to customer service and scrap. This relationship is normally very well defined due to a high level of emphasis by management in industry today. Increased costs associated with operations are harder to define, but can be dramatic.

To illustrate the potential impact of spray nozzle erosion on operation costs, consider a system designed to spray 5 gpm of a 1:20 aqueous solution of chemical. The process chemical used for this illustration is being consumed at 0.25 gpm and costs $0.50 per gallon. The system is operated 3 shifts, 5 days per week. If the nozzles used erode to the point where the system is consuming 15% additional solution, the annualized incremental costs of water, chemical and energy are as follows:
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MAINTENANCE CONSIDERATIONS

- Water: approximately $800 - based on water/sewage cost of $3.00/1000 gallons
- Chemical: approximately $7000
- Electricity: Approximately $450 ($0.08 per kW)
- Total: $8250

Obviously, this is a high price to pay compared with the establishment of a maintenance program that results in timely spray nozzle replacement. This example is pertinent because spray nozzle erosion resulting in a 15% increase in nozzle capacity may not result in obvious changes to spray performance in many cases (see Figure 11).

Erosion also results in changes to the spray pattern and drop size characteristics. These effects vary depending on the nozzle type and operating conditions. As Flatsprays wear, the spray angle gets smaller and the spray edges often become more pronounced (see Figure 12). This often results in substantial changes to the liquid distribution. If the nozzle is used multiply in a spray manifold, as in many conveyerized applications, the resulting composite spray distribution quality will also be compromised (see Figure 12).

Figure 11. Flatspray Distributions: New

Figure 12. Overlap Distribution Result for a 65º VeeJet Type Nozzle
Sometimes corrosion damage is confused with erosion (see Figure 13). This is because as the sprayed liquid or environment attacks the nozzle material, the spray carries material away. In advanced cases of corrosion damage, there is no mistaking the problem. The answer to corrosion damage difficulty lies in proper material selection for the nozzle.

Build up of material in the interior or, more often, on the exterior surfaces of the spray nozzle (see Figure 14) results in varying degrees of spray problems. This situation, termed “caking” in severe cases, results from the precipitation of dried solids on the nozzle surface. The solids come from either the liquid being sprayed or the nozzle environment. Any time solid deposits exist inside or outside the nozzle near the orifice, the spray is likely to be effected.

Occasionally, improper handling and installation or improper cleaning physically damages nozzles. The spray pattern emanating from a damaged nozzle is usually obviously defective. Cleaning of spray nozzles can often restore a defective spray to optimum performance. However, a common sense approach and some care in performing this operation are needed to avoid damaging the spray nozzles and forcing immediate replacement.

It is considered poor practice to clean the orifice of any spray nozzle with a metal object. The orifice is precision engineered and machined and represents much of the value of a spray nozzle. Use only a “toothbrush” or toothpick. If the nozzle is made of plastic, extreme care should be exercised to avoid damaging the orifice. As a rule, tools used to clean nozzles should be significantly softer than the material from which the nozzle is constructed.

Plastic nozzles should only be torqued into a fitting a sufficient amount to effect a seal. Otherwise, damage to threads or other permanent deformation (which may effect the spray) are likely to occur. Nozzles that have multiple components and that require disassembly for cleaning should be carefully handled and properly reassembled.

Spray nozzles should be thought of in the same way as that of any production component requiring scheduled maintenance. Establishing a maintenance program related to spray nozzles can involve the monitoring of nozzle flow rate or spray appearance directly or process monitoring of indirect variables such as spray pressures.

The nozzle performance variables’ cause and effect relationship with product or process uniformity should be established so that accurate criteria for maintenance intervals or nozzle replacement can be established. It is necessary to know what level of spray performance is critical to the application as well. Some applications are fairly insensitive to issues of spray nozzle performance degradation while others, as mentioned previously, are only possible through a narrow range of spray performance provided by a specific nozzle or nozzle system.

Currently the maintenance trend is to replace machine components before they deteriorate to the point of effecting the product or process adversely. Nowadays, maintenance schedules are often set-up based on statistical process control evaluation of the end result, through design of experiments, or other more direct analysis. This methodology can also be applied to spray nozzle maintenance.