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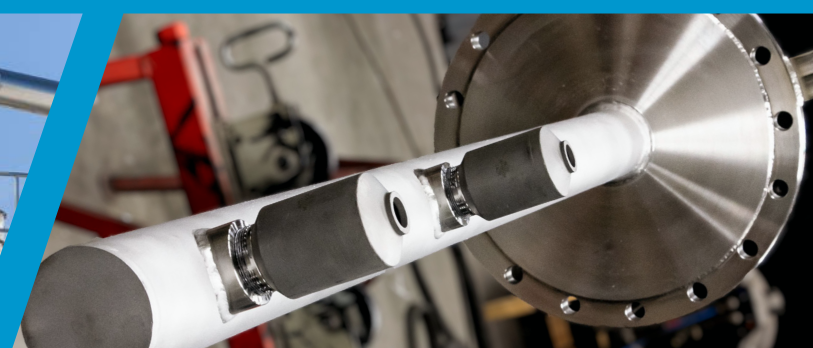
CO-CURRENT VS. COUNTER-CURRENT SPRAY IN GAS COOLING APPLICATIONS

A CFD-BASED PERFORMANCE ANALYSIS

APRIL 25, 2025



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ABSTRACT

CFD modeling comparing co-current to counter-current spray in a gas cooling application shows that a co-current full cone spray requires more duct length than a counter-current hollow cone spray. Other considerations for nozzle orientations are discussed.

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INTRODUCTION

Common processes such as incineration require that hot gases in a duct be cooled before entering a downstream process where heat could damage equipment. Cooling is often accomplished by evaporating small water droplets, and a design goal is to minimize cost by accomplishing the evaporation at the shortest possible length of the duct and at the lowest possible pump pressure.

Evaporation of water droplets cools the gas because heat flows from the hot gas to the cold droplet, providing the latent heat of vaporization required to transform the liquid water into water vapor. The mass flow rate of the gas, its thermodynamic properties, and the inlet and outlet temperatures determine the mass flow rate of water that needs to evaporate. Since evaporation is a heat transfer process, the rate depends on the surface area of the water exposed to the gas, convection of heat to the droplet, and diffusion of water vapor from the droplet surface.

Process designers can make decisions that optimize each of these factors.

For example, a nozzle increases the water's surface area by breaking it into droplets.
The type of nozzle, the nozzle size, and the operating pressure determine the droplet size. General trends are shown in Table 1.

Table 1
Droplet Size Trends

Relative Droplet Size for Several Nozzle Characteristics			
Nozzle Type	Full cone nozzle -> large drops	Hollow cone nozzle -> small drops	Air atomizing nozzle -> smallest drops
Water Pressure	Low pressure -> large drops	High pressure -> small drops	
Nozzle Size	Small nozzle size -> smaller drops	Large nozzle size-> larger drops	

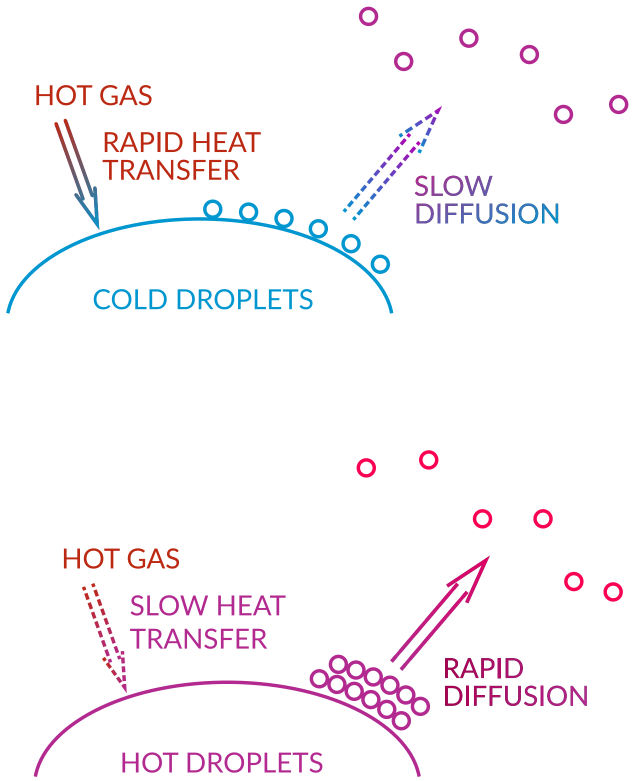
Designers can also influence convection. Convection is the movement of the gas relative to the droplet, which brings hot gas to the droplet. If there is little movement of the gas near the droplet surface, the gas near the surface cools, and less heat transfer to the droplet takes place. Spraying against the gas flow can increase the relative velocity between the gas and the droplets, which will increase convection.

Designers can influence the diffusion, too, since the rate of diffusion is influenced by the state of the gas surrounding the droplet. Diffusion is caused by a difference in vapor pressure near the droplet surface and the vapor pressure far from the droplet. Diffusion and convection take the evaporated water away from the droplet, which increases the concentration gradients, favoring additional evaporation. If a droplet is in an area where the gas is cooler or contains a high concentration of water vapor, then the rate of diffusion will be small.

The reason that spraying counter-current could be different from spraying co-current is that a counter-current spray will experience more convection since the droplets initially travel against the gas flow. However, they also travel in an area that's been cooled by previous droplets, and this may reduce the diffusion.

For an explanation of the two opposing processes, see the illustration in Figure 1, which shows how two effects determine the droplet surface temperature and evaporation rate. Heat transfer to the droplet is large if the droplet is cold, increasing the evaporation rate. However, the vapor pressure over a cold droplet is low, which decreases the rate of diffusion. The system comes to equilibrium when the droplet temperature is low enough that there is enough heat transfer to the droplet to evaporate the water that diffuses away. If enough water evaporates into the gas, the vapor pressure will be so high that evaporation ceases. This can happen near the droplets if the spatial concentration of water droplets is large.

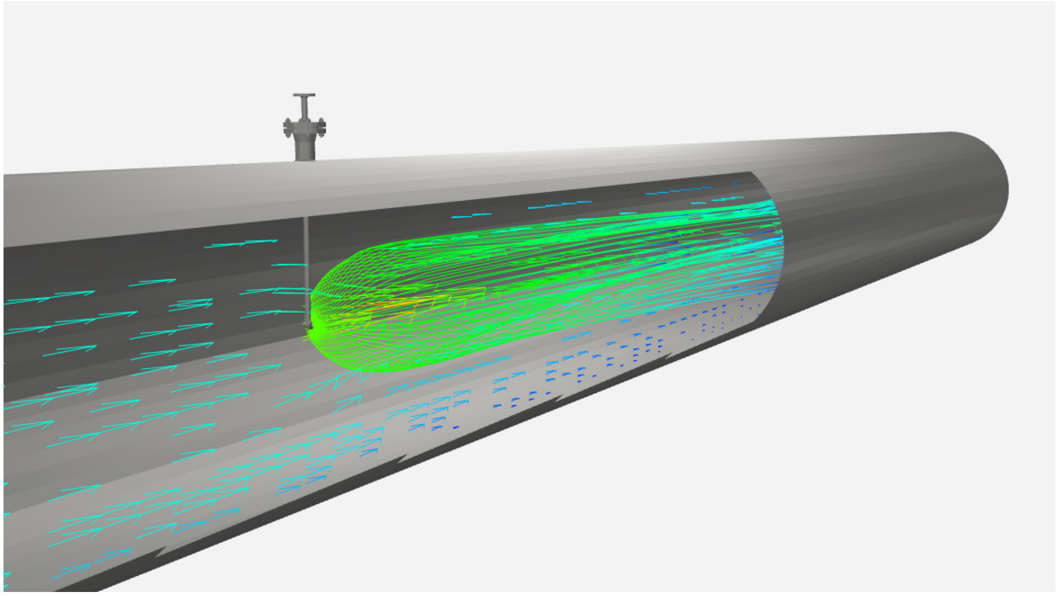
Figure 1
Droplet Trajectory and Evaporation History Comparison



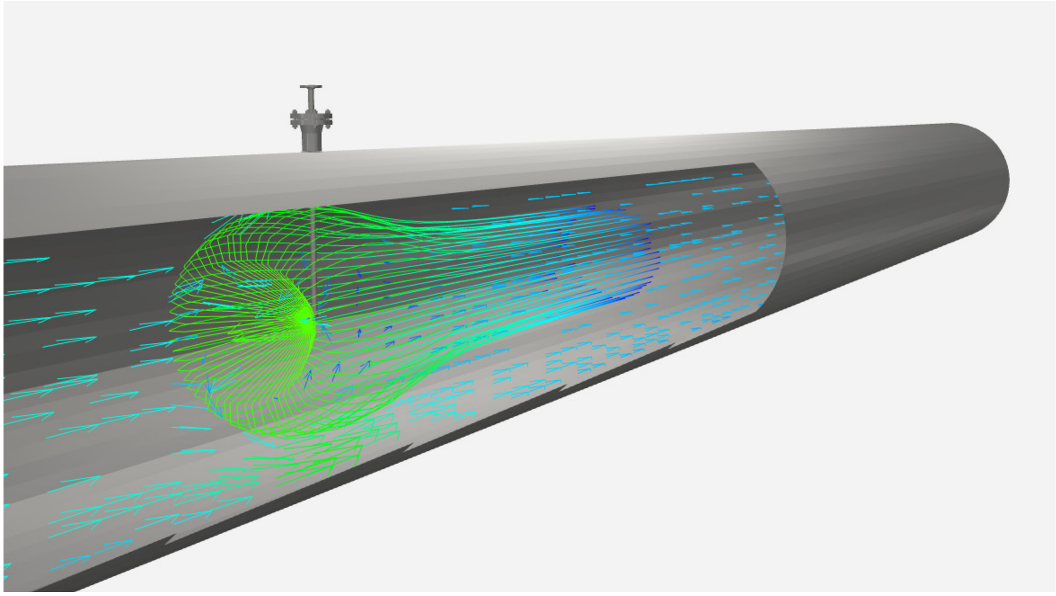
To minimize the duct length, the designer should provide for intense convection, large vapor concentration gradient, and uniform distribution of droplets within the duct.

When installing spray nozzles within the duct, one can choose to align the spray axis in the direction of the gas flow ("co-current") or opposite the gas flow ("counter-current"), as illustrated here. Engineers ask which will require the least duct length.

CO-CURRENT SPRAY



COUNTER-CURRENT SPRAY



Designers can also choose a full cone or a hollow cone spray pattern. The hollow cone pattern might provide better initial contact between the spray and the gas, but the dense spray of a hollow cone nozzle could result in local saturation, which would halt evaporation since the rate of diffusion would be less. The sparser full cone spray pattern may not saturate the gas, which would increase the rate of diffusion.

We compared the effect of each of these factors on the required duct length for a representative gas cooling process.

PROCEDURE

We used the discrete phase model in ANSYS® FLUENT® to compute the droplet trajectories and evaporation history in a 1.5 m diameter duct carrying 5 kg/s of air at 400 °C. Into this, we introduced 29 l/min of water droplets, each with a diameter of 117 µm with an initial droplet velocity of 45 m/s.

The discrete phase model introduces droplets of a specified size, velocity, and spray pattern into the gas flow. The evaporation of a cold droplet as it moves through the gas is calculated using a diffusion model until the droplet reaches the boiling point, at which point the rate of evaporation is determined by the heat transfer to the drop.

We compared four scenarios:

1. Hollow cone nozzle, co-current

2. Hollow cone nozzle, counter-current

3. Full cone nozzle, co-current

4. Full cone nozzle, counter-current

RESULTS

The qualitative comparison of the distance required for complete evaporation is shown in Table 2.

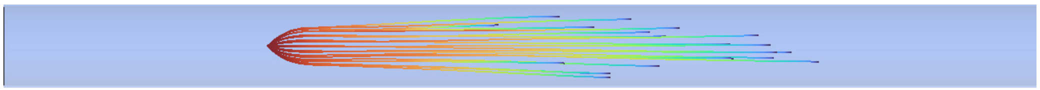
Table 2
Droplet Evaporation Length Comparison

Spray Orientation	Hollow Cone Nozzle Evaporation Distance	Full Cone Nozzle Evaporation Distance
Co-Current	Medium	Longest
Counter-Current	Shortest	Medium

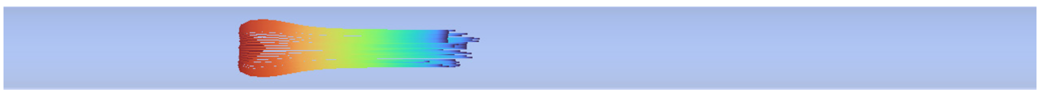
Figure 2 illustrates droplet trajectories and evaporation history for each case. The color along each droplet's trajectory shows the diameter of the droplet at each point. The diameter of each droplet decreases as it evaporates, and the minimum required duct length is where all the trajectories end.

Figure 2
Droplet Trajectory and Evaporation History Comparison

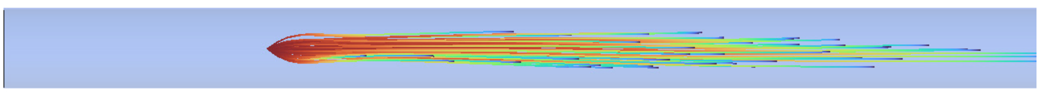
HOLLOW CONE NOZZLE SPRAYING CO-CURRENT



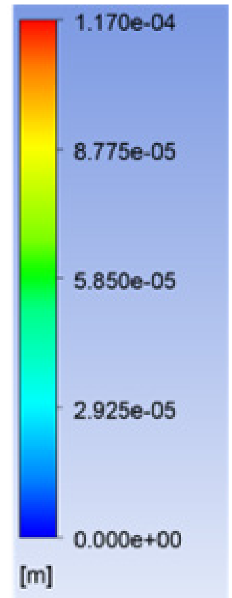
HOLLOW CONE NOZZLE SPRAYING COUNTER-CURRENT



FULL CONE NOZZLE SPRAYING CO-CURRENT



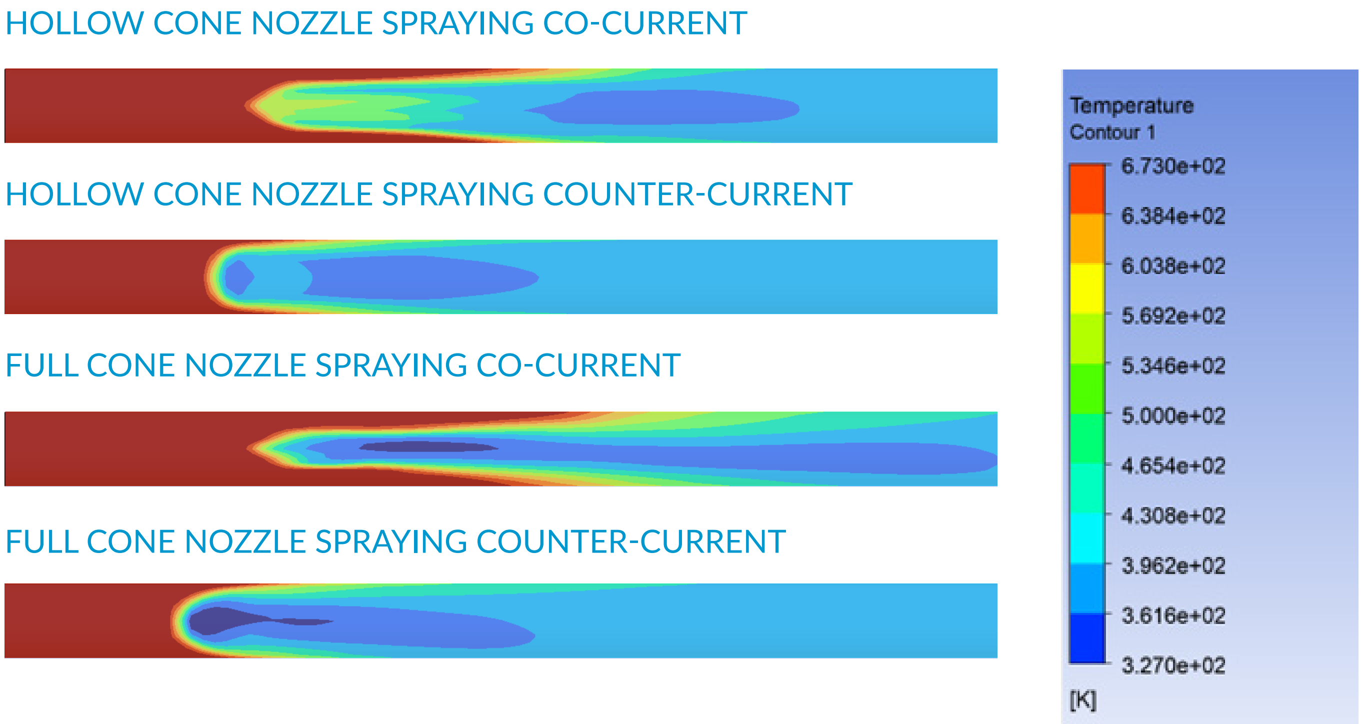
FULL CONE NOZZLE SPRAYING COUNTER-CURRENT



Droplet Diameter

Figure 3 shows the effect of evaporation on the gas temperature. There are areas at the end of the duct with the full cone co-current nozzle where the gas is barely cooled. This is consistent with the trajectory plot, which shows unevaporated droplets at the end of the duct.

Figure 3
Effect of Evaporation on Gas Temperature



DISCUSSION

The results show that the spray produced by the hollow cone nozzle spraying counter-current evaporates in the shortest distance. In this orientation, the droplets first travel upstream, which creates strong convection. When the droplets are entrained by the gas, they do not return along the same path, so they are exposed to the hottest gas along their entire trajectory.

However, the designer should consider at least three other things. First, nozzles spraying counter-current may clog with particulate in the gas if they do not spray continuously. Second, unevaporated spray returning downstream may form drips on the piping that supplies the nozzle, and the drips can pool and cause corrosion or fail to evaporate. Third, a counter-current spray pushes the gas back upstream, which increases the pressure drop and energy requirements to move the gas through the system.

This case is simplified, assuming a straight duct and droplets of a single size. A real duct may have non-uniform flow, and real sprays contain a variety of droplet sizes, each with their own evaporation and trajectory history. A more comprehensive CFD model could account for these effects for a specific application.

CONCLUSION

The best choice for gas cooling to minimize duct length, to avoid spray impingement on the supply piping, and to avoid external clogging is often a hollow cone nozzle spraying co-current in the center of the duct.

To minimize the required duct length, designers can also consider using multiple small nozzles in an array, increasing the supply pressure to the nozzle, or different types of nozzles.

GLOSSARY

Convection – Heat or mass transfer caused mainly by movement of the fluid. In gas cooling, movement of the gas near the droplet brings hot gas with little water vapor near the droplet to replace gas that has been cooled by the evaporation.

Counter-current spray – The nozzle is installed so that the axis of the spray cone points opposite to a gas flow.

Co-current spray - The nozzle is installed so that the axis of the spray cone points in the same direction as a gas flow.

Diffusion – Movement of molecules from a place of a high concentration to one of low concentration. For gas cooling, the concentration of water vapor is high near the surface of the droplet and low in the gas, so molecules tend to move from the droplet out into the gas.

Droplet trajectory – The locus of points through which a droplet passes.

Full cone spray pattern – A spray pattern in which droplets leaving the nozzle travel throughout a conical volume. Droplets are widely separated.

Hollow cone spray pattern – A spray pattern in which droplets travel mainly along a conical surface of revolution. Droplets are spaced closely together.

Latent heat of vaporization – The energy required to separate liquid molecules to form a gas. This heat only changes the form of the liquid. During vaporization at a constant pressure, the temperature of the evaporating liquid is the same as the gas that is formed.

Partial pressure – The pressure exerted by the molecules of just one component of a multi-component gas. In the standard atmosphere, for example, the total pressure is 101325 Pa. Each of the constituents, such as nitrogen, is responsible for a portion of this total pressure.

Saturation – The state of a gas in which the partial pressure of water is equal to the saturation pressure. When the gas is saturated, evaporation stops unless the droplet is heated. In gas cooling applications, the limit of cooling is when the gas temperature and the droplet temperature are such that the water vapor pressure over the droplet equals the water vapor pressure in the gas. This is the "wet bulb" temperature.

Vapor pressure – The pressure of a gas at equilibrium with its liquid at a given temperature. For example, the vapor pressure of water at atmospheric pressure (101325 Pa) is 100 °C.

ABOUT THE AUTHOR

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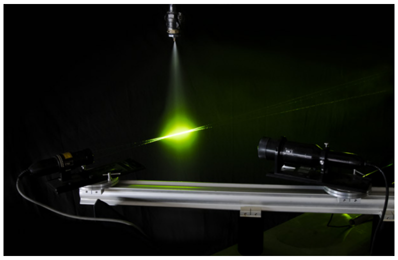
Daniel deLesDernier has worked for BETE for over 30 years and, for the past 25 years, has led BETE's spray laboratory, specializing in the experimental evaluation and development of spray solutions across various industrial processes. Supporting such a broad range of fields is what Daniel enjoys most about working at BETE.

As a graduate of the University of Massachusetts Amherst as a mechanical engineer with a concentration in thermal fluids and energy conservation, Daniel is committed to engineering problem-solving and technical collaboration. He has played a key role in the success of BETE's Advanced Spray Engineering Services (ASES) department, founded over a decade ago to work closely with customers on process-critical spray applications. By integrating physical testing, modeling, and design, ASES ensures each solution aligns with the customer's process constraints and performance goals—helping mitigate risk and improve outcomes.

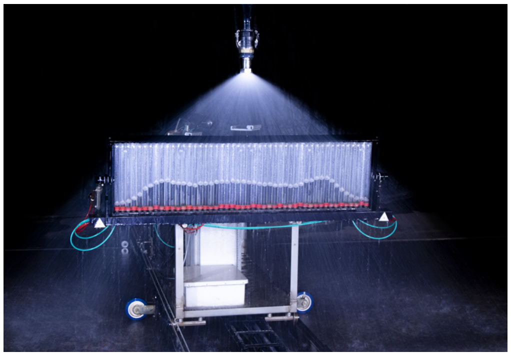
In his free time, Daniel enjoys traveling throughout Europe with his family, participating in outdoor sporting activities such as kayaking, bicycling, running an occasional road race, and flying. He is a Civil Air Patrol (CAP) mission pilot with over 30 years of flying experience.

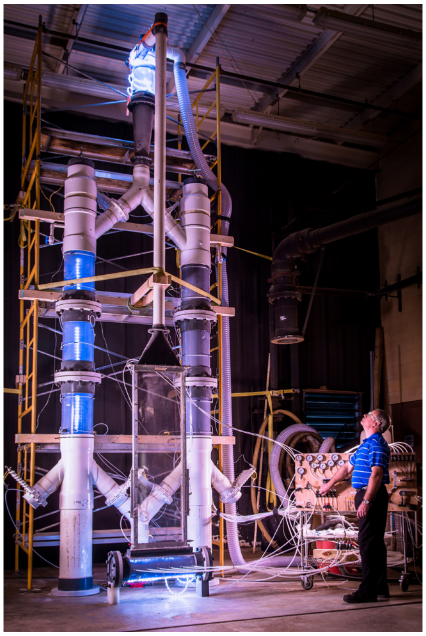
HOW ADVANCED SPRAY ENGINEERING SERVICES CAN HELP



Understanding nozzle performance and spray behavior within your specific process is essential for optimal operation and efficiency. BETE offers advanced expertise when our standard catalog information and complimentary Applications Engineering support are not enough to solve your spray challenge — guiding you through nozzle selection, troubleshooting existing spray issues, or developing entirely new spray systems. With capabilities in computational fluid dynamics (CFD), physical spray testing, and experimental design, our services offer significant enhancements for your spray processes, helping to reduce waste and support sustainable operations.

Advanced Spray Engineering Services begins by meticulously assessing your process objectives, challenges, and constraints, followed by a detailed concept proposal tailored to your requirements. Projects typically involve multiple phases, such as leveraging CFD modeling informed by physical models or laboratory spray analysis. Our facilities boast comprehensive testing capabilities such as flow rate and pressure measurements, droplet size, and velocity analysis using advanced instrumentation like imaging and phase-Doppler analyzers. Specialized studies include spray impact, coating uniformity, erosion patterns, and lifecycle testing.





BETE's engineering teams collaborate closely with our manufacturing and fabrication divisions, ensuring practical, manufacturable, and cost-effective solutions. Through our integrated approach, we offer scale testing, prototype validation, and detailed spray process analyses to address complex fluid handling scenarios effectively. Moreover, our experience testing high-viscosity fluid analogs and developing bespoke experimental setups further positions us to tackle unique industry challenges efficiently and effectively.

Ultimately, BETE's comprehensive spray engineering and testing services help ensure solution confidence by identifying and validating solutions that align with your operational goals.

BETE® PERFORMANCE SPRAY ENGINEERING DIVISION OF EXAIR®

A pioneer and innovator in all areas of spray nozzle engineering, manufacturing, and application solutions, BETE improves spray processes worldwide for numerous markets, including food and beverage, petrochemical, chemical, waste management and pollution control. We manufacture tens of thousands of different products, including misting and fogging nozzles, tank cleaning nozzles, chemical injection nozzles, custom spray lances, fabrications, and spraying systems.