Spray Gas Quench Design Considerations

Introduction

Rapid cooling or quenching of gas streams is used in a number of essential applications in the petrochemical industries. Examples of processes with gas quench systems include: reactor outlet, incinerator, coal gasifier, power plant absorber gas inlet. The selection and sizing of spray nozzles are the most critical decisions in the system design. BETE Fog Nozzle is qualified without equal to help you with your spray quenching needs. We have assisted in the design of hundreds of systems for our customers in the past 30 years.

We optimize gas-quenching systems to reduce quench vessel size, reduce atomization energy consumption, and minimize the risk of unexpected downtime, which obtains the economic benefits of capital and operational cost savings. Our Applications Engineers incorporate engineering fundamentals, product knowledge, design experience and your operating constraints to develop a reliable and cost-effective quench system.

Spray Quenching Fundamentals

The application of fundamentals in the design of spray quench systems is necessary to achieve the desired process robustness. Foundational to any design is the mass and energy balance. The bulk of the energy from gas cooling is absorbed in vaporizing the quench liquid. The rate of evaporation depends on heat and mass transfer, the drop surface area and relative motion of drops in the gas. The drop evaporation period as shown on the left is the most critical period. The gas inlet relative humidity determines the dew point temperature. With this temperature and the calculation in Equation 1 the residence time for the largest drop in the spray to evaporate can be calculated. Drop evaporation rate is proportional to the square of the drop size and inversely proportional to the temperature difference. In other words, if the drop size increases by a factor of two, then the evaporation time increases by a factor of four.

**Figure 1. Temperature profile**

**Equation 1.**

\[ \theta = \frac{\rho \lambda D_e^2}{8 k_e \Delta T} \]
Penetration and dispersion of the liquid drops into the gas stream is essential to maximize the evaporation rate and the uniformity of the cooling. The spray pattern in process applications narrows as the gas velocity increases. Figure 2 shows the effect of gas velocity on the spray width of various drop sizes. High gas density (elevated pressure and gas composition) and high gas velocity dramatically reduce the spray angle. Under extreme conditions a spray can collapse, resulting in limited dispersion of the drops into the gas stream. Therefore, drop trajectory calculations are essential to assure the design will provide sufficient drop penetration into the gas steam.

**Figure 2A.** 2.5 m/s gas velocity.
Gas velocity impact on drop trajectory with 45 psi nozzle pressure drop and 90 degree cone angle spray for 300 (red), 100 (blue) and 30 (black) micron drop diameters.
Analysis of spray penetration and evaporation requires a careful integration of the process conditions, gas velocity, nozzle spray pattern, and initial drop velocity. The droplet size distribution is a critical input to calculations of drop trajectory, evaporation time, and quenching rate. The well-characterized drop size distribution from BETE spray nozzles enables rapid analysis and optimization of a design. These analyses of quenching rate allow our customers to minimize vessel size and optimize system performance. The system configuration must also be considered to select the correct spray quench nozzle.

Figure 2B. 20 m/s gas velocity.
Gas velocity impact on drop trajectory with 45 psi nozzle pressure drop and 90 degree cone angle spray for 300 (red), 100 (blue) and 30 (black) micron drop diameters.

System Configuration

Spray quenches can be divided into configurations based on geometry and concept. The system geometry parameters are provided below.

- Orientation
  - Vertical systems may be up-flow or down-flow (direction of flow relative to gravity)
  - Horizontal
- Quench zone has a constant or a larger diameter than inlet piping
- Spray co-current or countercurrent with respect to gas flow

The design geometry decisions are determined by hardware constraints and other process considerations.

System geometry varies widely from horizontal or vertical configurations, up-flow or down-flow of the process gas, to in-line or process vessel. The “wet-wall” design concept uses a large excess of quench liquid, which results in a wetted vessel wall. Alternatively, a dry-wall design requires all of the spray drops to be completely evaporated without any liquid contacting the wall. A unique design is required for each application due to the large number of system geometries, process conditions, and performance specifications. Our engineering experience acquired over decades is incorporated into our recommendation for your application.

The process design concept is the most important factor in choosing a wet-wall or dry-wall system. Wet-wall quench systems must include hardware to remove and manage the large excess of quench liquid. Small diameter systems favor wet wall configurations. A dry-wall system requires an extremely small drop size to assure all drops evaporate in the short distance to the wall.
Wet-wall quench systems provide a very robust system when the process integration of quench liquid recovery from the gas stream and recirculation is optimized. Wet wall systems use a spray header at the wall to force gas thru dry (inlet)/ wet (quench area) interface. Excess water (10% or more) is used to assure gas cooling and assure all internal walls of vessel are wetted. Water on the wall also prevents particulate material collecting on the wall. An example of a recirculated wet-wall quench liquid system is shown in Figure 3. Some wet wall designs are direct contact coolers where the cooling is from heat capacity of cold liquid; not from the latent heat of liquid evaporation.

Dry-wall quench systems are used in most very large-scale flows. The spray nozzles are usually directed downstream co-currently or at an acute angle to the flow direction. Directing the spray against the flow increases gas pressure drop and yields some significant issues with managing turndown and can impede spray pattern development. Vessel geometry and size is dependent on process conditions, space available, and previous process experience. The simplest design geometry is the use of the piping as the quench vessel shown in Figure 4. A uniform fully developed turbulent velocity profile is expected in the pipe flow. Figure 5 shows the common inlet geometry of vessels used to provide residence time for gas quenching. The position and direction of the nozzles should consider recirculation zones. The vessel shape and inlet size determine the size and intensity of recirculation zones. System design must consider the recirculation zones in the placement of quench nozzles to prevent spray contacting the wall. Applications Engineers use process variables and BETE proprietary software to model the path of spray and recommend the most appropriate spray nozzle.

Figure 3. Wet-wall (direct contact) quench system recirculating the quench liquid. The quench liquid is common to the absorber tower.

Figure 4. Inline quench gas inlet at left showing a lateral header of spray nozzles

Figure 5. A and B: recirculation zones at inlet of vessel. The gas velocity downstream of the gas entry will result in a slightly higher gas velocity at the centerline.
Because of the wide variety of quench system sizes, configurations, and process requirements, there is no one best nozzle for all applications. Our design and application experience results in the optimal spray nozzle choice for your system. We assess your needs by determining the category of nozzle (single-fluid or two-fluid), the specific nozzle model, nozzle size, and material of construction. The range of operation from minimum capacity to design rate to a maximum rate is also considered in the nozzle selection. The spray angle and the arrangement of multiple nozzles are also design factors. Drop size, a critical design factor; is affected by pressure drop, spray angle, and nozzle orifice size as indicated in Figure 6. Increasing the orifice size to accommodate additional flow can be offset with a higher-pressure drop or a larger spray angle.

Table 1 shows specific nozzle models and types used in gas quench systems. Wet-wall quench designs often use single-fluid nozzles because of their simplicity and low cost. Wall washing flat fan nozzles are used to control the wet-dry wall interface to assure solids do not accumulate on the wall. Dry wall systems require a nozzle selection that provides a more finely atomized spray. Two-fluid nozzles are used in applications requiring a wide range of operation or when a short evaporation time is required.

The BETE SpiralAir™ nozzle provides highly efficient use of the atomizing air with a multistage atomization process and control of the spray pattern by the outlet passages design. Figure 7 shows examples of different spray patterns that can be used to optimize the spray dependent on gas velocity, residence time, and quench chamber dimensions.

BETE offers spray nozzle lance assemblies for single-fluid or two-fluid nozzles to meet process and materials requirements. Many of applications have specialized materials of construction needs to avoid corrosion and erosion caused by the quench liquid or the process gas. Our design and fabrication capabilities provide the broadest range of alloys for the nozzle and lance to meet your specific needs. We have fabricated quench nozzle lances from many different materials, such as stainless steel alloys, chrome alloys, nickel alloys, cobalt alloys, titanium, and duplex stainless steel alloys.

**Table 1. Nozzle types used for quenching.**

<table>
<thead>
<tr>
<th>Nozzle Type</th>
<th>BETE Nozzles</th>
<th>Quench Design</th>
<th>Nozzle Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-fluid flat fan</td>
<td>FF, SPN</td>
<td>Wet-wall</td>
<td>Fan pattern conforms well to wall wetting, high velocity assures solids do not accumulate on the wall</td>
</tr>
<tr>
<td>Single-fluid</td>
<td>Single-fluid</td>
<td>Wet-wall or</td>
<td>Fine atomization, simplified control dry-wall</td>
</tr>
<tr>
<td>Two-fluid</td>
<td>XA, SpiralAir</td>
<td>Dry-wall</td>
<td>Wide operating range, finest atomization for short residence times, variety of spray angles</td>
</tr>
</tbody>
</table>

**Figure 6. Factors affecting drop size.**

**Figure 7. Spiral Air™ spray patterns generated by various nozzles caps.**

**Figure 8. Lateral header with two-fluid nozzles.**
System reliability is influenced by many factors. Solids in the quench liquid are often the root cause of the two main factors that cause system downtime, plugging, and erosion of nozzles. Solids in the quenching media may cause nozzle clogging. Plugging internal passages of the spray nozzle leads to non-uniform and inadequate gas cooling. It is important to select the correct nozzle design and material of construction to maximize free-passage, reduce clogging and extend operating life. A strainer system in the upstream piping can also protect nozzles and maintain the nozzle performance by preventing repair work and unnecessary equipment shut downs.

The second factor is the erosion of internal passages and nozzle outlet that distorts the spray pattern and increases the drop size. Wear and erosion of nozzles depends on process specific conditions such as; the velocity of the liquid, the hardness of the particles in the liquid and the corrosive nature of the environment. Operational experience is frequently the best guide to assessing if erosion is a reasonable concern. Material selection is also an important design factor to minimize nozzle wear and extend the system operating life. BETE has the manufacturing capability and engineering experience to assist you in selecting the most appropriate nozzle construction material to withstand the operating environment.

Reliability Considerations

The process control of quench systems must be considered in the design phase to achieve the optimal result. The quench liquid flow is often controlled to achieve a desired quench zone exit temperature. Instrumentation to monitor single-fluid nozzle pressure drop is frequently used. Two-fluid nozzles require a more thoughtful and deliberate approach to control the atomizing gas and the liquid flow. One objective of nozzle control is to minimize the amount of atomizing gas (compressed air) and therefore, reduce the energy input to supply the atomizing media. Improved control reduces operational cost and stabilizes the system response to extreme conditions.

Process control

Wet-wall concept

The design of many wet wall quenches involves little process control because a constant liquid pressure is used to continually maintain the maximum required flow. This assures the quench spray system is always at peak performance. Highly variable inlet gas flows are robustly quenched with this simple control approach. The measured pressure drop is crosschecked with the expected spray nozzle pressure drop based on the measured flow. This measurement is valuable to identify any gross issues with the nozzles or flow measuring device. Control systems have many conditions that need to be evaluated. The spray design must be able to manage the possible situations given the combinations of flow paths and range of flows.
**Dry-wall concept**

Single fluid nozzles are often used with a narrow range of gas throughput, and where multiple lances are used to manage greater turndown requirements. The quench temperature control system determines the flow rate of quench liquid. Pressure drop control is used with multiple lances to maintain a minimum pressure drop to assure the drop size is smaller than a predetermined value. Turndown to less than 75% of design is managed by controlling the flow to the groups of nozzles to maintain the required drop size, as described in the first example.

Conventional flow control for two-fluid nozzles, shown in Figure 9, often used in dry-wall quench systems provides excellent and robust control. Numerous control strategies can be implemented based on overall system and process requirements. The design of large-scale systems with several second residence time, should consider the gas transit time from the spray to sensor as lag-time or dead time between controller action and the sensor response. This dead time varies depending on throughput and input temperature. Numerous potential control strategies can be implemented based on overall system requirements. One is a feed forward set point based on inlet temperature and mass flow. Multimode controllers using the combination of feedforward and feedback provide additional robustness, but add complexity.

Control of two-fluid nozzles is more complex than single-fluid nozzles; however, the range of operation is much broader. The myth is evaporation time is controlled by constant drop size. The reality is that under turndown conditions the gas residence time is longer and consequently the drop size required can be larger than in the maximum rate conditions. The flow control system described in Figure 10 can be used for internal-mix or external-mix nozzle types.

Internal-mix two-fluid nozzles need special attention on controller tuning because of the interaction between the gas and liquid control loops. For example, a slight increase in the liquid flow in a system with two independent mass flow controllers causes an increase in nozzle pressure drop which in turn causes the gas control valve to open. These actions result in feedback to the liquid control loop and ultimately overshoot of the liquid flow. The non-linear feedback can cause oscillatory behavior if the controller tuning parameters of the gas and liquid flows are not coordinated.

Backflow prevention is critical in internal-mix two-fluid nozzle piping to assure quench liquid does enter the compressed air header. Several features have been incorporated into the system as shown in Figure 13, recommended measurements of the flow and nozzle pressure drop for both the gas and liquid streams.

BETE Applications Engineering expertise can reduce the initial and long term cost of the quenching operation system.
**Maintenance Considerations**

Maximum reliability can often be enhanced with simple system configuration such as strainers to prevent small amounts of solids from plugging nozzles, as mentioned above. If nozzles are subject to high temperature environments and do not continually have a flow of liquid or atomizing gas, the nozzle will overheat and material failure can result. The risk of an unplanned shutdown is reduced with scheduled maintenance to manage wear or erosion of nozzles and to inspect for partial clogging and overheating nozzles. We recommend visual inspection and the development of a routine replacement plan. Some systems require nozzle change-out every 1 to 2 years to fully maintain the process performance. For clean liquid service an annual inspection is a starting point for a PM (Preventative Maintenance) program.

**Examples of Spray Quench Applications**

The examples below provide a perspective on the range of designs and considerations involved in system design.

**Pressurized Gas Quench**

A large-scale reactor gas dry wall quench system was used by a customer to cool a pressurized gas stream (~100 psi) from 1000°C to 250°C to protect downstream equipment. Because this system was refractory lined, a dry-wall design was essential to prevent excessive thermal stresses on the refractory. A high degree of turndown (8:1) was necessary to manage conditions from startup to full rate operation. The system geometry, shown in Figure 11, had a short distance between the liquid injection point and the end of the refractory lining. The customer initially used a nozzle (not from BETE) that cooled only to 500°C. The nozzle used was a spring-loaded pintle type designed as a steam-desuperheating nozzle, which resulted in a large drop size at a higher flow. BETE Applications Engineering analysis showed the excessive drop size produced by this nozzle and the system configuration were the root causes of inadequate cooling. The spray impinged on the refractory wall and liquid flowed at the bottom of the piping. The surface area of the liquid stream flowing co-currently with the gas limited the ineffective heat transfer.

The system designed in collaboration BETE Applications Engineering was a group of 19 BETE TF 8 FC nozzles arranged as shown Figure 11B. These were sized to operate at a pressure drop of 200 psi to achieve the desired drop size and spray penetration into the high velocity gas steam. The system required the addition of a high-pressure centrifugal pump to deliver quench water to the spray nozzles. Three lateral headers were used to manage the turndown. At low rate only one header would be in operation and a gas purge would cool the other headers. Full rate operation would have all three headers in operation.

The resulting quench system design only required fine-tuning of the transition points between the operation of one, two, and three headers. High reliability was achieved with careful consideration of all the operating modes and proper material selection even though the spray lances were in a harsh high temperature environment.

![Figure 11A. Cross section of original system showing nozzle centrally mounted in the 1 meter ID system.](image)

![Figure 11B. End view of header system and nozzles.](image)
Acid Gas Quench

A customer’s acid gas recovery from energy efficient thermal treatment systems required the cooling of Hydrogen Chloride acid gas between a heat recovery boiler exit from 250°C to 50°C at the entrance of an absorption tower. The quench liquid for this wet-wall design was the strong acid from the absorber tower. As with many wet-wall designs, the amount of evaporation of the quench liquid is approximately 10%. Entrainment of small droplets into the packed tower reduces the countercurrent absorption efficiency. Therefore, a larger drop size with sufficient surface area for heat transfer was needed. A cost effective solution was required that was compatible with the corrosive hot aqueous HCl.

The nozzle selected by BETE Applications Engineering BETE TF 16 FC made from glass filled PTFE. This material choice allows operations with HCl at approximately 30 psi to achieve the drop size of 350 micron required for the heat transfer. These nozzles were mounted in an ejector venturi inducing gas flow through the system.

Gas Cooling Example

A confidential process being developed by a customer required the cooling gas stream to be instantaneous and uniform. The drop size needed to achieve the 50-millisecond evaporation time and quench liquid flow rate restricted the nozzle type to the two-fluid nozzle. Steam was chosen as the atomizing gas medium because any non-condensable gas would add to the overall process complexity. The BETE XASR external-mix nozzle was selected to allow the most efficient use of steam. An internal mix nozzle would have required additional steam to preheat the liquid to saturation.

The process performance met all expectations for the entire range of operating conditions and rates.

Summary

An optimized spray quench design requires engineering analysis of the operating environment, spray nozzle performance and process reliability. BETE Applications Engineers will partner with you to develop and optimize the quench system for your application. Our analysis tools and experience with hundreds of applications provide a rapid and robust engineering design of your spray quench system. The result is a quench system that operates efficiently and reliably for your process.

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