Fiber bed mist eliminator refresher: theoretical fundamentals vs. real world

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This article provides insight on how mist particles are captured in diffusion fiber beds and what is required to assure sustained state-of-the-art fiber bed mist eliminator performance. The first part of this article briefly discusses the theory of mist capture mechanisms, and the second part describes real world design and quality control.

There are three main mist collection mechanisms utilized by high efficiency diffusion fiber bed mist eliminators, as illustrated in Fig. 1. They are: Impaction, Interception and Brownian Diffusion.

Impaction

The inertial impaction mechanism collects a mist particle in a gas stream when it impacts a fiber. A particle has volume and density. The bigger the particle, the more mass it contains. If the gas velocity is fast enough, the mass of the particle moving within the gas will have adequate momentum to cause it to impact a fiber and stick by weak Van der Waals forces rather than continue following the gas streamline around it. The larger the particle diameter, the more momentum it has, and the easier it is for capture by the impaction mechanism.

From a theoretical view, it is true that particles can be collected by impaction if momentum, as represented by the Stokes number, overcomes the drag force in a gas stream where no eddies are present downstream of the collecting fiber.

The Stokes number is represented as:

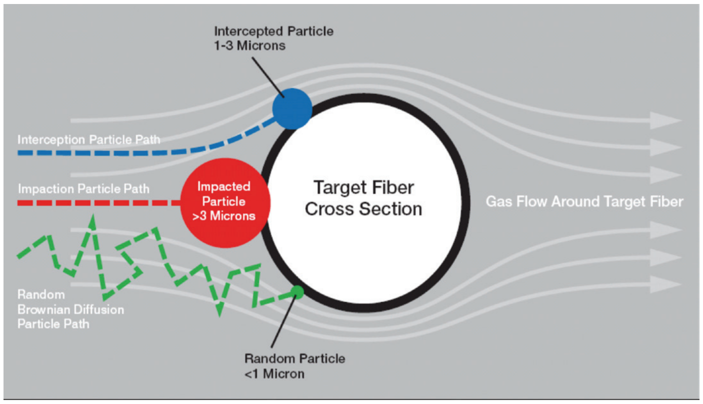

Fig 1: Illustration of mist capture mechanisms.

$$S_t = \frac{d_p^2 \rho_p V}{18 \mu_g d_f}$$

Where dp = mist diameter, ρp = mist density, V = mist velocity, µg= gas viscosity and df = fiber diameter.

Note "V" is the interstitial velocity, which is the velocity between the fibers that are present within the matrix of the fiber bed, so it must be corrected for the void space of the fiber bed in the fully wetted, steady state condition during operation to accurately calculate the Stokes number. Thus, the Stokes number is difficult to derive because it requires an understanding of how collected mist is distributed on individual fibers within the fiber bed. Further complicating this is that collecting fibers have a nominal fiber size distribution, so the Stokes number will vary as a function of the diameter of the fiber that the incident particle collides with.

The gas drag force is represented as:

$$F_D = \frac{1}{2} \rho_g A C_D v^2$$

Where ρg = gas density, v = speed of the mist particle relative to the gas, CD = gas drag coefficient and A = cross sectional area of the collecting fiber.

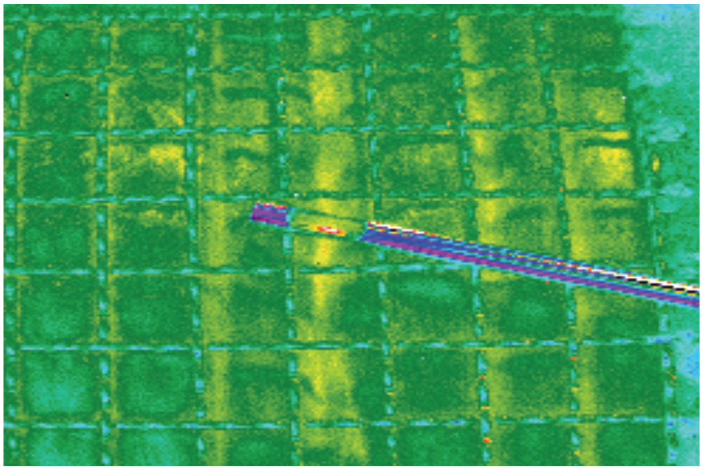

Fig 2: Example of a fiber bed thermographic image.

As such, the formulas described earlier can give a crude approximation of collection efficiency due to impaction. However, flow streams in a fiber bed are much more complicated than shown in Fig. 1 due to the complexity of the fiber matrix in the actual fiber bed and how coalesced mist is retained and/or migrates within the collecting fibers.

Interception

The second mist collection mechanism is direct interception. This means the mist particle is intercepted from the gas stream if it cannot squeeze between two fibers (or if it touches the tangent of a fiber as it passes within the barrier layer between the freely moving gas and the fiber surface, sticking to the fiber by means of weak Van der Waals forces). Consider a particle 1.0 micron in diameter that follows a gas streamline passing within 0.5 micron of a fiber. The particle will touch the fiber and be collected by interception. This mechanism is similar to the action of a mesh filter or sieve.

Brownian diffusion

Impaction and interception are the primary collection methods employed by devices that are designed to remove larger mists from a gas stream. In order to remove sub-micron mist particles out of a gas stream, however, a third mist capture mechanism called "Brownian

Motion" or "Brownian Diffusion" must be utilized. All molecules in a gas stream are in constant, random, thermally induced motion. This molecular motion causes collisions between gas molecules and suspended mist particles. As mist particles are bumped by surrounding molecules of gas, the momentum exchange causes a randomly oriented "zigzag" effect on mist particle motion. Since these collisions have little energy, this mechanism is effective for only very small particles (typically less than 1 micron) and decreases in intensity as the particle size increases. Therefore, the smaller the particle, the greater its random motion (also known as particle diffusivity) and the more likely an incident particle will collide with a fiber and stick (collect) by weak Van der Waals forces during transit through the fiber bed.

For describing mist capture by diffusion, the modified Stokes-Einstein equation for diffusivity is used:

$$D = \frac{k_B T C}{3\pi \mu_g d_p}$$

Where kB = Boltzmann constant, T = temperature, C = Cunningham slip correction factor, µg= dynamic gas viscosity, and dp = mist particle diameter

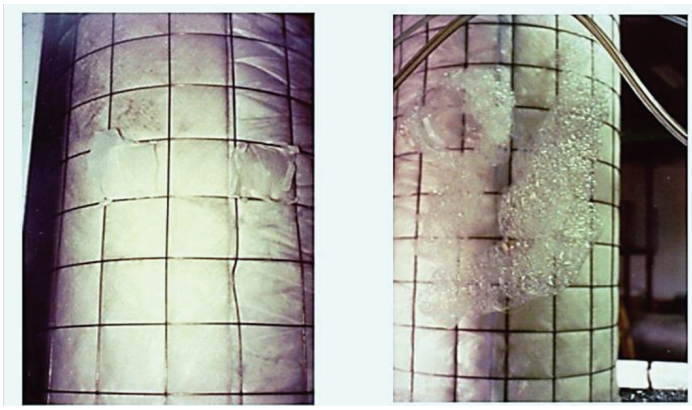

Fig. 4: Demonstration of effective gas/liquid separation using a drainage layer.

The Stokes-Einstein equation is the theoretical diffusivity of a particle and predicts only the intensity of the random motion a particle exhibits. It should not be inferred that this equation predicts mist collection, which would be true if a fiber bed consisted of a single fiber and the flow stream around the fiber were a "textbook" flow pattern, as shown in Fig. 1. In reality, the flow of process gas through a fiber bed is much more complex and the path the process gas takes through a fiber bed is torturous. (A single fiber bed for some sulfuric applications contains a length of glass fiber equal to the distance between the Earth and the Moon). Additionally, many other factors contribute to determining mist capture, including the amount of collected mist retained within the fiber bed at steady state, mist residence time as it passes through collecting fibers, mist properties, fiber bed uniformity and general fiber bed properties to name a few.

Many academia-based fiber bed mist elimination research studies have been performed in an effort to evaluate mist collection using very small scale filters, often in a dry operating state with very low inlet mist levels. These studies often assume homogeneous liquid distribution to simplify the prediction of mist collection when the filter is saturated. In reality, large diffusion fiber beds in sulfuric acid plant service are not homogeneously saturated, which adds another level of complexity in predicting performance. Therefore, technology provider experience, based on development of semi-empirical models supported by rigorous field measurements, is critical to accurate prediction of diffusion fiber bed collection efficiency and operating pressure drop. The MECS sulfuric acid field mist sampling database has over 50 years of field acid mist measurements in support of Brink® fiber bed design models.

Real world design & quality control

Diffusion fiber bed mist eliminators used in sulfuric acid plants are very large compared to, for example, cartridge filters. One of the product attributes that is very important to control is fiber bed packing uniformity (or homogeneity). As a means of obtaining a visual "qualitative" perspective of homogeneity, MECS developed a thermographic imaging technique in the 1970s. The test is performed by blowing a controlled flow rate of warm air through the fiber bed while using a forward looking infrared radiometer (FLIR) system to detect temperature variations (hot and cold spots) on the downstream side of the fiber bed as a function of position. Thermographs, however, are only a qualitative indication to determining whether there

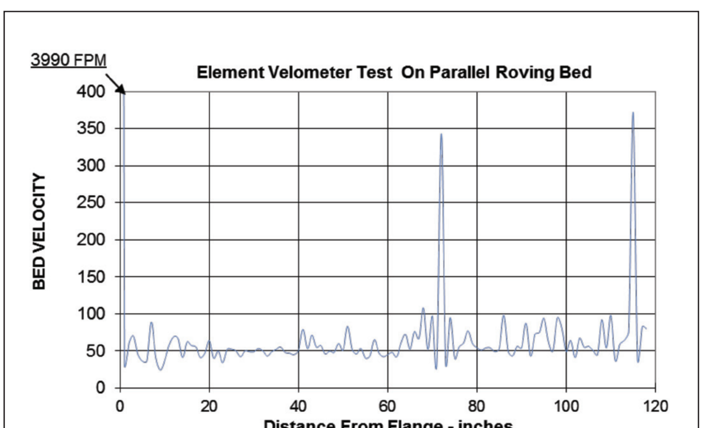

Fig 3: Example of a fiber bed velocity profile.

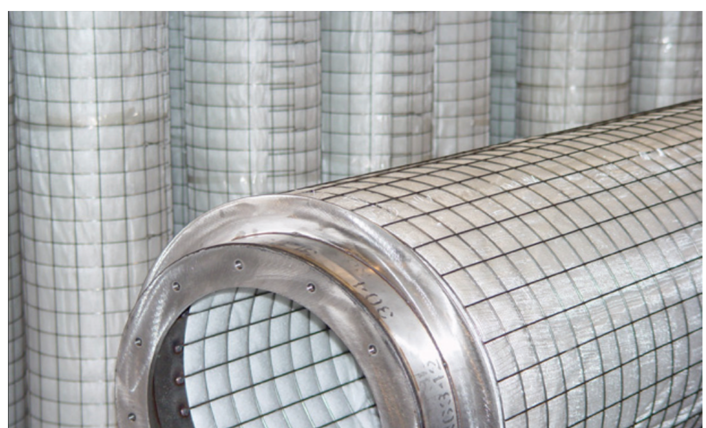

Fig. 5: Brink® XP™ Mist Eliminators.

are fiber bed non-uniformities. To be effective, they must be performed at close range to the element surface using a small temperature gradient with high color contrast.

Fig. 2 is a thermographic image demonstrating a significant "hot spot" observed on a parallel packed fiber bed at a weak spot in the packing. This is likely where parallel glass fiber rovings happened to line up when the element was hand wrapped.

The only sure way to quantify fiber bed uniformity is with velocity profiles using a velometer. A velometer also is shown in the Fig. 2 thermograph image directly measuring actual gas velocity at the hot spot. Complete velometry measurements are often carried out by MECS to allow for continuous improvement of Brink® fiber beds as these measurements relate to variance of raw material supplies and fiber bed manufacturing process. With the same parallel wrapped element shown in Fig. 2, a velocity profile was taken along the entire length of the element that crossed the "hot spot" (Fig. 3). Measurements indicated gas velocities over some areas were very high (3990 fpm, 340 fpm and 370 fpm) compared to the average over the rest of the length of the fiber bed (~ 50+ fpm).

High velocity spikes can significantly reduce theoretical capture of mist particles discussed earlier. When this type of element is placed in service, velocity spikes contribute to poor mist eliminator performance in two ways: penetration of submicron mist particles due to reduced contact time with collecting fibers, and formation of re-entrainment (large particle regeneration) due to increased shear of collected mist draining from the downstream exit gas surface of the fiber bed.

Another routine quality control measurement is dry element pressure drop taken at a controlled gas flow rate, which is a means of determining the fiber bed dry gas flow resistance. This QC measurement is a good quality check to ensure all elements have the same individual gas flows when placed in service, which ensures all elements work equally together. An imbalance in gas flow between elements will result in less than ideal performance.

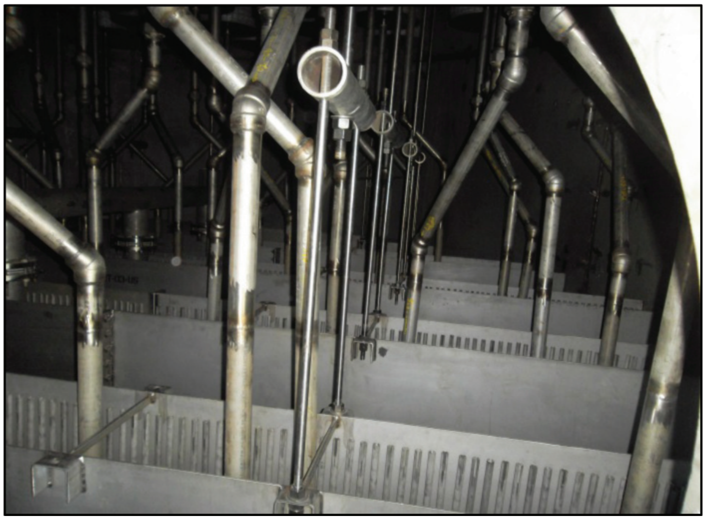

Fig. 6: Element seal legs routed to distributor troughs.

If one looks at the difference between fiber beds manufactured with identical dry gas flow resistance, one that is wrapped with computer controlled placement versus another that is hand packed, the difference is apparent. The hand wound element will contain velocity spikes as described earlier, while a properly packed fiber bed that was manufactured with the computer controlled placement technique will not. Thus, not only is it important to select a fiber bed with matched dry bed flow resistances, it is also important to manufacture the fiber bed with uniform packing density (high homogeneity) to assure best-in-class performance is achieved for protection of downstream equipment.

Also, even if angle and parallel wrapped roving fiber beds are made to the same dry bed resistance, this does not result in the same operating pressure drop in process service under identical inlet conditions. MECS developed the angle roving wrapped diffusion fiber bed mist eliminator in the 1970s as part of an extensive research program using sulfuric acid mist. It was discovered that equilibrium retention of collected mist (and steady state saturated operating pressure drop) is reduced by wrapping glass fiber roving at an angle instead of a parallel orientation (relative to the ground or support tubesheet). With less liquid retained in the fiber bed, this resulted in lower operating pressure drop, lower re-entrainment and higher overall collection efficiency of submicron mist.

Fig. 7: More space under elements using AutoDrain.

For many applications, even those outside sulfuric acid, angle wrapped roving diffusion fiber beds typically provide up to 20 percent more gas throughput compared to bulk packed fiber beds for the same operating pressure drop and collection efficiency (or equivalent reduction in pressure drop for the same number of elements). This is due to the fact that a fiber bed that is packed with computer controlled precision with the fiber at an angle is more uniform than a fiber bed that is packed by hand. Additionally, the angle wrapped interlocking roving is a more stable and uniform pack when compared to parallel hand wrapped roving, bulk packed or donut-style fiber beds. Mullins et. al. (Mullins, 2003) clearly demonstrates that fibers oriented at an angle relative to grade show a marked tendency to allow liquid droplets to flow when the mass of the liquid droplets on the fiber allows them to overcome adhesive forces. This paper supports MECS's research and development findings that a fiber bed with angle wrapping operates with lower liquid retention and lower operating pressure drop.

Another innovation developed with the angle wrapped diffusion fiber bed is the bi-component fiber bed design, which virtually eliminates particle regeneration (re-entrainment). A drainage layer comprised of proprietary coarse fiber media is oriented downstream of the collecting layer. Even with the most uniform fiber bed mist eliminator, if only collecting fibers are used, liquid films will easily form between fibers among the interstitial spaces. When these films break, droplets can be produced that add to emissions from the fiber bed. More importantly, if these films form on the gas discharge side of the fiber bed, the result will be particle regeneration of some portion of the collected mist back into the gas stream. The result of re-entrainment is normally mist particles a few microns in diameter or larger. The quantity of re-entrainment depends on several parameters, especially inlet mist loading, bed velocity and exit velocity.

MECS bi-component fiber bed offers a means of reducing the amount of re-entrainment by providing a downstream gas-liquid disengagement zone to allow collected liquid to drain away without further interaction with the gas phase. Re-entrainment control is very important to sulfuric acid customers to minimize downstream corrosion of ductwork, to protect catalyst and prevent high stack emissions. Unfortunately, since re-entrainment is difficult to measure, often clients will use fiber beds without a drain layer and realize only years later the effects of downstream equipment corrosion. Additionally, not all re-entrainment control materials are created equal. MECS experimented with many different materials as part of its research and development program in the 1980s to determine the proper orientation, fiber size and density for this material to achieve proper re-entrainment protection.

To illustrate the effectiveness of using a bi-component fiber bed design, two portions of a drain layer were removed from a standing research element shown on the left side of Fig. 4. Gas was pushed through the fiber bed from the inside to outside. When a water solution containing a small amount of soap was injected into the inside of the element, bubble formation was observed on the outside of the element coming from the two areas where the drain layer was removed. This illustrates the effectiveness of the drain layer under flow conditions in reducing formation of bubbles and films at the gas discharge surface of a fiber bed and how significant performance improvement can be realized in sulfuric acid plant service using bi-component fiber beds.

Recent diffusion fiber bed innovations

As a result of MECS' continuous improvement through research and development, there have been recent significant advancements in Brink® diffusion fiber bed technology with the introduction of the eXTra Performance XP™ mist eliminator and AutoDrain™.

Following a decade of research and development along with over 10 years of acid plant experience, MECS now designs and builds the XP for all acid towers (Fig. 5). For typical tower acid mist loadings, the XP offers the lowest pressure drop available in one-to-one match-ups when compared to other elements. Due to its patented uniform collecting fiber arrangement, XP operating pressure drop is up to 50 percent less compared to the original HE style hand packed fiber bed mist eliminator invented by Dr. Joe Brink in the 1950s. Thus, the new XP fiber bed technology can provide sulfuric acid plant installations with significantly lower operating pressure drop or fewer elements compared to conventional designs.

Beginning with the original Brink® hanging HE style fiber bed mist eliminator, element seal legs have been used since the 1950s. Another recently patented and demonstrated innovation is the Brink® AutoDrain™ for hanging style diffusion fiber bed mist eliminators. A novel arrangement integrated into the bottom of the element allows for collected mist to drain on the upstream gas side of the element, thus eliminating the need for seal legs.

As shown in Fig. 6, seal legs from hanging fiber beds routed to open distribution troughs result in a very congested space making maintenance very difficult. Fig. 7 shows the area under elements that use AutoDrain™. It is apparent the working space around the distributor is significantly more open for maintenance. In addition, using AutoDrain™ saves significant expense by eliminating element seal legs, plant downtime, and labor required for seal leg installation.

Wrap-Up

Providing outstanding diffusion fiber bed mist eliminators is not as simple as just using a theory-driven approach to design. In addition to theory, it is important to use field experience in actual sulfuric acid service to provide a product that will consistently meet or exceed industry needs. Since 1958, MECS, Inc., has been the pioneer in development, and improvement of successful Brink® Mist Eliminators. Along the way, MECS has improved semi-empirical design models upon which its invention is based. Beyond theory, in order to attain predictable, reliable performance, it is important to assure raw materials are always within specification and elements are made with consistent uniformity using the latest in manufacturing techniques. MECS QC relies on various methodologies to measure fiber bed properties, including but not limited to: velocity profiles, matched flow resistances, and dry bed manufacturing pressure drop measurements. Finally, continued investment in research and development programs help create new inventions and innovations that bring more value to clients.

In conclusion, world-class mist eliminator performance in sulfuric acid service is a result of using theoretically sound, semi-empirical design models that have been field-verified over many years. Optimum performance is maintained by providing proper designs, unwavering attention to manufacturing techniques, quality control, continuous improvement and customer support.

For more information, please visit www.mecs.com. ❑

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