Ultra-low entrainment spray nozzles for use in packing wash applications

Development and performance of new spray nozzle technology can greatly reduce entrainment from vacuum distillation wash bed sprays

Alejandro Lago and Ashwin Patni
Lechler Inc.

Entrainment of liquid gasoil droplets in the wash section of a vacuum distillation column can lead to critical process reliability issues and distillate purity issues. Entrainment can be reduced by using a new spray nozzle technology designed to generate coarser diameter droplets, ensuring a larger percentage of wash oil makes it into the wash bed packing. Extensive testing shows that in comparison to traditional maximum free passage-style spray nozzles, the new spray nozzle technology can produce a much more favourable spectrum of droplets, which can be correlated to a significant reduction in entrainment from a wash oil spray header. Theoretical Stokes' Law-based entrainment calculations based on this droplet data being sprayed in a counter-current tower of ~0.4°C factor result in an entrainment reduction of around 300% in comparison to traditional spray nozzles commonly used in this service.

VDU wash section

Vacuum distillation plays a critical role in various industries, such as petroleum refining and chemical processing, where the extraction of volatile components under reduced pressure is necessary. Refinery vacuum distillation units (VDUs) allow for the processing of heavier oil feeds slumped from upstream atmospheric distillation units. By drawing a vacuum in this column and thus reducing the boiling point of the feed, these heavier oil feeds separate more effectively.

A typical VDU is comprised of multiple levels of packing, trays, and/or spray nozzles. Spray nozzles are generally found in two regions: wash sections and pumparound sections. The focus of this article will be the VDU wash section, typically comprised of a short section of packing and a wash oil spray header located above this packing. The wash zone in a distillation column is responsible for removing non-volatile, entrained heavy metals and heavy end contaminates from the rising vapour.

In theory, the wash zone spray header feeds liquid gasoil to the packing to facilitate contact between the vapour and liquid on the surface area of the wash bed packing. The intent of this spray header is to provide evenly distributed liquid to the wash packing, which provides the wetted interfacial surface area for the liquid contact of incoming vapours. It is imperative that this packing remains wetted, as liquid dry-out can lead to operational upsets due to premature coking or fouling.

As refiners push VDU towers with the intent of optimising yields, they often face challenges in the wash section since high vapour velocities coupled with high wash rates create a perfect environment for the carryover of small droplets created by conventional, maximum free passage- style spray nozzles. This article aims to address the issue of entrainment of liquid gasoil in the wash section by using a new spray nozzle technology that produces a favourable droplet spectrum.

By increasing the percentage of large droplets and decreasing the percentage of small droplets created by the spray nozzle, more of the total volume of gasoil will overcome the drag forces of incoming vapour and allow for more effective washing of the packing. This can contribute to more efficient distillation in a column, extend the runtime of a distillation column, and help avoid unplanned shutdowns due to premature coking of the bed, which is generally caused by unwetted packing.

Entrainment in vacuum distillation

Entrainment is an undesirable phenomenon in which liquid droplets generated by a spray nozzle are carried away, or entrained, by a vapour phase in a distillation column in a counter-current arrangement. In vacuum distillation, droplet entrainment occurs when the velocity and momentum of descending liquid droplets are overcome by the drag forces of an ascending vapour stream. Spray nozzles generate a population of droplet sizes with corresponding velocities and mass.

A fraction of droplets are entrained if their mass, velocity, and droplet size are not sufficient to overcome the drag forces generated on the droplets by incoming vapour. For this reason, it is important to minimise the volume fraction of small droplets, which have a higher tendency of becoming entrained. Moreover, as vapour side velocity increases, it exerts a greater drag force on spray droplets, essentially increasing the threshold of entrained droplets to a larger droplet diameter.

Spray nozzle hydraulics also impact entrainment. As differential pressure across the spray nozzle increases, more energy for atomisation is introduced, creating finer droplets that are more easily entrainable. Entrainment thus becomes

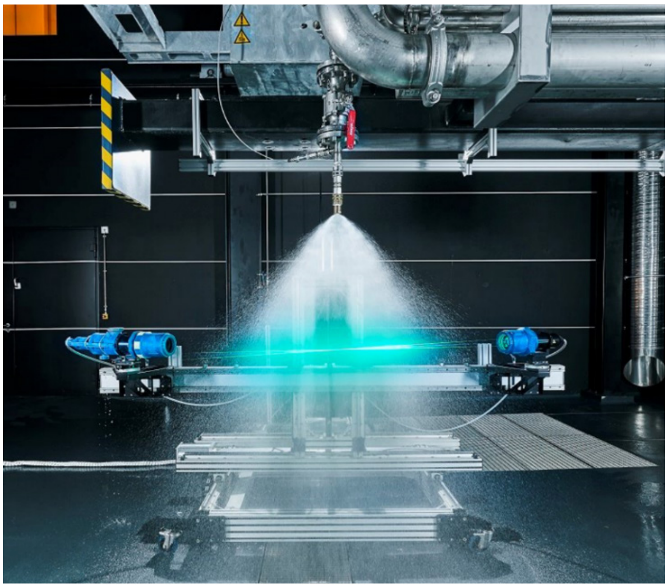

Figure 1 Image of traverse PDA spray plume analysis

more pronounced when both the liquid feed rates and vapour feed rates are relatively high. High levels of entrainment in a vacuum distillation column can pose undesirable consequences, such as a higher propensity for coking and reduced yield, which are detrimental to the overall distillation efficiency of a tower.

Guiding principles: Full cone spray nozzle design

In the field of spray nozzle development, several interrelated design levers can be adjusted to reach desired performance characteristics. The shape of internal and external spray nozzle geometries plays a major role in droplet sizes, droplet trajectories, spray angle, and clog resistance. However, certain guiding principles in full cone spray nozzle development cannot be circumvented. For instance, under identical operating conditions (same flow rate and differential pressure), two nozzles with different exit orifices will generate different droplet sizes.

Figure 2 SMDmax model 4HR.208 during testing

A nozzle with a larger exit orifice will generate larger droplet sizes and vice versa. Moreover, in the case of two full-cone nozzles delivering 10 gallons per minute (GPM) at 10 pounds per square inch gauge (psig) differential, the free passage of a nozzle with a 90-degree spray angle will be larger than that of a nozzle with a 120-degree spray angle. Also, it is generally observed that the spray angle of a nozzle is inversely related to its free passage, assuming all other factors remain constant.

Regarding droplet size, when two spray nozzles operating at the same differential pressure are observed, the nozzle with a greater flow capacity produces larger droplets than a smaller capacity nozzle. For example, a nozzle designed to spray 10 GPM at 10 psig will produce larger droplets than a mechanically identical nozzle designed for 5 GPM at 10 psig. It is important to consider all these guiding principles in chorus during the conceptual design phase of a new spray nozzle in an effort to satisfy both process and operational expectations.

Maximising free passage

Conventional spray nozzles that are widely used today in the wash sections of vacuum distillation columns were primarily designed to be fouling resistant. The design of these nozzles centres on maximising the ‘free passage’ of the spray nozzle in the hope of reducing nozzle clogging with little consideration for their atomisation characteristics. Traditional maximum free passage-style nozzles tend to create a significant percentage of fine droplets, especially when operating at higher differential pressures. In an effort to overcome limitations tied to conventional wash bed spray nozzles, Lechler embarked on a product development journey to design a spray nozzle specifically for use in counter-current wetting applications. During the conceptual design phase, a wish list of design parameters was gathered from key distillation stakeholders and ordered in terms of importance to both process and operational considerations: entrainment reduction, clog resistance, good distribution, and self-draining axial design.

Spray nozzle internals are critical to both droplet formation and clog resistance. Differential pressure is converted to kinetic energy within a spray nozzle to promote the rotational motion of the liquid being sprayed. A spray nozzle does not produce a uniform droplet size at any given operating condition; instead, the spray plume is comprised of a spectrum of droplet sizes. The characteristics of this droplet size spectrum are largely dependent on the mechanism of atomisation within the nozzle or, more specifically, the internal geometries of the spray nozzle. Since entrainment reduction was the key driver for this new product, the new spray nozzle design had to feature internal geometries that promoted the creation of coarse droplets while reducing the percentage of fine droplets. To achieve this, energy from differential pressure had to be dissipated within the spray nozzle to reduce the spray nozzle’s propensity to over-atomise.

Since clog resistance was a secondary design driver, experience with a vaneless swirl chamber design was leveraged to ensure the product featured both entrainment reduction and large maximum free passage characteristics. Traditional axial full cone nozzles rely on the constriction of an open cross-sectional area, known as a swirl vane or swirl insert, to increase liquid velocities and turbulence within the spray nozzle chamber. This turbulence promotes small droplet formation.

The internals of the proprietary SMDmax spray nozzle feature unique large-diameter channels to aid in the dissipation of energy from the liquid stream being sprayed. These channels feed an engineered swirl chamber to develop a spray plume without excessive turbulence and the penalty of a constricted cross-sectional area. This distinctive design of the internals of the spray nozzle allows for the production of very coarse droplets for spray nozzles that have relatively low flow rates.

In the process of making the droplet size bigger, the vaneless design also offered a much larger free cross-section area compared to the traditional free passage design. For similar nozzle capacities operating at the same differential pressure, a vaneless full cone design offers approximately a 90% larger free cross-section area. Additionally, the coarse droplets inherently have higher mass than finer droplets. Since momentum is directly proportional to a droplet's mass, the droplet's chances of reaching packing are greater when compared to a similar velocity but smaller diameter droplet.

Extensive spray testing was conducted to evaluate the performance of both the new SMDmax spray nozzles and conventional nozzles widely used in this application. The spray lab used to facilitate this testing was established in 2019 and features state-of-the-art measurement technology in a controlled environment, as seen in **Figures 1** and **2**. The experiments focused on gathering droplet size and droplet velocity data of spray nozzles traditionally used in the wash section of vacuum towers and the new nozzle design on the same Phase Doppler Analysis (PDA) equipment in order to draw conclusions on a comparable basis.

Traverse spray plume analysis (across the entire spray plume) was carried out at various operating points (3, 5, 7, 10 psi differential pressure) in an effort to holistically understand the spray plume's characteristics across the typical operating range of a wash bed spray nozzle. It is important to note that testing was conducted using water, spraying in a downward direction in atmospheric conditions. Test conditions differ from the actual operating conditions of a wash-bed spray header.

However, the intention of the spray testing was to illustrate directional improvements in performance against widely used traditional nozzles in this service. Trends in both droplet sizes and velocities would still hold true when comparing spray characteristics of liquids of different densities and surface tension.

The PDA equipment used to gather spray droplet information measures the droplet sizes of the entire spray plume in real time to populate droplets based on their diameter. A typical droplet size report illustrates the number of droplets of a certain diameter in addition to the cumulative volume percentage of liquid based on these measured droplet size values. **Figure 3** is an overlay comparison of droplet data between both a traditional maximum free passage-style nozzle and a comparable capacity Lechler nozzle (Part No. 4HR.148). Both nozzles have the same equivalent flow rate at differential pressure, and the data shown are for both nozzles at a differential pressure of 10 psig.

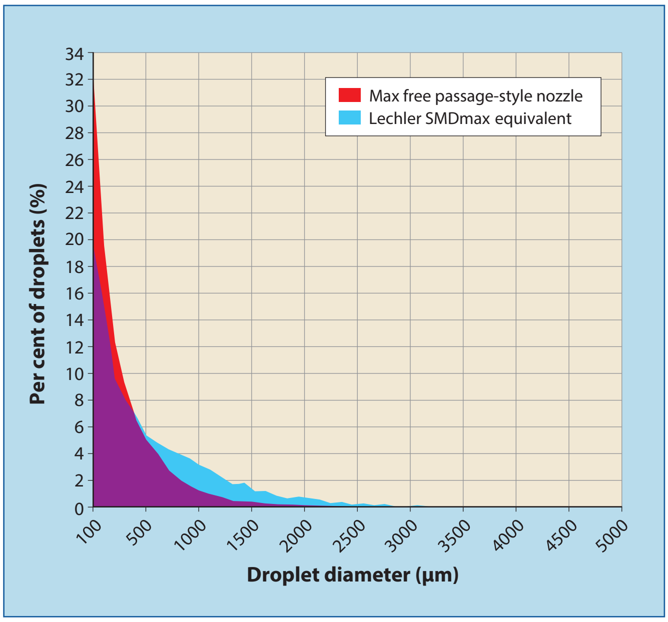

Figure 3 Droplet size summary of the Lechler SMDmax (4HR.148) compared to conventional nozzles

The SMDmax spray nozzle produces a significantly higher percentage of larger droplets when compared to a standard maximum free passage nozzle. The purple region in Figure 3 is droplet population that is common to both nozzles. The red region towards the top left of the plot represents droplets unique to the conventional nozzle that are below 500 microns.

Conversely, the light blue region represents a population of droplets unique to the SMDmax spray nozzle, which are

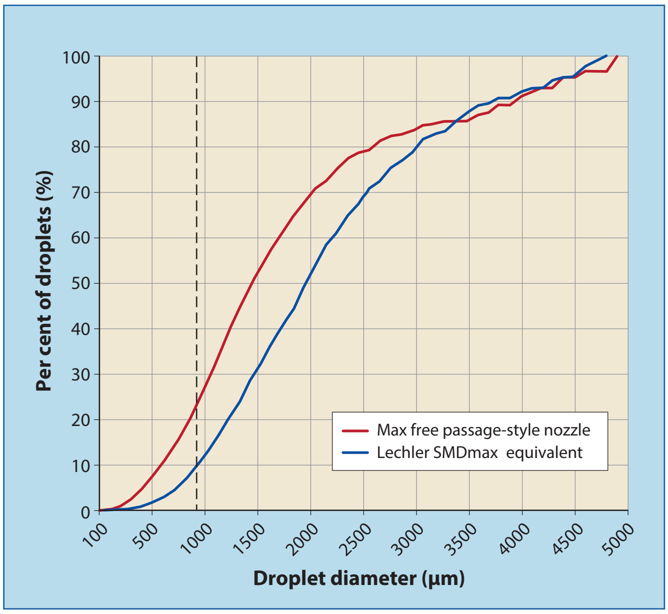

Figure 4 Cumulative volume per cent of Lechler SMDmax (4HR.148) compared to conventional nozzles

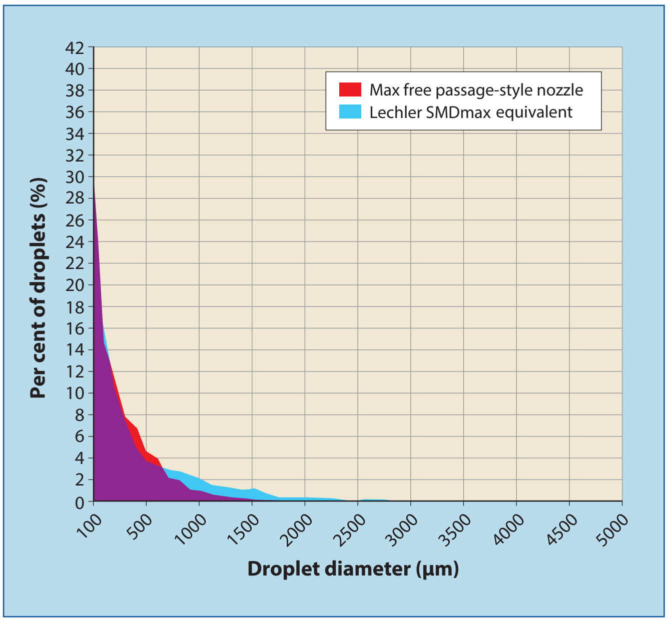

Figure 5 Droplet size summary of the Lechler SMDmax (4HR.008) compared to conventional nozzles

greater than 500 microns. This region represents 20.6% of total droplets produced by this nozzle. Moreover, since volume is a cubic function of diameter, the higher spectrum of larger droplets shifts the overall volumetric flow fraction towards the non-entrainment region, illustrated in **Figures 4** and **6**.

This variation in droplet size is also notable in terms of Sauter mean diameter (d32) particle size, which in this case is 1,912 microns for the SMDmax and 1,213 microns for the traditional nozzle. This large variation in droplet spectrum suggests a significant decrease in entrainment when using an SMDmax spray nozzle. Theoretical Stokes' Law-based entrainment calculations based on this droplet data sprayed in a counter-current tower of ~0.4 C factor result in a reduction of entrainment of around 300% in comparison to traditional spray nozzles commonly used in this service.

The cumulated volume curves (see Figure 4) illustrate the percentage of volume of liquid sprayed as a function of droplet size. If one was to suppose that droplets smaller than 975 microns in diameter were to be entrained, the cumulative volume percentage curves illustrate that 6% of the total volume sprayed from a Lechler (4HR.148) nozzle would entrain, whereas 24% of the total volume sprayed from a traditional maximum free passage-style nozzle would be entrained. This 18% difference represents a reduction in the uplift of gasoil and an increase in wash oil rate through the packing.

The use of the next-generation spray nozzle allows for more flexibility in operation. The refiner can choose to wash conservatively by ensuring more gasoil makes it to the vacuum tower bottoms or, conversely, reduce wash oil rates in an effort to maximise yields and improve distillation efficiency. This translates to either a reduction in operational costs by avoiding unplanned shutdowns due to premature dry-out-induced coking of the wash bed or reducing the uplift of gasoil, which is a high-value product.

The entire product line was spray tested to ensure directional improvement in both droplet sizes and free passage, irrespective of the capacity. Test data at 10 psig differential pressure of the smallest capacity Lechler SMDmax (part no. 4HR.008) compared to an equivalent capacity traditional maximum free passage spray nozzle commonly used in wash zones can be seen in **Figures 5** and **6**. The cumulated volume curves in Figure 6 illustrate an even larger offset than that of the larger nozzles in Figure 2.

At 10 psig differential pressure, the cumulative volume of droplets less than 975 microns is roughly 7% of the total volume from the new nozzle. In contrast, a traditional maximum free passage-style nozzle of the same capacity produces roughly 31% of the total volume in this droplet size range. If one assumes that droplets of less than 975 microns were to be entrained, this would suggest that 24% more gasoil by volume would be washing packing as intended using the next-generation spray nozzle.

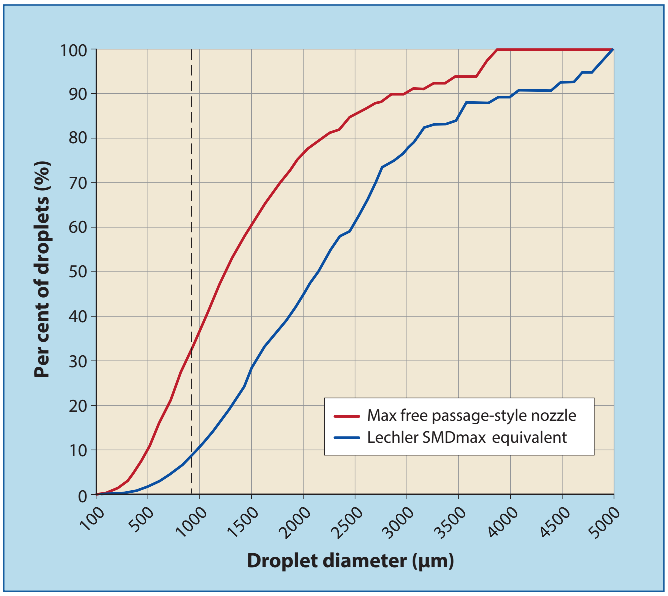

Figure 6 Cumulative volume per cent of Lechler SMDmax (4HR.008) compared to conventional nozzles

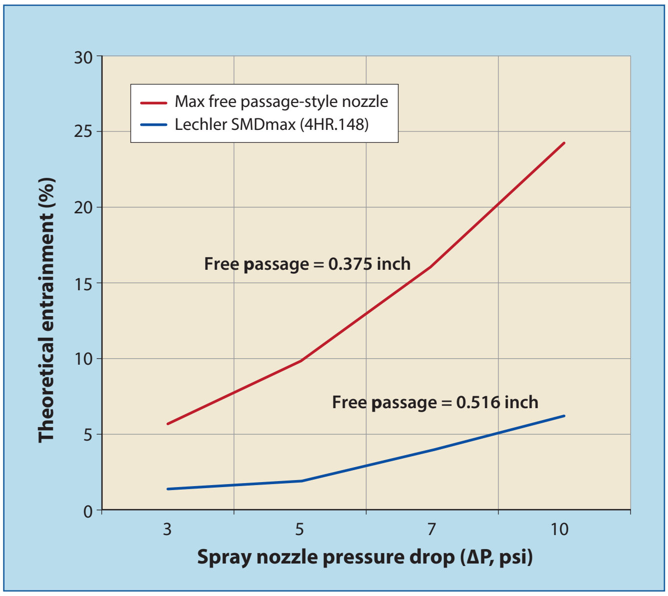

Figure 7 Theoretical entrainment per cent vs spray nozzle pressure drop for identical nozzle capacities

When there is suspected fouling in a wash bed or evidence of a little wash oil in the tower bottoms, there is a tendency for refiners to increase the flow rate to the wash bed spray header to try and avoid dry-out of packing. This practice can create an undesirable condition of very elevated entrainment since traditional spray nozzles atomise more effectively with higher differential pressure. Theoretical entrainment values based on empirical data show a very clear difference in behaviour between the maximum free passage-style nozzles and SMDmax at various differential pressures, as illustrated in **Figure 7**.

Even at relatively high differential pressures, the SMDmax spray nozzle tends to minimise over-atomisation, which is a very favourable performance characteristic of a spray nozzle in this service. Independent third-party testing also shows that this trend holds true up to a differential pressure of 25 psi, suggesting that these new spray nozzles not only create a favourable droplet spectrum, but do so for a larger range of flows. It is also important to note that the free passage of the nozzles depicted in Figure 7 is vastly different. The SMDmax spray nozzle has a 38% larger free passage by size, which equates to nearly a 90% larger free cross-sectional area.

Conclusion

Extensive droplet testing shows that a new nozzle technology can greatly reduce entrainment from vacuum distillation wash bed sprays. Reducing entrainment through the proper implementation and operation of the SMDmax spray nozzle technology has significant operational implications for the downstream community. At certain operating points, theoretical Stokes' Law-based entrainment calculations for a counter current spray application of the SMDmax in a tower of ~0.4°C factor result in a reduction of entrainment of 300% in comparison to traditional spray nozzles commonly used in this service.

This decrease in entrainment allows for greater operational flexibility of the wash bed spray distributor. Since more gasoil will make it to the wash bed packing, the refiner can choose to optimise yields by reducing wash rates or operate more conservatively, knowing that a greater volume of gasoil is making it through the packing and into vacuum tower bottoms. In addition, the refiner can leverage the new spray nozzle's favourable droplet spectrum across a large range or flow rates to avoid being entrainment limited at higher differential pressures. This next-generation spray nozzle not only features a larger free passage than maximum free passage-style nozzles but will ultimately help refiners address challenges with distillation efficiency and reduce the chances for unplanned shutdowns and maintenance.

SMDmax is a mark of Lechler Inc.

References

1 Hanson D W, Lieberman N P, Lieberman E T, *De-entrainment and washing of flash-zone vapors in heavy oil fractionators*, https://static1.squarespace.com/static/5c92ba8e01232c369bea6695/t/5d9f77b53c54f020a71d5647/1570731958072/deentrainment+and+washing+of+flash+zone+vapors.pdf

2 Pilling M, Roza M, *Vacuum Tower Wash Section Design: Myth and Reality*, https://folk.ntnu.no/skoge/prost/proceedings/distillation10/DA2010%20Conference%20Proceedings/8.%20Process%20Troubleshooting/OR52%20Roza%20Vacuum%20Tower%20Wash%20Section%20Design.pdf

3 Trompiz C J, Fair J R, *Entrainment from Spray Distributors for Packed Columns*, Masters Thesis, (Publication not in the public domain – University of Texas at Austin Chemical Engineering Masters).

4 Bete Original BETE MaxiPass® MP – Maximum Free Passage Product
https://bete.com/wp-content/uploads/2022/01/BETE_MaxiPass.pdf

Alejandro Lago is Regional Sales Manager and a Mechanical Engineer from University of Texas-Austin at Lechler USA.
Email: alejandrolago@lechlerusa.com

Ashwin Patni is Director of Process Technology at Lechler USA. He holds a graduate degree in chemical engineering from Missouri University of Science and Technology and an MBA from Northwestern University. *Email: ashwinpatni@lechlerusa.com*

LINKS

More articles from the following categories:
Crude and Vacuum Units
Mechanical Engineering