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VACUUM TOWER WASH SECTION DESIGN: MYTH AND REALITY

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Abstract
Entrainment from the vacuum tower flash zone is only one aspect which determines the quality and yield of vacuum gas oil which can be obtained for given crudes. All aspects influencing the vacuum gas oil quality must be considered: entrainment from the inlet device, de-entrainment characteristics of the internals in the wash section and entrainment from the wash oil distributor. The importance of all of these factors determine the maximum yield for a given quality of vacuum gas oil.

Keywords: refinery, vacuum tower, wash section, entrainment, flash zone

1. Introduction
In a refinery vacuum column, the flash zone provides a smooth transition for the high velocity two-phase feed from the transfer line into the column, separating the liquid and routing it to the bottom of the column while delivering the vapor uniformly to the upper sections of the column. The typical feed device for a vacuum column is a vapor horn or a similar device that uses the feed inertia to redirect the two-phase stream to contact and remove dispersed liquid particles. It is important to remove the entrained liquid in the upward flowing vapor stream because of the high concentration of heavy end contaminants such as metals and hydrogen deficient molecules. These contaminants are catalyst poisons, which adversely affect the distillate end point and color, and also tend to form coke.

A typical bottom configuration of a vacuum column consists of a wash section, which is a short, packed bed above the flash zone. The wash section is designed to remove heavier components in the upward flowing vapor from the flash zone by coalescing entrained liquid droplets and by condensing the heavier vaporized components. The packing itself acts as a coalescer and de-entrains liquid droplets in the vapor stream. Liquid gas oil is fed to the top of the wash section to wet the packing to prevent it from drying out and coking. Liquid leaving the bottom of the wash bed is collected in a slop stream which consists of coalesced liquid entrainment from the flash zone, the fractionated heavy components, and the heavy portion of the liquid gas oil feed that made it down through the packed bed without being vaporized. Process economics dictate that the gas oil feed stream to the wash section be minimized while maintaining a sufficient flow rate to prevent the bed from coking.

2. Optimizing the Flash Zone & Wash Section Design
From an operational standpoint, the main goal of the flash zone and wash section is to provide the best possible vapor feed to the distillation section above the wash section. This means minimizing the amount of entrained liquids as well as assuring uniform distribution of the vapor leaving the wash section. Since the intermediate conditions between the flash zone and the wash section can affect the performance of the wash section, the influence of the inlet feed device on the vapor distribution and the liquid entrainment needs to be well understood.

In order for the wash section to perform properly with respect to de-entrainment and coking resistance, it is important to have the vapor feed to the wash section evenly distributed. Since a packed bed acts as a vapor distributor, it can be assumed that the vapor leaving the wash bed is very well distributed. Therefore, when discussing vapor distribution, we need to focus on the region between the flash zone and the wash section.

From a practical standpoint, the flash zone section behaves as an initial vapor-liquid separator and the wash section behaves as a polishing bed where remaining droplets can be removed and fractionation takes place. Generally, the de-entrainment effects of the flash zone and the wash section are cumulative; the individual removal efficiency of the feed section or the wash section is not of interest, only the combined performance matters. The de-entrainment efficiency of both sections depends on the droplet particle size. If the flash zone or the feed inlet device is not designed to remove large diameter droplets, the wash section will be extremely efficient in removing those droplets. However, should a relevant percentage of small droplets leave the flash zone, the wash section will be less effective in removing these droplets. The object is to minimize the entrainment from the feed section to the wash section but not at the expense of poor vapor feed distribution to the wash section.

The following CFD study provides a review of an industrial column configuration with two types of feed devices. From this study, it can be seen that different feed design can have unexpected results with respect to vapor distribution and de-entrainment capabilities.

3. CFD Study: De-entrainment Versus Vapor Distribution

When studying the performance of various vacuum tower feed devices, it becomes apparent that vapor-liquid separation capabilities (entrainment removal) and vapor distribution quality to the wash section do not necessarily go hand in hand. In other words, a modification that decreases the entrainment to the wash section doesn't necessarily help the vapor feed profile to the wash bed. Often, the opposite can be true. This can be seen with CFD simulations shown in Figures 1 & 2. Figure 1 shows the vapor velocity profile leaving a 25% open area chimney tray above a cyclonic feed device at an elevation just below the packed bed above. The feed to the wash section has some distinct high velocity regions. However, from an entrainment standpoint, we know from in-house testing that a well designed feed device can have very low entrainment rates of less than 1%.[1]

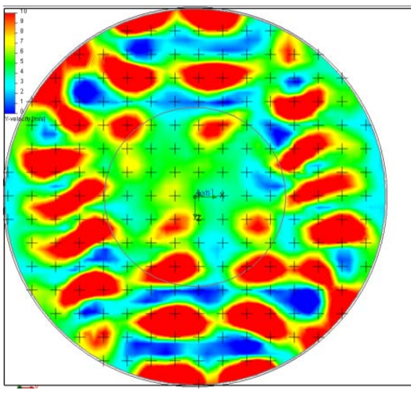

Figure 1. Velocity Above Cyclone

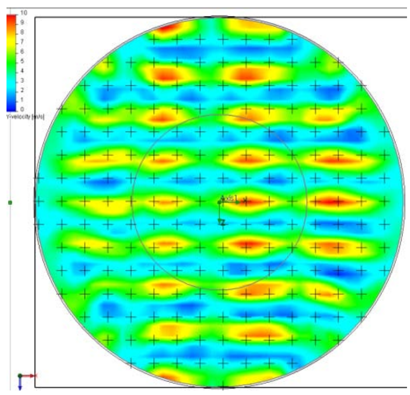

Figure 2. Velocity Above Baffled Horn

Figure 2 shows the CFD results below the packed bed after replacing the cyclone with a vapor horn feed device. The vapor horn has baffles and a vortex recovery mechanism to limit the swirling effect in the bottom of the column. The same 25% open area chimney tray is also used. The CFD results show that the vapor horn clearly provides a more uniform vapor flow to the wash section above. When operating at typical industrial conditions, a well designed vapor horn feed device like this can have entrainment levels as low as 2%. This is still relatively low, but higher than that of the cyclone. The entrainment rates discussed above have been measured in laboratory conditions with column diameters of 1-3 m. Entrainment rates from well designed industrial columns are typically in the range of 3-5%, so there is some scaling effect that is seen. The trend of entrainment versus vapor distribution should still hold true, regardless of scale.

4. **Vacuum tower example**

The example below shows the performance of an industrial column with a less than optimum wash section design. This example shows that even older, less efficient designs can provide excellent de-entrainment removal. The crude type for this example was a mixture of several crudes including heavy ones from South America. The feed temperature 406 °C, flash zone temperature 399 °C and pressure FZ pressure 36 mbar and F-factor in the beds (top bed 3.8 $Pa^{1/2}$, bottom bed 3.4 $Pa^{1/2}$).

4.1 Wash section

- Diameter: 10 m, double bed, Top 1.4 m M125Y, Bottom 1.0 m MG64Y
- Feed Inlet: two tangential 1.5 m parallel nozzles, simple galleries with top and side panel without baffles, extending about 120 degrees of circumference
- Spray nozzle distributor for the bottom wash bed, Sulzer VEP^{TM} gravity flow liquid distributor for the top wash bed
- Slop wax externally recycled to the top of the stripping section.

4.2 HVGO cut point and contaminants concentration

The cut point of the HVGO is 580°C and LVGO is 450°C. Based on stream analyses, the HVGO would have the following contaminants.

CCR = 1.45 wt%, Nickel = 0.51 wppm, Vanadium = 0.81 wppm

These values are obtained by adding the contaminant contents of the different assay cuts between the LVGO and HVGPO cut points. These data are compared with the results from the different simulations below.

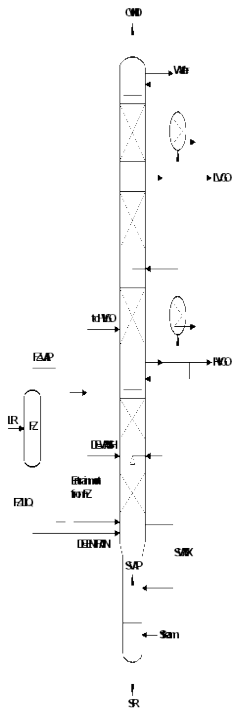

Figure 3. Vacuum Column Process Flow Diagram

4.3 Simulation

The feed zone is simulated as a flash with the pressure at the feed stage without considering any influence of the vapor (including water vapor) coming from the stripping section and assuming that a part of the liquid feed is entrained. The vapor and the separated liquids are fed to a stage representing the bottom of the wash section below the slop wax draw. The entrained liquid from the flash zone is split into two parts: one part is assumed to be de-entrained in the wash section and one part is assumed to pass through the wash section and will end up mainly in the HVGO. It must be noted that the liquid entrained to the HVGO is fed directly to the HVGO draw off stage without considering any cooling effect of passing though the wash section. In this manner, the influence of the superheating of the feed compared to the flash zone temperature is taken into consideration with respect to the inherent limitations of an equilibrium model used for such mass and heat transfer applications.

One theoretical stage is taken for each of the wash zones. On the product side draws, the HVGO and LVGO flow rate are specified. The slop wax pumparound in the bottom wash bed is fixed.

4.4 Results; Volatility of contaminants

The simulation is very helpful to get an idea on the volatility of the three contaminants, Vanadium (V), Nickel (Ni), and Conradson Carbon Residue (CCR) which have been studied for this column. The simulation shows that both the vapors from the flash zone as well as the vapor coming from the stripping section contain a significant amount of contaminants. The stripping vapor has an even higher concentration of V, Ni and CCR than the feed vapor. Just to get an idea of the absolute amounts we are speaking about. In the vapor phase of the feed which is 307.4 t/hr, we have 0.63 kg/hr V, 0.25 kg/hr Ni, 3187 kg/hr CCR. On top of that, we have stripping section vapor (58.2 t/hr) which has 0.35 kg/hr V, 0.14 kg/hr Ni, 1547 kg/hr CCR. In the HVGO, we have 217.6 t/hr which has 0.21 kg/hr V, 0.11 kg/hr Ni, 2800 kg/hr CCR. Bottom tower Short Residue 67.0 kg/hr V, 19.3 kg/hr Ni, 54.4 t/hr CCR. So we are speaking of very small numbers in large streams.

4.5 Entrainment

For this study, the percentage of entrainment from the flash zone was first varied while keeping the de-entrainment factor of the wash zone at 100%. This means that all entrained liquid will end up in the slop wax draw. The results are given in Table 2 below. The analysis shows that if the wash zone can cope with the entrained liquid, it does not really matter how much entrainment there is from the flash zone. The only negative aspect of high entrainment from the flash zone is that more liquid has to be drawn from the slop wax collector. This also means that if the slop wax is pumped to the top of the stripping section (where it belongs), some additional pump power will be required.

It has been stated that higher entrainment leads to faster than normal coking.[2] The main reason given is that the superheated entrainment vaporizes the wash oil and leads to a higher than expected dry out. The main contributor for this higher than expected dry out, however, is the superheated feed vapor as there is a much greater amount of vapor than entrained liquid at the bottom of the wash section. What should also be mentioned is that for the cases quoted in literature with a higher than expected dry out, spray nozzles are used for the wash oil. The measured dry out factor is based on metered flow of the wash oil fed to the distributor assuming zero entrainment back to the HVGO. This is most probably not correct. The effective wash oil rate was probably much lower than metered.[3,4] Further study could perhaps verify this hypothesis.

Table 2. Influence of entrainment from the flash zone with perfect de-entrainment from the wash zone Feed: 580,000 kg/hr, V 115 wppm, Ni 35 wppm, CCR 10 wt%, Evaporation: 53%

HVGO yield kg/hr	217559				
Entrainment from FZ	**0%**	**2%**	**5%**	**8%**	**10%**
Entrainment kg/hr	-	5'470	13'674	21'879	27'349
V ppm	0.97	0.98	0.99	1.00	1.01
Ni ppm	0.53	0.53	0.53	0.54	0.54
CCR wt%	1.29	1.29	1.29	1.29	1.29
Slops kg/hr	31'098	36'357	44'261	52'175	57'457

Since the previous case assumed 100% efficiency in the wash section, the next step is to review the influence of the wash section de-entrainment efficiency. In Table 3, the percentage de-entrained liquid is varied for a fixed entrainment of 5% from the FZ. It is interesting to see that the influence of entrainment to the HVGO is smaller for "components" with significant volatility (CCR) than for the vanadium which has the lowest volatility of the three contaminants. On the CCR side, the difference between perfect de-entrainment and only 95% de-entrainment is likely within the measuring accuracy. For vanadium, the difference will be measurable.

In general, it appears that if we can obtain 99% de-entrainment efficiency in the wash bed, we can, taking into account the accuracy of the measurements, probably be sure that we are within the required HVGO specification as calculated with a rigorous simulation. Sulzer in-house testing has shown that, depending upon the average droplet size entering the packed bed, at least a 98-99% efficiency is realistic and attainable.

4.6 Single wash section

The reason this tower was selected for review was because it used a double wash bed design. Double wash section designs are rarely, if ever, used today. One of the reasons, as illustrated in the case study below, is the risk of entraining slop wax to the HVGO. In order to estimate the effect of switching to a single bed wash section, two simulations where made with one simulation which just eliminated the bottom wash section pumparound and the other simulation which added an additional stage (filling the space created by eliminating the spray nozzle distributor).

The results with two theoretical stages but with a single wash section (without entrainment) are identical to the results with the small slop PA specified by the process design. With three stages, the HVGO quality improves slightly for the same yield, in other words, the vanadium content went from 0.97 wppm to 0.86 wppm, CCR from 1.29 wt% to 1.27 wt%. With one additional stage, the HVGO yield can be increased by 0.25%. The CCR is the determining contaminant for the possible yield increase. Vanadium is less sensitive and is at 0.91 wt-ppm, below the original content at this yield.

Table 3. Influence of de-entrainment of the wash zone at constant entrainment from the flash zone - Feed: 580,000 kg/hr, V 115 wppm, Ni 35 wppm, CCR 10 wt%, Evaporation: 53%

Entrainment from FZ		5.0%				
Entrainment fro m FZ	kg/hr	13674				
HVGO kg/hr		218240	217830	217700	217570	217'559
De-entraiment wash zone		**95.0%**	**98.0%**	**99.0%**	**99.9%**	**100.0%**
To HVGO	kg/hr	681.0	270.8	139.5	13.5	-
V	wppm	1.49	1.19	1.09	1.00	1.00
Ni	wppm	0.68	0.59	0.56	0.54	0.53
CCR	wt%	1.33	1.31	1.30	1.29	1.29
Slops	kg/hr	43'451	43'939	44'093	44'249	44'261

4.7 Distributor check

As this column is highly loaded it is interesting to verify the choice of distributor in the two wash sections. With the help of the entrainment estimation program developed by Sulzer based on literature data, spray nozzle distributors were designed for both sections. In the real column only the bottom section has a spray nozzle. In the following table the results of this calculation have been summarized.

Table 4. Spray nozzle design for top and bottom wash section

Section	**l**	**F-factor**	**Nozzles**	**Type**	**Expected entrainment**
	$m^3/m^2/hr$	**$Pa^{1/2}$**			**%**
Top	2.094	3.759	32	MP437 120°	64.30
Bottom	0.407	3.363	36	MP187 120°	93.00

Assuming the Sulzer program gives a good estimate (at least within 20-30%), it is clear that a spray nozzle distributor is not a very good choice for this vapor load. Sulzer in-house testing has actually showed data that indicate that these entrainment estimates may actually be conservative.[3,4] Based on this, it is possible that <u>the bottom wash section entrainment might actually have a more severe effect on the HVGO quality than the entrainment from the feed in this column.</u> The choice of a gravity flow distributor for the top bed is of high importance as it assures that the correct amount of wash oil enters the bed. With a spray nozzle distributor this would not be possible. In fact, the calculation shows that if more liquid is pumped through the spray nozzle distributor, less liquid actually goes to the bed due to the increased pressure drop and associated drop size decrease. At 120% of design, 74% will be entrained as per the correlations. Therefore, from a design standpoint, a Sulzer VEP distributor is the best choice for the top distributor which is the most critical for HVGO quality.

5.0 Conclusion

In order for a vacuum tower to operate effectively, the flash zone and the wash section must work together to provide the best possible feed quality to the sections above. To properly design a vacuum column, engineers need to be able to predict how much entrainment and associated contaminants will travel from the flash zone to the slop wax and HVGO draws. These numbers are based directly on the entrainment removal efficiency of the flash zone and the wash section. Sulzer's in-house design tools predict entrainment from most well designed flash zone internals to be 3-5%. An inlet device producing "zero" entrainment, even if it did exist, would almost certainly adversely affect the vapor distribution to the wash bed above. Since it is imperative that the wash section remove entrainment at extremely high efficiencies (>98%) and resist coking, the vapor distribution quality to the wash section must be excellent. Vapor distribution should not be sacrificed for the sake of ultra low entrainment levels in the flash zone.

A simulation of a commercial vacuum column with varying entrainment levels shows that near zero levels are not required in order for the column to meet HVGO specifications. Even with a moderate entrainment level, a properly designed wash section will provide excellent de-entrainment levels and excellent HVGO quality. In fact, even this particular column with severe entrainment of slop wax between the split wash beds still made the HVGO specification in actual operation. Sulzer studies indicate that, as long as the wash bed is performing properly, the contaminant levels in the HVGO draw will be well within the desired specifications. The feed and flash zone internals need to provide both low entrainment levels and high quality distribution to the wash section, but in the end, the wash section is the final protection for the HVGO product draw.

The analyses in this study show that, more or less independent from the amount of entrainment, it very important to properly estimate the capability of the wash section de-entrain the liquid carried over. In the past, the authors have already done some investigations on the de-entrainment efficiency.[3,4] From these data and other sources, a calculation method has been developed to predict the performance of various feed devices and the combined performance of the vacuum tower flash zone and wash sections to ensure proper operation of each vacuum tower.

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