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THE SUCCESSFUL REVAMPING STORY OF A NEW VDU

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This paper traces the success story of improving the performance of the vacuum distillation units (VDU) at SAUDI ARAMCO TOTAL Refining & Petrochemical company (SATORP) starting from a conventional design of their vacuum towers to an improved one with highest performance technologies, by means of latest generation design tools and criteria.

The improvement started from troubleshooting need, but over the years has set itself the goal of responding to and overcoming the continuous challenges posed by the market and economic drivers.

The refinery economics are continuously pushing operators to maximize yields and use less profitable and heavier crudes. This corresponds to higher severity and deeper cutpoints in crude vacuum towers. If proper design and operation procedures are not followed, these conditions can jeopardize product quality and unit reliability. Higher severity conditions, combined with longer run lengths, necessitate vacuum tower designs that prioritize reliability over performance. The wash bed design is frequently the key to achieve crude vacuum tower performance because has the most direct impact on the quality of the gas oil product. At the same time, the wash bed is most prone to coking. The focus then on vacuum tower performance and reliability must be the wash bed. However, the wash bed performance and reliability are determined by many factors. Feed characterization, simulation accuracy, vapor and liquid disengagement and distribution in the column flash zone, and wash bed design all play a major role in determining vacuum tower performance and reliability. Inaccuracies in any of these areas translate to a project that does not meet yield, quality, or reliability targets.

The improvements discussed in this article started in 2017 and ended up in 2021, involving the two most critical areas of existing vacuum towers which are recognized to be the most sensitive and important for the performance and reliability of the entire unit: the wash section and the flash zone.

SATORP is a refinery originally designed to process 400,000 barrels per stream day (BPSD) of Arabian Heavy Crude located in the Eastern Province of Saudi Arabia. The Refinery is arranged in two trains with own CDU/VDU each. The full process operation was attained starting from 2014.

Even though it is one of the world's most efficient integrated refining and petrochemical platforms, with an initial high complexity index, the refinery has been always focused on capacity improvement and performance enhancement soon after start-up.

To improve further the economics drivers, even though the refinery was designed for an Arabian Heavy Crude blend, it has to operate occasionally with a slightly heavier crude feedstock (100% Manifa), bringing additional challenges in term of production yields and operating reliability.

The VDU at SATORP refinery produces three discrete side-streams which are: Light Vacuum Gas Oil (LVGO), Medium Vacuum Gas Oil (MVGO) and Heavy Vacuum Gas Oil (HVGO). LVGO is routed to the HDS unit; whilst MVGO and HVGO are combined on the unit to produce vacuum gasoil (VGO) for routing to the MHC/DHC units and storage. Vacuum residue is used as coker feedstock.

Since the commissioning of the refinery, an increase in differential pressure in the wash bed section of both VDU-1 and VDU-2 has been observed. In August 2016, the wash section bed of VDU-2 was replaced in-kind, because coke formation was found on the bed. However, after the start-up the wash bed suffered a mechanical damage that forced the refinery to another unplanned shutdown in the mid-2017 to fix the issue. Instead of proceeding with a questionable replacement in-kind, SATORP studied with Koch-Glitsch the possibility to improve the reliability of the wash section from both process and mechanical standpoints.

Compared to the original design with a very deep wash bed without any uplift resistant provision, Koch-Glitsch proposed a shorter bed with the high fouling resistant PROFLUX® severe service grid packing, which is the cutting-edge heavy fouling resistant technology for this specific application. The bed was completed with top portion of FLEXIPAC® HC® structured packing to achieve the desired fractionation efficiency at the lowest cost of wash bed pressure drop; uplift resistant design with thru-rods assembly and a low pressure drop spray distributor relocated close to the top of the new shorter bed.

The modification was successfully implemented in VDU-2 in April 2017 and later extended to VDU-1 wash bed in January 2018 because of the evident improvement in column performance.

The function of the wash bed is to eliminate entrainment of residue in the feed to the HVGO product, and to provide some fractionations to improve the HVGO end point. The main entrainment concern to be addressed is minimizing the amount of micro concarbon residue (MCR) and heavy metals that end up in the HVGO.

There are many competing interests in the design of the wash bed and the packing types that are traditionally used in this application; first generation grid packing and structured packing have limitations. Maximizing gasoil product can potentially come at the expense of insufficient wash oil to maintain adequate packing wetting, a key requirement of preventing coke formation. The use of an open, low surface area, first generation grid packing for severe service offers good fouling resistance but does not provide adequate de-entrainment in vessels that are pushed past a moderate operating point. The use of a medium crimp structured packing offers high de-entrainment properties and provides good fractionation, but it comes at the expense of less reliability – it is susceptible to fouling, and too much fractionation can cause the bed to dry out the wash oil and promote coke formation. A deep bed provides more efficiency than a short bed does, but it also increases residence time which can lead to increased fouling. The ideal approach to select the grids and packing technology of a VDU wash bed is to balance the de-entrainment and fractionation requirements while maintaining reliability and maximizing gasoil yield. These sections have been often designed with grids combined with structured packing to increase the mass transfer efficiency and droplet de-entrainment.

The premature coking experienced by SATORP with the original wash section arrangement was primarily caused by a too deep packing section that was designed with an overall bed height of approx 3.4 m, composed 1.2 m of structured packing in the upper part e 2.3 m of structured packing grids in the lower part of the bed. Based on Koch-Glitsch expertise, typically wash sections are designed shorter than 2 m deep, and typically in the range of 1 to 1.8 m depending on the de-entrainment and efficiency requirements. Even in case of large crimp size structured packings (same of original arrangement in SATORP), Koch-Glitsch strongly discourage exceeding 2 m bed heights, since the excessive metal exposed to low liquid rates and high vapour temperature can easily cause premature coking of the bed. At the operating conditions of the wash beds, and in case of severe conditions (even temporary) - such as high COT and low wash oil - the lower portion of the bed can be dried out if the packing efficiency is excessive compared to the available wash oil. The packing surface exposed to the high temperatures, if dry, can give the possibility for heavy tails entrained from the flash zone to accumulate and coking. When the coking phenomena initiates, the fouling process is increasing exponentially along time since the fouling and coke act as nucleation center and start to build up fouling.

Furthermore, the original structured packing grids installed in the lower section of the wash bed can be assimilated with a large crimp size structured packing made by smooth metal sheets (*Figure 1 – right picture on next page)*. Koch-Glitsch has regularly applied this smooth style structured packing in fouling services, but always prefers grids for those more severe service applications.

Even if the smooth finishing help in fouling resistance,

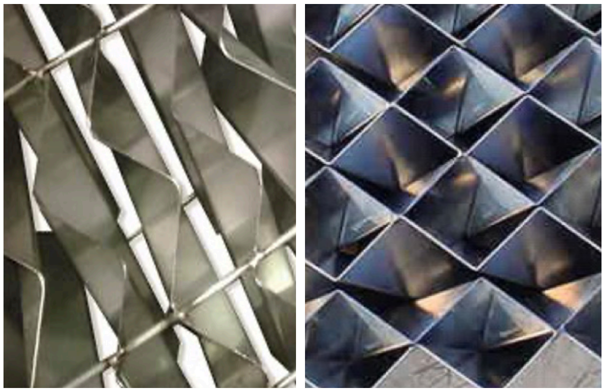


Figure 1 – High fouling resistant PROFLUX® severe service grid (US Patent 8298412B) on the left pic vs. large crimp size structured packing grids made by smooth metal sheets on the right pic (similar to the original installation)

the corrugated metal sheets contact each with the other. That geometry (even though is often categorized as grids) generates undesired contact points and dead area that could serve as potential sites for coking or accumulation of solids.

Over the last decade, Koch-Glitsch set out to provide the industry with a better packing product for fouling applications. With hundreds of existing vacuum column installations to draw from, the company looked to provide a packing that offered the de-entrainment characteristics of structured packing while improving upon the reliability of a traditional grid packing. De-entrainment tests that emulated vacuum column wash bed operating conditions were performed in the Koch-Glitsch pilot plant. The results confirmed what operating engineers have experienced in vacuum column wash beds around the world:

- Structured packing provides better de-entrainment than traditional grid packing at moderate and high gas velocities ($Cs > 0.35$ ft/s).
- For a given packing style, the amount of fouling is proportional to the surface area – higher surface area increases the fouling tendency.
- For the same surface area, the shape of the packing will influence the pressure drop and amount of fouling.

With respect to the last point, testing also confirmed that the structured packing geometry itself contributes to the fouling tendency, regardless the crimp size of packings. Contact points between sheets provide locations for solids to bridge and coke propagation.

The challenge of improving equipment performance in this severe service application is one of developing equipment that would simultaneously address issues around efficiency, capacity, pressure drop, de-entrainment, mechanical rigidity and fouling resistance. A novel product, called PROFLUX® severe service grid, was developed to specifically address these issues. A photograph of PROFLUX® severe service grid is shown in *Figure 1 - left picture.* The key features of this product are:

- The blades are shaped in a way that reduce the likelihood of fouling material adhering.
- The blades are spaced apart to remove contact points where stagnant liquid could coke or fouling material could be held up.
- A welded construction is used to obtain a high degree of rigidity.

In PROFLUX® severe service grid, the grid fouling resistance is obtained by shaping the sheets in a way that reduces the settling of fouling material, as well as spacing the sheets apart to eliminate crevices where fouling material can be trapped and increase the residence time.

In PROFLUX® severe service grid, grid mechanical rigidity is obtained by using an all-welded construction and by having the sheets with opposing crimp angles act as a type of lattice beam. Compression testing show that PROFLUX® severe service grid is significantly stronger than the conventional grid products that are being used in severe service applications – even with reduced material thickness. The combination of welded rods assembly and corrugated sheets of increased material thickness compared to structured packings provides a very robust design that resists damage because of tower upsets or erosion.

The maximum hydraulic capacity of low surface area packing cannot be defined without tying it to entrainment, especially in a VDU wash bed. The purpose of which is to control the HVGO quality and knock-down entrainment form the column flash zone. At high vapor velocities, liquid can be sheared off surfaces and the resulting droplets would be blown out of the bed if the packing is incapable of capturing the droplets. The same is true for droplets that have been generated somewhere else and hit the bed from below. For low surface area packing products, it is best to define the maximum useful hydraulic capacity at which a significant amount of entrainment is blown out of the bed.

The hydraulic capacity in a vacuum tower is often expressed as the vapour capacity factor C-factor above the wash bed, which is the point in the column with the highest vapour load and highest V/L ratio (because of the re-vaporization effect through the wash bed). The C-factor is traditionally discussed in ft/s. According to good engineering design practice of main engineering companies and operators, new columns are usually sized for a max C-factor in the order of 0.35 ft/s.

For revamp cases, it is not unusual to operate vacuum towers with C-factor of up to 0.45 ft/s provided that the best technology is applied in both flash zones and wash bed, and the performance of these sections is assessed as one and contextual approach. The possibility to operate wash beds at higher C-factor is positively proportional to higher throughput and/or higher yields at more severe operating conditions.

The C-factor at the top of the wash bed can be calculated with the following formula which assumes information usually available from a process simulation model, because it is not measured in field.

C-factor (m/s) = Vs $* \sqrt{\rho Vap \,/\, (\rho Liq \;-\; \rho Vap)}$

Where:

Vs (m/s) = vapour velocity from the top of the wash bed = vapour vol flow (m3/s) / wash bed cross sectional area (m2)
Vapour volumetric flow (m3/s) = mass flow of vapour from the top of the wash bed (kg/s) /ρap (kg/m3)
ρVap (kg/m3) = density of the vapour flow form the top of the wash bed
ρLiq (kg/m3) = density of the liquid flow to the top of the wash bed or HVGO actual density

Nevertheless, the operators can use the following simplified approach to estimate the parameters required for C-factor calculation at the top of the VDU wash bed. The method is based on data available from a typical VDU control scheme and the following assumptions: liquid density at operating conditions (HVGO density), the ideal behavior of the vapour flow and the molecular weight of the hydrocarbon vapour phase.

Even though the simplified methodology is reliable enough for preliminary assessments, only a process model can determine rigorously the C-factor.

Vapour volumetric flow (m3/s) = $\frac{\text{vapour mass flow (ton/h)} * 1000}{(3600 * \rho Vap)}$

Vapour mass flow from the top of the wash bed (ton/h) =
Vapour HC mass flow (ton/h) + Vapour H2O mass flow (ton/h)
Vapour HC mass flow (ton/h) = overall distillates rate (ton/h) + wash oil rate (ton/h)
Vapour H2O mass flow (ton/h) = stripping steam (ton/h) + heater velocity steam (ton/h)
Overall distillates rate (ton/h) = LVGO (ton/h) + MVGO (ton/h) + HVGO (ton/h)

ρVap (kg/m3) = $\frac{Vapour\ MW\ (kg/kmol) * Operating\ Pressure\ (mmHg}{62.36 * Operating\ Temperature\ (°K)}$

Vapour MW (kg/kmol) = $\frac{\text{Vapour mass flow from top of the wash bed (ton/h)}}{\frac{\text{Vapour HC mass flow (ton/h)}}{404} + \frac{\text{Vapour H2O mass flow (ton/h)}}{18}}$

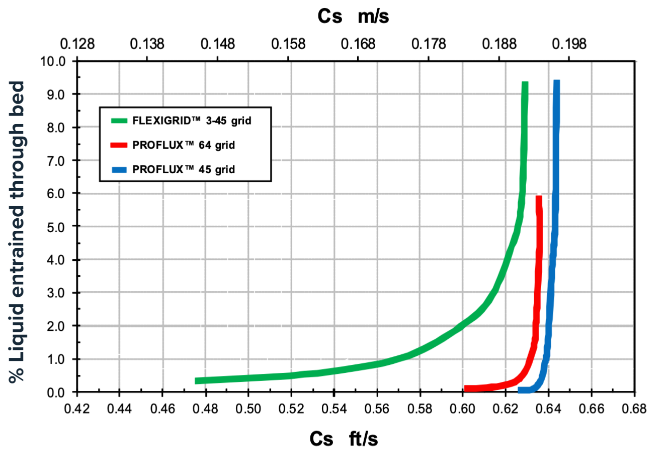
Operating Pressure (mmHg) = flash zone operating pressure (mmHg) – the wash bed pressure drop (mmHg)

Operating temperature (°K) = operating temperature of vapour from wash bed. If not available, the overflash temperature can be applied for #1 theoretical stage wash bed

ρLiq (kg/m3) = 800 kg/m3

PROFLUX® severe service grid and a conventional grid product were subjected to the following test: a 1.65 m deep bed was set up in a hydrocarbon distillation tower. A reflux rate of 2.4 m3/m2/h was dialed in, and the tower was operated at 9 kPa Abs. These conditions in term of pressure, wetting rate and fluids were selected to reproduce typical operating environment of a VDU wash bed. Liquid laced with a tracer was sprayed below the packed bed with a nozzle operated at 5 bar dP. The vapor rate was increased by increasing the boil-up, and the amount of tracer above the bed was monitored. An increase in tracer levels above the bed is an indication that entrainment is breaking through the bed. The percentage of tracer breaking through the bed is plotted versus the vapor Cs value in *Graph 1 (on next page).* It is evident that the PROFLUX® severe service grid is more effective in removing entrainment, and can be operated to significantly higher Cs values than the conventional grid product.

Thanks to the superiority of technology discussed here before and considering the capacity and efficiency requirement, Koch-Glitsch re-designed the wash bed with the following main features: bulk of the bed with PROFLUX® severe service grid (lower section), combined with FLEXIPAC® HC® structured packing to achieve the desired fractionation efficiency (upper



***Graph 1** – Entrainment removal efficiency of grid products. Tower operated with hydrocarbons at 9 kPa Abs and a constant liquid rate of 2.4 m3/m2/h.*

section). The overall bed height was reduced from original 3.4 m to approx 1.7 m.

Another improvement of the new wash bed was the protection design against uplift surge. Sudden upsets are quite common in vacuum towers, especially those ones operated with stripping steam at the bottom (fully wet scheme).

It is being understood that the key to handle uplift events is understanding what happened and prevent the phenomena in future operation; uplift resistant equipment design practices are also warmly recommended to minimize or eliminate severe damage during this occurrence.

Koch-Glitsch design practice for wash bed and stripping section of VDU is to design the column internals, trays and packing for at least 1 PSI and, at customer request or in case of historical damages (like in this specific case) to consider an uplift resistance design up to 2 PSI. On the contrary, the original support grid and packing of the wash bed were not protected against any uplift load and failed prematurely at the first opportunity.

The uplift resistant solution applied by Koch-Glitsch at SATORP VDU has been consolidated and successfully applied in the last two decades in hundreds of similar beds. The solution utilizes rods through the packed bed, so the packed bed becomes a single structural element with support grid and hold-down system. Practically, the hold-down grid and the new support plate will be tied together via rods which pass all the way through the packing & grids. The result of these features is that any surge will have to move the whole bed before any part of it can be damaged. The thru-rods approach eliminates the need for larger support structures that can interfere with the vapor and liquid flow and increase the possibility of fouling or coking.

Ultimately, the suitability of new hold-down system to meet the 2 PSI uplift resistance is intimately linked to the mechanical adequacy of the tower supports and main lattice beams beneath the bed which were checked with Finite Element Analysis (FEA) and found adequate for the purpose.

The main performance of the Vacuum Tower after upgrading of the wash bed (data collected in March 2020) have been summarized within *Table 1 (on next page)*. *Table 2* (on next page) also includes the main VGO quality parameters which meet the most stringent quality criteria typical for the downstream DHC and MHC units. The quality of the VGO was well within the applicable specs even at higher throughput and lower API crude, which validate the effectiveness of the shorter combo bed designed by Koch-Glitsch.

With the upgrading modification of their VDU and other changes, SATORP was able to operate the Refinery production reliably and efficiently up to 460,000 BPSD (+15% vs. original design) but kept a long-term vision to improve the performance and economics further.

On the wave of this vision, during the last couple of years, Koch-Glitsch has developed another assessment mainly focused on the flash zone area of the vacuum towers which was not a part of the original scope due to the TA window constraints.

In vacuum towers, the flash zone and the wash section function as a system: if the flash zone reduces entrainment to the wash bed and improve the vapour distribution, the wash bed operates with less troubles and can meet the VGO specs with more fouling resistant packing arrangements.

The main targets of that second revamp project were: maximizing the VGO yield while keeping the same crude feedstock and throughput; and improving the reliability of the wash bed operation and therefore extend the life cycle of the whole unit: all that the Refiners could want from their VDU.

The Computational Fluid Dynamic (CFD) is now a recognized and consolidated tool for designing vacuum tower inlet devices. Since each tower is different the interaction between the feed device, transfer line, vessel shell, and other internals will vary. CFD offers a way to analyze these interactions and optimize the feed device design for a given unit. Used in

	Original Design Case	Yield %wt	Year 2020 (after Wash Bed upgrading)	Yield %wt	Year 2021 (after Flash Zone upgrading with enhanced Vapour Horn + fine-tunned revamp of the Wash Bed)	Yield %wt
Crude Feedstock Type	Arabian Heavy Blend		100% Manifa Crude		100% Manifa Crude	
Crude Specific Gravity (API)	28.1		26.1		26.1	
Refinery Total Crude Throughput (BPSD)	400,000		460,000	+15% vs design	460,000	+15% vs design
Max C-factor above VDU-2 Wash Section (ft/s)	0.34		0.36		0.38	
Overall Vacuum Tower DP - Top-Flash Zone (mmHg)	18 (design)		12		13.5	
Atm. Residue to VDU-2 (T/H)	673.3		790	+17.3% vs design	805	+19.6% vs. design
VGO Prod from VDU-2 (T/H)	283.5	42.1%	330	41.8%	350	43.5%
Vac. Residue from VDU-2 (T/H)	349.1	51.9%	425	53.8%	416	51.7%

Table 1 – Process Table with feed throughput and products yields for VDU-2 (one train) - Post-revamps vs. Original Design

VGO Lab Analysis		Original Design Specs	May 2020 (after Wash Bed upgrading)	April 2021 (after Flash Zone upgrading)
SimDis 90%	°C	-	529.5	529.5
SimDis 95%	°C	≤ 560	550.5	551
SimDis FBP	°C	≤ 650	607.5	612.5
Sulfur content	%wt	-	3.42	3.38
CCR	%wt	≤ 0.5	0.42	0.39
Nickel	ppm	≤ 1	0.07	0.09
Vanadium	ppm	≤ 1	0.47	0.25
Asphaltenes	ppm	≤ 100	<50	<50

Table 2– Sample analysys of VGO of VDU-2 – Post-revamps vs. Original Design

conjunction with historical operating and inspection data, CFD can help to eliminate chronic problems due to feed maldistribution from a poorly designed feed device.

Following the CFD study of the whole column lower section (flash zone + wash section) and comparing the vapour distribution profiles at the future expansion capacity, Koch-Glitsch has recommended SATORP to revamp the flash zone with INTALOX® Model 758 Enhanced Vapor Horn from a 90° conventional horn. Whether the success of the second revamp project illustrates the benefit of the CFD modelling, it is fundamental to remark that the setting and analysis of CFD modelling must be developed by a company with deep knowledge of the design and hydraulics of the mass transfer equipment to be modelled. *Figure 2 (on page 7)* shows the main views of VDU flash zone with INTALOX® Model 758 Enhanced Vapour Horn (lower sketches) vs. Existing Conventional Vapour Horn (upper sketches).

The longer extension of the feed inlet device also required the re-design and modification of the overflash emergency overflow downpipes (from Chimney collector #7 to the stripping section) to fit with the new enhanced vapour horn design (see the piping marked with red colour in the relevant

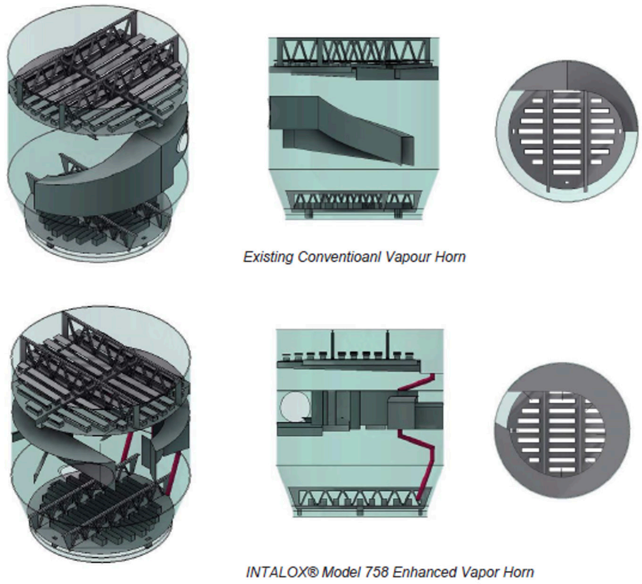


Figure 2 – Views of VDU flash zone with INTALOX® Model 758 Enhanced Vapour Horn (lower sketches) vs. existing conventional vapour horn (upper sketches)

3D sketches).

Properly feeding the vacuum tower is crucial to overall performance. The feed entering the tower is typically near the critical velocity and enters the column as a high momentum two-phase feed. The velocity of the feed is such that entrainment will be generated; the degree to which it occurs is a function of the device chosen and the gas velocity in the column.

A well-designed feed device will perform the following functions:

- Dissipate high inlet momentum and provide uniform vapour distribution while taking minimal pressure drop.
- Provide bulk phase separation between the vapour and liquid in the feed, thereby minimizing entrainment.

A uniform vapour velocity is critical as localized vapour superficial velocities can be detrimental to good wash bed performance, resulting in localized flooding and coke formation. This can consequently lead to inadequate gasoil quality and yield, along with propagation of coke over the run length of the unit. Furthermore, the ability of the feed device to provide good vapour distribution and minimize feed entrainment is paramount to maximizing vacuum column capacity. The majority of vacuum columns have throughput constrained by entrainment into the HVGO product, not by the hydraulic capacity of the packing.

Koch-Glitsch has an extensive and successful experience in designing and retrofitting Vacuum Towers with the patented INTALOX® Model 758 Enhanced Vapor Horn. The schematic 3D view of this innovative design is shown in *Figure 3 (below).*

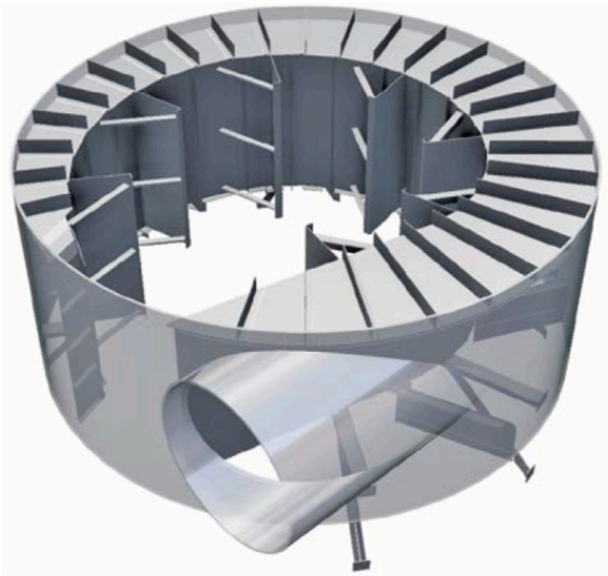


Figure 3 – INTALOX® Model 758 Enhanced Vapor Horn for single tangential inlet

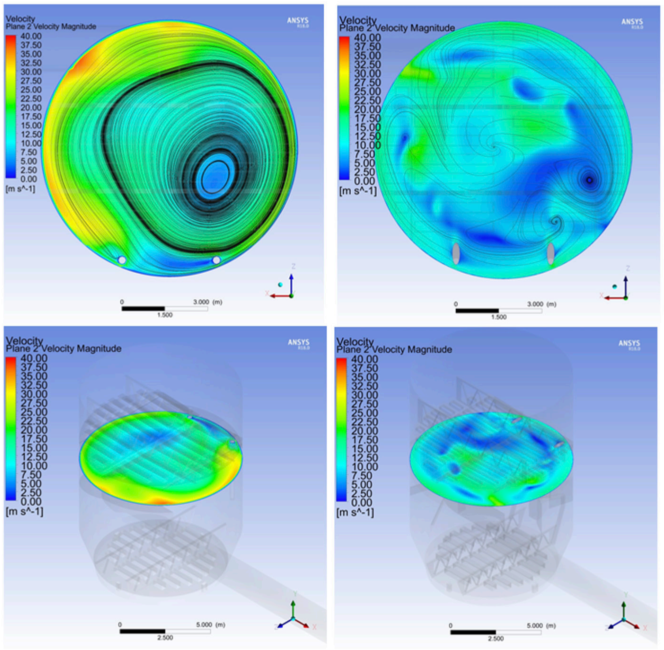
That item is an extension of the conventional vapor horn technology and provides improved vapor distribution and de-entrainment of the feed. For vapor/liquid phase separation, the open bottom construction and the centrifugal action induced to the feed stream will direct entrained liquid particles to the column wall, where they will flow down into the column bottom section. The device employs a tapered profile to reduce device footprint, thereby reducing gas velocity through the core area within the vapour horn, resulting in lower entrainment leaving the flash zone.

The patented enhanced vapor horn employs turning vanes baffles, in a proprietary arrangement, to avoid excessive impingement and feed splashing which can result in the formation of small liquid particles that are more likely to be re-entrained. The baffles help break the high feed inlet velocity for both improved vapor distribution and de-entrainment.

Uniform velocity (in both the vertical and horizontal direction) is desired to minimize re-entrainment of liquid. Once the bulk phase separation is complete and the swirling motion is no longer desirable, patented anti-swirl baffles eliminate the cyclonic motion of the vapor.

As the performance of the feed inlet device is critical to ensure adequate gas oil quality and yield, maximum column capacity and proper wash bed performance, Koch-Glitsch has applied both large scale laboratory testing and CFD analysis to evaluate, optimize and validate our design. Hundreds of successful worldwide installations in VDU with diameters up to 15 m prove the quality of the proposed technology.

The superior VDU flash zone performance resulted from successful installations of enhanced vapour horns over the last three decades, allowed regularly to utilize more fouling resistant packings and/or less packing height in the wash sections to meet the VGO specs requirements (versus having to use a lot of high efficiency packing which is more prone to fouling). With improved vapour distribution, it is regularly possible to design and operate VDU at C-factor as high as 0.45 ft/s vs. more traditional 0.35 ft/s criteria – as long as the design and operating parameters of the whole vacuum towers are optimized at once.



Existing Conventioanl Vapour Horn *INTALOX® Model 758 Enhanced Vapor Horn*

Figure 4 *– Velocity magnitude graphs from CFD analysys at debottlenekcing feed throughput comparing INTALOX® Model 758 Enhanced Vapour Horn (right views) vs. existing conventional vapour horn (left views)*

The CFD modelling developed by Koch-Glitsch for the second upgrading phase was completed for two scenarios: current operation at the time of the assessment and future operation at 120% original feed throughput. In both scenarios, the CFD model evidenced the distribution benefits of enhanced vapour horn compared to existing conventional horn.

The CFD covered the tower area between stripping section chimney tray and wash bed for the two feed inlet configurations: existing conventional horn and high performance INTALOX® Model 758 Enhanced Vapor Horn.

The benefit for installing the vapor horn will be reducing flash zone entrainment levels – which will increase the importance as you increase the feed rate and/or c-factor of this tower. The velocity magnitude graphs under *Figure 4* compare flash zone velocities of the existing conventional horn (two snapshots on the left) vs enhanced vapor horn (two snapshots on the right) demonstrate a significant improvement in flash zone velocities with the enhanced vapor horn.

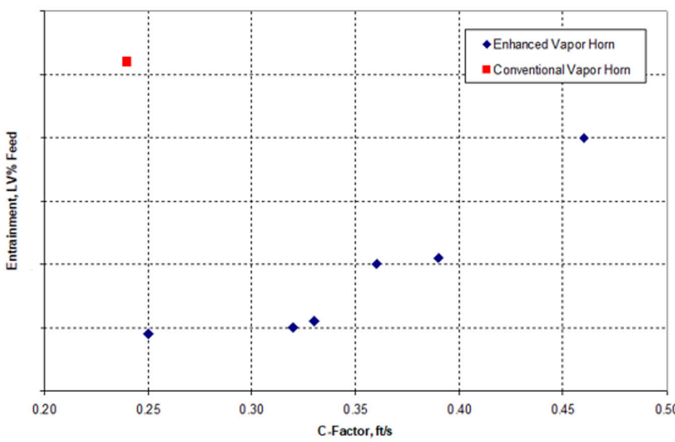
The existing conventional vapour horn presents higher flash zone velocity magnitudes, compared to the enhanced vapor horn. The difference in velocity magnitudes derives from higher planar velocities and stronger swirling motion for the conventional horn configuration, than for enhanced vapour horn.

This will translate to lower levels of entrainment – consistent with field observations that we have seen in other units when replacing a conventional horn with an enhanced vapor horn. However, even the best designs result in entrainment of 3÷5 wt% of vacuum tower feed.

Some comparative entrainment data from other commercial vacuum towers are summarized in *Graph 2 (on page 9)*. The graph compares the entrainment as liquid volume % against feed flowrate into the slop wax draw comparing Enhanced Vapour Horn vs. Conventional Vapor Horn at different flash zone C-factor.

The best practice to quantify the entrainment of vacuum resid into the slop wax stream (and the effectiveness of the design of transfer line, feed inlet nozzle and whole flash zone) is the metal balance on the VDU products.

The entrainment amount into the slop wax represents the level of heavy VR reaching the bottom portion of the packing



Graph 2 *– Resid entrainment data to Slop Wax for a commercial VDU comparing Enhanced Vapour Horn vs. conventional vapor horn*

wash bed and knocked down by the same. Lower level of entrainment from flash zone to the bottom of the wash bed will increase the reliability of the wash bed and consequently the run length of the whole VDU.

The slop wax draw stream should contain a mixture of true overflash (wash liquid that penetrates to the bottom of the bed) plus entrainment of resid from the flash zone that is knocked out in the wash bed and is collected on the slop wax collector tray. If slop wax is removed from the column via an external draw and can be measured and sampled, a metals mass balance can be used to determine the amount of flash zone entrainment. The "metals" or contaminant used in the mass balance can be Ni, V, Rams Carbon, Asphaltenes or some component of similar nature. Asphaltenes are preferred by some because they are associated with the resid stream and make the calculations simpler (and in some cases more accurate). In many cases, more than one metal/containment balance is used to verify the accuracy of the calculations.

In addition to the entrainment from the flash zone, with the true overflash awareness, the refiners can calculate the wettability at the bottom of the wash bed which is the most critical parameter to prevent coking phenomena. In fact, in order to ensure good wetting and reduce the risk of coking in the bed, the industry guidelines call for a minimum true overflash rate of 0.15 – 0.2 gpm/ft2. Therefore, only by knowing the true overflash, the refiners can safely optimize the wash as long as the bottom wetting rate allows and the HVGO specs are achieved.

As a further mechanical challenge of the second upgrading phase, the vessel is PWHT in the flash zone, so the mechanical design of the new horn was customized to be welded completely to the column cladding and not to the base material –that allowed to avoid post weld heat treatment and to optimize the plant downtime.

With new columns, if there is sufficient understanding and comfort with the strength of clad bond that the modern clad techniques provide (like explosion bond clad), it is nowadays not uncommon to weld partially or completely the feed inlet devices to the internal cladding.

Nevertheless, with older vessels that operated for years or experienced uplift events, it is still the standard practice to fix the primary structural elements of the vapour horns to the base material because of involved stresses and concerns on allowable stress of the clad bond.

Welding to cladding is typically limited to non-structural elements (functional components of the horn, such has vanes).

The new design proposed by Koch-Glitsch applied tailor-made reinforcement pads to distribute the load on a larger surface of the cladding to meet the allowed bond shear and tensile strength according not only to the existing vessel design, but to the most conservative Koch-Glitsch design criteria.

To validate this possibility of heavy-duty, feed inlet device welded to the cladding instead of the column base material, Koch-Glitsch developed a FEA which was reviewed by SATORP's engineers based on applicable codes. An extract of FEA on one support elements and reinforcing pad of the Enhanced Vapour Horn is shown as *Figure 5 (on page 10).*

The FEA models are now industrial practice in Koch-Glitsch designs for large columns to validate complex and challenging mechanical solutions.

Following a deep process study and mechanical assessment, the flash zone of VDU-1 has been finally upgraded with enhanced vapour horn in March 2021 in a LSTK contract awarded to Koch-Glitsch. Koch-Glitsch took also the opportunity to fine tune the design of the wash bed liquid distributor with the objective to reduce wash oil re-entrainment at the higher C-factors expected at increased VGO production. The modification to existing spray distributor consisted of new nozzles characterized by lower pressure drop at the future design wash oil rate. Furthermore, the distance between the spray nozzles and the top of the bed was slightly reduced.

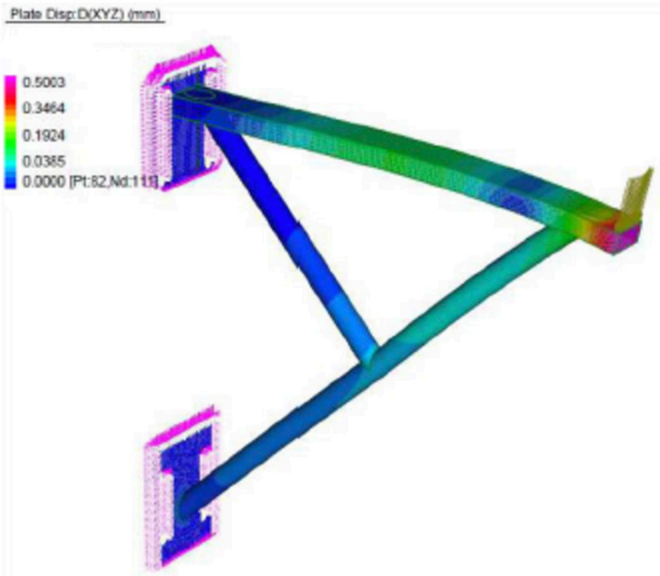


Figure 5 – *Extract of Finite Element Analysys on one support elements of the Enhanced Vapour Horn*

The reduced liquid droplets scattering and atomization resulting by the lower pressure drop, combined with the reduced distance to the bed, they improve the distribution quality and reduce the re-entrainment of the wash oil flow above the wash section.

Finally, thanks to the tailor-made mechanical design, long preparation to the modification and personnel experience, the site works were concluded in less than 14 calendar days, despite the massive welding activities in a 9 m ID vessel.

The changes made met all the process targets: operating reliably and efficiently the VDU up to +19.6% of the AR feed throughput, improving the VGO yield (-2% of VR) while reducing the pressure drop, resulting in significant savings in operating cost, as well as more reliable operation for a typically severe service.

Table 1 (on page 6) shows the current performance in terms of throughput and yields (after complete revamp of flash zone) vs. the revamp of the wash section only, and the Original Design performance.

The column pressure drop improvement (top column – flash zone) shall be valued considering both the VDU feed rate increasing and the VGO yield lift, after vs. before revamp performance.

The VGO lab analysis corroborates the good performance of

The VGO lab analysis corroborates the good performance of the discussed revamp – *Table 2 (on page 6).*

The results shall be read with the awareness that crude feedstock is heavier compared to the original design, and therefore obtaining the design VR yield with a current throughput of +15%, it is an outstanding result.

The VGO lab analysis, the distillates yield, and the wash oil confirm the general improvement realized with the revamping of the flash zone and the wash-oil section as a unique system.

This project demonstrated the benefits a Refinery with long-term vision can obtain when taking advantage of a maintenance turnaround as an opportunity to use modern grid and structured packings, and cutting-edge separation technologies.

In Vacuum crude oil distillation specifically, the potential for performance gains is possible due to the role that PROFLUX® severe service grid, and enhanced vapor horn play in de-entraining feed contaminants to and through the wash bed and maintaining a low column pressure drop.

In addition to the new generation technologies, when columns are pushed at their capacity edges, another fundamental precondition is the refinery operators' contribution with reliable data and historical knowledge of the unit operation. That was another key contribution to the project's achievements.

PROFLUX® severe service grid, FLEXIPAC® structured packing and Enhanced Vapor Horn are trademarks of Koch-Glitsch, LP.

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Alessandro Ferrari

Alessandro Ferrari is the Process & Technology Leader of Koch-Glitsch Italia and has over 20 years' experience providing solutions for mass transfer and separations designs in refinery, gas and petrochemical plants. His field of expertise is in process modelling for debottlenecking, troubleshooting and energy saving objectives of distillation process units. He is the mass transfer subject matter expert for Koch-Glitsch for all end users in Middle East. He holds the chemical engineering degree from Polytechnic University of Milan and is a member of the Koch-Glitsch Global Refining Team.

Abdulaziz Alshammary

Abdulaziz Alshammary graduated from King Fahd University of Petroleum & Minerals with bachelor degree in chemical engineering. He has an extensive technical experience in the Refinery and Petrochemicals sector. As a process engineer, he worked at multiple process units including CDU/VDU and hydrotreater, currently he is handling FCC and UGP complex. Abdulaziz holds a black built certificate in six sigma which qualified him to lead multiple project from implementing small changes to revamp units.

Madi M. Asiri

Mr. Madi Asiri is having more than 11 years of technical experience in Refinery and Petrochemicals sector. Mr. Asiri joined SATORP since earlier days and heavily involved in refinery pre-commissioning, commissioning, startup, stabilization, shutdown, turnaround, troubleshooting, debottleneck and optimization. Currently he is holding a position of Corporate Operational Excellence. In addition, he has a wide and deep knowledge in refinery and petrochemicals business management and project managements. He graduated as a chemical engineer from King Fahd University of Petroleum & Minerals [KFUPM], Saudi Arabia, and holds a postgraduate degree in refining and petrochemicals from IFP School, France. In addition, he is a certified ASQ Manager of Quality/Organizational Excellence. Furthermore, he is hold the title of chartered engineer [CEng] from Engineering Council-United Kingdom and registered engineer in EU [Ing. EurEta]. Also, he is chartered chemical engineer from Institution of Chemical Engineers [IChemE-UK] and chartered energy engineer from Energy Institute [EI-UK].

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