RECONNECT SYMPOSIUM 2022
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Continuous improvement of high pressure CO2 stripper design

19 May 2022

Utrecht, The Netherlands

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Stamicarbon 75 YEARS

TITLE OF PAPER

Conference name	Stamicarbon Symposium 2022 – Reconnect
Conference date	16th – 19th May 2022
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Classification	Public

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1. ABSTRACT

Along with the industrial trend of economy of scale, larger capacity high pressure (HP) strippers for urea production have been demanded over time. Accordingly, an improved design that respond to these specific needs has been identified by Stamicarbon: triggered by a higher than normal passive corrosion rate of heat exchanger (HEX) tubes in large capacity HP Strippers (>2700 MTPD), and by the absence of iron oxide deposits in the HEX-tubes located in the center of the tube-sheet, an extensive study was undertaken to analyze its root cause leading to an optimized design which is IP protected and forms nowadays part of our standards. After analyzing our worldwide largest capacity HP Strippers in operation, it has been concluded that condensate accumulation on traditional baffles shall be avoided by means of homogenously distributed free drain area tube supports, such as grids, sufficiently rigid to avoid vibration and buckling.

By applying this optimized design, the passive corrosion rate of Safurex® HEX tubes of larger capacity HP Strippers will be normalized again and will consequently lead to a comparable lifetime to the smaller capacity HP Strippers. An additional learning point was that the increased peripheral passive corrosion rate was not related to the material but rather to equipment design. In conclusion, upscaling the design of HP Strippers for urea production is definitely not straightforward and it is strongly recommended to consult an experienced and reputable licensor for equipment design and supply such as Stamicarbon.

2. INTRODUCTION

Stamicarbon has been offering its CO_2 stripping technology for more than 50 years, since the late 1960s. Based on vast experience and knowledge about typical corrosion mechanisms in urea plants, Stamicarbon is able to assess the integrity and remaining lifetime of the critical high pressure (HP) static equipment. An important aspect of these corrosion inspections is the measurement of the wall thickness of heat exchanger (HEX) tubes in the HP Strippers using eddy current inspection technology. If this is performed in consecutive turnarounds, a corrosion rate can be calculated and subsequently the remaining lifetime of the HP Stripper. HP Stripper HEX tubes are exposed to the most severe corrosive process conditions in urea plants: they suffer from ammonium carbamate corrosion that leads to a uniform inter-crystalline attack of the tube wall that progresses at a more or less constant and predictable rate, given that neither the process conditions nor the oxygen supply (passivation air) change over time. An extensive study was undertaken to analyze the root cause of the lack of iron oxide deposit build-up in the HEX tubes located in the center of the tube-sheet; and the observed higher passive corrosion rate of HEX tubes predominately located in the periphery of the tube-sheet in large capacity HP Strippers of urea plants with a nameplate capacity >2700 MTPD, compared to the HEX tubes located in the center of the tube-sheet (See Fig. 1.a and 1.b. from 2 different large scale reference HP Strippers. Note that the colour scale going from thinner to thicker tube wall is: red (thinnest), yellow, green, light blue, blue, dark blue and white (thickest);

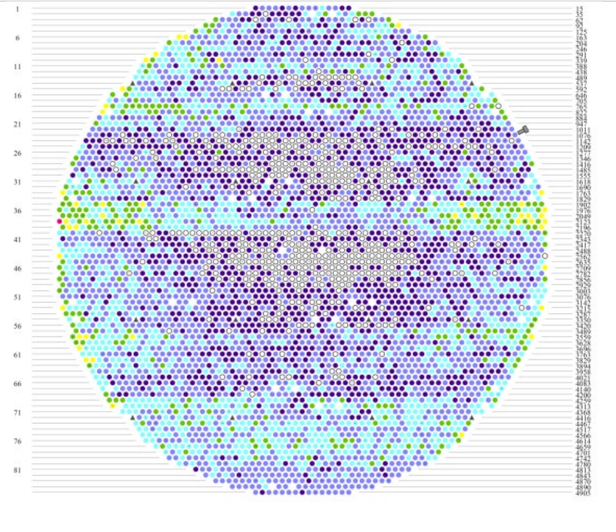

Fig. 1.a: Large capacity (second) reference HP Stripper after 3.5 years of operation.

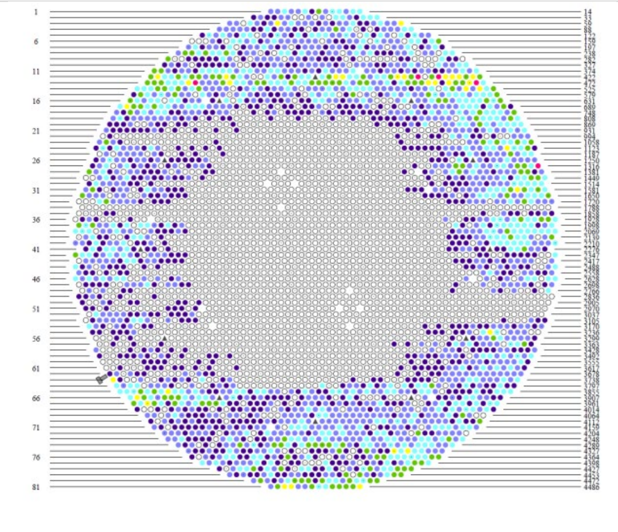

Fig. 1.b: Large capacity (main) reference HP Stripper after 12 years of operation.

3. ROOT CAUSE ANALYSIS (RCA) OF PERIPHERAL CORROSION

It is known that corrosion in HP Strippers is promoted by high temperature, low oxygen concentration and high ammonium carbamate concentration in the urea solution (USO) from the reactor. Thus, differences in corrosion rate between the HEX tubes located in the periphery compared to the HEX tubes in the center part of the tube-sheet could originate from an unequal distribution across the HP Stripper tubes of either flowrate of USO liquid feed, carbon dioxide and/or heat transfer (leading to uneven temperature distribution) at the HP steam shell side. In addition to those, Stamicarbon studied the differences in iron oxide depositing rate of large capacity (>2700 MTPD) HP Strippers compared to the smaller capacity HP Strippers (<2700 MTPD).

3.1. ANALYSIS OF THE SCALING PATTERN

The common observation during inspections is a randomly distributed wall thinning over the complete array of HEX tubes accompanied by a build-up of iron oxide deposits (scaling) close to the process outlet inside all of the tubes (Fig. 2.a). It is generally reported after inspection that outer tubes have slightly higher scaling deposits. Unexpectedly, iron oxide build-up in the large capacity reference HP Stripper is only observed in the tubes at the outer periphery. No scale build-up is noticed in the inner tubes. This has never been reported before in smaller capacity HP Strippers.

It is known that iron oxides can dissolve in ammonium carbamate as it is a strong acid. Changing conditions elsewhere in the process can cause the iron oxides to precipitate again. It is known that the deposit rate of iron oxides depends on their solubility in the ammonium carbamate solution. Lower temperatures and lower acidity (higher pH) decrease the solubility of iron oxides in ammonium carbamate.

The urea solution flows from the top of the HP stripper through the heat exchange tubes (HEX tubes). Going from the top to the bottom of the HEX tubes, the concentration of ammonium carbamate in the urea solution decreases and the urea concentration increases due to decomposition of the ammonium carbamate into gaseous NH_3 and CO_2. Also, analogously from top to bottom of the HEX tubes, the temperature increases and the acidity decreases. Generally, going from the top of the HP stripper HEX tubes to the bottom, the effect of decreasing acidity due to removal of ammonium carbamate is predominant over the effect of increasing temperature, which results in iron oxide deposits being formed in the lower part of the tubes.

As mentioned above, it is commonly observed that iron oxide deposits are present at the bottom of all the heat exchanger tubes independent of their position in the stripper. Therefore, it is concluded that in the reference large capacity HP Stripper, the stripping efficiency of the tubes in the outer periphery is higher than the tubes in the center, and that the stripping efficiency in the center tubes is even so low that no iron oxides precipitate.

To complete the study on scaling, iron deposits distribution on the top tube sheet was compared with the distribution of the iron oxide deposits inside the HEX tubes concluding that the former follows a typical pattern (Fig. 2.b) and that there is no correlation between them.

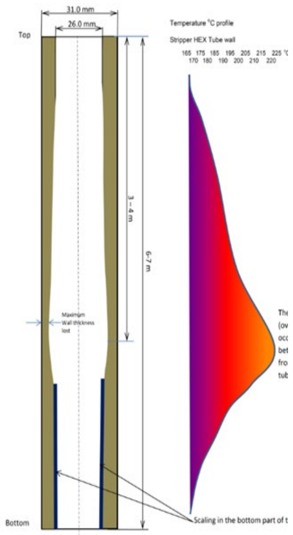

Fig. 2.a: Typical wall thinning & deposits in a HEX HP Stripper tube.

Fig. 2.b: Typical pattern of scale deposits onto the bottom part of the top tube-sheet of a HP Stripper.

3.2. UREA SOLUTION (USO) FEED

In the CO_2 stripper the urea solution flows downwards through a tube bundle, and is brought in contact with a gas phase (mainly CO_2) countercurrent-wise. For an operation of the HP Stripper according to design it is of great importance that the inlet liquid is evenly distributed over all the HEX tubes.

Stamicarbon has two main systems in operation that distribute a reduced velocity liquid from the periphery to the center to avoid turbulence as much as possible since it may result in a different liquid level above the liquid dividers which could subsequently cause a different hydrostatic height resulting in uneven flow across tubes.

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These 2 systems are:

- 180° "U" shape liquid inlet box after the feed pipe (Fig. 3).

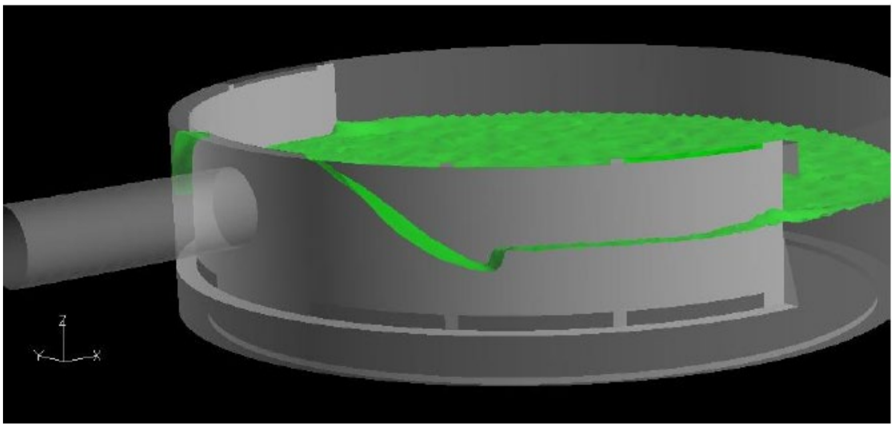

Fig. 3: Liquid level (green) inside the 180° inlet box ("U" shape section after inlet pipe on the left)

- 360° liquid inlet box: same principle as the 180° liquid inlet box but with a "O" shape section after the feed pipe, i.e., covering the complete perimeter around the pipe bundle (Fig. 4).

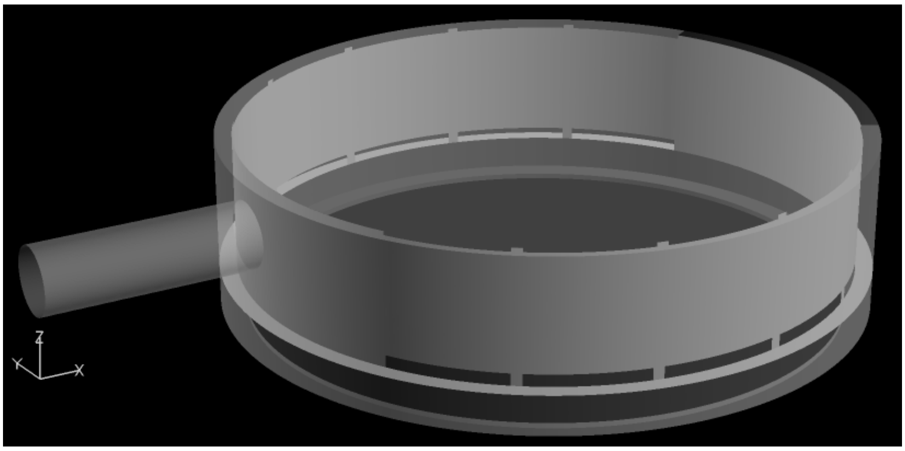

Fig. 4: 360° distributor ("O" shape section after inlet pipe on the left)

If the distribution of USO feed to the HP Stripper tubes is uneven, the outer tubes are expected to receive more liquid than the inner tubes due to the design of the liquid distribution system, which feeds USO from the outer to the inner side of the top tube-sheet (Fig. 5).

Fig. 5: Carbamate liquid level noticed in the liquid dividers when ordered according to their location over the HP Stripper radius. Level at the outer side is larger.

An unequal liquid distribution is pretty unlikely to be the root cause given that the HP Stripper efficiency (often measured as ammonia conversion expressed as moles fraction in a parameter called “alfa”) and therefore temperature, decrease with increasing tube load. The presence of substantial iron oxide scaling on the outer tubes and the lack of it on the inner ones indicates higher stripping efficiency in the peripheral tubes. This is contradictory to the initial hypothesis of larger USO feed distribution in the outer tubes, which would result in a lower stripping efficiency as modelled above. Therefore, liquid maldistribution was ruled out as potential root cause.

3.3. CO_2 MALDISTRIBUTION

Stamicarbon design introduces supercritical CO_2 to the HP Stripper bottom via a bended feed pipe of a certain diameter with an impingement plate on its discharge point (Fig. 6.a). Its functionality is to quench the inlet CO_2 velocity and to distribute this stream homogeneously or, in other words, to avoid CO_2 jets causing preferential flow streams trough tubes that could receive higher velocity CO_2 than others. While the CO_2 flows upwards, the stripped urea solution (GUSO) liquid phase flows downwards by gravity into the bottom chamber before it is discharged from the equipment (Fig. 6.b).

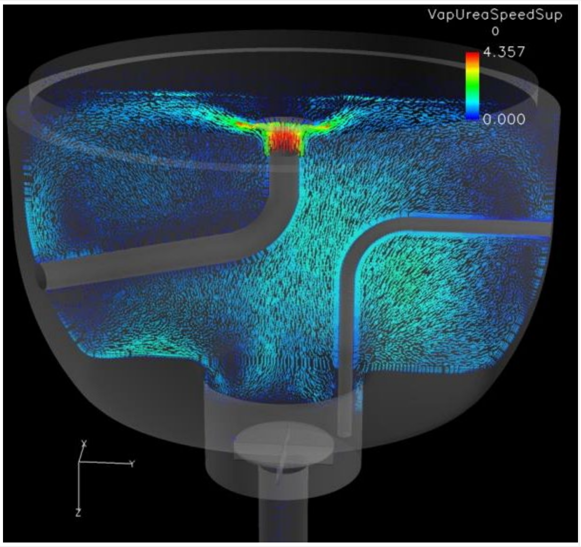

Fig. 6.a: CO2 gas flow in the HP Stripper bottom with an impingement plate.

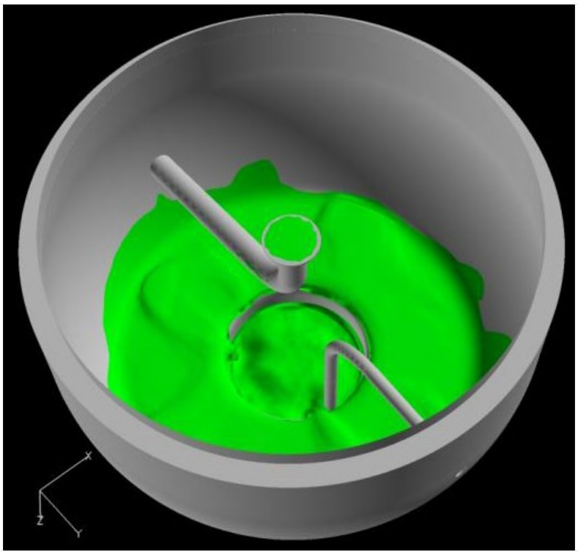

Fig. 6.b: Liquid outlet (GUSO) flows downwards into the bottom reservoir.

Two worst case scenarios with a guesstimated 20% more and 20% less CO_2 feed were studied keeping the rest of the variables the same as in the reference case. The difference in the maximum temperature achieved in both cases is hardly 1 °C. The lower CO_2 case showed the largest temperature peak. The cooling and dilution effects decreasing the process temperature in the larger CO_2 case seem to be more dominant than the larger HP Stripper efficiency (often quantified as ammonia conversion or "alfa"), leading to a larger carbamate break-up and therefore increase in the boiling point.
The largest corrosion is expected in the fewer CO_2 case since the tube is exposed to virtually the same temperature profile but to a more acidic pH as a result of the reduced carbamate break-up.
Assuming that the central tubes will get more CO_2 than those in the sides, the models showed that:

- The tubes in the outer diameter section would have less stripping efficiency than those in the center.
- The dissolved oxygen in the liquid leaving the peripheral stripper tubes would be somewhat less compared those in the center.
- The temperature of the process fluid that leaves the tubes in the center and outside periphery would hardly deviate despite the significant difference in ammonia efficiency: hardly 1 °C difference in the max. process temperature achieved in both cases.
- The peripheral tubes would be exposed to a more acidic average environment due to their HP Stripper efficiency, i.e., the lesser carbamate break-up would increase the carbamate concentration, which may contribute to a larger corrosion.

In conclusion, a mechanism motivating different corrosion rates according to different CO_2 distribution is identified. It describes how a larger corrosion in the peripheral tubes could be explained provided that there is more CO_2 load in the center than in the outer periphery. The process mechanism is that tubes with larger CO_2 load will have a much larger HP Stripper efficiency, slightly lower temperature, and a less aggressive acidic environment exposure that the peripheral ones since they achieve a greater carbamate decomposition. However, this mechanism seems unlikely to be the root cause of the observed corrosion pattern since:

- It is completely independent from the position of the disks and doughnuts (D&D), where the corrosion differences have been observed (Fig. 7.a and Fig. 7.b. Note that the colour scale going from thinner to thicker tube wall is: red (thinnest), yellow, green, light blue, blue, dark blue and white (thickest))

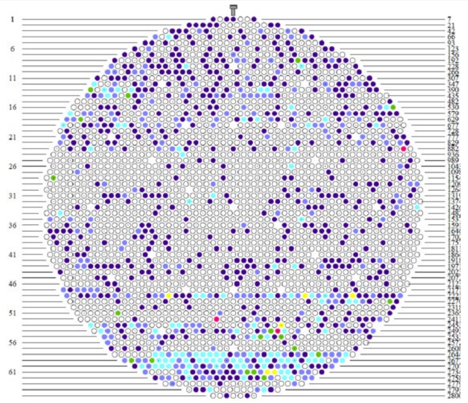

Fig. 7.a: Random corrosion pattern in standard size reference stripper

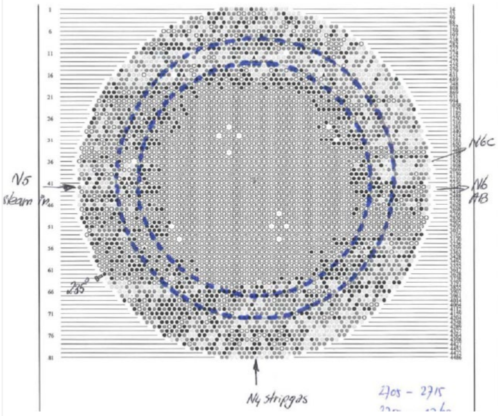

Fig. 7.b: Position of the edges of the D&D coincide with the peripheric corrosion

- The model estimates that almost 95% of the pressure drop over the HP Stripper HEX tubes comes from hydrostatic height. Therefore, even if the CO_2 had some velocity deviation over its bottom inlet to the tubes, the counter-pressure generated by the hydrostatic gas column would be able to compensate it. This compensation effect is even more evident when noticing that the pressure loss over a tube with less CO_2 becomes lower (ca. 3% lower for a 20% less CO_2 inlet), thus making such tube more prone to get additional CO_2 over a tube that already has more CO_2, which would have larger total pressure drop (ca. 2.5% less total pressure drop for a 20% additional CO_2 inlet). This means that a “pressure homogenization” effect is expected in the bottom of the tubes, where the CO_2 inlet is located.

The extent of CO_2 maldistribution was estimated assuming that it would originate in the bottom chamber of the HP Stripper when there may be a significant pressure drop difference for CO_2 flow into the inner tubes than into the outer. If CO_2 distribution would be uneven, the outer tubes are expected to receive less CO_2 than the inner ones due to the CO_2 distribution design, feeding from the inner to the outer side via an impingement plate. An estimation of the pressure drop of the CO_2 stream from its outlet starting at the impingement plate to the furthest tube in the outer perimeter was carried out. It was concluded that the CO_2 maldistribution center to periphery is in the order of magnitude of 5% and it has therefore a neglectable effect. Hence, it was excluded as the root cause of the peripheral corrosion.

3.4. HEAT LOAD MALDISTRIBUTION

Traditional baffles used in the shell side for steam distribution and tube support are single segmental (SS), double segmental (DS) (Fig. 8.a) and disk & doughnut (D&D). Since the introduction of the CO2 HP Stripper, Stamicarbon has chosen for the D&D design for the baffles
at the shell side (Fig. 8.b).

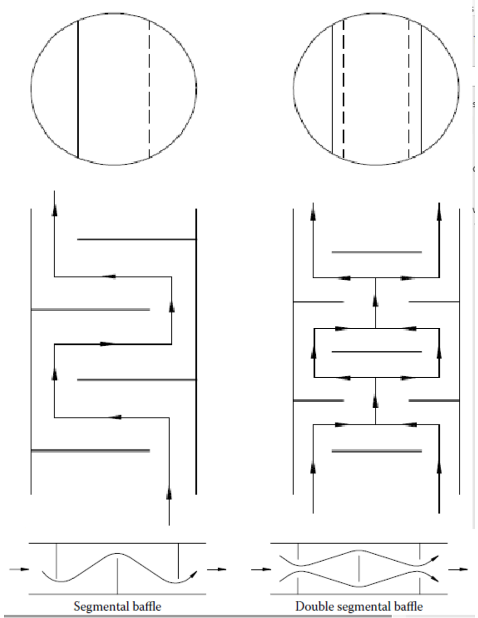

Fig. 8.a: Single Segmental (SS, left) and double segmental (DS, right) shell baffles

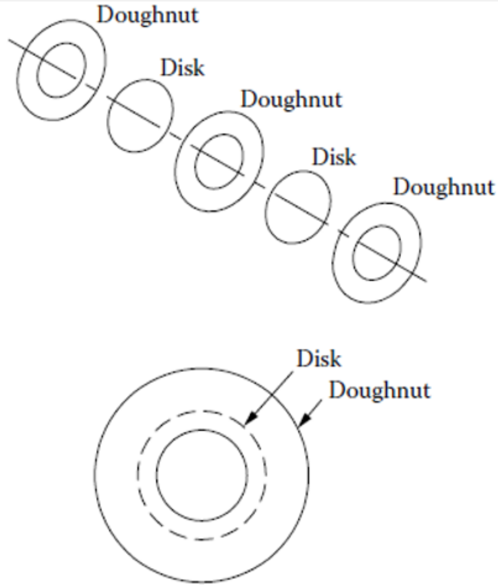

Fig. 8.b: Disk & Doughnut (D&D) baffles

There are 2 reasons to suspect a lower heat transfer at the HEX tubes located in the center of the tube-sheet, or a larger one at the peripherial HEX tubes:

- Local steam velocity differences, which are suspected to come from 2 sources:
  - Increased cross-flow steam velocity in larger HP Strippers, suspected to be highest around the edges of the D&D baffles.
  - Decreased heat transfer behind the D&D baffles.
- A different heat exchange mechanism than steam condensation caused by stagnant zones of accumulated condensate.

Calculations on the effect of the steam velocity in the overall heat exchange coefficient revealed that they could only be of significant impact if the heat exchange coefficient of the steam side was dramatically reduced. This was considered unfeasible due to the low velocities estimated inside the shell, even the maximum ones, in the order of magnitude of average 2 m/s and a maximum of 10 m/s. As a supporting fact, detailed calculations showed that the condensate flow is gravitational, meaning that it is circulating down the HEX tubes in a laminar regime independently of the surrounding steam velocity. Fig. 11 presents an sketch of the explained heat transfer model.

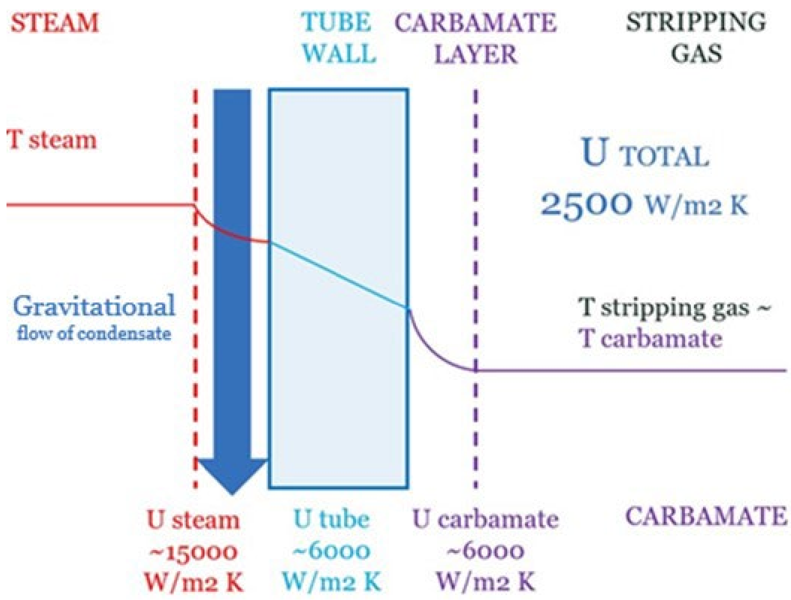

Fig. 9: Sketch of the heat transfer mechanism from the shell to the tube. Note that the U figures shown are taken from open literature remaining the calculated values IP of Stamciarbon

A difference in the horizontal plane of 20% between the heat transfer coefficient for the outer tubes (10% higher) and the inner tubes (10% lower) was modelled for the large capacity reference HP Stripper and yielded a process temperature peak difference of 3°C which could already explain the observed differences in corrosion rate between the outer and inner HEX tubes. Given that such a large difference over the heat exchange coefficient on the steam side could not be explained by local velocity differences led to conclusion that condensate accumulation on top of the central disks is the main root cause of the heat load maldistribution (Fig. 10).

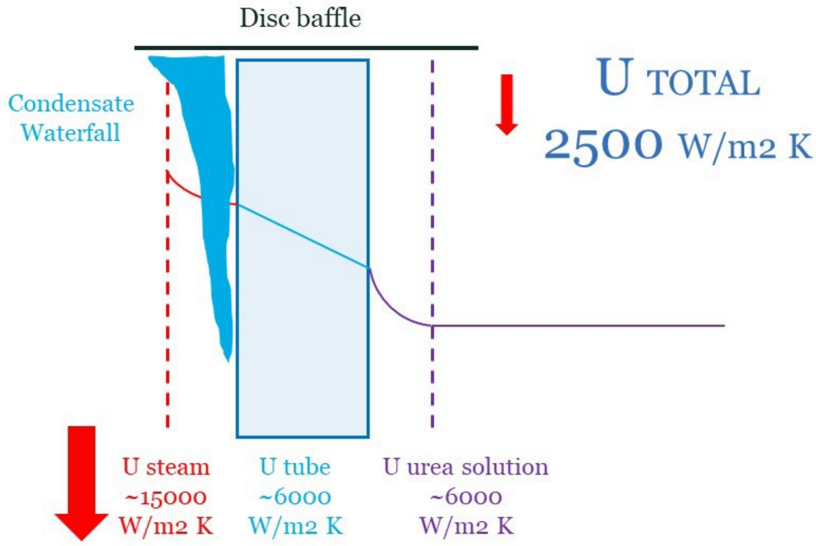

Fig. 10: Sketch of the heat transfer mechanism indicating that a significant decrease on the steam heat exchange coefficient caused by condensate waterfall can lead to a noticeable decrease in the overall heat exchange coefficient.

4. CFD ANALYSIS ON STEAM SHELL SIDE WITH TRADITIONAL BAFFLES

The above mentioned analysis pointed in the direction of a maldistribution of the thermal load in the steam shell side as possible root cause. To further confirm this a CFD simulation of the shell side of HP Strippers for large and standard capacity was carried out:

- Large capacity reference HP Stripper: 3200 MTPD and an inner shell diameter of 3 m.
- Standard capacity reference HP Stripper: 2000 MTPD and an inner shell diameter of 2.35 m.

For the lower 6 sections of both units the velocity induced by the baffles was found to be rather low, the velocity decreased due to mass transfer from steam to condensate and stagnant regions were observed. The kinetic energy imposed by the geometry alone is not sufficient to cause a significant velocity on the inner tubes. Furthermore, it was observed that the higher density of the fluid in the bottom section (due to condensed steam) reduces the penetration of the radial flows, more energy is needed to reach the center and flow is deflected.
The region where significant horizontal flow exists is reduced towards the bottom by these mechanisms. However, due to the buoyance forces on the (heavier) condensate, a vertical flow occurs near the center. Fig. 11 shows the bottom four sections (last two disks and doughnuts) of the half diameter shell for both large and standard units The quivers are used to indicate fluid flow direction and magnitude (size), the colors on the background indicate an upward (red) or downward (blue) motion of the fluid flow. Condensate accumulates on the bottom disks. Due to the high velocity around the baffles, much of the super-cooling occurs at them, and a fraction later, in the area below the disks, condensation occurs. The condensation process reduces pressure because of the lower specific volume of the condensate.

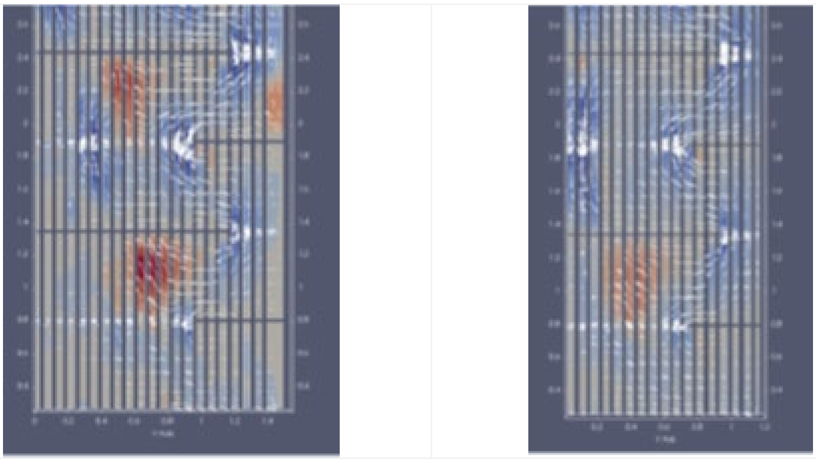

Fig. 11: Velocity profile of the bottom half-shell of large capacity (left) and standard capacity (right) HP Strippers. (Note that red means larger upwards velocity, white is neutral velocity and blue larger downwards velocity).

The distribution of such condensate is shown in Fig. 12 below:

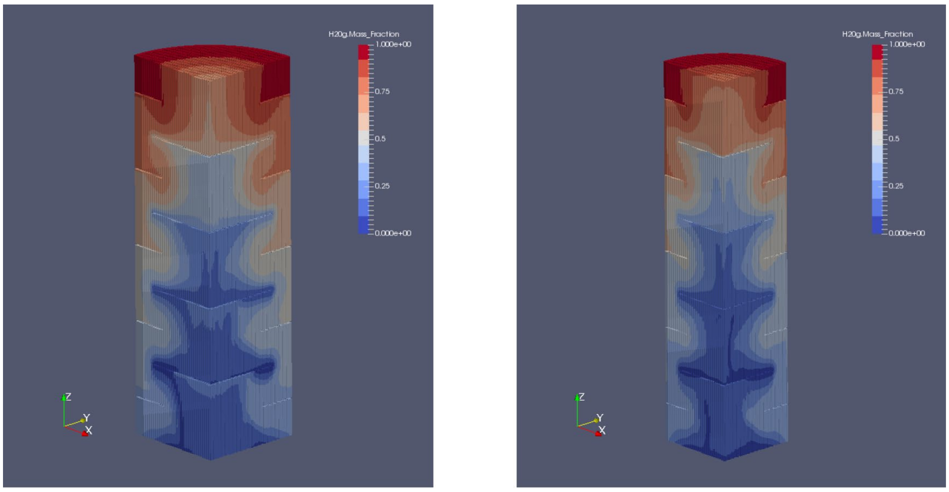

Fig. 12: Steam mass fraction profile in large capacity (left) and standard capacity (right) HP Strippers (Note that just ¼ of the stripper volume is depicted)

In conclusion, the differential corrosion of the HEX tubes in the horizontal plane can be explained by a combination of a larger accumulation of condensate in the central disks of the D&D baffles, leading to a lower heat transfer and thus to a lower internal skin temperature; and an enhanced steam refreshment in the outer perimeter, leading to a higher heat transfer and thus to a higher internal skin temperature.

On top of that, the overall heat transfer at a given shell side steam pressure may be lower in larger strippers, due to which a higher shell side steam pressure needs to be applied to reach to a certain stripping efficiency. A higher shell side steam pressure contributes to increase even more the temperature profile in the outer side of the tube-sheet and to therefore make the difference with the central part more acute.

5. OPTIMIZED DESIGN: VALIDATION OF GRID DESIGN VIA HTRI AND CFD

The technical team of Stamicarbon proposed a grid design to provide a minimum amount of TEMA supports, to avoid both vibration and buckling. It was confirmed with HTRI that the overall heat exchange coefficient and the pressure drop over the shell will not be compromised. Both the HTRI models and the final design were challenged both internally and by an external company. The Stamicarbon team concluded that the overall performance of the optimized design HP stripper will be, at least, the same as the HP Strippers with the baffle design.

CFD showed that the formed condensate in a HP Stripper with a grid support design is distributed and leads to a fairly equal condensate distribution in the radial direction of the heat exchanger, for both replacement (Safurex® Stripper; Fig. 13 left) and grassroot (Fig. 13 right) HP strippers. At the bottom grids, the condensate is pushed from the center and accumulates towards the outer edges, but no condensate is trapped.

No significant difference is observed between the two models: In the axial direction, the region where the steam mass fraction is still predominant (see orange inlet area at the top) extends further down for the replacement model because the flow is driven more downward compared to the grassroot model. Regarding the radial direction, since steam distribution is dominated by condensation rates, both steam distribution and condensation rate are identical in both cases.

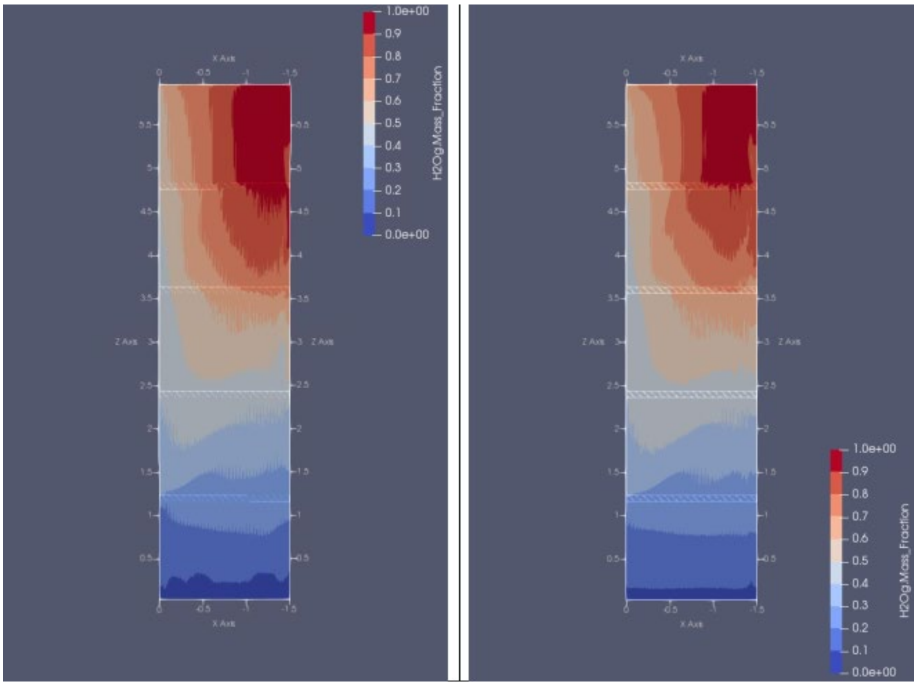

Fig. 13: CFD modelled steam mass fraction profile inside HP Strippers with grid supports replacing traditional baffles for both replacement (left) and grassroots (right)

The grids did not show condensate accumulation in any of the models. Therefore a more homogeneous steam/condensate distribution is maintained both above and below the grids leading to an improved and more homogeneous heat exchange in the radial direction of the stripper.

This means that the grids have the effect of pushing the condensate outwards from the center, but a relatively constant steam/condensate distribution is maintained both above and below the grids. For the top region of the heat exchanger, where mostly steam exists, the grids have the effect of guiding the steam flow into a vertical direction.

The optimized design for large capacity HP strippers is part of Stamicarbon's standard design since 2018 and has already been constructed and implemented in several commercial projects (Fig. 14). The overall heat exchange coefficient of the first HP stripper in operation with a grid design has been confirmed to be the same to somewhat higher than initially estimated, strengthening the suitability of this design choice.

Fig. 14: Grid design under construction in workshop

6. CONCLUSIONS

In view of the results, it is concluded that replacing traditional baffles in the shell side of large capacity HP Strippers (> 2700 MTPD) by homogenously distributed free drain area tube supports, such as a grids, in a sufficient number to comply to vibration and buckling TEMA requirements leads to an optimized design since:

- There is no condensate accumulation on the grids. This means that they have an adequate and continuous condensate draining capability when compared to traditional baffles.
- Heat transfer distribution is more homogeneous and it is therefore expected to lead to less corrosion in the outer periphery of the tube bundle.
- Since condensate discharge throughout the shell becomes easier due to the evenly distributed draining surface, less tube area is covered with condensate, on average resulting in at least the same heat transfer as compared to the HP strippers with a baffle design.

To wrap up, highlights of the present study are summarized below:

- The increased peripheral passive corrosion rate is not related to the material but rather linked to equipment design. This confirms once more the strength and reliability of Safurex®.
- The optimized design for HP Strippers >2700 MTPD will restore the originally forecasted lifetime and, when combined with Safurex® Star, even larger lifetimes can be expected.
- Upscaling the design of HP Strippers is definitely not straightforward and it is strongly recommended to consult an experienced and reputable licensor for equipment design and supply such as Stamicarbon.

The overall heat exchange coefficient of the first HP stripper in operation with a grid design has been confirmed to be the same to somewhat higher than initially estimated, strengthening the suitability of this design choice.

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