CHEMICAL ENGINEERING TRANSACTIONS

VOL. 69, 2018

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Elisabetta Brunazzi, Eva Sorensen

ISBN 978-88-95608-66-2; ISSN 2283-9216

Troubleshooting a Thermosiphon Reboiler – Why New Is Not Always Better than Old

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During an ethylene plant turn-around, a 38-year-old tube bundle of a vertical thermosiphon reboiler was replaced with a new, seemingly identical one. However, when the plant returned to full operation after the turn-around, the reboiler was not able to reach the same duty as the old tube bundle.
Systematic troubleshooting using detailed column and thermosiphon simulation, neutron backscatter, plant data reconciliation and flow regime analysis ruled out possible reasons such as thermosiphon inlet line plugging, or lowered heat transfer due to steam superheat, or the presence of non-condensables in the steam, leaving reduced heat transfer on the tube side as the strongest suspect.
To avoid plant shut-down, the issue was temporarily solved by switching from low pressure (1.6 barg) to medium pressure (7.2 barg) steam as heating medium. With the higher steam pressure and increased ΔT across the exchanger the original duty was successfully recovered.
To investigate the reduced heat transfer, light, laser and electron microscopy studies revealed that the surfaces of old and new reboiler tubes were very different in roughness and cleanliness, causing differing heat transfer characteristics. The gradual degradation of the tube surface, which occurred over the years, is believed to have increased the maximum heat transfer duty of the old reboiler. This theory is supported by a report from the old tube bundle's first year of operation when similar capacity problems occurred.

1. Introduction

1.1 Circulating vertical thermosiphon reboilers

Circulating vertical thermosiphon reboilers are compact, achieve high heat transfer rates, have relatively low fouling tendency, require little plot space and simple piping, and have relatively low capital cost and no pumping cost. This reboiler is usually the preferred type in the chemical and petrochemical industry (Kister, 1990). Liquid to the reboiler is supplied from the tower base. Often, a preferential baffle splits the tower base into a constant-head reboiler draw sump and a level-controlled bottom draw sump (Fig. 1a).
Figure 1b is a schematic of a reboiler tube. Liquid from the column base arrives at the reboiler slightly subcooled due to the liquid static head. Upon entry, the liquid is preheated by sensible heat transfer only, with a relatively low heat transfer coefficient. Once the boiling point is reached, boiling starts, generating a two-phase mix of lower density than the liquid. Thermosiphon reboilers utilize the density difference between the liquid in the tower base and the mixed-phase fluid in the reboiler and return line to drive reboiler process flow. Unvapourized liquid returns to the tower base.
The lowest boiling zone is "bubble flow". The bubbles form by nucleation at the heating surface and are dispersed in the liquid. With more heating, more bubbles form, coalesce to larger bubbles, and then to slugs of vapour, termed "slug flow". Each reboiler tube slugs at a different pace so overall no instability develops. Upon further heating, an annular flow zone forms, where the liquid flows as an annulus and the vapour flows inside as a core. The vapour shear drags the liquid film up with it. Heat is removed from the wall by convection, with vaporization taking place at the vapour-liquid interface. Further heating boils off the liquid film, the wall dries up, and a mist flow zone sets in. Heat is transferred via a vapour film that has a high thermal resistance, and

the tube wall temperature approaches the heating medium temperature. This condition is often termed “burnout”, and may lead to metal overheating, fouling and poor heat transfer, so it needs to be avoided.

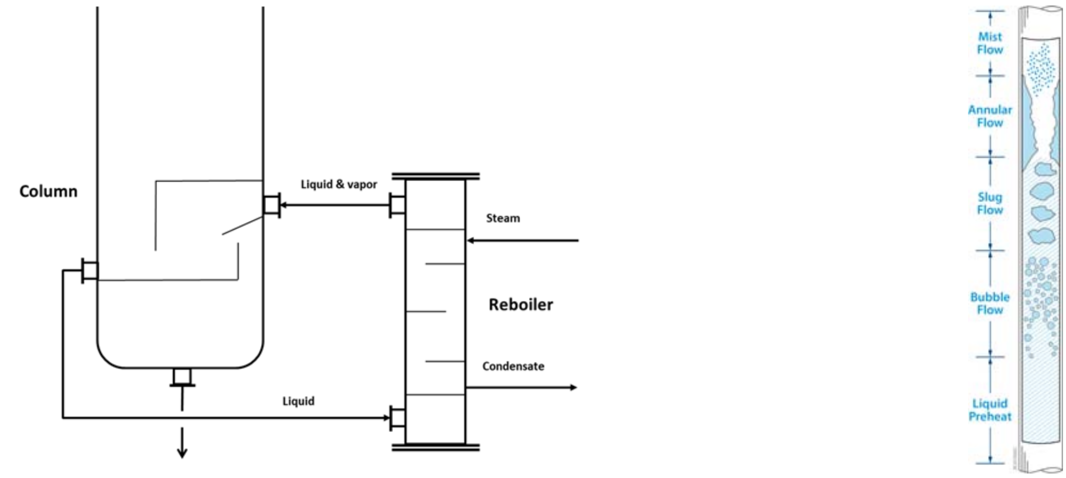

Figure 1. a) Circulating vertical thermosiphon reboiler b) Schematic of reboiler tube

At low liquid level in the reboiler sump, there is little driving head to push the liquid into the reboiler and the circulation rate is low. The little liquid that gets into the reboiler is totally vaporized, generating a dry-wall mist flow zone. Raising the liquid level intensifies circulation, lowers the fractional vaporization, lengthens the wet-wall boiling zone, and shrinks the dry-wall mist flow zone. Once the mist flow is eliminated, the reboiler reaches its maximum heat transfer rate. To keep a comfortable margin from mist flow, the industry’s practice for pressure services has been to maintain the reboiler sump level (the top of the overflow baffle in Fig. 1a) at the top of the reboiler tubes (Kister, 1990).

HTRI research (Lestina and Sofka, 2015) found that the wet-wall regimes described above may not be attained in many light hydrocarbon services. Nucleate boiling depends on the microscopic properties of the wall surface rather than the macroscopic geometry. Vapour bubbles form in the superheated boundary layer within micro cavities in the heated surface. The wall superheat is the temperature difference between the wall and the local liquid saturation temperature. Bubbles grow at the wall and detach. Convective boiling occurs simultaneously with nucleate boiling. Convective boiling tends to dominate in the annular flow zone, under vacuum, and in wide-boiling mixtures, while nucleate boiling tends to dominate in the bubble flow zone, at higher pressure, and with narrow-boiling mixtures. When the wall superheat exceeds a certain value, known as the Leidenfrost point, a stable vapour film forms between the hot tube surface and the bulk liquid and blankets the wall. This is termed “film boiling”. The vapour film has high thermal resistance, which drops the heat transfer rate. Film boiling is promoted by high heat fluxes, large temperature differences, and clean tube surfaces. A transition region exists between the wet-wall boiling (nucleate and/or convective) and the dry film boiling region. This region has intermittent wet wall and dry wall portions and can be highly unstable.

To prevent film boiling in hydrocarbon and organic thermosiphon reboilers, it has been recommended to keep the heat flux below 38,000 W/m^2 (Kern, 1950). This criterion is somewhat conservative, and an updated equation by Palen (1988) has been recommended (Serth and Lestina, 2014).

Most reboilers are designed for nucleate boiling as that regime typically achieves high heat transfer rates and therefore minimizes the needed heat transfer area. In the nucleate boiling regime, the control of the heat flux is robust as the heat transfer increases linearly with increasing ΔT between surface and fluid. – (Figure 2).

A tower malfunction survey (Kister, 2003) found circulating thermosiphon reboilers to be among the least troublesome reboiler types. That comparison is based on the process side only, as issues on the heating side are common to all reboiler types. The process-side malfunctions reported usually reduce the heat transfer coefficient, and include fouling; excessive circulation, usually due to too high a liquid level in the reboiler sump or insufficient pressure drop in the reboiler inlet line; insufficient circulation, usually due to low liquid level in the reboiler sump or plugging or excessive pressure drop in the reboiler circuit; insufficient delta T and resulting pinches, caused by either excessive pressure drop in the reboiler tubes or outlet line or by vaporization of light components, leaving the harder-to-boil heavy ones behind; surging, which is an instability caused by cyclic depletion of low-boilers in the tower base when the reboiler feed contains mostly high-boilers; and inability to initiate thermosiphon action at low heat fluxes.

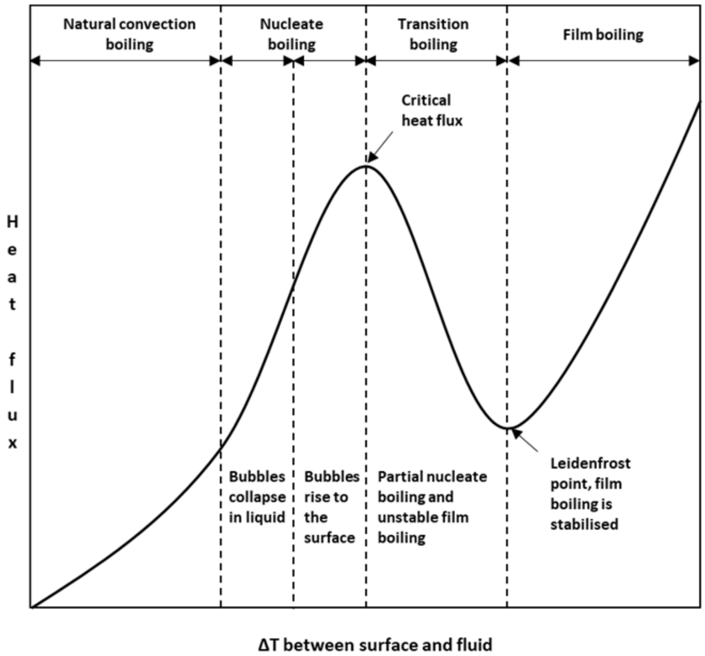

Figure 2. Boiling regimes as a function of the difference between surface temperature and liquid saturation temperature, based on Farber and Scorah (1948)

Recently, experiences were reported in which reboiler performance at high heat flux did not improve after cleaning (Serth and Lestina, 2014, and Lestina and Sofka, 2015) because cleaning promoted a change from nucleate to film boiling. It was also reported that reducing the reboiler temperature difference by throttling the steam supply to a reboiler can change the boiling mechanism from film boiling to nucleate boiling, thereby improving heat transfer (Hagan and Kruglov, 2010). Another experience was reported (Lieberman, 2016) of loss of heat transfer following retubing of a circulating horizontal thermosiphon reboiler due to a reduction of nucleation sites. Later sandblasting restored the nucleation sites and reinstated good heat transfer. This article follows in this vein, reporting a detailed analysis of a case history in which replacing an age-roughened tube bundle by a brand new smooth one led to a large reduction in heat transfer rate.

1.2 Reboiler Operating Problem

In this case history, a steam-heated circulating vertical thermosiphon reboiler is boiling a propane-propylene mix. Bottom tray liquid is preferentially diverted to the reboiler using a horizontal preferential baffle. Steam flow to the reboiler is controlled via a control valve in the condensate outlet line, which keeps a condensate level in the shell. Increased condensate flow lowers the liquid level on the shell side, making more area available for condensing steam. Normal operating conditions before replacement in 2015 are shown in Table 1:

Table 1: Normal operating data for the reboiler before tube bundle replacement.

Shell side	Tube side
Steam condensing (at ~1,6 Bar(g))	Boiling C3 hydrocarbons
Tin 130°C	Tin 66 °C
Tout 66°C (subcooled, note temperature approach)	Tout 66°C

During the cracker turn-around in 2015 the fixed tube-sheet bundle was replaced. The reason for replacement was several tube leaks the year before turn-around, which caused plant shutdown for repair. The old replaced bundle was 38 years old (it was installed in 1977). Prior to bundle replacement, the reboiler had excess capacity and was normally operating with significant sub-cooling and condensate temperature approaching process side temperature. It was therefore decided to replace it with an identical one with only minor differences.

- The old reboiler had 28 out of 725 tubes plugged and therefore the new one had slightly more area.
- The new reboiler had thicker tubes. Minimum wall thickness was increased from 2.11 to 2.77 mm.

When the new reboiler started up the design capacity could not be achieved. As a maximum 11.5 t/h of steam could be condensed when 100% of the surface area was utilized (no condensate sub-cooling). Previously the reboiler could easily condense ~14.5 t/h of steam with significant sub-cooling. Figure 3 shows the delta-T between condensate out and process side in before and after replacement.

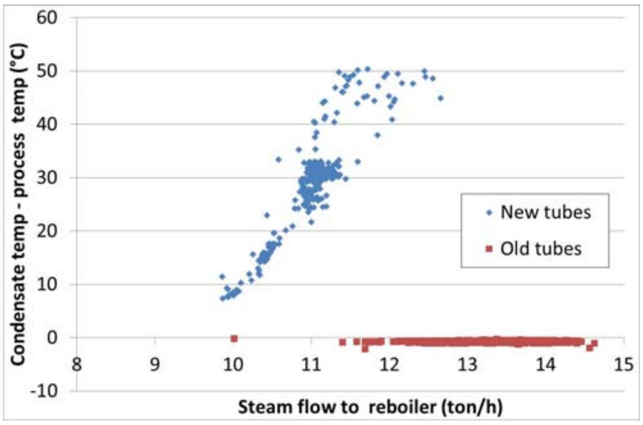

Figure 3: ΔT between condensate and process side before and after replacement of reboiler.

2. Troubleshooting

In order to solve the problem and recover reboiler capacity, systematic troubleshooting was conducted. The method adopted was to list all possible causes and then work through the list in a structured manner. Listing of all possible causes was done open minded by brainstorming.

2.1 Plant data reconciliation plant tests and scanning

First the most probable root causes were checked and excluded.

- Instrumentation was checked and calibrated.
- Process data was collected and mass and energy balance around the system were compiled
- Steam side of exchanger was vented to atmosphere to remove possible light components.
- Steam temperature to exchanger was adjusted to reduce steam superheat.
- Feed rate was reduced and column bottom temperature increased to minimize light components on process side.
- Neutron backscatter scanning to check liquid levels in the column and possible restrictions.
- X-ray of exchanger to check for damaged baffles, assembly error, impingement plate assembly.

None of the above actions solved or explained the root cause of the problem.

2.2 Neutron Backscatter

Reboiler scans showed the condensate level just above the draw nozzle, concurring with the little sub-cooling. The level in the tower bottom sump scan matched the level transmitter. The reboiler draw sump scan showed frothy liquid of varying density. Near the top of the sump it showed mostly vapor, then the density increased to near the liquid density at the centerline of the 16” draw nozzle, then linearly declined to almost vapor density at the bottom of the sump. Gamma scans of the reboiler draw pipe indicated that the pipe was not full of liquid and a vapour phase existed at the top of the pipe. The reboiler return pipe had about 35% liquid by mass.

2.3 Calculation of heat transfer coefficient

Based on the collected plant data the heat transfer coefficient for the condensation area (area utilized above the condensate level) was calculated (Figure 4). It was concluded that the heat transfer coefficient was significantly reduced for the new exchanger. Fouling was considered as a root cause for the reduced heat transfer but review of inspection reports from previous turnarounds concluded that the exchanger had always been clean. Start-up data showed no entry of foulants during start-up. During search for old data, a report from 1978, after the installation of the old reboiler, was found, indicating capacity limitation at less than 12 t/h steam to the reboiler.

This is well in line with the capacity achieved for the new exchanger (~11.5 t/h). Due to the lower plant throughput at that time it was then not considered as a major problem.

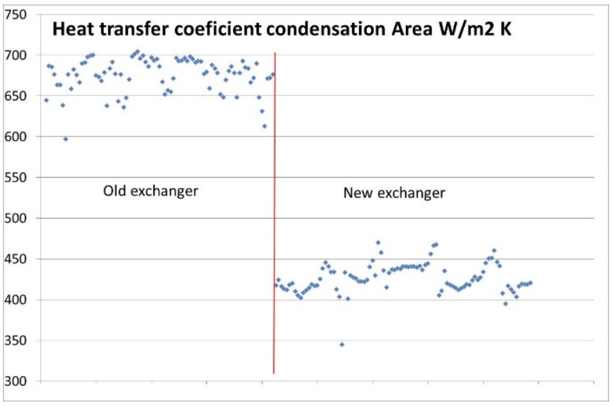

Figure 1. Heat transfer coefficient, condensation area for old and new reboiler developed over time.

2.4 Process and heat exchanger simulation

An Aspen Plus simulation model of the tower and reboiler was built, using their EDR (Exchanger Design and Rating) tool, which allows detailed implementation of exchanger geometry. Inlet and outlet piping of the reboiler were included in the model.
This allows estimating thermosiphon circulation rate, which is set by elevation between liquid levels and density differences between column and exchanger.
Distillation and reboiler simulation parameters were matched against plant data. Thermosiphon circulation rate was adjusted so that the pressure drop through the thermosiphon loop (including reboiler and nozzles) matches the hydrostatic pressure provided by liquid levels. According to the simulation model, reboiler heat transfer limitation lies mainly on the tube (process) side. The reboiler has too little surface area to perform its design duty with low pressure (1.6 bar(g)) steam. High heat flux, indicating risk of film boiling, was predicted for the tube side. Increasing steam pressure did not have a major effect on the heat transfer coefficient, but increased the heat flux through increased ΔT over the reboiler. The slight difference in tube wall thicknesses of old and new reboiler tubes played no major role in the overall heat transfer. Simulation study for the reboiler was verified by an external consultant.

2.5 The effect of steam pressure

To verify the simulation results, a plant test was performed. The inlet steam was throttled to a lower pressure to see the effect on capacity. It was concluded that lower steam pressure had a negative impact on capacity.
Based on the outcome of the simulations and the plant test it was decided to build a permanent line with medium pressure steam and perform a hot-tap to connect to the reboiler inlet piping. The reboiler capacity was successfully restored. The reboiler is now operating at full capacity with a steam pressure of 7,2 bar(g) and sub-cooling of the condensate (condensate level 30 % of the tube bundle). ΔT between steam and process side inlets increased from 65 ºC to 105 ºC but the heat transfer coefficient for the condensing area did not change with higher steam pressure and remained in the region of 400-450 W/m^{2}K.

2.6 Light, laser and electron microscopy

Samples from both old and new reboiler tubes were sent to a metallurgical laboratory for surface analysis. Figure 5a and 5b show the difference in the roughness of the tube surfaces.
Confocal laser microscopy was performed for measuring the surface roughness of the tubes. Confocal laser scanning microscopy (CLSM) combines high-resolution optical imaging with depth selectivity, which allows to optical sectioning. With CLSM, visual sections of tiny structures can be viewed and 3-D structures can be constructed from the obtained images. In terms of absolute numbers, the roughness of the old tubes was 40-50 µm and the roughness of the new tubes 3 µm.
For chemical analysis of surface deposits, image scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM/EDX) was performed. For the rougher old tubes, EDX-analysis revealed deposits or corrosion products containing significant amounts of Al, Si, Na and K likely present in an oxide form. For newer tubes with lower roughness, mainly carbon-deposits and Fe-oxide were detected. The roughened surface was therefore likely caused by the formation of deposits and corrosion products from Na, K, Si, Al impurities as well as from carbon-deposits/fouling.

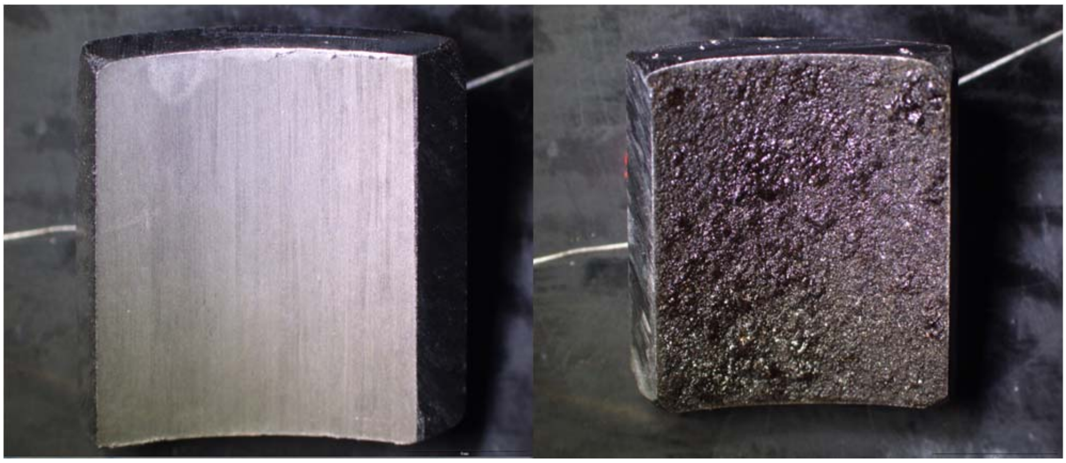

Figure 5a (left) and 5b (right): Pictures showing the difference between surfaces of the new reboiler tubes (5a) and old reboiler tubes (5b)

2.7 Discussion

Cai, Resetarits and Chambers' (2014) observations through viewing ports in a hydrocarbons kettle reboiler showed that at low heat fluxes the tube surfaces were not where nucleation began. Instead, nucleation started first on rusted segmental support baffles and rusted support rods. We believe a similar mechanism is active in our reboiler.

There are tens of thousands reboilers in newly-constructed plants, or fitted with new tubes, yet this poor heat transfer appears uncommon. Only one literature source reported a similar experience (Lieberman, 2016), and in his case the higher steam pressure made the loss of reboiler capacity marginally worse. Then there is some mystery about the aeration of the reboiler draw sump as determined by the neutron backscatter scans. So while there is considerable evidence to support the theory of surface roughness being the root cause of the reboiler problem, and to advance it as the leading theory, it cannot be regarded as conclusive.

3. Conclusions

This case shows that the surface roughness developed in an old exchanger over time may have a significant beneficial effect on its heat transfer. Mechanical investigation of the tubes from before and after the replacement revealed large differences in surface characteristics of the tubes. The old tubes had been mechanically roughened, due to corrosion and deposits during 38 years of operation, which is believed to have resulted in a reboiler capacity increase by more than 50%.

This case serves as a lesson for engineers changing old heat transfer equipment to new. The smooth and clean tubes in the new equipment may not always act positively on overall heat transfer. Checking the reboiler rating and ability to achieve its duty should be carefully performed also in cases of like-to-like replacement.

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