TROUBLESHOOT PACKING MALDISTRIBUTION UPSET
PART 2: BOILING AND FLASHING IN PACKED TOWER DISTRIBUTORS

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This paper describes troubleshooting the poor performance of a packed distillation tower and a condition called "upset" in which rapid heating up occurred near the top of the tower. The investigation combined surface temperature surveys, grid, distributor and CAT gamma scans, simulation, and a hydraulic analysis. Part 1 describes the field tests; Part 2 the simulation, hydraulic analysis and fix.

A simulation of test data gave poor efficiencies in both top and bottom beds. The hydraulic analysis concurred with the field tests in identifying maldistribution of feed and reflux as the root causes for the poor performance. The reflux, as well as the feed maldistribution, were caused by boiling and flashing of reflux or feed in the distributors and in the reflux distributor tubes. Neither distributor was designed to handle boiling or vapor. A major contributor was the nature of the reflux mixture, which contained a large fraction of a volatile component among high boilers. This low boiler readily boiled in the reflux distributor. The "upset" was zonal dryout due to the distributor boiling. The maldistribution and "upset" were fully eliminated by new, well-designed distributors and flashing feed inlets.

KEYWORDS: liquid distributors, packed towers, troubleshooting, tower feed, flashing, maldistribution, boiling in distributors

INTRODUCTION

In Part 1 of this paper, we described a tower that experienced poor performance and a condition called "upset" in which rapid heating up occurred near the top of the tower. Using temperature surveys and gamma scans we identified severe maldistribution in both top and bottom beds with vapor flowing in the central regions and liquid in the peripheral regions. We also identified spraying of liquid from the reflux and feed distributors. There were no indications of flooding nor of damage. The tests identified maldistribution of feed and reflux as the major root causes for the poor performance.

This Part 2 describes the application of simulation to determine packing efficiency, to gain insight into the upset condition, and to supply the basis for the hydraulic analysis. The hydraulic analysis checked the operation of packing and distributors, identified bottlenecks, and formed a basis for formulating and testing theories. Based on the theories, modifications were made to the reflux and feed entries and distributors that eliminated the maldistribution and the "upset" condition.

Literature references for both parts are included in Part 1 of our paper.

SIMULATION AND HYDRAULIC ANALYSIS

A simulation capable of predicting the normal and upset conditions very well was developed jointly with the client. Best match to the plant data was obtained by simulating each of the two beds by four theoretical stages. Table 1 compares measured data to simulated values. Figure 1 in Part 1 of our paper is a tower sketch showing the location of the temperature indicators (TI's).

Table 1 shows a close match between the measured and simulated heat, mass and component balances. The only exception was the concentration of impurity 2 in the bottom for the normal operations case.

Table 1. Comparing measurements & simulation

|	Normal		Upset	
	Measured	Simulated	Measured	Simulated over reboil
Theoretical stages top/bottom	–	4/4	–	4/4
Feed, kg/h	4400	4400	4300	4300
Top product, kg/h	430	440	560	530
Bottom product, kg/h	3870	3950	3750	3760
Reflux, kg/h	2940	2940	2880	2880
Reflux to Feed ratio	0.67	0.67	0.67	0.67
Reflux Accum temp, °C	87	87	87	87
Reboiler duty, kW	650	610	670	630
Condenser duty, kW	580	500	520	540
OVHD product impurity, wt %	1.68	1.69	11.5	9.3
Btm product impurity 1, wt %	0.42	0.40	0.17	0.16
Btm product impurity 2, wt %	0.082	0.025	0.015	0.014
Pressures, mbars				
Top	33	33	33.5	33.5
Bottom	46	46	46	47
Temperature, °C				
Overhead Vapor	175	172	195	190
Top of upper bed (T1)	177	208	223	225
Mid of upper bed (T2)	182	229	190	234
Bottom of upper bed (T3)	194	237	223	239
Feed region	237	238	241	239
Bottom bed	243	240	244	241
Below bed	246	248	246	249
Bottom	248	250	249	250
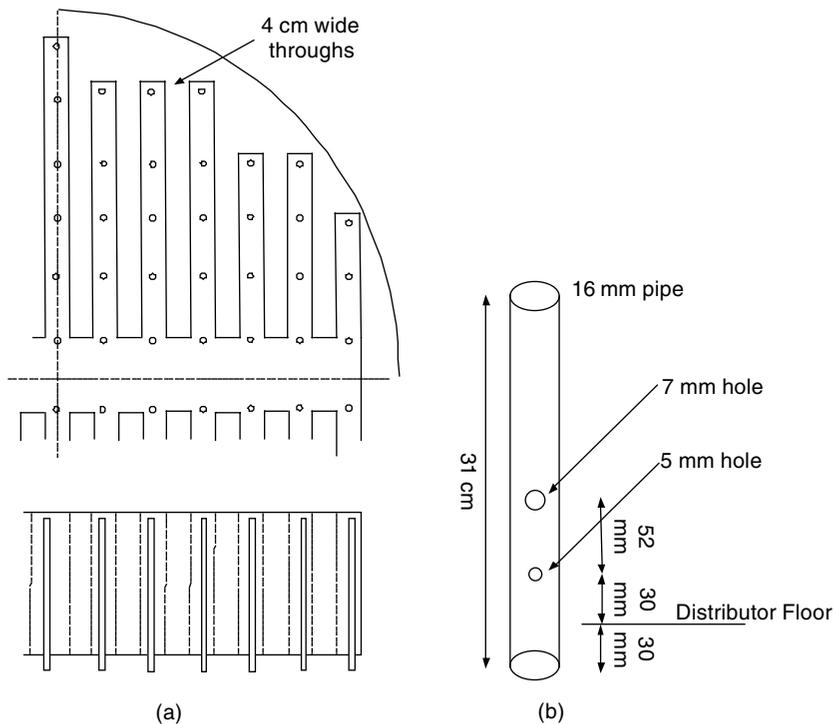
Figure 1. Feed distributor (a) plan and elevations (b) flow tube details

The only large discrepancies were in the temperature profile in the top bed, with measured temperatures up to 40–50 °C colder than simulated. This is consistent with the temperature surveys and scans that showed preferential liquid flow near the walls (where the temperatures were measured). Worsening the problem, the upper bed TI's, T2 and T3, were in the northwest, where particularly cold temperatures were observed in our temperature survey.

Comparing the 4/4 stage simulations of the upset and normal conditions shows that the main difference is the mass and component balances. At the upset condition the tower was simply overreboiled. As expected, the overreboil reduced the bottom impurity while largely increasing the overhead impurity. The simulation changes match those measured.

The tower watchdog for overreboil prevention is the tower temperature control, which comes from T3, near the bottom of the upper bed. Due to the severe maldistribution, this temperature controller could not be made to be effective in preventing overreboil. Keeping this temperature cold prevented the overreboil from setting in, and an upset

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Table 2A. Packing evaluation, normal condition

Bed	Packing	HETP (m)		Liquid flow m³/m²h (gpm/ft²)	C-factor m/s (ft/s)
		Actual	Predicted		
1	0.7 inch random 220 m²/m³	1.22	0.46	2.4 (1.0)	0.061 (0.20)*
2	Structured	1.22	0.53	6.1 (2.5)	0.068 (0.22)

*%Flood = 55%

Table 2B. Packing evaluation, upset condition

Bed	Packing	HETP (m)		Liquid flow m³/m²h (gpm/ft²)	C-factor m/s (ft/s)
		Actual	Predicted		
1	0.7 inch random 220 m²/m³	1.22	0.46	2.3 (0.9)	0.061 (0.20)*
2	Structured	1.22	0.53	6.2 (2.5)	0.072 (0.24)

*%Flood = 55 to 60%

would not initiate. But once T3 got warm, it got close to a point where the reboil exceeded the reflux, and an upset initiated. This matched the plant experience.

Table 2 compiles some hydraulic and mass transfer parameters based on the tests simulation. Table 2 shows very little variation between the packing hydraulics and mass transfer between the normal and upset conditions. It therefore argues against a packing issue causing the upset. The packing throughout the tower appeared to have been operating a comfortable margin away from flood. These calculations, together with pressure drop measurements that showed no pressure drop rise, and gamma scans that showed no flood, deny the possibility that packing flood caused the upset.

The packing efficiency was very poor in both beds, with HETP much higher than expected for the packing. Efficiencies so poor in non-flooded packing are almost always indicative of maldistribution.

DISTRIBUTOR HYDRAULIC EVALUATION
Both feed and reflux distributors were of a similar design. Figure 1 specifically shows the feed distributor, but the diagram is used to depict both.

FEED DISTRIBUTOR
The feed distributor consisted of 4 cm wide troughs with 16 mm tubes inside. Each tube was 31 cm total length, with 3 cm protruding below the distributor floor. Each tube had a
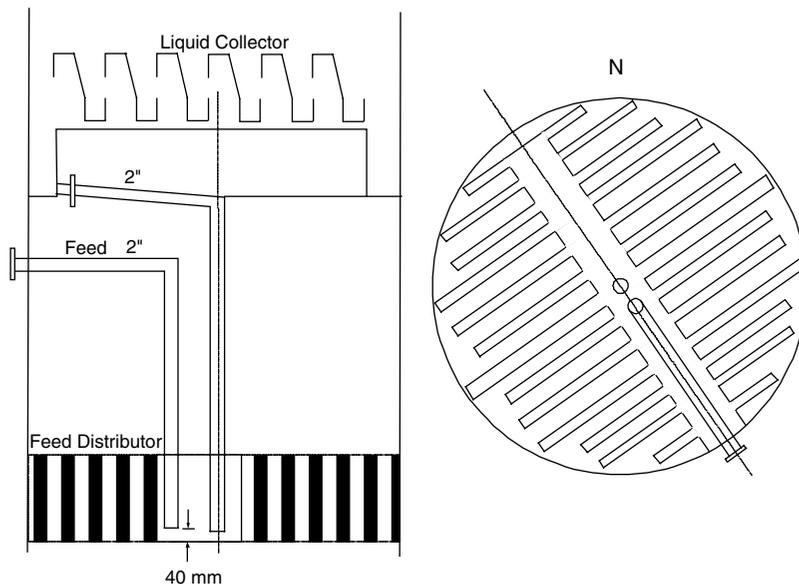
Figure 2. Feed entry arrangement

5 mm hole at 3 cm above the floor, and a 7 mm hole at 8 cm above the floor. The feed entered the distributor 150 mm south-east of the center of the parting box (Figure 2) via a downward-elled 2-inch pipe which terminated 40 mm above the floor of the parting box. Prior to installation, the distributor was water-tested at the vendor shop with good results.

Listening to the column near the feed point, one could clearly hear banging and popping sounds, indicating that the feed was flashing. A flash calculation confirmed that 2.8% of the feed by weight, or 99.4 by volume, was vapor. The feed distributor was a liquid distributor that is inadequate for any significant vapor in the feed. Gamma scans show entrainment from the distributor, most likely caused by the high flashing feed velocities spraying liquid all around.

Small holes of 5 mm are prone to plugging. There were past episodes of plugging, but the tests shed no light on this possibility. The calculated liquid levels for both normal and upset conditions were 8.5 cm above the floor, compared to 7 to 9 cm as measured by the gamma scans. Had all bottom holes been plugged, the calculated liquid level would have risen to 11 cm. So within the accuracy of the level measurement, the tests were inconclusive on distributor plugging. Subsequent inspection at the next turnaround showed no plugging.

In conclusion, flashing in the feed distributor was identified as the root cause of the bottom bed maldistribution.

REFLUX DISTRIBUTOR

Like the feed distributor, the reflux distributor (Figure 1) consisted of 3 cm wide troughs with 12 mm tubes inside. Each tube was 31 cm total length, with 3 cm protruding below the distributor floor. Each tube had a 3 mm hole at 3 cm above the floor, and a 5 mm hole at 8 cm above the floor. Reflux entered the distributor via a downward-elled 2-inch pipe that terminated 40 mm above the floor of the parting box right at the tower center. Prior to installation, this distributor too was water-tested at the vendor shop with good results. In a recent turnaround, the distributor was water-tested in situ, and qualitatively observed to distribute the water well.

We heard no crackling noises that would confirm flashing near the reflux inlet. Also, flash calculations at steady state did not suggest flashing of the reflux. Although 3 mm holes are considered extremely small, and could easily plug up, there was no evidence nor experiences of plugging in this distributor.

The temperature survey and the grid gamma scans strongly support flashing or vaporization of the reflux. The gamma scans did not see clear vapor above the reflux distributor. To give this indication, there needs to be quite a massive quantity of liquid in the vapor space above the distributor. The only sources of liquid in this region are the distributor and the top of the bed. For the top of the bed to be the source, the top bed needs to be flooded, and this is unlikely, as shown in Table 2. In the absence of flooding, the only conceivable source is the distributor.

Observation 2 for the upper bed temperature survey (Part 1) is key. There were cold, maldistributed temperatures near the top tangent line, as much as 80 °C colder than the overhead vapor temperature. This is very unusual, and suggests that subcooled reflux is likely to have been sprayed upwards – with vengeance. This spraying is likely to be have been caused by flashing of the reflux.

The reflux was condensed in a direct-contact condenser at 29 mbars (4 mbars less than the top of the tower) and 87 °C. From the condenser it entered the reflux drum via a submerged pipe, and from there it was pumped to the tower via a control valve. The reflux line between the reflux drum and the top of the column was insulated and traced with 120 °C steam to prevent freezing. So the steam tracing heated the reflux. It would not have taken too much heating to have it heated above the bubble point of the mixture. The coldest temperatures measured inside the tower during the tests were 106 °C–108 °C (on the northwest), but these temperatures were heated some by the tower vapor. So the reflux temperature at tower entrance would have been somewhere between 87 °C and 108 °C, which was enough to induce flashing.

EFFECT OF RANDOM PACKING SIZE

Surface area per unit volume of 5/8 and 1 inch Pall rings are 32 and 19 m^2/m^3, respectively. Despite the 70% higher surface of the smaller rings, they offer little efficiency enhancement, as can be inferred from the test efficiency values listed on pages 656 to 658 of *Distillation Design* (3). The likely cause is that the smaller rings are far more prone to maldistribution. Studies showed that the higher the ratio of tower to packing diameter ratio, the greater the efficiency loss due to maldistribution (4–6). Even under

near-perfect distribution, such as that usually encountered in pilot-scale tests, the 5/8 inch Pall rings fail to provide much better efficiency than the 1 inch Pall rings. On the other hand, under equal poor distribution conditions, the efficiency of the 5/8 Pall rings can be substantially worse (by as much as 50%) than that of 1 inch Pall rings. The above comparison extends to other random packings, and was in line with the packing vendor comments.

On this basis, we identified the small packing size to be a factor aggravating the effects of maldistribution on efficiency, and recommended going to a larger (1 inch) packing.

CAUSES OF MALDISTRIBUTION IN THE UPPER BED

Reflux to the tower consisted of two major components, with boiling points 90 °C apart. The reflux was condensed at a bubble point of about 87 °C at a pressure 4 mbars below the tower top pressure. It does not take much to heat it to the bubble point. It is likely that the steam tracing on the reflux line provided enough heat to exceed the bubble point, so some reflux flashing took place immediately upon entry, spraying liquid from the tower center (where the reflux entered) towards the walls.

The remaining reflux liquid proceeded to the troughs. The reflux entered the distributor at the center of the tower, at about 87 °C, while the tower overhead vapor was at about 176 °C (normal condition). The narrow troughs and the multitude of drip tubes provided lots of heat transfer area, and the delta T (90 °C) was tremendous. The volatile component boiled rigorously inside the troughs, but especially inside the drip tubes. The heat curve of the reflux was such that much of the boiling would take place at temperatures very close to the bubble point, so the boiling is likely to have been extensive. There was ample residence time in the distributor and parting box (we estimate an average of about a minute), giving plenty of opportunity for heating and boiling to take place. Even more so, there was intense boiling in the 12 mm tubes through which the distributor liquid descended onto the packing. These tubes had a large area to volume ratio. With condensation on one side of the tubes and boiling on the other, there was a good heat transfer coefficient. These tubes became an efficient heat exchanger that boiled the descending liquid. Our heat transfer calculations leave little doubt that extensive vaporization took place in these tubes.

This boiling was most intense in the regions rich in the volatile component, and short of residence time, i.e., near the center of the tower. Due to the high concentration of the volatile component, it is likely that the tubes became "falling-film reboiler" tubes, so that little liquid descended in this region. As one moved away from the center, some of the volatile component was depleted from the troughs, leaving the heavy boiler, which remained in the liquid. Boiling in the peripheral regions was therefore diminished, and the liquid descended onto the packing as intended. This gave the observed pattern of preferential vapor flow in the center and uneven peripheral liquid flow around the sides.

This mechanism also provides the only conceivable explanation we have to the tower upsets.

CAUSES OF THE UPSET CONDITION
In a falling-film reboiler, vapor ascends while unboiled liquid descends in counter-flow. If the quantity of vapor generated in the reboiler tube exceeds a certain high value, the vapor will not allow liquid to descend. In this case, the tube will flood and any liquid entering it will be entrained upwards. This condition is referred to as "system limit" or "ultimate capacity" and is also used extensively in evaluating the ultimate capacity of towers (and knock-out drums).

We theorize that the upset condition initiated due to heating up near the top of the bed, probably due to a slight overreboil. This heating up led to a higher delta T, which in turn increased vaporization in some of the central distributor tubes. At the higher vapor rate, the ultimate capacity limit was reached in these tubes. As pointed above, the central tubes (closest to the reflux inlet) had the highest concentration of the more volatile component and were the ones to encounter the limit. Our heat transfer calculations, based on 90 °C delta T and a boiling/condensation heat transfer coefficient, confirm that the boiling in the central tubes is likely to have generated enough vapor to bring these tubes close to their ultimate capacities. Once one or a few tubes reached this ultimate capacity, a self-accelerating process would set in. Less liquid descended in that region, the vapor became hotter (as observed), delta T across the tubes increased, vapor generation in the neighboring tubes was stepped up, and these tubes would reach the ultimate capacity as well. The end result was drying and heating up of the tower center, as observed and confirmed by the CAT scans.

KEY FINDINGS FROM THE TROUBLESHOOTING INVESTIGATION
- Reflux flashing upon tower entry, and boiling in the liquid distributor, generated terrible liquid distribution to the upper bed. Both the flashing and boiling were promoted by a 90 °C gap in the boiling points of the two major components in the reflux. The flashing was induced by steam tracing of the reflux line. The boiling was induced by the tremendous delta T (90 °C) and the extensive heat transfer area of the troughs and multitude of drip tubes. Boiling preferentially occurred near the tower center, the region rich in the volatile component. The peripheral regions, leaner in the volatile component, had less boiling. This created the observed preferential vapor flow in the center and uneven peripheral liquid flow, which led to the observed poor efficiency.
- The upset initiated due to heating up near the top of the bed, probably due to a slight overreboil. This heating up led to the ultimate capacity limit being reached in some of the central distributor drip tubes, a region rich in the volatile component. Once a few tubes reached this ultimate capacity, a self-accelerating process set in. Less liquid descended in that region, the vapor heated up (as observed), delta T across the tubes increased, vapor generation in the neighboring tubes was stepped up, and these tubes reached the ultimate capacity as well. The end result was drying up and heating up of the tower center, as observed and confirmed by the CAT scans.
- The small packing in the top bed aggravated the effects of maldistribution on bed efficiency.

- Poor liquid distribution in lower bed was caused by feed flash. There was a preferential flow of liquid along the periphery and on the east, and a preferential flow of vapor in a circular zone just off from the center. This caused the poor efficiency in the bottom section.

TOWER IMPROVEMENTS
We implemented the following modifications:

- **Redesign the reflux inlet to accommodate flashing, to minimize boiling in the distributor, and to eliminate boiling in the distributor tubes.** A flash box was added at the reflux entry to adequately separate any flashed vapor from the reflux before feeding the liquid to the reflux distributor. The previous distributor with the drip tubes was replaced by a different type of distributor without drip tubes. This new distributor eliminated the tubes in which much of the intense boiling took place. A thermal shield was built around the distributor walls and bottom to minimize boiling. Also, this distributor had larger holes, giving a much better plugging resistance.
- **Redesign the flashing feed inlet.** A flash box was added at the feed entry to adequately separate the flash vapor from the feed, and to adequately mix the feed liquid with the liquid collected from the bed above, before feeding the liquid to the feed distributor. The previous distributor with the drip tubes was replaced by a different type of distributor without drip tubes.
- **Replace 0.7 inch random packing in upper bed by 1 inch, same type packing**. This made the packing more robust and less sensitive to maldistribution. The packing installation was closely supervised to ensure it followed good packing practices.
- **Replace structured packing in lower bed by same type and surface area but with steeper slopes at the interfaces of packing layers**. This was done for maintenance and for modernization. There was no problem with the bottom section packing.
- **Improve reboiler return design to provide better vapor distribution**. Minor modifications were performed to improve vapor distribution and prevent the reboiler return from impinging on the base liquid. There were no major problems there.

RESULTS
Following the modifications, the tower has been performing very well. Test data taken 6 months after the revamp were best simulated with 8 stages in the upper bed and 8 stages in the lower bed. This is double the previous number of stages in each bed. The current HETP's are well in line with predictions (see Table 2A). The better staging gave dramatic improvements in product purities.

The plant ran a one day capacity test of the tower, raising the feed rate to 50% above the rate prior to modifications. Operation was stable and there were no problem in or around the tower. The plant could not increase the feed further due to capacity restrictions downstream.

The "upset" condition completely disappeared and is now just a memory.