8

APPLICATION TO PLATE PROCESSES

8.1 INTRODUCTION

Examples of plate processes are fractionation towers, extraction towers, absorption towers, or any process that depends on mechanical design to provide intimate contact between two phases followed by a zone where phase separation is achieved. The intimate contacting followed by phase separation allows equilibrium between the two phases to be achieved or approached.

The information provided in this chapter is intended to provide a basis for the problem solver to successfully complete step 3 of the problem-solving discipline: "Develop a theoretically sound working hypothesis that explains as many specifications of the problem as possible."

Since much of what occurs in a plate process is not visible to the naked eye and may not be easily understood by X-rays, it is important to be able to correctly imagine what is occurring inside the equipment.

Fractionation using sieve trays is discussed in this chapter since it is the most common application. However, the principles are applicable to all fractionation tray designs and any other plate processes.

8.2 FRACTIONATION WITH SIEVE TRAYS

The purpose of a sieve tray is to provide as close an approach to equilibrium between the liquid and vapor phase as is reasonably possible. The concept of vapor-liquid equilibrium was discussed in Chapter 5. To obtain or approach equilibrium, the following three zones are required:

Problem Solving for Process Operators and Specialists, First Edition. Joseph M. Bonem.

1. *A high intensity vapor-liquid contact zone*. In this zone, liquid must be the continuous phase. That is, vapor bubbles must exist as discrete entities surrounded by a liquid phase regime. Vapor will be bubbling up through the liquid. Due to the energy being expended, the liquid will appear as a frothy mixture of liquid and vapor.
2. *An entrained liquid separation zone*. This vapor-continuous zone is immediately above the continuous liquid phase. In this zone, the liquid droplets entrained with the rising vapor disengage and return to the liquid phase under the influence of gravity.
3. *A vapor-froth separation zone*. The liquid leaving each tray contains vapor that has not yet disengaged from the liquid. The downcomer provides time for disengagement to occur. This will result in vapor-free liquid exiting the downcomer on the tray below.

Figure 8-1 shows a typical sieve tray illustrating these three zones. In addition, it indicates two other important parameters for a fractionating tray design. These are as follows:

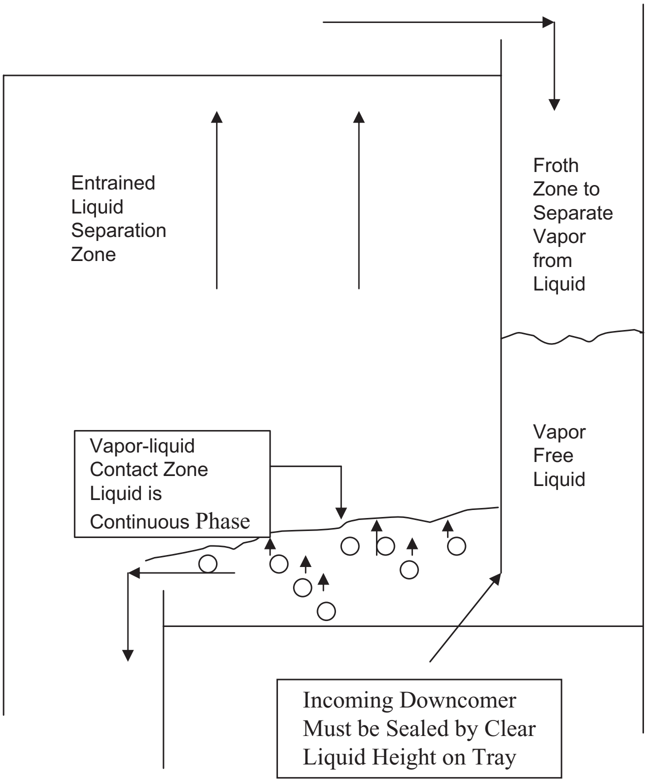


Figure 8-1 Typical fractionation tray.

1. The inlet downcomer must be sealed to prevent vapor from going up the downcomer. The sealing is accomplished by insuring that the pressure head of the clear liquid on the tray is greater than the clearance between the downcomer and the tray deck. The clear liquid head is the height the liquid would attain if there were no vapor present bubbling through the liquid. This sealing criterion will force liquid to build up in the downcomer so that the downcomer is sealed. If this criterion is not met, the level in the downcomer will be minimal. This will allow vapor to flow up the downcomer rather than through the holes on the tray above.
2. The hydraulic gradient (the difference in clear liquid height between the inlet downcomer and outlet downcomer) must be minimized. If the hydraulic gradient is too great, the trays will have a tendency to weep liquid on the inlet side of the tray. Weeping is a tendency of liquid to flow down through the holes on the tray rather than flowing through the downcomer.

Tray stability diagrams provide an analytical means to help visualize what is occurring on a fractionating tray. Figure 8-2 provides an example of a tray stability diagram. The four areas of unacceptable operation are:

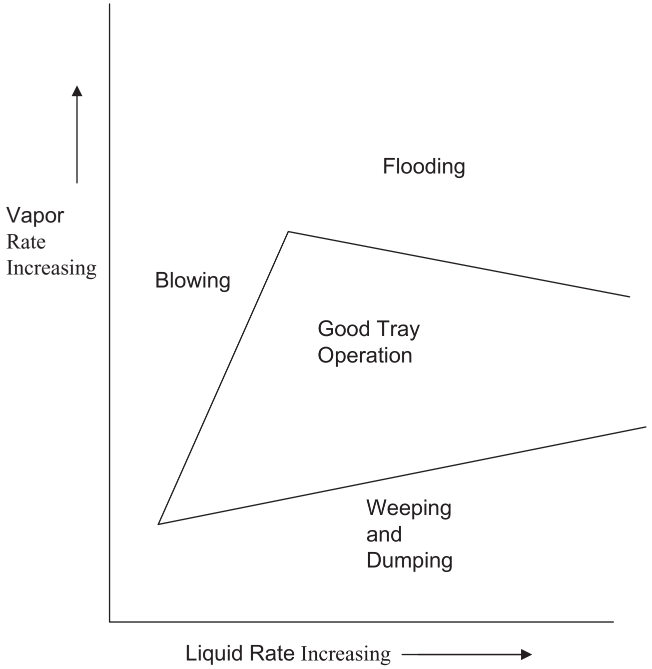


Figure 8-2 Typical tray stability diagram.

1. *Flooding*: This condition is marked by vapor velocities based on the tower cross-sectional area being so high that large amounts of liquid are carried up into the continuous vapor phase regime. This liquid does not adequately disengage from the vapor and is carried up into the tray above. This condition leads to excessive loading in the tray outlet downcomer as the entrained liquid returns to the tray below via the downcomer. This excessive loading causes the liquid level in the downcomer to build up to an unacceptable level. Flooding tends to start at one tray and propagate upward through a section of the tower. It may often be detected by a measurement of differential pressure across a section of the tower.
2. *Downcomer Filling*: This condition is marked by the downcomer either completely filling or filling to the point that adequate vapor disengagement from the liquid cannot occur. It can be caused by flooding, as indicated earlier, or by excessive liquid rates. It can also be caused by tray or downcomer restrictions. In a similar fashion to flooding, it can propagate upward through each tray in a fractionating tower.
3. *Blowing*: In this condition, vapor velocity through the holes in a fractionating tray is so high that the vapor phase becomes the continuous phase in the high intensity vapor-liquid contact zone. If the fractionating column were made of clear material, this condition would be observed as one in which the liquid is blown off the trays. It is usually caused by a combination of low liquid rates and high vapor rates.
4. *Weeping/Dumping*: In this condition, the vapor rates are so low that liquid pours down the holes in the tray. This results in a very low liquid level on the trays. This usually results in the loss of the downcomer seal, causing vapor to flow up the downcomer. This single unsealed downcomer will likely cause a high degree of frothing, which will lead to liquid holdup in the downcomer. This may result in downcomer flooding in the trays above the tray that is weeping and/or dumping. It should be noted that tray weeping/dumping could also be caused by mechanical damage such as a tray segment that has come loose and is hanging down from its support.

As a general rule, the symptoms of “flooding” and “downcomer filling” are a higher-than-normal pressure drop across the tower and loss of fractionation. The “blowing” and “weeping/dumping” symptom is loss of fractionation in the tower. Pressure drop for these conditions may be normal or slightly lower than normal.

The tray stability diagram can be developed by the following procedure.

1. Assume a liquid rate.
2. Vary the assumed vapor rate at this assumed liquid rate until the weeping, blowing, flooding, or downcomer filling limits are encountered.
3. Repeat this calculation for several different liquid rates until the tray stability diagram can be completed.

The calculation techniques for determining the various tray limitations are beyond the scope of this book. Adequate references are available in the open literature within this field or in individual company literature. The key point is that a tray stability diagram provides a means to visualize what is happening in the tower and thus will be helpful in steps 3–5 of the disciplined problem-solving approach.

8.3 PROBLEM-SOLVING CONSIDERATIONS FOR FRACTIONATING TOWERS

Assuming that the fractionating tower was designed correctly, problems will almost always be associated with process changes or mechanical damage. Confirmation that the fractionating tower was designed correctly can be attained through development of a tray stability diagram. This tray stability diagram will allow operators to plot operating conditions on the diagram to confirm that they are within the specifications of "good operations." Developing this tray stability diagram is also consistent with the premise of this book: Calculations should be made prior to developing hypotheses that might explain the problems being encountered.

Mechanical damage to trays can create tray performance problems. Some of these possible areas of tray damage or improper tray installations are described in the next few paragraphs.

A tray segment can fail. Most sieve trays are designed to be installed and/or removed through manways that have a diameter of 18 to 36 in. This approach also facilitates tray inspection and replacement. Thus a single tray will consist of several segments connected together. If one of these connections should fail, a condition similar to weeping/dumping will occur. As indicated earlier, this can propagate upward, causing a potential loss of several trays.

The trays may not be level. While this is almost always an installation problem, it might also occur after an extended period of operation. This delayed manifestation could be due to extreme foundation settling. In addition, problems associated with uneven trays might not show up under all operating conditions. A tray slope of less than 0.2% is generally acceptable and slopes of up to 0.7% have provided good operations. Slope is the amount of elevation change per inch of tray diameter expressed as a percentage. Thus an elevation change of 0.5 in in a 6-ft diameter tower is equivalent to a slope of 0.7%. Highly critical towers (e.g., vacuum towers) are special cases.

There may be restrictions in the tray. The presence of solids in a fractioning tower will often lead to plugging of a downcomer or plugging of holes in sieve trays. Solids can be present in the tower due to various causes, such as:

- *Construction debris*: It is not unheard of to discover items such as rags, tools, or even safety equipment left behind in a tower after construction or repairs. Unfortunately, there have been occasions on which an

inspection of the tower prior to startup did not find the debris which blocked a downcomer. Following the startup of the tower, problems were experienced and a subsequent shutdown and inspection revealed the debris in the downcomer.
- *Entrainment from a drum containing solids*: Very fine particles can often be entrained from a vapor-liquid disengaging drum and carried into a tower. If these particles are not soluble in the liquid on the trays in the tower, they can accumulate in either the downcomer or sieve tray holes.
- *Corrosion of the tower internals*: If the liquid on the trays contains a corrosive compound, the trays may begin to corrode. This could cause the holes in the sieve trays to enlarge. In addition, it is possible that some of the corrosion products could be deposited lower in the tower as the composition of the liquid changes. Because of this possibility, sieve trays are often fabricated from a corrosion-resistant material, such as stainless steel.
- *Reaction of trace components inside the tower*: While this would seem like an unlikely event, there have been instances during which small quantities of water reacted with a soluble material in the liquid phase on the tower trays and formed an insoluble material. This material would accumulate in the sieve tray holes and the downcomers and create plugging problems which manifest similarly to the item discussed earlier.

The vapor inlet flow pattern may change. For example, the holes in a sieve tray may enlarge or become irregular due to corrosion, or the valves in a valve tray may be loosen. Either of these occurrences may cause significant disturbances to the vapor inlet flow pattern and result in poor tray performance.

Process changes causing poor tray performance may be due to known changes, such as an increase in rates, or very subtle changes. For example, there may be instrumentation errors that cause excessive vapor or liquid rates. Even at constant liquid and vapor rates, foaming caused by trace quantities of a surface active ingredient may occur. An even more subtle change might be the tower that appears to be operating perfectly normally until an event such as that described earlier. The presence of water from an exchanger leaks reacts with a soluble material to form solids. These solids lead to plugging of the holes in the sieve tray. The first indication of such a problem might be the increased differential pressure across the tower.

8.4 DEVELOPMENT OF THEORETICALLY SOUND WORKING HYPOTHESES

Once step 1 (verify that the problem actually occurred) and step 2 (write out an accurate specification of the problem) have been completed, the following guidelines can be used to develop a working hypothesis.

Calculations can be performed to determine the following:

- *Tray stability diagram*: This will highlight the areas of unacceptable tray operation as well as indicate the current point of operation. If the current operations are in an unacceptable area, this must be corrected before any other calculations are considered.
- *Number of theoretical stages required for the degree of separation being encountered*: Knowing the concentrations at various points in the tower, the number of theoretical stages required to make this separation can be estimated by computer or manual techniques. These manual techniques and their place in the modern world are discussed in Chapter 13.
- *Estimated tray efficiency*: The tray efficiency is the theoretical stages divided by the actual stages and expressed as a percentage. It is a technique to allow one to estimate the number of actual stages required if the number of theoretical stages is known. While this book does not cover these techniques, there are multiple methods available to estimate the tray efficiency.

While these calculations are beyond the scope of this book and would normally be performed by a graduate engineer, the process operator serving as a problem solver needs to be aware of them. These calculations are important in assessing and answering the question of "Was the tower designed correctly and is it operating correctly?" If the process operator is aware of what kind of calculations can be performed, he will be able to develop a better plan of action.

It should be noted that these calculations will require accurate plant data and tower/tray design information. Instrumentation should be calibrated before using plant data to perform these calculations, to avoid having to redo the calculations.

Assuming that the calculations described above indicate that the tower should be performing better than what the actual data indicates, the list of questions given in Chapter 6 can be used to help formulate a working hypothesis. Once a hypothesis is formulated, it may be of value to develop a plant test to confirm the hypothesis. Measurements of tray temperatures, pressures, and compositions will be helpful in determining what areas of the tower are worthy of future analysis. Several meaningful approaches are shown in Table 8-1. In addition, x-rays can be utilized to examine the suspect area of the tower either to help formulate a hypothesis or to provide a mechanism to test the hypothesis (step 4: provide a mechanism to test the hypothesis). Some examples of the use of x-rays are shown in Figure 8-3.

8.5 PROBLEM SOLVING AND REBOILER CIRCUITS

Reboilers, which are often straightforward in the conceptual stage, are often a significant part of a plant fractionation problem. The most frequent culprit

Table 8-1 Evaluation of trays by sampling/data analysis

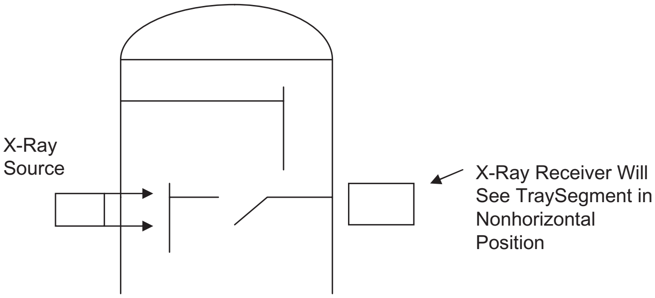
Measurement	Typical Values	Meaning of Atypical Values
Pressure drop across trays	Should be measured across as few trays as possible Check measurements with calculations Normal values 0.05–0.20 psi/tray. Lower for vacuum towers	Trays plugged, damaged or flooded
Temperature change across trays	Should be equivalent to that estimated from fractionation calc. or equivalent to historical values.	Tray damage or process changes
Composition of liquid on trays	Should be equivalent to that estimated from fractionation calc.	Numerous
Venting sample bomb of tray liquid	For pressure towers, vaporizing liquid should cool off bomb	Liquid phase is not present on tray
Composition of vapor on trays	Should be equivalent to that estimated from fractionation calc.	Numerous
Venting sample bomb of tray vapor	No temperature change	Tray flooding

is the vertical thermosiphon reboiler. A typical flow sheet is shown in Figure 8-4.

Thermosiphon reboiler problems are often due to hydraulics. Since these reboilers do not have a pump associated with them, circulation depends on the hydraulic balance around the tower bottoms and reboilers. The operation of this class of reboilers depends on a delicate balance of elevation, fluid densities, and pressure drop. The density of the return line to the tower is a function of the percentage vaporization. These thermosiphon reboilers almost never operate with pure vapor in the return line to the tower. Thus the amount of vaporization (percent vaporization) in the reboiler will determine the density in this tower return line. There must be sufficient head to cause the system to circulate with no application of external work. Some of the possible causes of hydraulic problems are described in the following paragraphs.

There may be inadequate elevation head of liquid in the tower bottom. If the liquid level in the bottom of the tower is not high enough, the driving force to cause the process liquid to flow will be inadequate. This may result in a lower-than-design liquid level in the reboiler and/or a lower-than-design circulation rate. The low reboiler level will cause the surface area available for vaporization to decrease with a likely loss of heat input to the tower. In addition, if the process liquid flow decreases and the heat input remains the same, the percentage vaporization will increase. In some applications, this may create reboiler fouling.

1. Dropped Tray Segment



2. Plugged Downcomer

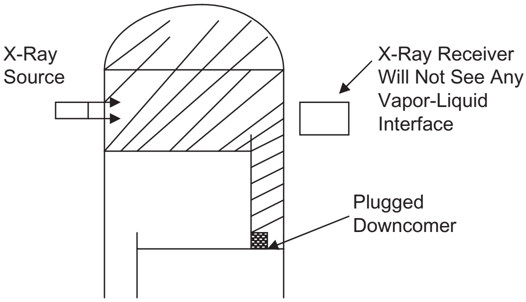


Figure 8-3 Examples of tray problems detectable by X-rays.

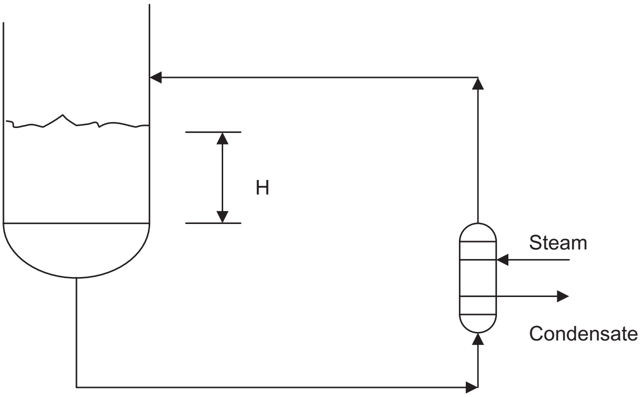


Figure 8-4 Thermosiphon reboiler operating principles. H, liquid height that causes reboiler to circulate. Feed to reboiler is all liquid. Vapor return line contains a mixture of liquid and vapor. Typically, this line contains 5 to 25% vapor. The amount of vapor in this line, which is also referred to as the percent of vaporization, is set by the pressure drop in the liquid and vapor return line.

There may be restrictions in the reboiler inlet or outlet piping. This will create additional frictional piping loss. The result of this problem will be similar to that discussed in the earlier paragraph, that is, the increased circuit pressure drop may result in a lower-than-design liquid level in the reboiler and/or a lower-than-design circulation rate.

There may be excessive elevation head in the tower bottoms. A high level in the tower bottom may cause cycles in a reboiler operation. This high level leads to a high circulation rate through the reboiler circuit. This will result in a high fluid density (low percentage vaporization) in the reboiler outlet. With the higher fluid density, the circulation rate will decrease. The reduced circulation rate will cause the percentage vaporization rate to increase, which will increase the circulation rate. The result of this can be a wildly cyclic operation of the reboiler circuit.

Another problem is that the tower level may be higher than the reboiler return line. While avoiding this seems obvious, the instrumentation is sometimes designed so that what seems to be a reasonable tower level is actually above the reboiler inlet.

If an inadequate reboiler performance is thought to be associated with a hydraulic problem, the best approach to generating a theoretically sound working hypothesis is to either redo or review the original hydraulic calculations. These calculations might be in error, or may be based on an incorrect length of equivalent piping. It is possible that the actual piping detail is radically different than that assumed by the process designer. This review should also include confirmation that the tower elevation relative to the reboiler is the same as it is in the original design. If the original calculations appear to be correct and consistent with the actual installation and operating details, then it is likely that there is a piping restriction somewhere in the reboiler piping circuit. The more common problem-solving tool of changing the level in the tower without first considering the hydraulic calculations will not be helpful. It is likely that these hydraulic calculations will require the assistance of a graduate engineer.

Another possible reboiler problem is associated with inadequate drainage of the steam condensate. This will cause a high level of condensate in the reboiler, resulting in some of the reboiler surface area being covered with condensate rather than condensing steam. This can also lead to poor stability in the reboiler control circuit. Some of the reasons for inadequate removal of condensate are described in the following paragraphs.

The steam traps can be improperly sized or can be malfunctioning. If this occurs, condensate will build up in the reboiler until the trap opens to discharge condensate.

Steam pressure modulation control systems often create problems when low pressure steam is used. If the reboiler is controlled by a control valve in the inlet steam line, it is possible for the pressure on the steam side of the reboiler to be lower than the pressure of the condensate return system. Since the steam pressure in the reboiler is lower than that in the condensate system, the condensate level in the reboiler will increase, covering some of the tube area with condensate. As the tube area is covered, the steam pressure must increase to compensate for this. As the steam pressure increases, the condensate is drained from the reboiler. This cycle will be repeated, leading to instability in the condensate removal system. This instability in the condensate removal system is often transmitted to the tower.

The temperature-driving force needs to be at an optimum level. The temperature difference between the heating medium and process side must not be too great or too small. A large difference (>100°F) can produce film boiling instead of nucleate boiling. This film boiling causes a vapor film to exist at the tube wall. Under some conditions, this will result in a much lower heat transfer coefficient than design. On the other hand, operating with a close approach between the heating fluid and process fluid can cause the reboiler to surge. That is, the reboiler will cycle between no heat input and greater-than-design heat input. This surging can be caused by depletion of volatile materials in the reboiler. If low pressure steam is used on a reboiler that heats a mixture of a volatile material (propane) and a nonvolatile material (octane), depletion of the volatile material will cause the boiling point of the process side to increase above that of the condensing temperature of the steam. This will cause the reboiler to stop condensing any steam until the inventory of the volatile material on the process side is replenished. In addition, the same effect can be observed due to depletion of water from a water low-volatility hydrocarbon two-phase mixture. In a similar fashion to that described above, this will result in a rapid change in boiling point and cause the reboiler to stop condensing steam until the water concentration is replenished.

Solving a reboiler problem can require almost no engineering, or it can require a great deal of engineering problem-solving skills. However, regardless of the technical complexity, the principles of problems solving can still be applied. The questions given in Chapter 6 will still be of value. In addition, simple instruments can be utilized for step 3 (develop a theoretically sound working hypothesis that explains the problem) and step 4 (provide a mechanism to test the hypothesis) of the problem-solving approach. Examples of these instruments are:

- An infrared thermometer, used to measure the temperature of a suspect steam trap.
- A gage glass and pressure gauge, used to measure the condensate level and pressure in a reboiler that is cycling excessively.

More complicated instrumentation might be used as follows:

- A highly sensitive pressure drop instrument might be connected to a high speed recorder or a process control computer with a rapid scan frequency. This could be used to diagnose reboiler hydraulic problems.

- A device such as a calorimeter that is capable of determining the enthalpy of a process stream could be used to measure the enthalpy of a stream leaving a reboiler. This will allow determination of the percentage vaporization that is occurring in the reboiler.

EXAMPLE PROBLEM 8-1

A propane/butane fractionation tower (T-1) had ceased to operate like it should. The data shown in Table 8-2 represents good versus current operation.

In Table 8-2, the term "saturated liquid" refers to a liquid stream that is at the boiling point of the liquid. For example, water at atmospheric pressure and 212°F is a saturated liquid. A schematic flow diagram is shown in Figure 8-5. In addition to the data shown above, the chronological information shown in the following paragraphs was available.

A routine repair and inspection downtime on the tower occurred sometime after the "good operation" data was recorded. During this downtime, the existing trays, which showed evidence of corrosion, were removed, and new trays with an identical design were installed. While this seemed to go well, the normal mechanical supervisor was off sick during the tray installation procedure. No obvious change in performance was noticed immediately. However, it was several weeks before full rates were achieved due to limited product demand.

The laboratory began using a different gas chromatograph (GC) than was used during the "good operation" period. This GC was thoroughly checked out in a series of cross checks with the old GC and other laboratory GCs. One of the laboratory technicians that had analyzed this sample for 10 years reported that he found a film of heavy hydrocarbons or oils in the GC after each analytical run on the distillate product. All flow meters and temperature instruments had been confirmed to be accurate.

Table 8-2 T-1 operating conditions

	Good Operation	Current Operation
Feed rate, lb/hr	100,000	100,000
Feed composition, wt % C_3	30	40
Feed enthalpy	Saturated liquid	Saturated liquid
Vapor boilup, lb/hr	79,500	124,000
Reflux rate, lb/hr	31,300	65,000
Reflux enthalpy	Saturated liquid	Saturated liquid
Distillate comp., wt % C_3	95	80
Control tray comp., wt % C_3	60	60
Bottoms, comp., wt % C_3	2	2

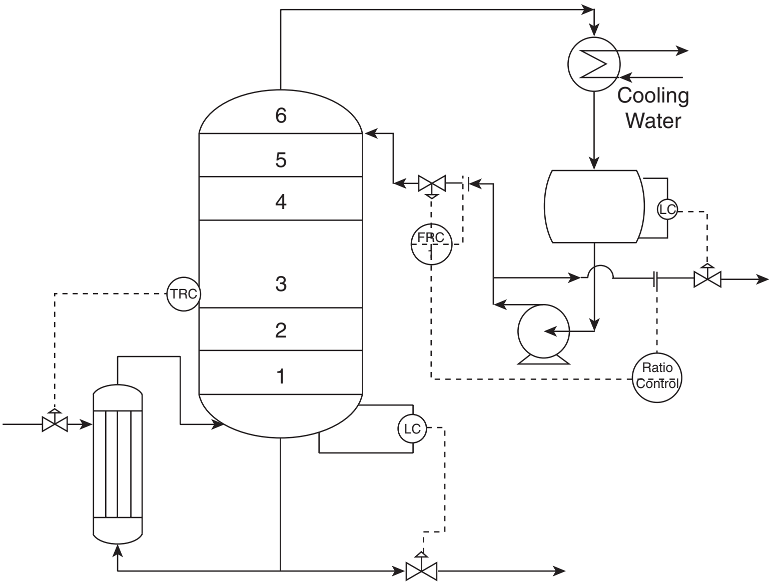


Figure 8-5 Schematic flow for Problem 8-1.

When the problem solver was assigned the problem, he began by using the five-step procedure discussed earlier. He combined steps 1 and 2 as follows:

Step 1: Verify that the problem actually occurred.

Since all indications were that there was a real problem, the problem solver simply combined the verification with the problem statement given in step 2.

Step 2: Write out an accurate statement of what problem you are trying to solve.

The problem statement that he developed was as follows:

> Currently, T-1, the plant propane/butane splitter, is operating poorly based on historical standards. The current plant data indicates that the rectification section (the section of the tower above the feed tray) is not performing well even though the reflux rate is well above that required for good performance previously. There were several changes made recently. These changes consisted of the installation of new trays, the use of a new GC, and a feed composition change. All of these occurred prior to observation of the loss of fractionation. The loss of fractionation was not noticed until the product demand increased so that the tower began operating at design rates. Determine the reason for the poor performance of the rectification section of T-1.

Step 3: Develop a theoretically sound working hypothesis that explains as many specifications of the problem as possible.

When the chronological history was reviewed, it was tempting to believe that the trays were installed wrong. While this was a strong possibility, it did not represent a theoretically sound working hypothesis without adequate calculations and additional analysis. The questions in Chapter 6 were utilized, along with a tray stability diagram, to formulate hypotheses.

While this series of questions did not provide an exact diagnosis of the problem, it was apparent that the tower was operating well beyond the region of experience and operating directives. The first question that the problem solver sought to answer was "Do the current operating rates of the tower variables by themselves explain the poor tray performance?" Two types of calculations using the data were made to answer this question.

A tray stability diagram was developed and is shown in Figure 8-6. This diagram indicates that the top part of the tower is being overloaded and is probably operating in a flooded condition.

The internal tower vapor rate was calculated by material balance and heat balance using the principles discussed in Chapter 5. These calculated rates were then compared. If flooding was occurring, the vapor rate as determined by material balance would be higher than that determined by an overall heat

Table 8-3 Questions/comments for Problem 8-1

Question	Comment
Are all operating directives and procedures being followed?	No. Operating conditions appeared operating to be well outside the normal targets.
Are all instruments correct?	All instruments had been calibrated.
Are laboratory results correct?	The new GC had been thoroughly calibrated.
Were there any errors made in the original design?	Not applicable, since no design changes were made.
Were there changes in operating conditions?	Yes. In addition to the known changes, it is possible that whatever caused the percentage C_3 in the feed to increase might have also caused an extraneous component to be introduced into the tower.
Is fluid leakage occurring?	Damaged trays might cause internal tray leakage, which might explain the problem.
Has there been mechanical wear that might explain the problem?	No.
Is the reaction rate as anticipated?	Not applicable.
Are there adverse reactions occurring?	Not applicable.
Were there errors made in the construction?	Maybe; the tray installation might not have been correct.

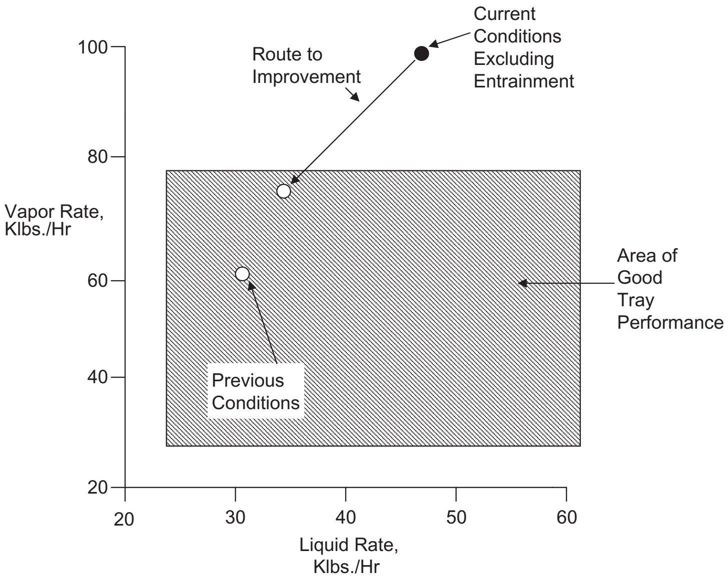


Figure 8-6 Tray stability for Problem 8-1.

balance. This is because as the tower floods, liquid would be carried over with vapor from the top tray into the reflux condenser. The total vapor (including entrained liquid) going into the condenser and accumulator would be greater than that estimated from a heat balance on the tower. Regardless of what control scheme was being used, this excess liquid must be pumped back to the tower and would show on the reflux flow meter. In summary, if the vapor rate calculated by material balance, and that calculated by heat balance, did not agree, it could be assumed that the excessive vapor rate based on the material balance must be related to liquid being carried out the top of the tower and showing up as reflux that is being pumped back to the tower.

The problem solver calculated the vapor and liquid loading in the top of the tower by material balance and heat balance as follows:

1. He calculated the distillate rate by material balance:

$$F = B + D \tag{8-1}$$

$$F \times X_F = B \times X_B + D \times X_D \tag{8-2}$$

where

F = feed rate, lb/hr
B = bottoms rate, lb/hr
D = distillate rate, lb/hr

X_F = feed concentration, wt %
X_B = bottoms concentration, wt %
X_D = distillate concentration, wt %

For the two cases given in Table 8-2, the calculated results are shown in Table 8-4.

2. He estimated the vapor and liquid loading in the top of the tower: Since the reflux is not subcooled (reflux is a saturated liquid), the liquid rate (*L*) in the top of the tower is simply the reflux. In addition, the vapor rate (*V*) in the top of the tower can be estimated as follows and is shown in Table 8-5.

$$V = L + D \tag{8-3}$$

3. Using the principle of "equal molal overflow," he calculated the top vapor rate (*V*) based on the heat input to the reboiler. The equal molal overflow principle states that for systems with minimal nonideality, the vapor rate throughout the tower expressed in mols/hour is equal as long as no other vapor or heat input is introduced. The tower feed is a saturated liquid (liquid at the boiling point), therefore there is no other vapor generated when the feed is added to the tower. In addition, there is no other heat input to the tower. Thus the equation below was used to estimate the vapor rate at the top of the tower from the heat input to the bottom of the tower. The results of this calculation for past and current operations are shown in Table 8-6.

Table 8-4 Estimated material balance rates

	Past Operation	Current Operation
Distillate (*D*), lb/hr	30,100	48,700
Bottoms (*B*), lb/hr	69,900	51,300

Table 8-5 Estimated vapor and liquid rates in top of tower

	Past Operation	Current Operation
Liquid (*L*), lb/hr	31,300	65,000
Vapor (*V*), lb/hr	61,400	113,700

Table 8-6 Top vapor rate based on heat input to bottom

	Past Operation	Current Operation
Vapor rate bottom, lb/hr	79,500	124,000
Molecular weight, top	44.54	46.23
Molecular weight, bottom	57.63	57.63
Vapor rate top, lb/hr	61,400	99,500

Table 8-7 Vapor rates calculated from material balances and heat balances

	Past Operation	Current Operation
Calculation method		
Top material balance, lb/hr	61,400	113,700
Bottom heat balance, lb/hr	61,400	99,500
Comments	Good check	Poor check

$$V_T = V_B \times M_T / M_B \tag{8-4}$$

where

V_T = vapor rate at the top of the tower, lb/hr
V_B = vapor rate at the bottom of the tower, lb/hr
M_T = molecular weight of vapor top of the tower
M_B = molecular weight of vapor bottom of tower

The problem solver compared the top vapor rate as estimated from the overhead material balance and, from the vapor rate at the bottom, developed Table 8-7 as shown above.

The problem solver now had two independent calculations that indicated that the tower was flooding. The tray stability diagram indicated that the tower was operating in the flooding regime. In addition, the comparison of the heat balances and material balances indicated that there was more material leaving the top of the tower than could be accounted for by a heat balance. The fact that this approach had previously given a good comparison was proof that there was a significant change in the operation of the tower. The problem solver then developed the following hypothesis:

> The poor performance of T-1 is due to flooding of the rectification section (top section of the tower) that is being caused by the excessive vapor and liquid loading. This excessive vapor and liquid loading might be caused by one of the following:
>
> - *Operator error*: The reboiler steam rate or tower reflux rate was set too high by operator error.
> - *Tray installation error*: There may have been an error in the tray installation which resulted in poor fractionation and caused the control system or operator to increase the tray loadings in an attempt to compensate for this. This caused the tower to operate in a flooded regime.
> - *Foaming*: The presence of a surface-active material might have caused the tower to originally function poorly, which then caused a manual or automatic intervention to compensate for this uncovered problem. This intervention caused the tower to begin to operate in a flooded regime.
> - *Other*: There may be other as yet undiscovered explanations for the changes which moved the tower operation into the flooding regime.

Note that in this problem hypothesis, the problem solver expressed the need to explore what may have caused the excessive tower loadings rather than to just assume that it was due to an operator or control system error. It should also be noted that, while the increased C_3 concentration in the feed to the tower is unlikely to be the root cause of the problem, it did indicate that the source of the C_3/C_4 liquid might have changed. This new source might have resulted in a different trace impurity or an increase in the concentration of an existing trace impurity that would cause foaming in the tower. The possible trace impurities in a C_3/C_4 liquid stream could include materials used for deicing exchangers (methanol), materials used for removing water (glycol) or materials used for neutralizing acidic compounds (amines).

Step 4: Provide a mechanism to test the hypothesis.

The problem solver decided to test the hypothesis by reducing the tray loadings to safe levels as indicated by the tray stability diagram. If this test returned the operation to "past operation" levels, then the mechanism to test the hypothesis becomes a partial solution.

He also considered what would happen if the operation did not return to the conditions and results previously experienced when the tray loadings were reduced. If that contingency occurred, he believed that additional tests or investigations would be required. These additional tests would include one or more of the following:

- Perform more detailed testing using some of techniques shown in Table 8-1.
- Conduct some sort of foaming test. This would probably require some type of pressure-rated laboratory equipment with a sight glass.
- Take X-rays of the appropriate parts of the tower to determine if tray damage is obvious.
- Determine if there has been a change in the source of the C_3/C_4 liquid and if there was any information on the trace impurities that might be present in this source.

If the reduction of the tray loadings does not solve the problem, it is likely that an expedient solution of reducing the feed rate to the tower may be required to ensure producing an overhead product that meets the specifications. However, this is not the solution to the problem, but only a stop-gap approach to allow the facility to continue to make on-specification product.

Step 5: Recommend remedial action to eliminate the problem without creating another problem.

The actual recommendation for remedial action will depend on the results of step 4. If reducing the tray loadings does not solve the problem, then the other tests listed in step 4 must be executed and carefully analyzed to determine the required remedial action.

If reducing the tray loadings does solve the problem, it should be recognized that the basic questions outlined in step 3 still remain. It is unlikely that improper tray installation would be a transient problem. It is also unlikely that an operator purposefully set the ratio controller outside the range of standard operations without a reason. Thus the most logical possibility is that there was a transient condition that was due to the presence of a trace impurity or some other external event. When the operator encountered this external transient event, he tried to respond to the unmeasured and unknown disturbance by increasing the ratio controller, which caused the tower to begin flooding. Since this transient condition might well recur, the tower should be monitored daily to determine when the problem reoccurs. It will be of value to be proactive and plan what analyses or actions will be taken when daily monitoring indicates that the transient condition is returning.

The test of reducing the reflux rate so that the operations were in the good tray-operating region was successful in returning the operations to normal rates and purities. A review of the possibility that the sources of the C_3/C_4 liquid had changed indicated that the source had changed, but since the problem only occurred as the production rate increased, it was impossible to connect this change with the change in tower operation.

As indicated earlier, in this circumstance it is necessary to monitor the tower closely and to develop a contingency plan to allow response to the likely return of the transient condition. The problem solver took the following actions:

- He developed a fractionation index which allowed him to follow the operation of the tower on an hourly basis.
- He developed a list of samples that were to be obtained the next time the fractionation index dropped below a specified value.
- He worked with the laboratory to develop new analytical techniques for the bomb samples to determine if there were surfactants present in any of these samples. The analytical techniques and GCs used for volatile hydrocarbons would likely not be sensitive enough for very low concentrations of surfactants.
- He developed a foaming test that would be used in the case of a significant decrease in the fractionation index.
- He collected the specified samples and used the new analytical techniques to determine the possible presence and concentrations of surfactants in the base case with good operations. He also tested the foaming potential of these samples.

Lessons Learned While this problem is a fictitious example, it has many elements of real problem solving. One such example is that multiple events occur at the same time, making isolation of a single root cause difficult. The presence and subsequent disappearance of a trace impurity that leads to an unsuspected problem is also a potential real event. Therefore, there are lessons to be learned from this semi-fictitious example.

There was great value in doing calculations to prove that the tower was flooding. The tray loading diagram was a useful tool for problem solving as well as in selling the problem solution to management.

It should be recognized that, if daily monitoring had been utilized, the problem would have been spotted immediately, as opposed to having to wait until demand increased to the point at which the tower was required to operate at full capacity. While this may seem like an isolated occurrence, many industrial problems lie dormant until it is necessary to increase rates. Also note that it is never too late to begin a daily monitoring system.

This problem also illustrates that there will be occasions when the exact root cause of the problem cannot be determined. In these instances, the problem solver should develop a system that will be effective in collecting data when the next occurrence of the event happens.

While it could be argued that all problems have an obvious root cause, it should be recognized that multiple events that may seem to be related to the problem do occur. Thus the multiple events (the mechanical supervisor being sick, installation of a new GC, possible change in source of C_3/C_4 feed, and oil in the GC) that may be a cause of this problem are often typical of industrial problem solving. The problem solver must not discard any set of data or observations, but rather must incorporate them in his problem statement or problem analysis.

NOMENCLATURE

B	Bottoms rate, lb/hr
D	Distillate rate, lb/hr
F	Feed rate, lb/hr
M_B	Molecular weight of vapor bottom of tower
M_T	Molecular weight of vapor top of the tower
V_T	Vapor rate at the top of the tower, lb/hr
V_B	Vapor rate at the bottom of the tower, lb/hr
X_F	Feed concentration, wt %
X_B	Bottoms concentration, wt %
X_D	Distillate concentration, wt %