PlantCalcKit

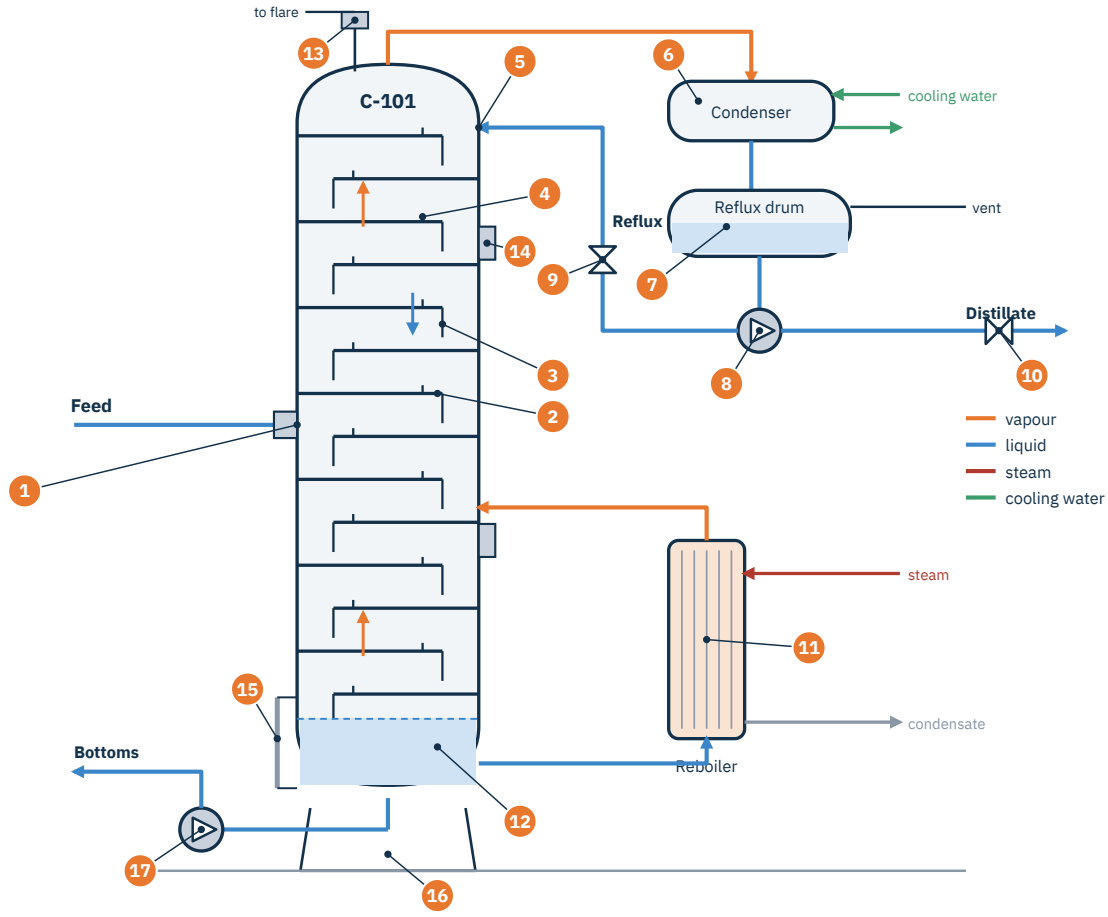
Distillation, Absorption and Packed Columns Made Simple

A field guide to distillation, absorption and packed columns

Vapour pressure and equilibrium · reflux and stages · McCabe-Thiele · trays and flooding · tray efficiency · reboilers · monitoring and troubleshooting · packing and pressure drop · absorbers and scrubbers · pinch analysis · start-up and shutdown

Tray distillation column system

Our running example C-101 with its condenser, reflux drum, pump and thermosyphon reboiler.



FREE SAMPLER — Chapters 1 to 3

Edition 1.0 · November 2026

PlantCalcKit

Distillation, Absorption and Packed Columns Made Simple
A field guide to distillation, absorption and packed columns
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Written in our own words from published engineering sources, listed in Appendix G. All diagrams and charts are original PlantCalcKit artwork; every number in the worked examples was computed by PlantCalcKit with the same methods as the matching Excel toolkits. No equipment maker, supplier or brand is named or recommended. The running examples are generic, not real plants. Example costs are illustrative.

This guide is for training and engineering estimates. It does not replace an approved design, the column or packing maker's rating, a process simulation, the relevant codes and standards, or your plant's operating procedures and safety rules. Methods based on published procedures are aligned with the publicly documented method; they are an engineering estimate, not an official rating.

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This free sampler contains the guide, Chapters 1 to 3, their sources and answers. The full book has 19 chapters, 10 picture pages and Appendices A to G.

GUIDE

How to use this book

This book explains distillation columns, packed columns, absorbers and scrubbers in plain words. It also covers the energy these columns use and how to save some of it with heat integration. You do not need to be an expert. If you can read a temperature gauge and follow a recipe, you can follow this book.

Who it is for

- **Plant operators** who run columns every shift and want to know what the readings mean.
- **Young engineers** who must check, test, troubleshoot and report on a column.
- **Senior engineers** who want a quick refresher and a set of worked numbers to check their own spreadsheets against.

How the book is built

The book has four parts. You can read them in order, or jump to the part you need.

Part	What you learn	Chapters
A	Basics: vapour pressure, boiling and vapour-liquid equilibrium	1 to 3
B	Distillation: stages, reflux, trays, efficiency, reboilers, monitoring and troubleshooting	4 to 11
C	Packed columns, absorbers and scrubbers	12 to 16
D	Energy, heat integration (pinch analysis), start-up and shutdown	17 to 19

At the back you will find a glossary, a units page, a one-page equation summary, printable checklists, answers to every exercise and quiz, a FAQ and the list of books and papers we used.

Our four running examples

We follow four pieces of equipment through the book. All four are generic examples, not real plants. They are the same example cases that come pre-filled in the matching PlantCalcKit Excel toolkits, so you can check every number in this book against the workbook.

Tag	What it is	Main numbers
C-101	Tray distillation column for a benzene-toluene-type mixture	Feed 400 kmol/h (882 lbmol/h) at 45 mol % light key; 24 trays; 2.2 m (7.2 ft) diameter; top pressure 1.2 bar a
C-301	Packed column sized from scratch	Gas 18,000 kg/h (39,683 lb/h); liquid 25,000 kg/h (55,116 lb/h); 50 mm metal ring class packing
T-201	Packed gas absorber (scrubber) with a water solvent	Gas 12,000 kg/h with 2.00 mol % solute in, 0.10 mol % out; 1.2 m diameter; 5.0 m of packing
Unit 400	Six-stream heat recovery area that includes a column overhead and a reboiler loop	Hot utility now 1,500 kW; cold utility now 1,670 kW

C-101 has its own small family of equipment: **E-101** overhead condenser, **V-101** reflux drum, **P-101** reflux pump, **E-102** steam reboiler and **E-103** feed preheater.

The boxes you will see

- **Field check**: what you see in the plant, what it may mean, and the first thing to check.
- **Engineer's calculation corner**: a worked calculation, step by step, with every number shown.
- **Try it**: a short exercise for you. The answers are in Appendix E.
- **Watch out**: a common mistake or a safety point.
- **Try it with PlantCalcKit**: the free online calculator or the Excel toolkit that does the calculation, with QR codes you can scan with a phone.
- **Quick quiz**: five questions at the end of each chapter. Answers in Appendix E.

Units

We use SI units first, with US units in brackets. For example: 1.2 bar a (17.4 psia), 2.2 m (7.2 ft). Pressures are absolute (bar a) unless we write bar g. Compositions are in mole percent (mol %) unless we say mass percent. Appendix B has a conversion table.

Where the numbers come from

Every number in a worked example was computed with a short Python program that is kept with this book. Where a property was needed (vapour pressure, steam latent heat, water density), it was taken from published equations and checked against an open-source property library. Correlations are the published ones, named where they are used, and listed in Appendix G. Where we could not check a constant against its original source we say so.

Free tools

These free PlantCalcKit calculators work in any browser and match the methods in this book. Scan a code with your phone camera, or type the address.

Vapour pressure and boiling point
plantcalckit.com/tools/vapour-pressure/

Column base pressure and temperature check
plantcalckit.com/tools/column-pressure-check/

Reboiler sizing screen
plantcalckit.com/tools/reboiler-sizing/

Steam tables
plantcalckit.com/tools/steam-tables/

The four Excel toolkits that match this book are:

Excel toolkit	What it does	Chapters
Distillation Column Performance Evaluation	Material balance, relative volatility, minimum reflux, stages, feed stage, tray efficiency, duties and flooding approach	2 to 11, 17
Packed Column Sizing and Pressure Drop	Flooding, diameter, pressure drop, wetting, packed height and turndown	12 to 14
Absorber and Scrubber Performance Evaluation	Minimum L/G, absorption factor, stages, NTU and HTU, rating of an installed column, hydraulics	15, 16

Excel toolkit	What it does	Chapters
Heat Integration and Pinch Analysis	Utility targets, pinch temperature, composite curves, area and units targets	18

Distillation Column Performance Evaluation
plantcalckit.com/shop/distillation-column-performance-evaluation-excel/

Packed Column Sizing and Pressure Drop
plantcalckit.com/shop/packed-column-sizing-and-pressure-drop-excel/

Absorber and Scrubber Performance Evaluation
plantcalckit.com/shop/absorber-and-scrubber-performance-evaluation-excel/

Heat Integration and Pinch Analysis
plantcalckit.com/shop/heat-integration-and-pinch-analysis-excel/

LIMITS

Limits of this book, in plain words

This book teaches you to understand and check columns. It is not a design code and it does not replace an approved design, the column maker's rating, a process simulation, your plant's operating procedures or your safety rules. Columns hold large amounts of flammable, toxic or hot material under pressure. Never change a column's operation, bypass a trip or open equipment because of something you read here. Use the plant's approved procedures, permits and management of change. Where this book gives typical values, they are for training and quick checks only.

PART A

Basics

Vapour pressure, boiling and vapour-liquid equilibrium

Chapters 1 to 3

CHAPTER 1

What columns do

A column is a tall vessel where a gas and a liquid meet again and again. Each time they meet, some material moves from one to the other. Repeat this enough times and you can separate a mixture almost completely. That is the whole idea behind distillation, absorption, stripping and scrubbing.

1.1 Why plants need separation

Almost every process makes a mixture. A reactor gives product plus unreacted feed and by-products. A gas stream carries a little of something we do not want to release. A solvent picks up water. The plant must separate these mixtures to make a product that meets its specification, to recycle valuable material and to keep emissions within the permit.

Columns are the main tool for this job. In many plants they are also the biggest users of steam. So a column that runs well saves money every hour, and a column that runs badly can limit the whole plant.

1.2 Four jobs, one idea

Job	What goes in	What happens	Typical example
Distillation	A liquid mixture	Heat boils part of it. The vapour is richer in the lighter part, the liquid in the heavier part	Splitting two solvents; making a pure product
Absorption	A gas mixture plus a liquid solvent	The solvent dissolves one part of the gas	Removing a sour gas or ammonia from a gas stream
Stripping	A liquid with something dissolved in it plus a gas or steam	The dissolved material moves into the gas	Regenerating a solvent; removing gas from water
Scrubbing	A gas with something harmful plus a liquid	Absorption used to clean a vent or exhaust	Cleaning a vent before it goes to air

In all four, a gas (or vapour) and a liquid flow past each other, usually **countercurrent**: the gas goes up and the liquid comes down. Each contact moves the two phases a little closer to balance, called **equilibrium**. A column is simply a stack of many such contacts.

1.3 Trays or packing

There are two ways to make the gas and liquid meet inside a column.

- **Trays** (plates) are flat decks with holes, valves or caps. Liquid flows across each tray and down a pipe-like channel called a **downcomer** to the tray below. Vapour bubbles up through the liquid on each tray. Chapter 7 explains trays in detail.
- **Packing** is a bed of shaped metal, plastic or ceramic pieces (random packing) or of corrugated sheets (structured packing). Liquid runs down over the surface as a thin film. Gas flows up through the open spaces. Chapters 12 to 14 explain packing.

Trays handle dirty service and high liquid rates well and are easy to inspect. Packing gives a lower pressure drop and often more capacity in the same shell, which is why it is used in vacuum columns and most absorbers. Chapter 12 compares the two.

1.4 The parts of a distillation column system

A distillation column is never alone. It needs a heat source at the bottom and a heat sink at the top.

1. **Feed**: the mixture enters part way up the column.
2. **Reboiler**: at the bottom, it boils some of the liquid to make vapour that rises up the column.
3. **Condenser**: at the top, it turns the vapour back into liquid.
4. **Reflux drum**: collects the condensed liquid.
5. **Reflux**: part of the liquid goes back to the top of the column to flow down over the trays.
6. **Distillate** (top product): the rest of the condensed liquid.
7. **Bottoms** (bottom product): liquid drawn from the base.

The reboiler and the reflux are what make the column work. Without vapour from the reboiler and liquid from the reflux, there is nothing to contact. Picture page 1 in Chapter 4 shows a full column with every part numbered.

1.5 Meet the running examples

You met the four running examples in "How to use this book". Here is why we chose them.

- **C-101** is a classic two-component (binary) column. It separates a lighter liquid (the **light key**) from a heavier one (the **heavy key**), like benzene from toluene. Its feed is 400 kmol/h (34,331 kg/h) with 45 mol % of the light key. The top product must be 98 mol % pure and the bottoms may hold only 2 mol % of the light key. It has 24 trays and runs at a reflux ratio of 1.75. We use it from Chapter 2 to Chapter 11 and again in Chapter 17.
- **C-301** is a packed column that we size from a blank sheet in Chapter 13.
- **T-201** is a packed absorber that removes a gas from an air stream with water. We use it in Chapters 15 and 16.
- **Unit 400** is a small group of hot and cold process streams. In Chapter 18 we find how much steam and cooling water it really needs.

1.6 What can go wrong

Columns are tall, hot, full of flammable or toxic material, and connected to steam, cooling water, pumps and flare systems. Here are the main hazards.

Hazard	Where you meet it	How plants control it
Overpressure	Loss of cooling to the condenser while the reboiler keeps heating; blocked outlet; fire	Relief valves sized for the worst case; reboiler heat cut on high pressure
Vacuum collapse	Steam-out followed by cooling with all valves shut	Vacuum breakers; procedures that keep a vent open
Fire	Leaks of hot hydrocarbons at flanges and pumps	Leak checks, gas detection, fire protection
Toxic exposure	Sampling, draining, opening equipment	Closed sampling, permits, breathing protection
Pyrophoric deposits	Opening packed columns with iron sulfide deposits	Wet the packing; follow the opening procedure
Confined space	Entry for inspection	Permit, gas test, standby person, isolation
Hot surfaces and steam	Reboiler, steam lines, drains	Insulation, gloves, careful draining

WATCH OUT

A column that suddenly loses its condenser cooling can build pressure very quickly while the reboiler is still heating. This is one of the main sizing cases for the column's relief valve. If cooling water to the condenser fails, follow the plant's emergency procedure, which normally starts by cutting the reboiler heat.

1.7 How a column earns its keep

Three numbers tell you most of what you need to know about a column:

1. **Product purity**: are both products on specification?
2. **Capacity**: can it handle the feed rate the plant wants, or is it close to flooding?
3. **Energy**: how much steam does the reboiler use per tonne of product?

A column can meet purity by using more reflux, but more reflux means more steam. It can take more feed until the trays flood. Most of this book is about these three numbers and the trade-offs between them.

FIELD CHECK

Is the column healthy?

What you see	What it may mean	First thing to check
Top product slowly going off specification	Feed has changed, reflux too low, or trays damaged	Feed analysis and reflux ratio against the usual values
Pressure drop across the column rising	Flooding, foaming or fouling	Feed rate, reboiler duty, and the trend over weeks
Reboiler steam creeping up for the same feed	More reflux than needed, fouled exchanger, or poor control	Reflux ratio and product purities (are they better than needed?)

TRY IT 1.1

A column makes 10 t/h of top product and its reboiler uses 12 t/h of steam. A month later it makes the same product with 13 t/h of steam. What is the steam use per tonne of product before and after, and what are two possible reasons for the change?

TRY IT WITH PLANTCALCKIT

The **Distillation Column Performance Evaluation** Excel toolkit does the material balance, minimum reflux, stage count, tray efficiency, duties and flooding check for a column like C-101. The **Absorber and Scrubber Performance Evaluation** toolkit does the same job for T-201.

Distillation Column Performance Evaluation
plantcalckit.com/shop/distillation-column-performance-evaluation-excel/

Absorber and Scrubber Performance Evaluation
plantcalckit.com/shop/absorber-and-scrubber-performance-evaluation-excel/

QUICK QUIZ 1

1. Name the four separation jobs that columns do.
2. In a countercurrent column, which way does the liquid flow?
3. What two pieces of equipment give a distillation column its vapour and its reflux?
4. Give one reason to choose packing instead of trays.
5. What are the three numbers that tell you most about a column?

CHAPTER 2

Vapour pressure and boiling

Every column works because different liquids boil at different temperatures. The property behind this is vapour pressure. Once you understand vapour pressure, column temperatures and pressures start to make sense.

2.1 What vapour pressure is

Put some liquid in a closed, empty container and keep it at a fixed temperature. Some molecules escape from the surface and fill the space above it as vapour. After a while, as many molecules come back as leave. The pressure of the vapour at that point is the **vapour pressure** of the liquid at that temperature.

- Vapour pressure depends only on the liquid and its temperature, not on how much liquid there is.
- It rises steeply with temperature. A rise of 10 °C (18 °F) often increases it by 30 to 50 %.
- A liquid **boils** when its vapour pressure equals the pressure around it.

So the **boiling point** is not a fixed number. Water boils at 100 °C at sea level, but at a lower temperature on a mountain and at a higher temperature inside a pressure cooker. The same is true inside a column: raise the column pressure and every temperature in it goes up.

2.2 Light and heavy

In a mixture, the component with the higher vapour pressure at a given temperature is called **light** or **more volatile**. The one with the lower vapour pressure is **heavy** or **less volatile**. "Light" here has nothing to do with density. It only means "boils more easily".

For C-101 the light key is like benzene and the heavy key is like toluene. At 100 °C (212 °F) the light key has a vapour pressure of 180.5 kPa (26.17 psia) and the heavy key only 74.3 kPa (10.77 psia).

2.3 The Antoine equation

Engineers describe vapour pressure with simple fitted equations. The most common is the **Antoine equation**:

> $\ln P = A - B / (T + C)$

where P is the vapour pressure, T the temperature in °C, and A, B and C are constants fitted to measured data for one liquid. Watch the form: some tables use the natural logarithm and kPa, others use the base-10 logarithm and mmHg. The constants are different for each form, so always use constants with the equation they were fitted for, and only inside the temperature range they were fitted over.

The Distillation Column Performance Evaluation toolkit uses the natural-log, kPa form. Its example constants for the two keys of C-101 are:

Key	A	B	C	Form
Light key	13.7819	2726.81	217.572	ln(P/kPa), T in °C
Heavy key	13.9320	3056.96	217.625	ln(P/kPa), T in °C

These are generic example values that match the published constants for benzene and toluene. To check them, we compared them with an open-source equation of state for the two pure liquids. Between 70 and 120 °C (158 and 248 °F) they agree within 0.2 %.

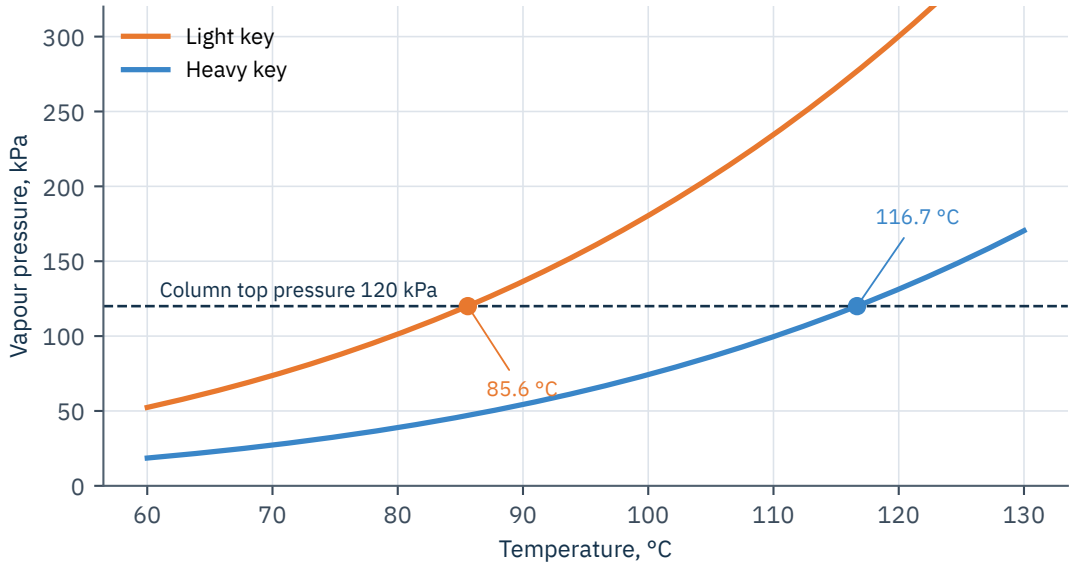


Figure 2.1 Vapour pressure of the two keys of C-101 from the toolkit's Antoine constants. The dashed line is the column top pressure, 120 kPa. Where each curve crosses it is that liquid's boiling point at the column top.

ENGINEER'S CALCULATION CORNER

Vapour pressure from Antoine

Find the vapour pressure of the light key at 80 °C (176 °F).

1. ln P = 13.7819 − 2726.81 / (80 + 217.572) = 13.7819 − 9.1635 = 4.6184
2. P = e^4.6184 = 101.3 kPa (14.70 psia)

So at 80 °C the light key's vapour pressure is just about one standard atmosphere (101.3 kPa). This is why its normal boiling point is 80.0 °C. The same sum for the heavy key gives 38.9 kPa, so at 80 °C the heavy key is far from boiling.

Check: the property library gives 101.1 kPa and 38.9 kPa. The free PlantCalcKit calculator, which uses base-10 constants in mmHg from a different published set, gives 101.0 kPa and 38.8 kPa. Different sources agree within a few tenths of a percent, which is normal.

2.4 Boiling point at the column pressure

Turn the Antoine equation around to find the temperature at which a liquid boils at a given pressure:

$$T = B / (A - \ln P) - C$$

At the C-101 top pressure of 1.2 bar a (120 kPa, 17.4 psia):

- the pure light key boils at 85.6 °C (186.1 °F),
- the pure heavy key boils at 116.7 °C (242.0 °F).

Any mixture of the two boils somewhere between these. The top of C-101, which is almost pure light key, should be close to the lower number. The base, which is almost pure heavy key, should be close to the higher one. This simple check is your first tool for reading a column (Chapter 10).

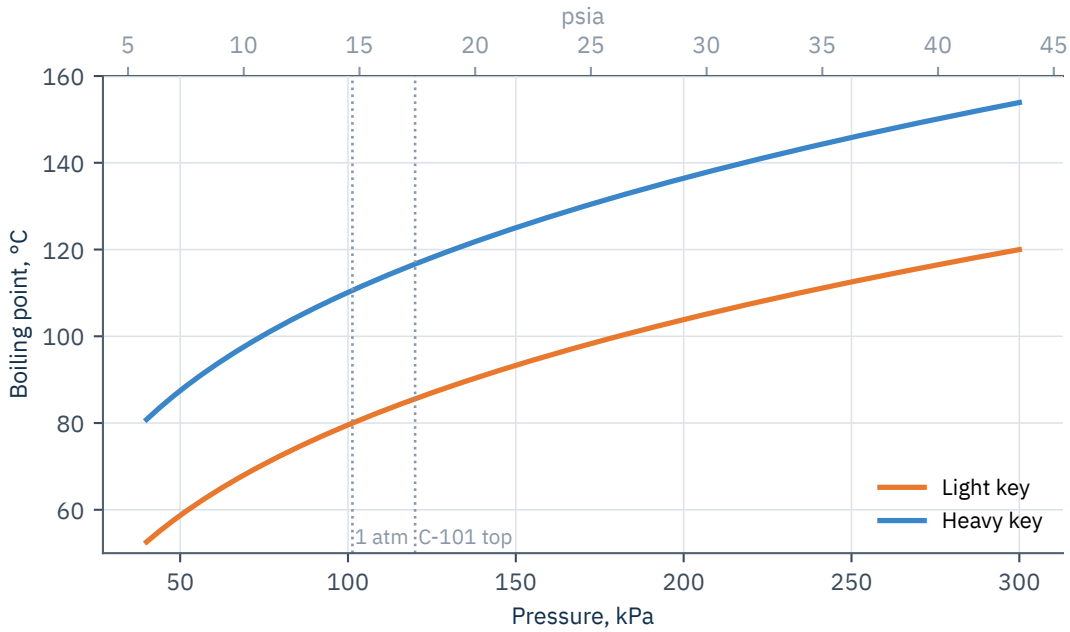


Figure 2.2 Boiling point of the pure light and heavy key against pressure. Raising the column pressure raises every temperature in the column.

2.5 How much does the temperature move with pressure?

Plant pressure readings are never perfectly steady. How much does a small pressure change move the boiling point? The slope of the boiling curve answers this. From the Antoine equation:

> $dT/dP = (C + T)^2 / (P \times B \times \ln 10)$ (base-10 constants)

The free vapour pressure calculator shows this slope. For the heavy key at 120 kPa it is 0.304 °C per kPa, so a pressure change of 10 kPa (1.45 psi) moves the base temperature by about 3.04 °C. This matters when you use a tray temperature to control product purity: if the pressure moves, the temperature moves too, even when the composition has not changed. Good control schemes correct the temperature for pressure. Chapter 10 comes back to this.

FIELD CHECK

Temperatures that do not fit

What you see	What it may mean	First thing to check
Top temperature higher than the light key's boiling point at the top pressure	Heavy material in the top product, or the pressure reading is higher than you think	Top product analysis; pressure transmitter calibration
Base temperature lower than expected	Light material in the bottoms, or the base pressure is lower	Bottoms analysis; column pressure drop
All temperatures move together	The column pressure moved	Pressure controller and condenser cooling

2.6 Vapour pressure and safety

Vapour pressure also tells you how a liquid behaves when it leaks or when equipment is blocked in.

- A liquid stored above its normal boiling point (like the base of a pressurised column) will partly flash to vapour if it escapes. This makes leaks bigger and more dangerous.

- A heat exchanger or pipe full of liquid that is blocked in and then heated can build very high pressure. This is called **thermal expansion** and needs relief protection.
- A column that is cooled down with all valves shut can go under vacuum as the vapour inside condenses (Chapter 19).

WATCH OUT

Never use Antoine constants outside the temperature range they were fitted for, and never mix constants from one table with the equation form from another. A wrong form can give a vapour pressure that is wrong by a factor of ten or more, yet looks believable.

TRY IT 2.1

Using the free calculator values, the heavy key's vapour pressure at 110 °C (230 °F) is 99.5 kPa (14.44 psia). At what pressure would C-101's base need to run for pure heavy key to boil at 110 °C? What would happen to the base temperature if the column pressure were raised to 1.4 bar a?

TRY IT 2.2

Water at 60 °C (140 °F): the low-range Antoine constants in the free calculator give 19.87 kPa. The property library gives 19.95 kPa. What is the difference in percent? Is it important for a quick check?

TRY IT WITH PLANTCALCKIT

The free **Vapour pressure and boiling point** calculator gives the vapour pressure of 25 common process liquids at any temperature, the boiling point at any pressure, and the slope dT/dP. In the **Distillation Column Performance Evaluation** toolkit you can enter Antoine constants for your two keys and the workbook finds the bubble and dew points and the relative volatility for you.

Vapour pressure and boiling point
plantcalckit.com/tools/vapour-pressure/

Distillation Column Performance Evaluation
plantcalckit.com/shop/distillation-column-performance-evaluation-excel/

QUICK QUIZ 2

1. What is the vapour pressure of a liquid?
2. When does a liquid boil?
3. What does "light" mean in a column?
4. Why must Antoine constants always be used with the equation form they were fitted for?
5. If the column pressure rises, what happens to the temperatures inside the column?

CHAPTER 3

Vapour-liquid equilibrium

When a liquid mixture boils, the vapour it makes is not the same as the liquid. The vapour is richer in the light component. This difference is what a column uses, one stage at a time. This chapter shows how to predict it.

3.1 Equilibrium in one picture

Take a pot of liquid mixture and heat it until it just starts to boil. Collect a little of the first vapour and analyse it. You will find more light key in the vapour than in the liquid. If you keep the pot boiling at a steady temperature and pressure, the liquid and the vapour above it settle at fixed compositions. This state is **vapour-liquid equilibrium** (VLE). A perfect tray, called an **equilibrium stage** or **theoretical stage**, sends out a vapour and a liquid that are in equilibrium with each other.

3.2 Raoult's law

For mixtures of similar molecules, like two hydrocarbons of the same family, a simple rule works well. **Raoult's law** says that each component contributes a partial pressure equal to its mole fraction in the liquid times its pure vapour pressure:

> $p_i = x_i \times P_{sat,i}$ and $y_i = x_i \times P_{sat,i} / P$

Here x is the mole fraction in the liquid, y the mole fraction in the vapour and P the total pressure. Mixtures that follow Raoult's law are called **ideal**.

3.3 Bubble point and dew point

A mixture does not boil at one temperature. It boils over a range.

- The **bubble point** is the temperature at which a liquid mixture just starts to boil, at a given pressure. At the bubble point the partial pressures add up to the total pressure: $x_1P_1 + x_2P_2 = P$.
- The **dew point** is the temperature at which a vapour mixture just starts to condense. At the dew point: $y_1/P_1 + y_2/P_2 = 1/P$.

Between the two, the mixture is part liquid and part vapour.

ENGINEER'S CALCULATION CORNER

Bubble and dew point of the C-101 feed

Data: feed 45 mol % light key, pressure 1.2 bar a (120 kPa), the Antoine constants of Chapter 2.

1. Guess a temperature, compute both vapour pressures, then check whether 0.45 P_1 + 0.55 P_2 equals 120 kPa.
2. Adjust the guess until it does. A spreadsheet solver or a few steps of trial and error will do.
3. Result: bubble point **99.4 °C** (211 °F).
4. Repeat with the dew point rule, 0.45/P_1 + 0.55/P_2 = 1/120. Result: dew point **106.0 °C**.

So the feed of C-101 starts to boil at 99.4 °C and is fully vapour at 106.0 °C. Our feed enters at 80 °C (176 °F), which is 19.4 °C below its bubble point. It is a **subcooled liquid**. Chapter 6 shows why that matters.

3.4 The T-x-y diagram

If you repeat the bubble and dew point calculation for every composition from 0 to 100 % light key, you get the **T-x-y diagram**. The lower curve is the bubble point line (liquid), the upper curve is the dew point line (vapour). A horizontal line at any temperature between the curves joins a liquid and the vapour in equilibrium with it.

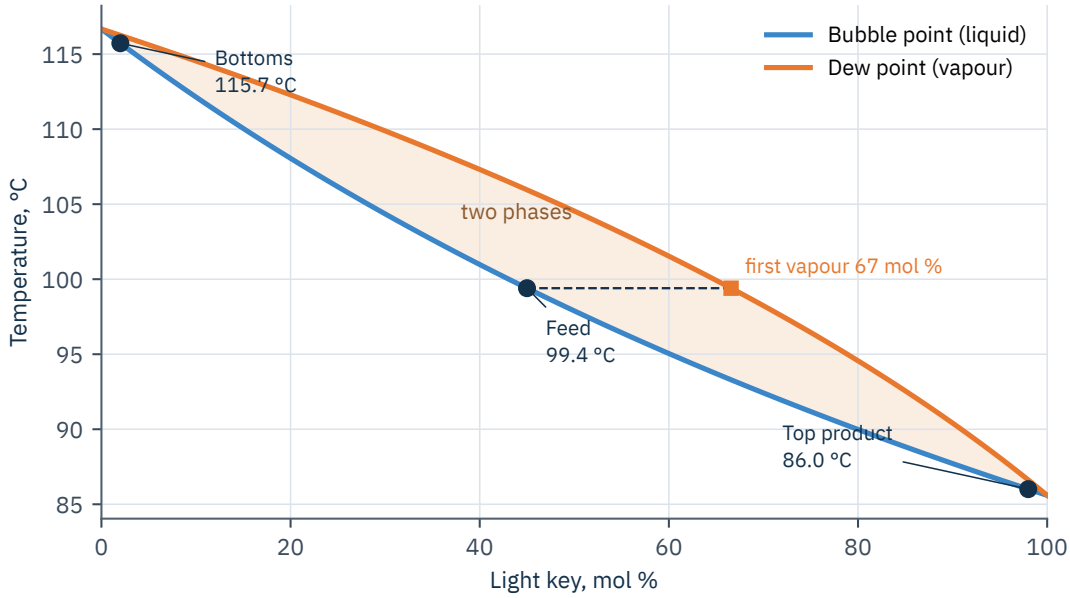


Figure 3.1 T-x-y diagram of the C-101 mixture at 1.2 bar a from the toolkit's Antoine constants and Raoult's law. The marked points are the top product, feed and bottoms.

Read the diagram at the feed: liquid of 45 mol % light key boils at 99.4 °C, and the first bubble of vapour holds much more light key. That enrichment, repeated stage by stage, is distillation.

3.5 Relative volatility: one number for "how easy"

The **relative volatility** α (alpha) compares how readily the two keys vaporise:

> $\alpha = (y_1/x_1) / (y_2/x_2) = P_{sat,1} / P_{sat,2}$ (ideal mixture)

For an ideal mixture α is just the ratio of the two vapour pressures. The bigger α, the easier the separation:

α	What it means
1.0	No separation possible by simple distillation

α	What it means
1.1 to 1.5	Hard: many stages and high reflux
1.5 to 3	Normal distillation
above 3	Easy: few stages

For C-101, α changes a little along the column because the temperature changes. The toolkit calculates it at the bubble point of the top product, of the bottoms and of the feed:

Where	Temperature	α
Top (98 mol %)	86.0 °C	2.549
Feed (45 mol %)	99.4 °C	2.435
Bottom (2 mol %)	115.7 °C	2.314
Geometric mean of top and bottom		**2.4286**

The toolkit uses the geometric mean, 2.4286, as the single α for the whole column. We use the same value from here on.

3.6 The x-y diagram

With a constant α, the vapour in equilibrium with any liquid is:

> $y = \alpha x / (1 + (\alpha - 1) x)$

Plot y against x and you get the **x-y diagram** or **equilibrium curve**. The 45° diagonal is where y = x. The further the curve bows above the diagonal, the easier the separation. This diagram is the base of the McCabe-Thiele method in Chapter 6.

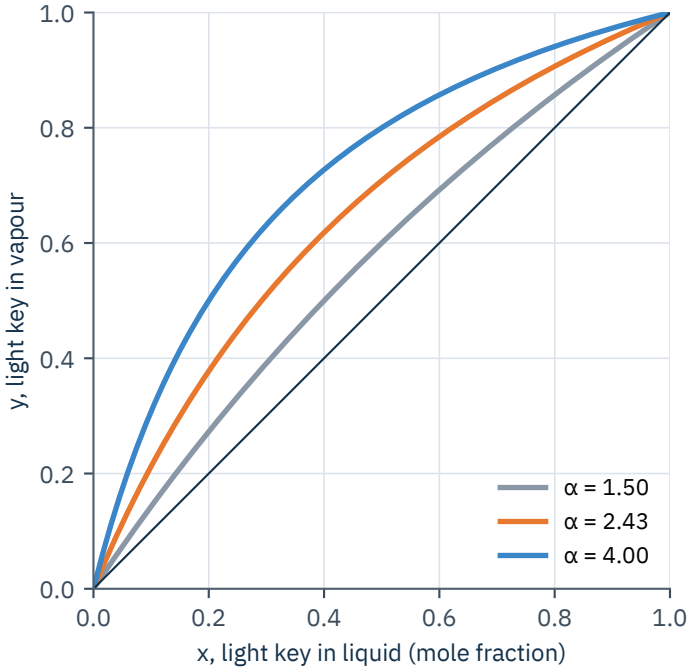


Figure 3.2 Equilibrium curves for three values of relative volatility. C-101 sits on the middle curve, α = 2.43.

For example, liquid with 45 mol % light key in C-101 is in equilibrium with vapour holding 66.5 mol % light key. One perfect stage raises the light key from 45 to about 67 mol %.

3.7 When Raoult's law fails

Raoult's law is an approximation. Real mixtures of very different molecules, for example water with an alcohol or an acid, do not follow it. Their molecules attract or repel each other, and the vapour pressure of the mixture is higher or lower than Raoult predicts.

- Engineers correct for this with **activity coefficients** from models such as Wilson, NRTL or UNIQUAC. These need fitted parameters for each pair of components.
- Some mixtures form an **azeotrope**: at one composition the vapour and liquid are the same, $\alpha = 1$, and ordinary distillation cannot go past that point. Ethanol and water is the best-known example.
- Polar mixtures, electrolytes and mixtures near their critical point need a proper property package in a process simulator.

WATCH OUT

The constant-α and Raoult's law methods in this book and in the toolkit are for **ideal or nearly ideal** binary mixtures. For a non-ideal or azeotropic system, use measured equilibrium data or a simulation, or enter an effective α that has been measured on your own column. Never extrapolate an ideal model across an azeotrope.

FIELD CHECK

Does the equilibrium make sense?

What you see	What it may mean	First thing to check
Column needs far more reflux than design for the same purity	Effective α lower than design (a new impurity, pressure higher than design)	Feed analysis for a third component; column pressure
Purity stops improving however much reflux you add	Azeotrope or pinch near the product end	Equilibrium data for the actual mixture
Model and plant temperatures disagree by several degrees	Wrong constants, wrong pressure or a non-ideal mixture	Pressure readings first, then the property data

TRY IT 3.1

Using $\alpha = 2.43$, find the vapour composition in equilibrium with a liquid of 10 mol % light key and with 90 mol % light key. In which part of the column, top or bottom, does each stage make the bigger change in composition?

TRY IT WITH PLANTCALCKIT

The **Distillation Column Performance Evaluation** toolkit calculates the bubble and dew points of the feed and products and the relative volatility (constant, mean of top and bottom, or at the feed) from Antoine constants you enter. The free **Vapour pressure** calculator gives the pure-component vapour pressures behind α.

Vapour pressure and boiling point
plantcalckit.com/tools/vapour-pressure/

Distillation Column Performance Evaluation
plantcalckit.com/shop/distillation-column-performance-evaluation-excel/

QUICK QUIZ 3

1. What is an equilibrium (theoretical) stage?
2. State Raoult's law in words.
3. What is the difference between the bubble point and the dew point?
4. What does a relative volatility of 1.0 mean?
5. Name one type of mixture for which Raoult's law is a poor model.

SOURCES

Sources for Chapters 1 to 3

This sampler is written in our own words. No text, tables or figures were copied. The full list of sources is in Appendix G of the full book; the numbering below is the same.

1. Seader, J.D., Henley, E.J. and Roper, D.K., *Separation Process Principles*, 3rd ed., Wiley, 2011. Ch. 2 and 4 (phase equilibrium, single stages), ch. 6 (absorption and stripping, Kremser, transfer units, packed column hydraulics), ch. 7 (binary distillation, McCabe-Thiele, tray efficiency), ch. 9 (approximate multicomponent methods: Fenske, Underwood, Gilliland, Kirkbride). Used in Chapters 3 to 8, 15 and 16.
2. McCabe, W.L., Smith, J.C. and Harriott, P., *Unit Operations of Chemical Engineering*, 7th ed., McGraw-Hill, 2005. Ch. 18 (gas absorption) and ch. 21 (distillation). Used in Chapters 4 to 6, 15 and 16.
3. Treybal, R.E., *Mass-Transfer Operations*, 3rd ed., McGraw-Hill, 1980. Ch. 5 (interphase mass transfer), ch. 6 (equipment for gas-liquid operations: trays and packing), ch. 8 (gas absorption), ch. 9 (distillation). Used in Chapters 7, 12 to 16.
4. Kister, H.Z., *Distillation Operation*, McGraw-Hill, 1990. Troubleshooting, start-up and shutdown practice, column instrumentation. Used in Chapters 10, 11 and 19.
5. Perry, R.H., Green, D.W. and Maloney, J.O. (eds), *Perry's Chemical Engineers' Handbook*, 7th ed., McGraw-Hill, 1997. Sections 13 (distillation) and 14 (gas absorption, gas-liquid systems). The packed-column flooding and pressure drop method of Chapters 13 and 16 follows this edition: generalized pressure drop correlation, Fig. 14-48 with Eq. 14-150 and 14-151 (p. 14-41), incipient flooding at about 1.5 in water/ft (p. 14-41) and measured flood points of 2.0 to 2.5 in water/ft (p. 14-42); packing factors in Table 14-7b (p. 14-43). Other editions print different charts: use the edition you work to. Used in Parts B and C.
6. Smith, J.M., Van Ness, H.C. and Abbott, M.M., *Introduction to Chemical Engineering Thermodynamics*, 7th ed., McGraw-Hill, 2005. Ch. 6 (vapour pressure, Antoine), ch. 10 (vapour-liquid equilibrium, Raoult's law, bubble and dew points). Used in Chapters 2 and 3.
7. NIST Chemistry WebBook, NIST Standard Reference Database 69 (Antoine constants used by the free vapour pressure calculator).
8. Bell, I.H., Wronski, J., Quoilin, S. and Lemort, V., "Pure and pseudo-pure fluid thermophysical property evaluation and the open-source thermophysical property library CoolProp", *Industrial and Engineering Chemistry Research*, 53(6), 2014 (checks of vapour pressures, steam properties, water density and viscosity, liquid viscosities).

ANSWERS

Answers for Chapters 1 to 3

Try it 1.1: Before: 12 ÷ 10 = 1.2 t of steam per tonne of product. After: 13 ÷ 10 = 1.3 t/t, about 8 % more. Possible reasons: more reflux than needed (products purer than specification), loss of tray efficiency, a colder or leaner feed, a fouled reboiler or poor condensate drainage, higher heat losses.

Try it 2.1: The base would need to run at about 99.5 kPa, just under 1 atm (about 1.0 bar a). At 1.4 bar a (140 kPa), pure heavy key boils at about 122.4 °C, so the base temperature rises by several degrees.

Try it 2.2: (19.87 – 19.95) ÷ 19.95 = -0.38 %. This is far smaller than the accuracy of a plant pressure gauge, so it does not matter for a quick check.

Try it 3.1: At x = 0.10, y = 21.3 mol % (a change of 11.3 points). At x = 0.90, y = 95.6 mol % (a change of 5.6 points). With constant α, each stage makes the bigger change in the lean, bottom part of the column; near a high-purity top, stages make smaller changes and crowd together.

Quiz 1: (1) Distillation, absorption, stripping, scrubbing. (2) Down. (3) The reboiler (vapour) and the condenser with reflux drum and pump (reflux). (4) Lower pressure drop (vacuum), more capacity, corrosive service, small diameter. (5) Product purity, capacity, energy use.

Quiz 2: (1) The pressure of its vapour in equilibrium with the liquid at a given temperature. (2) When its vapour pressure equals the surrounding pressure. (3) More volatile: higher vapour pressure at the same temperature. (4) Each form uses different units and logarithms; mixing them gives large errors. (5) They all rise.

Quiz 3: (1) An ideal contact where vapour and liquid leave in equilibrium. (2) Each component's partial pressure equals its liquid mole fraction times its pure vapour pressure. (3) Bubble point: liquid starts to boil; dew point: vapour starts to condense. (4) No separation is possible by simple distillation. (5) Polar mixtures such as alcohol-water, acids, electrolytes, or any azeotrope-forming mixture.

Enjoyed the free sample?

The full book continues with 16 more chapters: how a distillation column works, reflux and minimum reflux, McCabe-Thiele, trays and tray hydraulics, tray efficiency, condensers and reboilers, monitoring, troubleshooting, packed columns and packing, packed column hydraulics, distributors, gas absorption, absorber and scrubber design, energy use, heat integration and pinch analysis, and start-up and shutdown. It has 10 picture pages, 27 figures, printable checklists, a glossary, a FAQ and the answers to every exercise.

Free calculators and Excel toolkits at **plantcalckit.com** · questions: hello@plantcalckit.com

PlantCalcKit shop: the full book
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Distillation Column Performance Evaluation
plantcalckit.com/shop/distillation-column-performance-evaluation-excel/

Free vapour pressure calculator
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