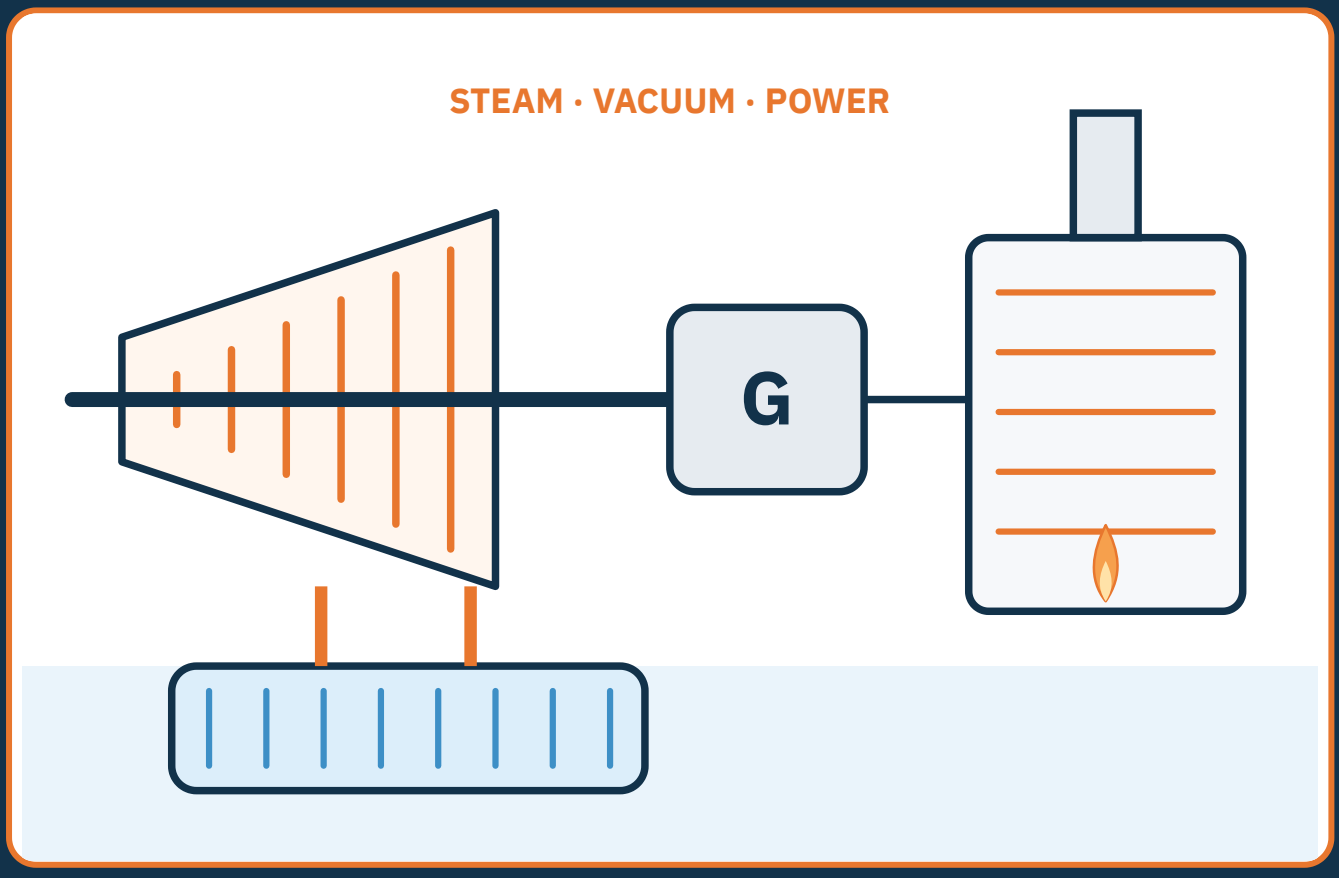
PlantCalcKit

Steam Turbines, Condensers and Combined Cycle Made Simple

A field guide to steam power, condensers and combined cycle plants

Steam properties · Rankine cycle · Turbine efficiency · Wet steam · Extraction and back-pressure · Compressor drives · Surface condensers · Vacuum and cooling water · Combined cycle · Monitoring and troubleshooting



FREE SAMPLER — Chapters 1 to 3

Edition 1.0 · November 2026

PlantCalcKit

Steam Turbines, Condensers and Combined Cycle Made Simple
A field guide to steam power, condensers and combined cycle plants
Edition 1.0 · November 2026 — free sampler (Chapters 1 to 3)

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Written in our own words from published engineering sources, listed in Appendix G. All diagrams, picture pages and charts are original PlantCalcKit artwork; charts are computed from the worked examples. No equipment maker, chemical supplier or brand is named or recommended.

Site S and all its equipment are made up. Every example value is generic; costs and prices are illustrative.

This guide is for training and engineering estimates. It does not replace your equipment maker's instructions, your water-treatment specialist's advice, the published codes and standards, or your plant's approved procedures and safety rules. Where a method follows a code or standard, the calculation is aligned with the publicly documented method; no result in this book claims to meet a code.

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PART A — STEAM BASICS

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GUIDE

How to use this book

This book explains steam turbines, surface condensers and combined cycle plants in plain words. You do not need to be an expert. If you can read a gauge and use a calculator, you can follow every example.

Who it is for

- **Plant operators** who run turbines and condensers and want to know what the numbers mean.
- **Young engineers** who must check performance, find losses and write reports.
- **Senior engineers** who want a quick refresher or a training text for their team.

How the book is built

Part	What you learn	Chapters
A	Steam power, steam properties, the Rankine cycle	1 to 3
B	Turbine expansion, efficiency checks, wet steam	4 to 6
C	Extraction, back-pressure and compressor-drive turbines	7 to 10
D	Surface condensers and cooling water	11 to 14
E	Combined cycle plants	15 to 17
F	Monitoring, trending and troubleshooting	18 and 19

Each chapter is short and stands alone. At the back you will find a glossary, an FAQ, units and conversions, a formula sheet, printable checklists, answers to all exercises and quizzes, and the list of sources.

The boxes you will see

- **Field check**: a table of what you might see on the plant, what it may mean, and what to check first.
- **Engineer's calculation corner**: a worked example with every step and number, using Site S's equipment.
- **Watch out**: a common mistake or a safety point.
- **Try it**: a short exercise; answers are in Appendix F.
- **Free tools**: QR codes to the free online calculator and the matching Excel toolkit for the chapter.
- **Quick quiz**: five questions to check you have the main ideas.

Site S and the numbers

All examples follow one made-up plant, Site S (Chapter 1). Its units use the example cases of the matching PlantCalcKit Excel toolkits, so you can open a toolkit and see the same calculation. Every number in the worked examples was computed with a script, not typed by hand. Costs and prices are illustrative only.

Units

SI units come first, with US customary units in brackets where it helps, for example 5,300 m³/h (23,335 US gpm). Pressures are marked "bar g" or "kPa g" (gauge) or "bar a" or "kPa a" (absolute). Appendix C has the conversions.

What this book is, and is not

This book helps you understand and check equipment. It is **not** a design code, an approved design calculation or a safety study, and it does not replace your equipment maker's instructions, your plant's approved procedures or the engineer responsible for the equipment. Where a method follows a published code or standard, we say it is "aligned with the publicly documented method": we used the published equations, not that the result meets the code. Safety-critical items (steam admission and drains, overspeed and trips, vacuum systems, compressor surge, pressure relief) are explained so that you can understand and question them; decisions on them belong to the responsible people and procedures at your site.

FREE TOOLS

Free calculators and Excel toolkits

Every chapter ends with two QR codes: a free online calculator for a quick check, and the matching PlantCalcKit Excel toolkit, which carries out the full calculation of the chapter's worked example with the same numbers. The toolkits show every formula, check every input and print a report. Shop pages are information pages; nothing is bought by scanning a code.

All free calculators
plantcalckit.com/tools/

All Excel toolkits
plantcalckit.com/shop/

Ch.	Chapter	Free calculator	Excel toolkit (does the chapter's calculation)
1	Steam power in a process plant	Steam tables (IAPWS-IF97) plantcalckit.com/tools/steam-tables/	Steam Turbine Performance **USD 39** plantcalckit.com/shop/steam-turbine-performance-excel/
2	Steam properties made simple	Steam tables (IAPWS-IF97) plantcalckit.com/tools/steam-tables/	Steam Turbine Performance **USD 39** plantcalckit.com/shop/steam-turbine-performance-excel/
3	The Rankine cycle and its efficiency	Steam tables (IAPWS-IF97) plantcalckit.com/tools/steam-tables/	Steam Turbine Performance **USD 39** plantcalckit.com/shop/steam-turbine-performance-excel/

PART A

Steam basics

Steam power, steam properties and the Rankine cycle

CHAPTER 1

Steam power in a process plant

Steam is the plant's energy carrier. A boiler turns fuel into high-pressure steam; a turbine turns part of that steam's energy into shaft power; a condenser or a process header takes the rest. This chapter introduces Site S, the made-up plant used in this book, and shows where the energy goes.

1.1 Why steam?

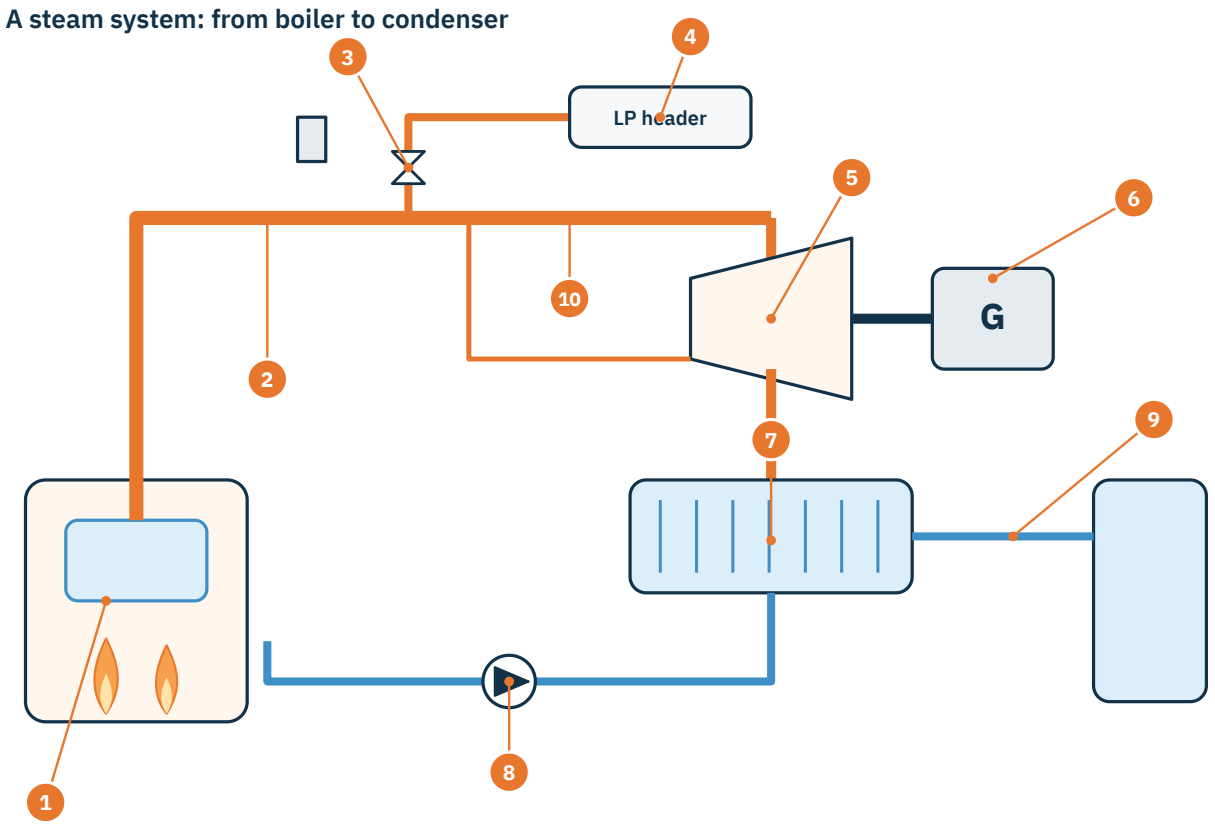
Water is cheap, safe to handle in large amounts and carries a lot of energy per kilogram when it changes to steam. Steam also moves through pipes easily and can be reused: first to make power, then to heat a process. That is why almost every refinery, fertiliser plant, paper mill and power station has a steam system.

Three machines do most of the work in this book:

- The **steam turbine** lets steam expand from high pressure to low pressure and takes the work out as rotation.
- The **condenser** turns the turbine's exhaust steam back into water at a very low pressure, so the turbine can expand the steam further.
- The **combined cycle plant** adds a gas turbine in front: its hot exhaust makes the steam, so the same fuel is used twice.

PICTURE PAGE 1

A steam system



Generic steam system of the kind found on Site S. Not to scale.

No.	Part	What it does
1	**Boiler**	Burns fuel to make steam at 60 bar a and 480 °C.
2	**High-pressure header**	Distributes steam to turbines and users; its pressure is held by the boiler and the PRVs.
3	**Pressure-reducing valve (PRV)**	Lets steam down to a lower header when turbines cannot supply it; wastes the power the steam could have made.
4	**Low-pressure header**	Carries steam at process pressure to heaters, reboilers and dryers.
5	**Steam turbine**	Turns the steam's expansion into shaft work.
6	**Generator**	Converts shaft power to electricity.
7	**Surface condenser**	Condenses the exhaust at low pressure; sets the turbine's exhaust pressure (Chapters 11 to 14).
8	**Condensate / feed pump**	Returns the condensate to the boiler feed system.
9	**Cooling water circuit**	Carries heat from the condenser to a tower or a river.
10	**Extraction line**	Takes partly expanded steam to a lower header (Chapter 7).

1.2 Site S

Site S is a made-up plant. Every tag and number is generic, but each unit uses the example case of one PlantCalcKit Excel toolkit, so you can open the toolkit and see the same calculation. Figure 1.1 shows how the units connect.

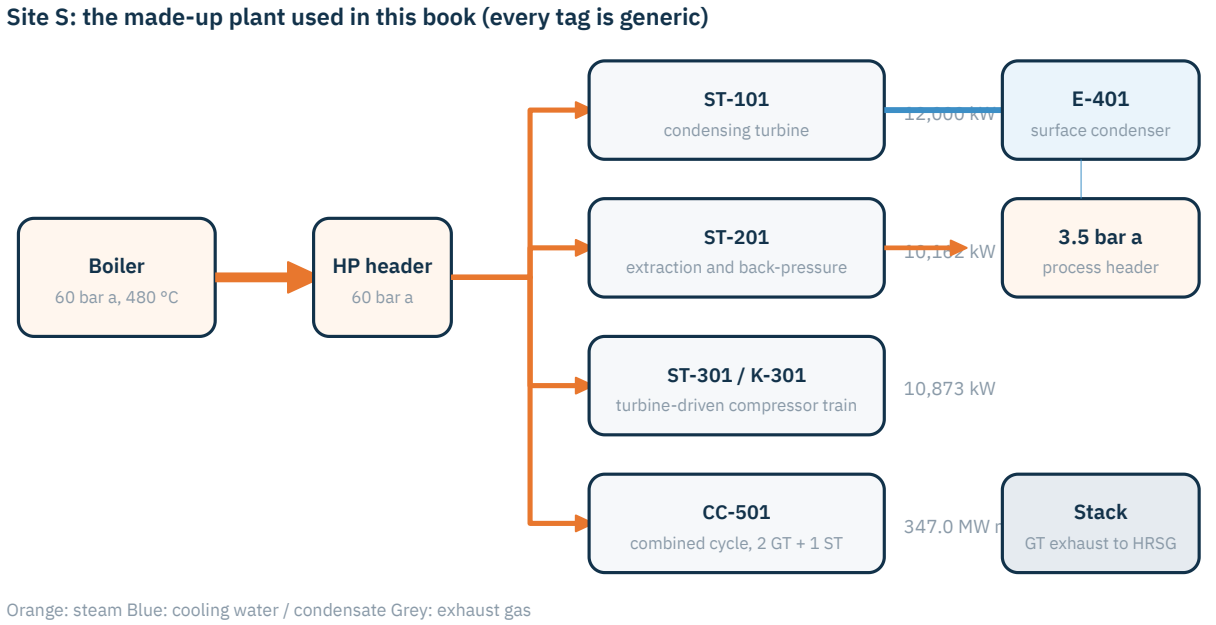


Figure 1.1 — Site S: one 60 bar a steam system feeding a condensing turbine, an extraction and back-pressure turbine, a turbine-driven compressor train and a combined cycle block. Tags are generic.

Tag	What it is	Chapters	Excel toolkit
ST-101	Condensing turbine, 60 bar a / 480 °C steam, 48 t/h, 12,000 kW	4 to 6	Steam Turbine Performance
ST-201	Extraction and back-pressure turbine, 80 t/h in, two extractions, 3.5 bar a header	7 and 8	Steam Turbine Extraction and Backpressure Evaluation
ST-301 and K-301	Condensing turbine driving a two-casing compressor train	9 and 10	Steam Turbine and Compressor Train Performance
E-401	Surface condenser, 90 t/h of exhaust steam at 9.0 kPa a	11 to 14	Steam Condenser Performance
CC-501	Two-on-one combined cycle, 347.0 MW design	15 to 17	Combined Cycle Plant Performance

Different units use slightly different steam conditions because each toolkit has its own example case. The text says so where it matters. All costs, tariffs and prices are illustrative.

1.3 Where does the energy go?

Take ST-101 as the simplest case. Steam enters at 60 bar a and 480 °C and leaves at 10 kPa a. The turbine makes 12,000 kW at the generator terminals from 48 t/h of steam. Measured from the steam's heat above the liquid water that leaves the turbine, the steam brings 42.45 MW into the turbine. Of that:

- **28.3 %** leaves as electricity (12,000 kW);
- **1.3 %** is lost in bearings, gears and the generator;

- **70.4 %** (29.89 MW) leaves with the exhaust steam and must be removed by the condenser.

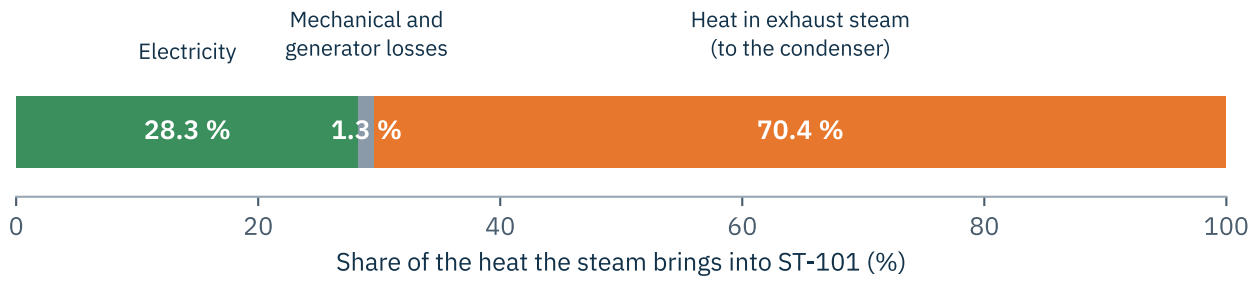


Figure 1.2 — Where the steam heat goes in ST-101. Most of it is not lost in the turbine: it is carried to the condenser by the exhaust steam.

The big surprise for new engineers is that the condenser takes more than two-thirds of the energy. That is not a fault of ST-101. It is a rule of nature: a heat engine must reject heat to a colder place, and the colder that place, the more work you get. Chapter 3 explains why, and Chapters 11 to 14 look at the condenser that does the rejecting.

1.4 Three numbers to know

You will meet these three again and again:

1. **Isentropic efficiency** (Chapter 4): how close the real turbine gets to a perfect, loss-free expansion. ST-101 reaches 77.5 %.
2. **Steam rate** (Chapter 4): kilograms of steam per kilowatt-hour. ST-101 uses 4.000 kg/kWh (8.82 lb/kWh).
3. **Heat rate** (Chapters 4 and 15): kilojoules of heat per kilowatt-hour. ST-101 is 12,734 kJ/kWh (12,069 Btu/kWh). Its inverse is the efficiency: 3,600 ÷ 12,734 = 28.27 %.

Why 3,600? Because 1 kWh equals 3,600 kJ. If a plant needed exactly 3,600 kJ of heat to make 1 kWh, it would be 100 % efficient.

ENGINEER'S CALCULATION CORNER **Worked example: ST-101 energy split**

Given: steam at 60 bar a, 480 °C (870 psia, 896 °F), 48,000 kg/h (105,822 lb/h), exhaust 10 kPa a, generator output 12,000 kW (16,092 hp), mechanical efficiency 98.5 %, generator efficiency 97.0 %.

1. Shaft power = 12,000 ÷ 0.970 = **12,371.1 kW**. Internal (blade) power = 12,371.1 ÷ 0.985 = **12,559.5 kW**.
2. Mechanical and generator losses = 12,559.5 − 12,000 = **560 kW**.
3. Inlet enthalpy h_1 = 3,375.2 kJ/kg. The liquid water at 10 kPa a has h_f = 191.8 kJ/kg. Steam heat = 13.33 kg/s × (3,375.2 − 191.8) = **42,445 kW**.
4. Exhaust enthalpy (Chapter 4) = 2,433.2 kJ/kg, so the exhaust carries 13.33 × (2,433.2 − 191.8) = **29,886 kW**.
5. Check: 12,000 + 560 + 29,886 = 42,445 kW. The three parts add up to the whole.

All values come from the IAPWS-IF97 steam equations (Chapter 2) and match the Steam Turbine Performance toolkit example.

FIELD CHECK **Reading the steam system on a walk-round**

What you see	What it may mean	First thing to check
Turbine power lower than usual at the same steam flow	Efficiency has dropped, or inlet steam is cooler or lower in pressure	Inlet pressure and temperature, exhaust pressure (Chapter 5)
Exhaust (condenser) pressure higher than usual	Warm or low cooling water, fouled tubes, air in the condenser	Cooling water inlet temperature and rise, air depression (Chapters 11 to 13)
Header pressure falling when a turbine trips	The turbine was supplying that header	Which PRV is passing and how much (Chapter 8)
Plant electricity output lower in summer	Warm ambient air and warm cooling water	Corrected values, not raw ones (Chapter 16)

1.5 How this book is organised

Parts A and B cover steam properties, the Rankine cycle and turbines. Part C looks at extraction, back-pressure and compressor-drive turbines. Part D takes the condenser and its cooling water apart. Part E adds the gas turbine to build a combined cycle. Part F shows how to monitor these machines and find faults. The gas turbine and heat recovery boiler themselves are kept light: see the companion book *Gas Turbines, HRSG and Compressors Made Simple*.

Watch out — a note on steam safety

Steam at 60 bar a and 480 °C is invisible, silent and can cut through a person. A small leak of high-pressure steam is a serious hazard. This book teaches you to understand and check performance; it does not replace the maker's manual, the isolation and lock-out rules of your site or the judgement of the engineer in charge.

TRY IT

A turbine with a heat rate of 12,734 kJ/kWh makes 6 MW. How much heat does the steam bring in? What share of it must the condenser remove if the turbine and generator lose 1.3 %? (Answer in Appendix F.)

FREE TOOLS **Do this chapter's calculation**

Free calculator
Steam tables (IAPWS-IF97) calculator
plantcalckit.com/tools/steam-tables/

Excel toolkit: Steam Turbine Performance (USD 39)
plantcalckit.com/shop/steam-turbine-performance-excel/
Topics: Condensing or back-pressure · Efficiency from your readings · Exhaust and wetness · Cost of the shortfall · What-if tables · Print-ready report

QUICK QUIZ

1. Name the three main machines in this book and say what each does.
2. Why does a condensing turbine reject more than half of its steam heat to cooling water?
3. What is the relation between heat rate and efficiency?
4. What is the isentropic efficiency of ST-101?
5. Why can Site S units use different steam conditions?

CHAPTER 2

Steam properties made simple

Every steam calculation starts with a few properties: temperature, pressure, enthalpy, entropy, volume and dryness. This chapter explains them in plain words, shows how to read steam tables and why a vacuum condenser is so large.

2.1 Saturated steam: the link between pressure and temperature

Water boils when its vapour pressure equals the pressure around it. At 1 bar a that happens at 99.6 °C. At 60 bar a it happens at 275.6 °C. At 10 kPa a (the condenser of ST-101) it happens at only 45.81 °C. Steam and water that are in balance at the boiling temperature are called **saturated**. For each pressure there is exactly one saturation temperature (Figure 2.1).

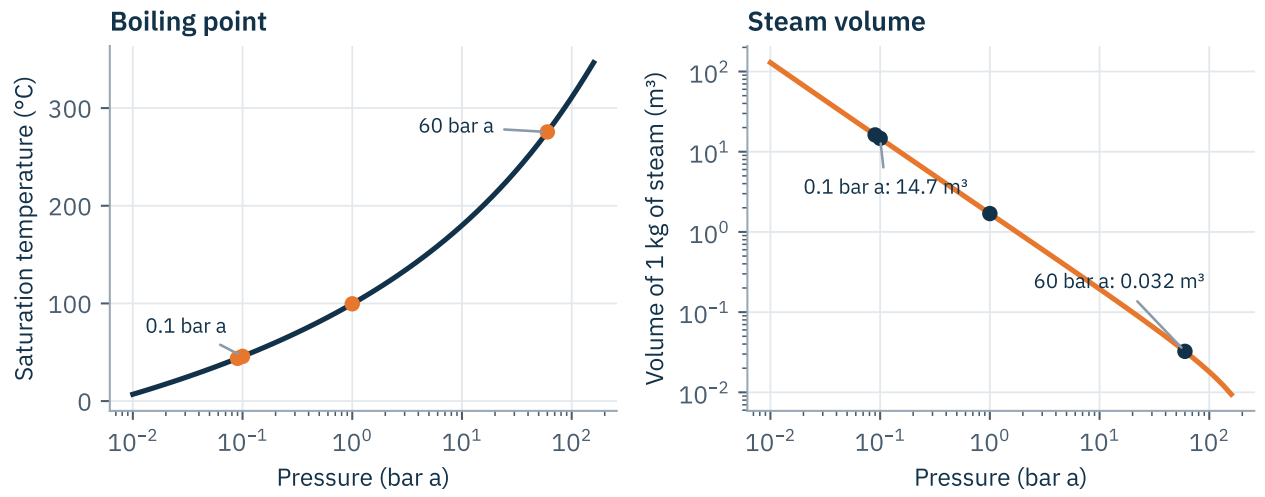


Figure 2.1 — Saturation temperature against pressure (left) and the volume of one kilogram of saturated steam (right). Dots mark pressures used on Site S. Computed with IAPWS-IF97.

This link is the key to condenser work. If you know the pressure in a condenser, you know the temperature at which steam condenses there, and the other way round. Chapter 11 uses it every time.

Absolute pressure	Boiling point	Where on Site S
−92.3 kPa g (9.0 kPa a)	43.8 °C	E-401 condenser
12 kPa a	49.4 °C	a warm-day condenser
20 kPa a	60.1 °C	a poor vacuum
101.325 kPa a	100.0 °C	atmosphere

2.2 Enthalpy, entropy and volume

Enthalpy (h) is the energy content of one kilogram of steam or water, in kJ/kg, counted from a fixed starting point (liquid water at the triple point). Only differences matter. When steam gives up 100 kJ/kg to a turbine, its enthalpy falls by 100 kJ/kg.

Entropy (s), in kJ/kg·K, is a measure of how spread out the energy is. You do not need to feel it; you need one rule: *a perfect turbine keeps entropy constant*. A real turbine increases it. The gap between the two is what Chapter 4 measures.

Specific volume (v), in m³/kg, is the space one kilogram takes up. It explains the size of everything on the cold end. One kilogram of saturated steam at 10 kPa a takes 14.67 m³; at 60 bar a it takes 0.0324 m³. The low-pressure steam is 452 times bulkier. That is why the last blades of a condensing turbine are long, and why the exhaust duct and condenser neck are as big as a room.

2.3 Saturated steam table (computed)

Pressure, bar a	Saturation temperature, °C	Liquid h_f, kJ/kg	Latent heat h_{fg}, kJ/kg	Vapour h_g, kJ/kg	Vapour volume v_g, m³/kg
0.05	32.88	137.8	2,423.0	2,560.8	28.19
0.1	45.81	191.8	2,392.1	2,583.9	14.67
1	99.61	417.4	2,257.5	2,674.9	1.694
3.5	138.86	584.3	2,147.7	2,732.0	0.5242
8	170.41	721.0	2,047.3	2,768.3	0.2403
20	212.38	908.6	1,889.8	2,798.4	0.09958
60	275.59	1,213.7	1,570.8	2,784.6	0.03245

The three enthalpy columns tell a story. Liquid enthalpy h_f is the heat in the water at the boiling point. Latent heat h_{fg} is the heat needed to turn that water into steam without changing its temperature. Vapour enthalpy $h_g = h_f + h_{fg}$. Note that h_{fg} shrinks as pressure rises (2,392 kJ/kg at 10 kPa a, 1,571 kJ/kg at 60 bar a): when the water is already hot, less extra heat is needed to make steam.

2.4 Superheated steam and wet steam

If you add heat to saturated steam at constant pressure, the temperature rises above the saturation temperature. This is **superheated** steam. ST-101's inlet steam is at 480 °C and 60 bar a, whose saturation temperature is 275.6 °C, so it carries **204.4 K of superheat**. Superheated steam has h = 3,375.2 kJ/kg, s = 6.8198 kJ/kg·K and v = 0.05489 m³/kg.

If you take heat away from saturated steam, some of it turns to liquid droplets and you get **wet steam**. The share that is still vapour is the **dryness fraction x** (also called quality). For wet steam:

$$h = h_f + x \times h_{fg} \text{ so } x = (h - h_f) \div h_{fg}$$

In wet steam the pressure and temperature are tied together, so a thermometer tells you nothing about dryness; you need the enthalpy or a direct measurement. Wet steam is hard on turbine blades, as Chapter 6 shows.

2.5 How the numbers are calculated

All steam values in this book come from the **IAPWS Industrial Formulation 1997 (IAPWS-IF97)**, the standard set of equations for water and steam in power engineering. We used the revised release (2007) through the `iapws` Python package. Older printed steam tables differ by a few hundredths of a percent, which does not matter for plant work. The free *Steam tables (IAPWS-IF97)* calculator and the Excel toolkits use the same equations, so a number you read in this book is the same number they give.

ENGINEER'S CALCULATION CORNER **Worked example: reading ST-101's exhaust state**

Given: ST-101 exhaust pressure 10 kPa a. From the table: h_f = 191.8 kJ/kg, h_{fg} = 2,392 kJ/kg, saturation temperature 45.81 °C.

1. A test finds the exhaust enthalpy is 2,433.2 kJ/kg (Chapter 4 shows how).
2. Dryness x = (2,433.2 − 191.8) ÷ 2,392 = **93.70 %**. The steam is 6.3 % water by mass.
3. The exhaust temperature is the saturation temperature, **45.8 °C** (114 °F), because the steam is wet.
4. Quick check with another enthalpy: if h were 2,400 kJ/kg, x = (2,400 − 191.8) ÷ 2,392 = 92.3 %.

Remember: wet steam has the saturation temperature, so a measured exhaust temperature of 45.8 °C only confirms the pressure. It does not tell you the dryness.

FIELD CHECK **Steam property sanity checks**

What you see	What it may mean	First thing to check
Steam temperature below the saturation temperature for the pressure	Not steam: it is water, or a gauge or thermocouple is wrong	Both instruments; are they at the same place?
Exhaust "temperature" higher than saturation at the vacuum	Superheated exhaust (fine for a back-pressure turbine) or a wrong pressure reading	Pressure tapping, vacuum gauge zero
Vacuum gauge reads in mmHg or inHg and the number looks backwards	Gauge pressure and absolute pressure mixed up	Is it "vacuum" (below atmosphere) or "absolute"?
Steam density from a meter does not match the table	Meter set up for different design conditions	Pressure and temperature compensation of the flow meter

2.6 Pressure language: absolute, gauge and vacuum

Steam tables use **absolute** pressure: zero is a perfect vacuum. A gauge reads the difference from the atmosphere. A condenser at 9.0 kPa a is −92.3 kPa g, or a vacuum of 27.3 inHg when the barometer reads 29.92 inHg. In absolute terms it is 2.66 inHg a or 68 mmHg a. Mixing up the two is one of the commonest errors in condenser work, so this book always writes "a" or "g". Appendix C lists conversions.

Watch out — "vacuum" can mean three things

A "better vacuum" means a *lower* absolute pressure. A vacuum gauge that reads a *higher* number (more inHg of vacuum) also means a better vacuum. Reports that say "vacuum went up" can mean the condenser got better or worse, depending on who wrote them. Always state absolute pressure in kPa a (or bar a) with the unit.

TRY IT

Find the superheat and the enthalpy of steam at 20 bar a and 300 °C. How many degrees of superheat does it have? (Answer in Appendix F.)

FREE TOOLS **Do this chapter's calculation**

Free calculator
Steam tables (IAPWS-IF97) calculator
plantcalckit.com/tools/steam-tables/

Excel toolkit: Steam Turbine Performance (USD 39)
plantcalckit.com/shop/steam-turbine-performance-excel/
Topics: Condensing or back-pressure · Efficiency from your readings · Exhaust and wetness · Cost of the shortfall · What-if tables · Print-ready report

QUICK QUIZ

1. What does "saturated" mean?
2. What is dryness fraction, and how do you get it from enthalpy?
3. Why does a thermometer not tell you the dryness of wet steam?
4. Why is the steam at 10 kPa a so much bulkier than steam at 60 bar a?
5. Convert 9.0 kPa a into gauge pressure.

CHAPTER 3

The Rankine cycle and its efficiency

Every steam power plant, from a small mill turbine to a combined cycle, runs on the Rankine cycle: pump the water up, boil it, expand the steam in a turbine, condense it. This chapter walks round the loop, explains what sets its efficiency and why higher steam pressure and a deeper vacuum both help.

3.1 The four steps

The cycle has four machines in a closed loop (Figure 3.1):

1. **Pump** (1 to 2): raises the pressure of the condensate to boiler pressure. It needs little work because liquid water hardly changes volume.
2. **Boiler** (2 to 3): adds heat, boils the water and superheats the steam.
3. **Turbine** (3 to 4): the steam expands to condenser pressure and delivers work.
4. **Condenser** (4 to 1): removes heat until the steam is liquid again.

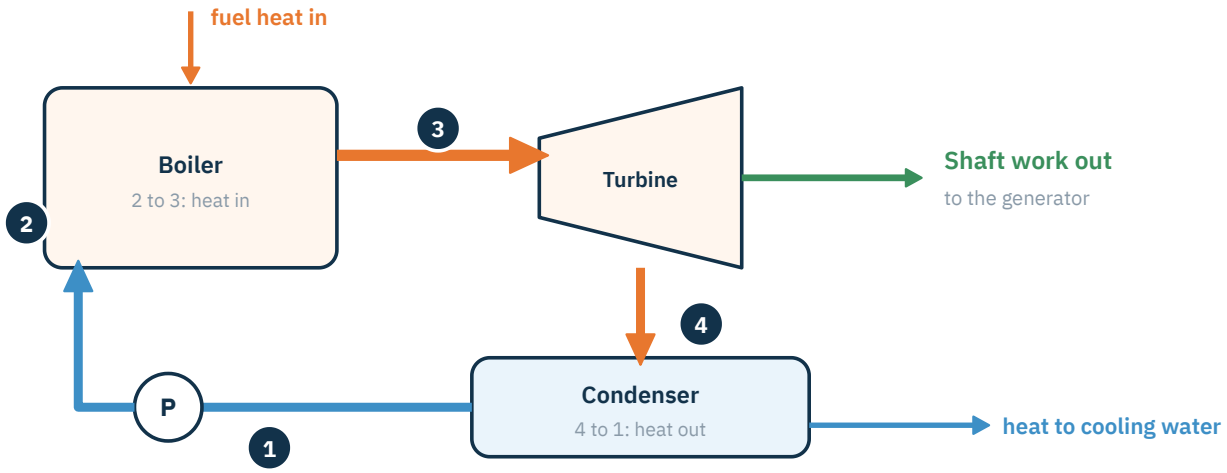


Figure 3.1 — The Rankine cycle as a loop. The numbers 1 to 4 match the points on the temperature-entropy chart in the next figure.

3.2 The ideal cycle for ST-101

The *ideal* cycle has a perfect turbine and pump and no pressure drops. Using ST-101's conditions (60 bar a, 480 °C, 10 kPa a), the chart is drawn in temperature against entropy (Figure 3.2). The area inside the loop is the net work; the area under the heat-addition line is the heat in.

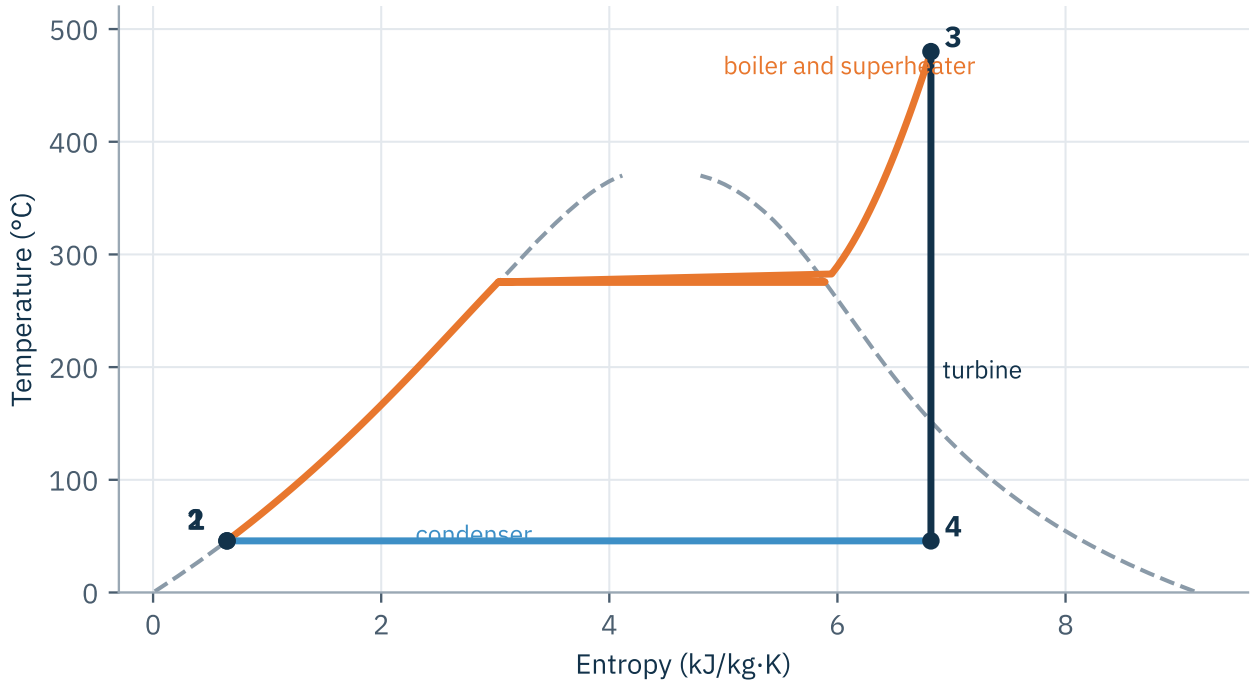


Figure 3.2 — Ideal Rankine cycle for ST-101 on a temperature-entropy chart. The dashed line is the saturation dome. Steam enters the turbine superheated (3) and leaves wet (4).

ENGINEER'S CALCULATION CORNER **Worked example: the ideal Rankine cycle for ST-101 conditions**

Given: boiler 60 bar a, 480 °C; condenser 10 kPa a.

1. Point 1, saturated liquid at 10 kPa a: h_1 = 191.8 kJ/kg, specific volume 0.001010 m³/kg.
2. Pump work = v × ΔP = 0.001010 m³/kg × (60 − 0.10) × 100 kPa = **6.05 kJ/kg**. Point 2: h_2 = 197.9 kJ/kg.
3. Point 3: h_3 = 3,375.2 kJ/kg, s_3 = 6.8198 kJ/kg·K.
4. Point 4 (perfect expansion to 10 kPa a, same entropy): h_4 = 2,160.0 kJ/kg, dryness 82.3 %.
5. Turbine work = 3,375.2 − 2,160.0 = **1,215.2 kJ/kg**. Net work = 1,215.2 − 6.05 = 1,209.2 kJ/kg.
6. Heat in = h_3 − h_2 = **3,177.3 kJ/kg**.
7. Efficiency = 1,209.2 ÷ 3,177.3 = **38.06 %**.

The pump takes only 0.50 % of the turbine's work. The real ST-101 reaches 28.3 % because the turbine is not perfect (Chapter 4) and because that figure is counted on a slightly different heat base (Chapter 1).

3.3 What sets the efficiency?

A neat way to think about it: the efficiency of the ideal cycle equals 1 − (average temperature at which heat leaves) ÷ (average temperature at which heat enters), with temperatures in kelvin. For ST-101 the heat leaves at 45.8 °C (319.0 K) and enters at an average of 242 °C (515 K): 1 − 319.0 ÷ 515 = **38.1 %**, the same as the full calculation.

So there are only two ways to improve a Rankine cycle: **raise the average temperature of heat addition** (higher boiler pressure, higher steam temperature, reheat, feedwater heating) or **lower the temperature of heat rejection** (a deeper condenser vacuum). Every trend in Figure 3.3 follows from that rule.

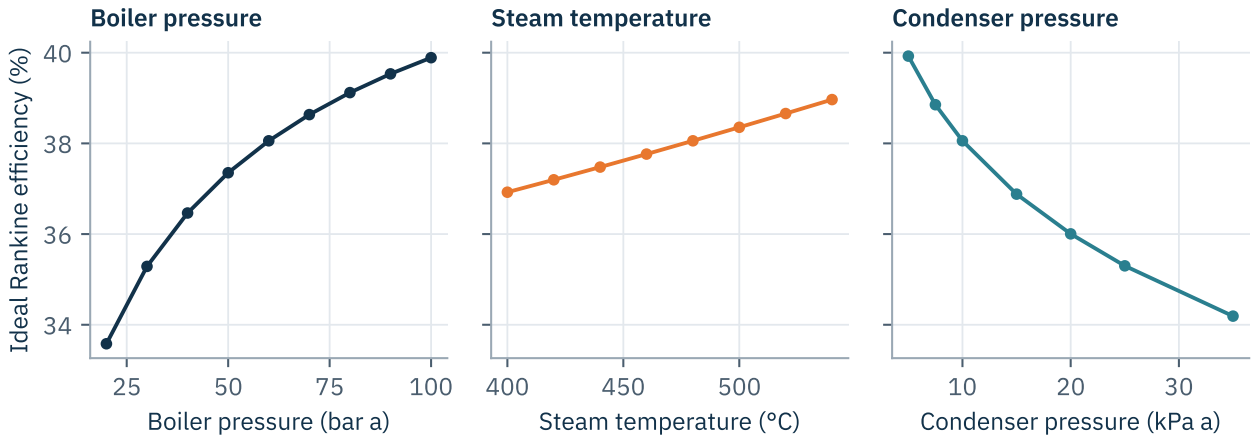


Figure 3.3 — Efficiency of the ideal Rankine cycle for different boiler pressure, steam temperature and condenser pressure (all other values as ST-101). Computed with IAPWS-IF97.

Boiler pressure, bar a	Steam temperature, °C	Condenser pressure, bar a	Ideal efficiency, %	Exhaust dryness, %
20	480	0.1	33.6	89.7
40	480	0.1	36.5	85.1
60	480	0.1	38.1	82.3
100	480	0.1	39.9	78.4
60	400	0.1	36.9	78.6
60	540	0.1	39.0	84.7
60	480	0.05	39.9	80.1
60	480	0.2	36.0	84.6
60	480	0.35	34.2	86.7

Read the table three ways:

- **Boiler pressure** from 20 to 100 bar a lifts efficiency from 33.6 % to 39.9 %, but the exhaust gets wetter: dryness falls from 89.7 % to 78.4 %.
- **Steam temperature** from 400 to 540 °C lifts efficiency from 36.9 % to 39.0 % *and* dries the exhaust (78.6 % to 84.7 %).
- **Condenser pressure** from 35 kPa a down to 5 kPa a lifts efficiency from 34.2 % to 39.9 %. A good vacuum is the cheapest efficiency a plant can have, and a fouled or leaking condenser throws it away.

3.4 Reheat and feedwater heating

Two refinements are common in larger plants.

Reheat. After part of the expansion the steam goes back to the boiler to be heated again, then expands in a second turbine section. With one reheat at 20 bar a back to 480 °C, the ideal efficiency of the ST-101 cycle rises from 38.1 % to **39.5 %** and the exhaust is drier (89.7 % instead of 82.3 %).

Feedwater heating. Some steam is taken from the turbine part-way down and used to warm the boiler feed water. That steam has already done some work, and its latent heat is not thrown to the condenser. With one open feedwater heater at 8 bar a (taking 20.0 % of the steam), the ideal efficiency rises to **40.5 %**. Extraction turbines (Chapter 7) are close relatives.

Reheat and feedwater heating raise the average temperature of heat addition; they do not change the idea of the cycle.

FIELD CHECK **Reading the cycle on the plant**

What you see	What it may mean	First thing to check
More fuel for the same electricity	Higher heat rate: weaker turbine, poorer vacuum or cooler steam	Compare turbine efficiency and condenser pressure with the baseline (Chapters 5, 11)
Boiler feed temperature lower than design	A feedwater heater out of service	Heater extraction valves, drains, level controls
Steam temperature dropping at the turbine	Boiler problem or attemperator spray too high	Superheater outlet temperature, spray valve position
Condenser pressure creeping up	Fouling, air or warmer cooling water	Condenser pressure against expected (Chapter 12)

Watch out — ideal is not real

The ideal cycle is a yardstick. Real plants lose pressure in pipes, heat from surfaces, and efficiency in the turbine. When someone quotes "Rankine efficiency", ask whether they mean the ideal cycle or the plant. A 38 % ideal cycle gives about 28 % for ST-101 on the same heat base.

TRY IT

Compute the ideal Rankine efficiency for steam at 40 bar a and 400 °C with a condenser at 10 kPa a. Hint: you need h_3, s_3, then h_4 at the same entropy, and the pump work (about 4 kJ/kg). (Answer in Appendix F.)

FREE TOOLS **Do this chapter's calculation**

Free calculator
Steam tables (IAPWS-IF97) calculator
plantcalckit.com/tools/steam-tables/

Excel toolkit: Steam Turbine Performance (USD 39)
plantcalckit.com/shop/steam-turbine-performance-excel/
Topics: Condensing or back-pressure · Efficiency from your readings · Exhaust and wetness · Cost of the shortfall · What-if tables · Print-ready report

QUICK QUIZ

1. Name the four steps of the Rankine cycle and say which machine does each.
2. Why does the pump need so little work?
3. Give two ways to raise Rankine efficiency and one way to lower it by accident.
4. Why does higher boiler pressure make the exhaust wetter?
5. What does reheat do to the exhaust dryness?

APPENDIX G

Sources

Every chapter was written in our own words from the published references below. No text, tables or figures were copied; all diagrams and charts are original PlantCalcKit artwork, computed from the worked examples. Where a method follows a code or standard, the calculation is aligned with the publicly documented method; that is not a claim that any result meets the code. **Edition caveat:** editions are given as the ones we consulted or as commonly cited; standards and handbooks are revised, so check the edition your contract or site names before relying on any detail. No constants were taken from tables of any standard. Constants that come from the PlantCalcKit toolkits and have no published source named here are listed as open risks in the book's brief.

General (all chapters)

- IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam (IAPWS-IF97), revised release of 2007, as implemented in the Python package `iapws`; check the current IAPWS release for later revisions. All steam and water properties.
- NIST Special Publication 811, *Guide for the Use of the International System of Units*: unit conversions.
- *Fundamentals of Engineering Thermodynamics* (Moran and Shapiro), 8th ed.: Rankine cycle, isentropic efficiency, mixtures.
- *Powerplant Technology* (El-Wakil), 1984: steam turbine expansion, wetness, condensers.

Chapter 1 — Steam power in a process plant

- *Thermodynamics: An Engineering Approach* (Çengel and Boles), 7th ed., ch. 10: vapour power cycles and energy accounting.

Chapter 2 — Steam properties made simple

- IAPWS-IF97 (see General). Saturation table and superheated values computed with `iapws`.
- *Fundamentals of Engineering Thermodynamics* (Moran and Shapiro), 8th ed.: dryness fraction, steam tables.

Chapter 3 — The Rankine cycle and its efficiency

- *Fundamentals of Engineering Thermodynamics* (Moran and Shapiro), 8th ed., ch. 8: ideal Rankine, reheat, open feedwater heater.
- *Thermodynamics: An Engineering Approach* (Çengel and Boles), 7th ed., ch. 10.

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