14 Properties of Water and Steam

It takes about 800,000 kJ of energy to get a steam engine from cold start to working pressure. This amount of energy would power a house for 7 days, run a 1.5 kW electric heater for 150 hours, run a 100 horsepower engine for 3 hours, drive a car for 150 to 200 miles or lift a 1000 kg mass against gravity to a height of 80 km. And that's just getting the engine ready to roll. A working traction boiler is already a large energy reservoir before it does a single stroke of useful work.

An energy input of 800,000 kJ (≈ 222 kWh) is comparable to the total stored energy in three to four large modern electric-vehicle battery packs. Most contemporary passenger EVs carry batteries in the 60–80 kWh range, while even large long-range vehicles rarely exceed 100 kWh of usable capacity. It is also roughly equivalent to the energy stored in nearly half a million wooden matches — counting only the wood, not the match heads.

Modern lithium-ion battery packs achieve pack-level volumetric energy densities on the order of 300–400 Wh/L once structure, cooling, and protection systems are included. 222 kWh corresponds to roughly 550–740 litres of battery volume. For comparison, a modern Toyota Camry has a 428L trunk capacity. On a typical home Level-2 charger (7–11 kW), charging 222 kWh would take 20–30 hours of continuous charging.

The sections that follow provide a guided progression from the familiar to the slightly more technical. Starting with the basic terms used in steam work, they build a simple picture of how water turns into steam, and then put it all to work in a few concrete examples. By the end, the energy required to warm-up a boiler won't feel mysterious—it'll just be a sequence of sensible steps with sensible numbers attached.

14.1 Core Quantities Used in Steam Work

Steam and boiler calculations rely on a small set of physical quantities. Students will see these repeatedly in warm-up problems, firing-rate estimates, and steam-table work.

- Mass — amount of water or steam
- Volume — water space, steam space, tender, wagon
- Temperature — sensible heat, saturation temperature
- Pressure — boiler pressure, steam-table lookup
- Energy — heat added or removed
- Power — rate of heat transfer
- Specific heat & latent heat — how water stores energy
- Specific volume — why small steam masses fill large spaces

These eight quantities form the backbone of all boiler physics.

14.2 Units Used in SI and Imperial Systems

The machines discussed here were conceived in a world of inches and pounds, long before the widespread adoption of SI units. The physics that governs their behaviour, however, is most clearly expressed in kilograms, metres, and seconds. As a result, this document necessarily lives in both worlds: historical dimensions are presented as originally specified, while analytical discussions convert those quantities into SI form. Any apparent mixing of unit systems reflects this historical reality rather than inconsistency.

Historical boiler pressures were measured and reported using gauge instruments, and are therefore understood as gauge pressures (PSIG), referenced to local atmospheric pressure. In this document, pressures derived from historical sources are treated in the same way. When required for thermodynamic analysis, gauge pressures are converted to absolute pressure by adding atmospheric pressure; when analysing forces, flow, and momentum, gauge pressure is used directly, as only pressure differences are physically relevant. This distinction is made explicit where it affects the analysis.

14.2.1 Mass

- SI: kilogram (kg)
- Imperial: pound-mass (lb)

14.2.2 Volume

- SI: liter (L), cubic meter (m^3)
- Imperial: gallon (US gal), cubic foot (ft^3)

Boiler capacity and steam-space volume are always given in these units.

14.2.3 Temperature

- SI: degrees Celsius (°C), kelvin (K)
- Imperial: degrees Fahrenheit (°F), Rankine (°R)
- $T_{Kelvin} = T_{Celcius} + 273$
- $T_{Rankine} = T_{Fahrenheit} + 459.670$

Key point: $\varDelta_T$ uses K or °R (°C and °F cannot be mixed directly).

14.2.4 Pressure

- SI: kilopascal (kPa), bar
- Imperial: pounds per square inch (psi)
- $1\,\mathrm{kPa} = 100\,\mathrm{bar}$
- $1\,\mathrm{bar} = 14.504\,\mathrm{psi}$

Steam tables use absolute pressure (relative to a perfect vacuum); boiler gauges show gauge pressure (relative to atmospheric pressure).

14.2.5 Energy

- SI: joule (J), kilojoule (kJ), megajoule (MJ)
  - $F = M \cdot A$ (Newton's second law)
  - $1\,\mathrm{N} = 1\,\frac{\mathrm{kg}\cdot\mathrm{m}}{\mathrm{s}^2}$
  - $1\,\mathrm{J} = 1\,\mathrm{m}\cdot\mathrm{N} = 1\,\frac{\mathrm{kg}\cdot\mathrm{m}^2}{\mathrm{s}^2}$
- Imperial: British thermal unit (BTU)
  - $1\,\mathrm{BTU} = 1055.056\,\mathrm{J}$

Used for sensible heat, latent heat, and preheating energy.

Intuitively, 1 joule is the energy required to:

- lift a small apple about 100 cm (40 inches) against gravity
- operate a 1-watt device for 1 second
- raise the temperature of 1 gram of water by about 0.239°C

1 BTU is the amount of heat required to raise the temperature of 1 pound of water by 1 degree Fahrenheit at standard pressure.

14.2.6 Power

- SI: watt (W), kilowatt (kW)
- Imperial: BTU/h, boiler horsepower (BHP) 1 BHP = 33,475 BTU/h = 9.81 kW.

Intuitively, energy is the capacity to do work, while power is the rate at which that work is done or energy is transferred.

14.2.7 Heat

14.2.7.1 Specific Heat

- SI: kJ/(kg·K)
- Imperial: BTU/(lb·°F)

Used in all heat calculations: $Q = m \cdot c \cdot \varDelta_t$ where Q is energy, m is mass, c is a coefficient determined by the type of mass, and $\varDelta_t$ is the change in temperature.

Material	Phase	Specific Heat	Temp Range
		kJ/kg·°C	approx.
Water	Solid (ice)	2.1	< 0 °C
Water	Liquid	4.18	0–100 °C
Water	Gas (steam)	2.0	> 100 °C
Steel	Solid	0.49	< 1500 °C
Steel	Liquid	0.80	~1500–2800 °C
Steel	Gas (vapor)	1.0	> 2800 °C

14.2.7.2 Latent Heat

- SI: kJ/kg
- Imperial: BTU/lb

Latent heat of fusion: used when a solid changes phase to liquid.

Latent heat of vaporization: used when a liquid changes phase to vapor

Phase Change	Water		Steel	
	Heat	Temp	Heat	Temp
Fusion	334 kJ/kg	0 °C	247 kJ/kg	1538 °C
Vaporization	2257 kJ/kg	100 °C	6090 kJ/kg	2861 °C

14.2.8 Specific Volume

- SI: m^3/kg
- Imperial: ft^3/lb

Explains why tiny steam masses occupy large volumes.

Specific volume is the inverse of density; thermodynamics prefers it because energy and state equations are cleaner when written per unit mass.

14.2.9 Unit Table

Quantity	SI Unit	Imperial Unit	Notes
Mass	kg	lb	Used in all heat calculations
Volume	L, m^3	gal, ft^3	Boiler capacity, steam space
Temperature	°C, K	°F, °R	ΔT uses K or °R
Pressure	kPa, bar	psi	Steam tables use absolute
Energy	kJ, MJ	BTU	Warm-up energy, latent heat
Power	kW	BTU/h, BHP	1 BHP = 9.81 kW

Quantity	SI Unit	Imperial Unit	Notes
Specific heat	kJ/kg·K	BTU/lb·°F	Water ≈ 4.18 kJ/kg·K
Latent heat	kJ/kg	BTU/lb	Steam formation
Specific volume	m³/kg	ft³/lb	Key for pressure rise

14.3 Steam tables

Steam tables give the thermodynamic properties of water and steam at different temperatures and pressures. Every table is built around three core ideas:

- Saturation — the boundary between liquid water and steam
- Phase — whether the substance is liquid, vapor, or a mixture
- Property sets — the values needed for energy and volume calculations

Steam tables are not derived from simple formulas; they are compilations of experimentally determined data. Over limited ranges, however, portions of the data can be approximated numerically, allowing tabulated values to be represented by fitted equations for computational use.

How to Read Steam Tables

14.3.1 Identify the table type

- Saturated table: use when water is boiling (T and P linked).
- Superheated table: use when steam is hotter than saturation.
- Compressed water table: rarely needed in boiler work.

14.3.2 Convert gauge pressure to absolute

- $P_{abs} = P_{gauge} + 101.300\,\mathrm{kPa}$ (or 14.7 psi).

14.3.3 In the saturated table

- Find the row for your pressure or temperature.
- numerically

  $$T_{sat(P)} \rightarrow 100 + 35.400 \ln P$$

- Read: v_f, v_g, h_f, h_{fg}, h_g where the subscripts *f* and *g* stand for fluid and gas.
- Latent heat: $h_{fg} = h_g – h_f$.

14.3.4 For wet steam (quality x)

- $h = h_f + x \cdot h_{fg}$
- $v = v_f + x \cdot (v_g - v_f)$
- Numerically,

  $$v_{v(P)} \rightarrow \frac{0.004(T_{sat}(P)+273)}{P}$$

  $$H_{v(P)} \rightarrow 2257 - 2.300(T_{sat}(P) - 100)$$

The factor *x* applies only in the two-phase (wet steam) region where liquid water and steam coexist at saturation conditions. It's value ranges from 0 (dry steam) to 1 (wet steam).

14.3.5 In the superheated table

- Start with pressure section.
- Move across to the temperature column.
- Read h, u, v for superheated vapor.

14.3.6 Common mistakes to avoid

- Using gauge pressure instead of absolute.
- Mixing SI and Imperial units.
- Confusing h_f (liquid) with h_g (vapor).
- Assuming latent heat is constant.
- Misreading v_g (steam volume) by orders of magnitude.

14.4 Numerical approximation

Accounting for warm-up, boiling, pressurization at the boiling point, and pressurization to the operating pressure, the system's response can be modeled as a piecewise process in which added energy raises temperature and pressure over distinct regimes.

14.4.1 Piecewise numerical model

This model describes the three physical stages a boiler goes through as it warms from ambient temperature to operating pressure. Each stage corresponds to a distinct thermodynamic regime.

$$T_{(P_{set}, T_0, V_s, m_w, m_s, q)} \rightarrow \begin{cases} T_0 & \text{if } q < 0 \\ T_0 + \frac{q}{C_{warm}} & \text{if } q < q_1 \\ T_{sat}(1) & \text{if } q < q_2 \\ T_{sat}(P(q)) & \text{if } q < q_3 \\ T_{sat}(P_{set}) & \text{if } q \geq q_3 \end{cases} \text{ where } \begin{cases} C_{warm} \rightarrow m_w \cdot c_w + m_s \cdot c_s \\ q_1 \rightarrow C_{warm} \cdot (T_{sat}(1) - T_0) \\ \Delta_q \rightarrow \frac{V_s}{v_v(1)} \cdot H_v(1) \\ q_2 \rightarrow q_1 + \Delta_q \\ q_3 \rightarrow q_2 + C_{warm} \cdot (T_{sat}(P_{set}) - T_{sat}(1)) + \frac{V_s \cdot H_v(}{v_v(P_s} \\ P_{(q)} \rightarrow 1 + \frac{(P_{set}-1)\cdot(q-q_2)}{q_3-q_2} \\ c_w \rightarrow 4.190 \\ c_s \rightarrow 0.490 \\ T_{sat(P)} \rightarrow 100 + 35.400 \ln P \\ v_{v(P)} \rightarrow \frac{0.004(T_{sat}(P)+273)}{P} \\ H_{v(P)} \rightarrow 2257 - 2.300(T_{sat}(P) - 100) \end{cases}$$

The model might look complicated at first glance, but that's because it's a composition of several pieces. The first and last pieces ($q < 0$ and $q \geq q_3$) are there to catch out-of-bound inputs. The middle three pieces capture the ideas of warmup, conversion to steam, and raising pressure. The definition items to the right are there to provide all of the supporting ideas in one place.

The model is used to create the graph in Fig. 1. But first,

$$bar_{(psig)} \rightarrow (psig + 14.700) \cdot 0.069$$

is a convience function to convert PSI to bar and

$$T_{(q)} \rightarrow T(bar(125), 20, 0.340, 1190, 9980, q)$$

applies model parameters for set pressure, initial temperature, volume of steam space, mass of water space and mass of boiler steel to produce a simple function that maps energy onto temperature. That is, as the amount of energy increases, the result of the model determines the temperature that would be achieved by applying that amount of energy.

The plot is produced by connecting adjacent points in the following sequence with line segments.

$$\left(\left\langle \frac{q}{10666.700}, T(q) \right\rangle \mid q \in 0 \overset{100000}{\cdots} 2000000\right)$$

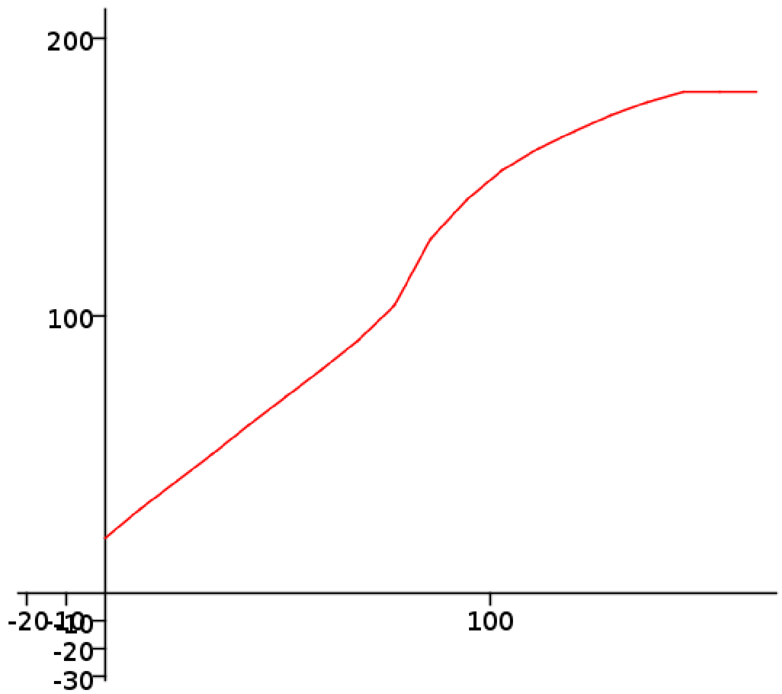

Fig. 1 Temperature vs Energy

The Y-axis is in degrees Celsius and the X-axis is scaled in increments of $10666.700\,\mathrm{J}$ units to accommodate the range 0 to $2\,\mathrm{mJ}$ in steps of $100\,\mathrm{kJ}$.

14.5 Boiler warmup model

14.5.1 Warmup: Heating water + steel from ambient to 100 °C (1 bar)

Energy range: $0 \leq q < q_1$

At first, all the heat goes into raising the temperature of the water and the steel shell. Nothing boils yet. Pressure stays at 1 bar.

The required energy is:

$$q_1 \to C_{warm}(100 - T_0) \text{ where } C_{warm} \to m_w \cdot c_w + m_s \cdot c_s$$

Physical meaning: Heat is being applied to a large thermal mass. No steam is produced. No pressure rise occurs. The temperature increases.

14.5.2 Boiling at constant temperature: Filling the steam space at 1 bar

Energy range: $q_1 \leq q < q_2$

Once the water reaches 100 °C, temperature stops rising. All additional heat now goes into phase change—boiling water to fill the steam space with saturated steam at 1 bar.

The energy required is:

$$\Delta_q = \frac{V_s}{v_v(1)} \cdot H_v(1)$$

$$q_2 = q_1 + \Delta_q$$

Physical meaning: Temperature stays at 100 °C while enough 1-bar steam is generated to fill the steam space. This is pure latent heat—no temperature change.

14.5.3 Pressurization: Heating to the saturation temperature at P_{set}

Energy range: $q_2 \le q < q_3$

After the steam space is filled at 1 bar, further heat does two things:

a. Sensible heating of the entire boiler

$$C_{\text{warm}}\,[T_{\text{sat}}(P_{\text{set}}) - 100]$$

This raises the temperature of:

- all the water
- all the steel
- and the existing steam

from 100 °C to the saturation temperature at the final pressure.

b. Additional steam generation at higher pressure

$$\tfrac{V_s}{v_v(P_{\text{set}})}\,H_v(P_{\text{set}})$$

At higher pressure, steam is denser, so the same steam space contains more mass. this additional mass of steam must be generatec at the higher pressure.

Physical meaning: Pressure rises only after the steam space is full. Everything is heated to the higher saturation temperature and the extra steam mass required at that pressure is generated.

14.5.4 Final state: Boiler at operating pressure

Energy range: $q \ge q_3$

Once q_3 is reached, the boiler is:

- full of saturated steam at P_{set}
- water and steel at $T_{\text{sat}}(P_{\text{set}})$
- ready for work

Temperature stays fixed at the saturation temperature for that pressure.

Terms explained

$$T_{sat(P)} \to 100 + 35.400 \ln P$$

"Saturated steam" is steam that is in equilibrium with liquid water at a given pressure. That means:

- the water and the steam have the same temperature, and
- that temperature is fixed by the pressure, not by how much heat is added.

This is why boiling water stays at 100 °C at 1 bar: the system is pinned to the saturation curve.

If the pressure is increased on boiling water, the boiling point goes up. This is a fundamental property of water:

- At 1 bar, water boils at 100 °C
- At 2 bar, it boils around 120 °C

- At 10 bar, it boils around 180 °C

So the saturation temperature is a monotonically increasing function of pressure.

The T_{sat} function is a simple empirical approximation to the real steam-table saturation curve.

- The 100 anchors the curve at 1 bar:
- The $35.400 \ln P$ term gives the correct shape: -- slow rise at low pressure -- faster rise at moderate pressure -- flattening at high pressure

This logarithmic form is a common engineering shortcut because it mimics the curvature of real saturation-temperature data without needing full steam tables. It’s not exact, but it’s good enough for conceptual modeling, plotting, and energy-budget calculations.

$$H_{v(P)} \to 2257 - 2.300(T_{sat}(P) - 100)$$

This is the latent heat of vaporization: the amount of energy needed to turn 1 kg of saturated water into 1 kg of saturated steam at the same pressure.

At 1 bar, this value is about 2257 kJ/kg. That’s the energy needed to break the liquid-phase bonds without raising temperature. This is why boiling takes so much heat even though the temperature stays fixed.

As pressure rises:

- the saturation temperature increases
- liquid water becomes more like the vapor phase
- the energy gap between liquid and vapor shrinks

So the latent heat gets smaller at higher pressure. This is a fundamental thermodynamic trend: near the critical point, latent heat goes to zero.

$$v_{v(P)} \to \frac{0.004(T_{sat}(P)+273)}{P}$$

This is the specific volume of saturated steam at pressure P. Put simply, it tells how much space 1 kg of saturated steam occupies at a given pressure.

- At low pressure, steam is “fluffy” → large volume per kg
- At high pressure, steam is denser → smaller volume per kg

This is why the same steam space V_s contains more mass at higher pressure. Think of a balloon at atmospheric pressure and imagine its size at 300 feet below the surface of a lake.

Saturated steam always sits on the saturation curve:

- Pressure determines the saturation temperature
- Temperature and pressure together determine the density of the vapor

The expression $v_v(P) \propto \frac{T}{P}$ is essentially the ideal gas law in engineering form: $v = \frac{RT}{P}$

Steam is not a perfect ideal gas, but at boiler pressures it behaves close enough that this approximation captures the right trend:

- Increase pressure → volume per kg decreases
- Increase temperature → volume per kg increases slightly

The expression: $v_v(P) = 0.00417\,\frac{T_{\text{sat}}(P)+273}{P}$ is a simplified engineering approximation derived from:

- the ideal gas law

- a fitted gas constant for water vapor
- the need to express temperature in Kelvin (hence +273)
- the desire for a compact formula that tracks real steam-table values reasonably well

The constant 0.00417 is a tuned coefficient that makes the curve match saturated-steam data around the 1–10 bar range.

$$\Delta_q \rightarrow \frac{V_s}{v_v(1)} \cdot H_v(1)$$

Δ_q is the energy needed to boil enough water at 1 bar to fill the steam space with steam at 1 bar.

$\frac{V_s}{v_v(1)}$ gives the mass of steam needed to fill the steam space at 1 bar.

- V_s = steam-space volume
- $v_v(1)$ = specific volume of saturated steam at 1 bar
- So $\frac{V_s}{v_v(1)}$ = kilograms of steam required At 1 bar, steam is very "fluffy," so v_v(1) is large and the mass is small.

$H_v(1)$ is the latent heat of vaporization at 1 bar—the energy needed to turn 1 kg of 100 °C water into 1 kg of 1-bar saturated steam. At 1 bar, this is about 2257 kJ/kg.

Δ_q uses 1-bar values because it describes the last thing that happens before pressure begins to rise. At this stage:

- the boiler is at 100 °C
- the pressure is still 1 bar
- all steam generated is 1-bar saturated steam

Pressure rise only begins after the steam space is full.

The model predicts only a very brief interval during which the boiler temperature remains at 100 °C before pressurization begins. This behavior is consistent with the underlying thermodynamics of the system.

First, once the water and steel structure reach 100 °C, no further sensible heating of these components occurs during the initial formation of saturated steam. Because the steel mass represents a substantial portion of the total thermal capacity during warm-up, the cessation of metal heating significantly reduces the energy required to maintain the system at 100 °C.

Second, the steam space volume is relatively small, and the specific volume of saturated steam at 1 bar is large. As a result, the total mass of steam required to fill the steam space is minimal. The latent heat needed to generate this small mass of vapor is correspondingly small, producing only a narrow energy interval between the completion of sensible heating and the onset of pressure rise.

Together, these factors explain why the model produces a very short plateau at 100 °C: the system transitions rapidly from saturated boiling at atmospheric pressure to the pressurization phase, with only a negligible dwell time at the boiling point.

Summary The model describes a boiler warming through three regimes—heating to 100 °C, boiling at constant temperature to fill the steam space, and then heating + generating denser steam to reach the final pressure—each with its own clean, physically meaningful energy requirement.

Pressure			T_{sat}		H_v	
psig	**bar**	**psia**	**°C**	**°F**	**kJ/kg**	**BTU/lb**
100	7.91	114.7	170	338	2048	880
105	8.25	119.7	172	342	2042	877
110	8.60	124.7	174	345	2036	874

Pressure			T_{sat}		H_v	
115	8.94	129.7	176	349	2030	871
120	9.28	134.7	178	352	2024	868
125	9.63	139.7	180	356	2018	865

14.6 Worked Example: How Long Does It Take to Boil a Kettle?

A simple, everyday problem that uses exactly the same physics as a boiler warm-up.

Step 1 — Identify the known quantities

- Mass of water:

  $M = 2.0\,\mathrm{kg}$

- Initial temperature:

  $T_{\mathrm{initial}} = 20^{\circ}\mathrm{C}$

- Final temperature:

  $T_{\mathrm{final}} = 100^{\circ}\mathrm{C}$

- Temperature rise:

  $\Delta T = T_{\mathrm{final}} - T_{\mathrm{initial}} = 100 - 20 = 80\,\mathrm{K}$

- Specific heat of water:

  $c \approx 4.18\,\mathrm{kJ/(kg{\cdot}\,K)}$

- Heater power:

  $\dot{Q} = 2.0\,\mathrm{kW} = 2.0\,\mathrm{kJ/s}$

Step 2 — Compute the energy required

Use sensible heat:

$$Q = m \cdot c \cdot \Delta T$$

$$Q = 2.0\,\mathrm{kg} \cdot 4.18\,\mathrm{kJ/(kg{\cdot}\,K)} \cdot 80\,\mathrm{K}$$

$$Q \approx 2.0 \cdot 4.18 \cdot 80\,\mathrm{kJ}$$

$$Q \approx 668.8\,\mathrm{kJ}$$

We can round this to: $Q \approx 670\,\mathrm{kJ}$

Step 3 — Convert energy and power into time

Time is energy divided by power:

$$t = 335\,\mathrm{s}$$

Convert to minutes:

Result With a 2.0 kW kettle, heating 2.0 kg of water from 20 °C to 100 °C (with no losses) takes about:

$$t \approx 5.5\text{–}6 minutes$$

Why this example matters This is the exact same structure you'll use for a boiler:

- compute $Q = m \cdot c \cdot \Delta T$ for the water mass,
- divide by the net heat rate $\dot{Q}$ to get time. The only difference at boiler scale is that m is hundreds of kilograms and $\dot{Q}$ comes from fuel and efficiency, not a neat 2 kW label on the side.

14.7 Raising Pressure in a Sealed Boiler

Once boiling begins, temperature and pressure follow the saturation curve. The entire water mass must be heated from $T_{\mathrm{sat}}(0\ \mathrm{psig})$ to $T_{\mathrm{sat}}(P_{\mathrm{target}})$: $Q_{\mathrm{pressurize}} = m\,c\,(T_{\mathrm{sat,target}} - T_{\mathrm{sat,initial}})$

Latent heat contributes only a small amount because the steam space contains very little mass: $m_s = \frac{V_{\text{steam space}}}{v_g}$

14.7.1 Effect of Firing Rate

Increasing firing rate increases heat transfer $\dot{Q}$, reducing the time required to raise pressure even though the energy requirement is large.

14.7.2 Relating Firing Rate to Time

$$t = \frac{Q}{\dot{Q}}$$

This relation underlies all warm-up and pressure-rise calculations.

14.8 How a Boiler Heats: From Cold Water to Working Pressure

1. Heating Water Before Boiling
   A cold boiler behaves like a large, heavy pot of water. All heat goes into raising the temperature of liquid water.

- Heat capacity of water is high: $c \approx 4.18\ \mathrm{kJ/kg{\cdot}K}$.
- Temperature rise is slow and predictable.
- Pressure barely changes because liquid water expands very little.

  The governing relation is: $Q = m \cdot c \cdot \mathit{\Delta} \cdot T$ Example: 100 kg of water heated from 20 °C to 100 °C requires about 33 MJ of heat. At a 50 kW firing rate, that's roughly 11 minutes just to reach boiling. Take-away: Before boiling, the boiler is sluggish. Lots of heat, slow temperature rise, almost no pressure.

2. Reaching the Boiling Point (0 psig)
   At 100 °C (212 °F) the water reaches its saturation temperature at atmospheric pressure. From this point onward, temperature and pressure are locked together by the saturation curve. This is the transition into the "pressure-building" regime.

3. Heating During Boiling (Two-Phase Region)
   Once boiling begins, the physics changes completely.

- Added heat no longer raises temperature much.
- Instead, it converts liquid water into steam.
- Steam occupies hundreds of times the volume of the same mass of liquid.
- The boiler volume is fixed, so pressure must rise.

  The pressure–temperature relationship is governed by: $\frac{dP}{dT} = \frac{L}{T\,(v_g - v_f)}$ Because $v_g \gg v_f$, the slope is steep. A few degrees of temperature increase can mean tens of psi. Take-away: After boiling starts, pressure rises rapidly. This is the "live" part of boiler operation.

4. Time to Raise Pressure
   Raising pressure from 0 psig to 50 psig requires:

- Only ~48 °C of temperature rise (100 °C → 148 °C)
- But a large amount of latent heat to generate the steam that forces pressure up

  This stage is much faster than the pre-boil warm-up because the temperature rise is small, but the pressure response is large.

5. Foreshadowing Injectors: Why Steam Velocity Matters
   Steam at boiler pressure has:

- Huge specific volume
- High speed of sound (~450–500 m/s)
- Nozzle velocities of 300–500 m/s

  Water at the same pressure moves only ~40–50 m/s through a nozzle. This velocity difference is the foundation of injector operation: a high-velocity steam jet entrains water, condenses, and drives the mixture into the boiler. Take-away: The same physics that makes pressure rise quickly also makes steam extremely fast—fast enough to power an injector.

14.9 Worked Example: Heating a 25 BHP Traction Boiler From Cold to 100 psi

This example models a typical 25 BHP traction-engine boiler:

- Water capacity: 250 gal (≈ 946 kg or 2,085 lb)
- Heating surface: 250 ft²
- Fuel: wood
- Initial condition: cold start, ~68 °F (20 °C)
- No steam usage: the boiler is not powering anything until 100 psi is reached
- Target pressure: 100 psi (≈ 170 °C / 338 °F saturation temperature)

The heating process has two distinct phases:

- Heating liquid water from cold to first boil (0 psig)
- Raising pressure from 0 psig to 100 psig with no steam consumption

A third phase—fueling while working—belongs in the horsepower section and is not included here.

14.9.1 Aside — water space and steam space

The water space is the volume in the boiler occupied by water. The steam space, the volume above the water space, is occupied by steam. The sum of the two volumes is the volume of the boiler. We are going to be interested in the weight of water in the boiler as well as the weight of steam.

We will need several auxiliary functions. The first calculates the volume of a cylinder, which is the area of a circle times the length of the cylinder.

$$V_{cyl_{(D,L)}} \rightarrow \left(\pi \left(\frac{D}{2}\right)^2 L\right)$$

The second function calculates the steam space, which lies above the water line. A transverse view of steam space shows the barrel as a circle and the water line as a horizontal chord. The area above the chord is called a circular segment. Knowing the radius R of the barrel and the perpendicular distance H from the chord to the boiler (along a radius intersecting the centre point of the chord),

$$A_{seg_{(R,H)}} \rightarrow R^2 \cdot cos^{-1}\left(\frac{R-H}{R}\right) - (R-H) \cdot \sqrt{2RH - H^2}$$

Multiplying the area of a circular segment by the length of a cylinder gives the volume of the segment projected along the cylinder.

$$V_{seg_{(D,H,L)}} \rightarrow A_{seg}\left(\frac{D}{2}, H\right) \cdot L$$

14.9.2 Boiler volumes

To calculate the total boiler volume, calculate the volume of the barrel, the wrapper, and the dome; from the sum of these, subtract the volume of the tubes and the firebox.

$$V_{barrel} \rightarrow V_{cyl}(D_{barrel}, L_{barrel}) \text{ where } \begin{cases} D_{barrel} \rightarrow 30\,\text{in} \\ L_{barrel} \rightarrow 96\,\text{in} \end{cases}$$

$$V_{wrapper} = (V_{lower} + V_{upper})\ \text{in}^3 \text{ where } \begin{cases} V_{lower} \rightarrow H_{wrapper} \cdot L_{wrapper} \cdot W_{wrapper} \\ V_{upper} \rightarrow \frac{V_{cyl}(D_{wrapper}, L_{wrapper})}{2} \\ L_{wrapper} \rightarrow 48\,\text{in} \\ H_{wrapper} \rightarrow 31\,\text{in} \\ D_{wrapper} \rightarrow 31\,\text{in} \\ W_{wrapper} \rightarrow 31\,\text{in} \end{cases}$$

$$V_{dome} \rightarrow V_{cyl}(D_{dome}, H_{dome}) \text{ where } \begin{cases} D_{dome} \rightarrow 14\,\text{in} \\ H_{dome} \rightarrow 18\,\text{in} \end{cases}$$

$$V_{firebox} \rightarrow (L_{firebox} \cdot W_{firebox} \cdot H_{firebox})\ \text{in}^3 \text{ where } \begin{cases} L_{firebox} \rightarrow 44\,\text{in} \\ W_{firebox} \rightarrow 25\,\text{in} \\ H_{firebox} \rightarrow 33\,\text{in} \end{cases}$$

$$V_{flues} \rightarrow (V_{cyl}(D_{tube}, L_{tube}) \cdot N_{tube}) \text{ where } \begin{cases} N_{tube} \rightarrow 40 \\ D_{tube} \rightarrow 2\,\text{in} \\ L_{tube} \rightarrow 96\,\text{in} \end{cases}$$

$$V_{barrel}^{steam} \rightarrow V_{seg}(D_{barrel}, H_{steam}, L_{barrel} + L_{wrapper})\ \text{in}^3 \text{ where } \begin{cases} H_{steam} \rightarrow 7\,\text{in} \\ D_{barrel} \rightarrow 30\,\text{in} \\ L_{barrel} \rightarrow 93\,\text{in} \\ L_{wrapper} \rightarrow 48\,\text{in} \end{cases}$$

$$V_{steam} \rightarrow V_{barrel}^{steam} + V_{dome}$$

Volume	$inch^3$	ft^3
V_{barrel}	$67858.401\,\text{in}^3$	$39.270\,\text{ft}^3$
$V_{wrapper}$	$64242.423\,\text{in}^3$	$37.177\,\text{ft}^3$
$V_{firebox}$	$36300\,\text{in}^3$	$21.007\,\text{ft}^3$
V_{flues}	$12063.716\,\text{in}^3$	$6.981\,\text{ft}^3$
V_{dome}	$2770.885\,\text{in}^3$	$1.604\,\text{ft}^3$
V_{barrel}^{steam}	$17674.336\,\text{in}^3$	$10.228\,\text{ft}^3$
V_{steam}	$20445.220\,\text{in}^3$	$11.832\,\text{ft}^3$

Then

$$
\begin{aligned}
V^{total}_{boiler} &= (V_{barrel} + V_{wrapper} + V_{dome} - V_{firebox} - V_{flues}) \\
&= 86507.993\,\mathrm{in}^3
\end{aligned}
$$

$$
\begin{aligned}
V_{boiler} &= \frac{V_{barrel} + V_{wrapper} + V_{dome} - V_{firebox} - V_{flues}}{12^3}\,\frac{\mathrm{ft}^3}{\mathrm{in}^3} \\
&= 50.062\,\mathrm{ft}^3
\end{aligned}
$$

$$
\begin{aligned}
V^{steam}_{boiler} &= \frac{V_{steam}}{12^3}\,\frac{\mathrm{ft}^3}{\mathrm{in}^3} \\
&= 11.832\,\mathrm{ft}^3
\end{aligned}
$$

$$
\begin{aligned}
V^{water}_{boiler} &= (V_{boiler} - V^{steam}_{boiler})\ \mathrm{ft}^3 \\
&= 38.231\,\mathrm{ft}^3
\end{aligned}
$$

$$
\begin{aligned}
\overset{gal}{V}{}^{water}_{boiler} &= \left(V^{water}_{boiler} \cdot 6.229\,\frac{\mathrm{gal}}{\mathrm{ft}^3}\right) \\
&= 238.132\,\mathrm{gal}
\end{aligned}
$$

In SI:

$$
\begin{aligned}
\overset{SI}{V}_{boiler} &= (V_{boiler} \cdot 0.028)\ \mathrm{m}^3 \\
&= 1.418\,\mathrm{m}^3
\end{aligned}
$$

$$
\begin{aligned}
\overset{SI}{V}{}^{steam}_{boiler} &= (V^{steam}_{boiler} \cdot 0.028)\ \mathrm{m}^3 \\
&= 0.335\,\mathrm{m}^3
\end{aligned}
$$

$$
\begin{aligned}
\overset{SI}{V}{}^{water}_{boiler} &= ((V_{boiler} - V^{steam}_{boiler}) \cdot 0.028)\ \mathrm{m}^3 \\
&= 1.083\,\mathrm{m}^3
\end{aligned}
$$

14.9.3 Boiler mass

To calculate the total boiler mass, calculate the plate area of each boiler section, mutliply by thickness to get plate volume and multiply by mass per unit of boiler plate to get section mass. The sections are the barrel, the front tube sheet, the wrapper, the throat sheet, the backhead, the dome and the tubes; subtract the holes in the front and rear tubesheets.

$$D_{mp} \to 0.284\,\frac{\mathrm{lb}}{\mathrm{in}^3}$$

$$T_{bp} \to 0.375\,\mathrm{in}$$

$$T_{tube} \to 0.135\,\mathrm{in}$$

$$A_{barrel} = (\pi D_{barrel} L_{barrel})\ \mathrm{in}^2 \text{ where } \begin{cases} D_{barrel} \to 30\,\mathrm{in} \\ L_{barrel} \to 120\,\mathrm{in} \end{cases}$$

$$A_{wrapper} = (A_{lower} + A_{upper})\ \mathrm{in}^2 \text{ where } \begin{cases} A_{lower} \to 2(H_{wrapper} \cdot L_{wrapper})\ \mathrm{in}^2 \\ A_{upper} \to \left(\frac{\pi D_{wrapper}}{2} L_{wrapper}\right)\ \mathrm{in}^2 \\ L_{wrapper} \to 48\,\mathrm{in} \\ H_{wrapper} \to 31\,\mathrm{in} \\ D_{wrapper} \to 31\,\mathrm{in} \end{cases}$$

$$A_{throat} = \left(D_{wrapper} \cdot H_{wrapper} - \frac{\pi\left(\frac{D_{wrapper}}{2}\right)^2}{2}\right)\ \mathrm{in}^2 \text{ where } \begin{cases} L_{wrapper} \to 48\,\mathrm{in} \\ H_{wrapper} \to 31\,\mathrm{in} \\ D_{wrapper} \to 31\,\mathrm{in} \end{cases}$$

$$A_{backhead} = \left(D_{wrapper} \cdot H_{wrapper} + \frac{\pi \left(\frac{D_{wrapper}}{2} \right)^2}{2} \right) \text{ in}^2 \text{ where } \begin{cases} L_{wrapper} \rightarrow 48\,\text{in} \\ H_{wrapper} \rightarrow 31\,\text{in} \\ D_{wrapper} \rightarrow 31\,\text{in} \end{cases}$$

$$A_{dome} = (\pi D_{dome} H_{dome}) \text{ in}^2 \text{ where } \begin{cases} D_{dome} \rightarrow 14\,\text{in} \\ H_{dome} \rightarrow 18\,\text{in} \end{cases}$$

$$A_{firebox} = 2(L_{firebox} \cdot H_{firebox} + W_{firebox} \cdot H_{firebox}) \text{ in}^2 \text{ where } \begin{cases} L_{firebox} \rightarrow 44\,\text{in} \\ W_{firebox} \rightarrow 25\,\text{in} \\ H_{firebox} \rightarrow 33\,\text{in} \end{cases}$$

$$A_{crown} = (L_{firebox} \cdot W_{firebox}) \text{ in}^2 \text{ where } \begin{cases} L_{firebox} \rightarrow 44\,\text{in} \\ W_{firebox} \rightarrow 25\,\text{in} \\ H_{firebox} \rightarrow 33\,\text{in} \end{cases}$$

$$A_{flues} = (N_{tube} \cdot (\pi D_{tube} L_{tube})) \text{ in}^2 \text{ where } \begin{cases} N_{tube} \rightarrow 40 \\ D_{tube} \rightarrow 2\,\text{in} \\ L_{tube} \rightarrow 96\,\text{in} \end{cases}$$

$$A^{holes}_{flue} = \left(2N_{tube} \cdot \pi \left(\frac{D_{tube}}{2} \right)^2 \right) \text{ in}^2 \text{ where } \begin{cases} N_{tube} \rightarrow 40 \\ D_{tube} \rightarrow 2\,\text{in} \end{cases}$$

$$A_{boiler} = \left(A_{barrel} + A_{wrapper} + A_{throat} + A_{backhead} + A_{dome} + A_{firebox} + A_{crown} - A^{holes}_{flue} \right)$$

$$\overset{lb}{M}_{boiler} = (A_{boiler} \cdot T_{bp} \cdot D_{mp} + A_{flues} \cdot T_{tube} \cdot D_{mp})$$

Section	**Plate Area**	**Plate Volume**	**Mass**
Area	in^2	in^3	lbs
A_{barrel}	11309.734	4241.150	1204.487
$A_{wrapper}$	5313.345	1992.504	565.871
A_{throat}	583.616	218.856	62.155
$A_{backhead}$	1338.384	501.894	142.538
A_{dome}	791.681	296.881	84.314
$A_{firebox}$	4554	1707.750	485.001
A_{crown}	1100	412.500	117.150
A_{flues}	24127.432	3245.140	921.620
A^{holes}_{flue}	251.327	71.377	26.766
$\overset{lb}{M}_{boiler}$			3556.369

In SI:

$$\begin{aligned} M_{boiler} &= \left(\overset{lb}{M}_{boiler} \cdot 0.454 \right) \text{ kg} \\ &= 1613.142\,\text{kg} \end{aligned}$$

14.9.4 Phase 1 — Heating From Cold to First Boil (0 psig)

Energy required

Water mass:

$$\begin{aligned} M_{water} &= \frac{\overset{gal}{V_{boiler}^{water}} \cdot 10\ \frac{\text{lb}}{\text{gal}}}{2.200\ \frac{\text{lb}}{\text{kg}}} \\ &= 1082.417\,\text{kg} \end{aligned}$$

Temperature rise:

$$20^\circ\text{C} \rightarrow 100^\circ\text{C} \quad (68^\circ\text{F} \rightarrow 212^\circ\text{F})$$

Sensible heat:

$$\begin{aligned} Q_{water} &= M_{water} \cdot c \cdot \mathit{\Delta}_T \text{ where } \begin{cases} c \rightarrow 4.180\ \frac{\text{kJ}}{\text{kg}\cdot\text{K}} \\ \mathit{\Delta}_T \rightarrow 80\,\text{K} \end{cases} \\ &= 361960.381\,\text{kJ} \end{aligned}$$

$$\begin{aligned} Q_{boiler} &= M_{boiler} \cdot c \cdot \mathit{\Delta}_T \text{ where } \begin{cases} c \rightarrow 0.490\ \frac{\text{kJ}}{\text{kg}\cdot\text{K}} \\ \mathit{\Delta}_T \rightarrow 80\,\text{K} \end{cases} \\ &= 63235.164\,\text{kJ} \end{aligned}$$

$$\begin{aligned} Q_{required} &= (Q_{water} + Q_{boiler}) \\ &= 425195.544\,\text{kJ} \end{aligned}$$

Observed warm-up time: operators report ~2 hours to “lift the pin.”

Net power requirement

$$\begin{aligned} \dot{Q} &= \left(\frac{Q_{required}}{7200\,\text{s}} \cdot 1\ \frac{\text{kW}\cdot\text{s}}{\text{kJ}} \right) \\ &= 59.055\,\text{kW} \end{aligned}$$

This is the actual heat reaching the water and the boiler, not the heat released by the fuel.

What this implies about wood firing

Realistic field values:

- Wood LHV: 8–12 MJ/kg (3,500–5,200 BTU/lb)
- Boiler efficiency on wood: 30–45%

$M_{poplar} \rightarrow 460\ \frac{\text{kg}}{\text{m}^3}$

Using mid-range values ($Q_{fuel} = 10000\ \frac{\text{KJ}}{\text{kg}}$, $\eta = 0.350$ efficiency):

$$\begin{aligned} Q_{fuel} &= \frac{Q_{required}}{\eta} \\ &= 1214844.412\,\text{kJ} \end{aligned}$$

$$\begin{aligned} M_{wood} &= \frac{Q_{fuel}}{10000\ \frac{\text{kJ}}{\text{kg}}} \\ &= 121.484\,\text{kg} \end{aligned}$$

$$\begin{aligned} \overset{lb}{M_{wood}} &= \left(M_{wood} \cdot 2.200\ \frac{\text{lb}}{\text{kg}} \right) \\ &= 267.266\,\text{lb} \end{aligned}$$

Phase 1 summary: A 25 BHP traction boiler warming from cold to first boil in ~2 hours is realistically burning just under 150 lb of wood per hour, depending on moisture and firing quality. At the point of boiling, approximately 300 lb of wood has been contributed, and whatever fuel remains in the firebox will contribute energy to the next phase.

14.9.5 Phase 2 — Raising Pressure From 0 psig to 100 psig

Once boiling begins, the physics changes:

- Temperature and pressure are locked by the saturation curve.
- Almost all added heat goes into latent heat (making steam), not temperature.
- The boiler is not venting and not using steam, so the steam space is compressed by newly generated steam.

Required auxiliary functions

Convert PSIG to bar	$bar_{(psig)} \rightarrow (psig + 14.700) \cdot 0.069$
Temperature at pressure	$T_{sat(P)} \rightarrow 100 + 35.400 \ln \frac{P}{1}$
Specific volume of vapor at pressure	$V_{v(P)} \rightarrow \frac{0.004(T_{sat}(P)+273)}{P}$
Latent heat of vaporization	$H_{v(P)} \rightarrow 2257 - 2.300(T_{sat}(P) - 100)$

100 psi is $7.909\,\mathrm{bar}$ so use 8 bar.

Saturation temperature at $8\,\mathrm{bar}$ ≈ 170 °C (338 °F) (from the steam tables) or $173.612\,\mathrm{C}$ using the interpolative formula.

$$\Delta T = 170 - 100 = 70^{\circ}\mathrm{C} \quad (338 - 212 = 126^{\circ}\mathrm{F})$$

Heat for phase 2 includes sensible heat for both the water and the boiler as well as the latent heat required to produce a mass of steam sufficient to pressurise the steam space.

Recall the volumes:

$$M_{water} \rightarrow 1082.417\,\mathrm{kg}$$

$$M_{boiler} \rightarrow 1613.142\,\mathrm{kg}$$

$$\overset{SI}{V}{}^{steam}_{boiler} \rightarrow 0.335\,\mathrm{m}^3$$

$$Q_{water}(P) = M_{water} \cdot c_w \cdot \mathit{\Delta}_t \text{ where } \begin{cases} c_w \rightarrow 4.180 \\ \mathit{\Delta}_t \rightarrow T_{sat}(P) - 100 \end{cases}$$

$$Q_{boiler}(P) = M_{boiler} \cdot c_s \cdot \mathit{\Delta}_t \text{ where } \begin{cases} c_s \rightarrow 0.490 \\ \mathit{\Delta}_t \rightarrow T_{sat}(P) - 100 \end{cases}$$

$$Q_{steam}(P) = M_{steam} \cdot h_{fg} \text{ where } \begin{cases} M_{steam} \rightarrow \frac{\overset{SI}{V}{}^{steam}_{boiler}}{V_v(P)} \\ h_{fg} \rightarrow H_v(P) \end{cases}$$

$$\begin{aligned} Q_{phase2} &= (Q_{water}(8) + Q_{boiler}(8) + Q_{steam}(8)) \\ &= 394377.172\,\mathrm{kJ} \end{aligned}$$

Breaking the three summands into individual values:

$$Q_{water}(8) \quad 333058.888\,\mathrm{kJ}$$

$$
\begin{array}{ll}
Q_{boiler}(8) & 58186.018\,\mathrm{kJ} \\
Q_{steam}(8) & 3132.267\,\mathrm{kJ}
\end{array}
$$

Phase 2 Summary: The energy requirement in Phase 2 is very similar to that in Phase 1. This is not surprising because Phase 1 raised water 80 degrees while Phase 2 raised it 70 degrees with an additional small amount of energy used to water to steam pressure.

Other factors to consider:

- the two hour time for Phase 1 includes building the fire. It takes 20 to 30 minutes from light-off to build a fire to its full energy production phase. In addition, a good operator will warm a boiler gently to reduce thermal shock.
- Phase 2 benefits from the use of steam-induced draft after 5 to 10 PSI is achieved.
- the boiler efficiency is subject to a more detailed analysis

The value for $Q_{steam}(8)$ requires some explanation. Raising boiler pressure does not require boiling all the water — only forming enough steam to occupy the available volume. It accounts for the energy necessary to fill the steam space with enough steam to pressurise the boiler.

14.9.6 Latent-heat component

In a sealed boiler, pressure rise is dominated by:

- the latent heat needed to generate steam
- the steam-space volume
- the enormous ratio v_g/v_f

Even a small mass of steam dramatically increases pressure because steam occupies hundreds of times the volume of liquid. For a typical traction boiler steam space ($0.335\,\mathrm{m}^3 \text{ where } \begin{cases} gal_{US} \rightarrow 88.520 \\ gal_{imp} \rightarrow 73.700 \end{cases}$), the latent-heat requirement to reach 100 psi is small compared to the sensible heat needed to raise the entire water and steel mass from 100 °C to 170 °C.

Practical result With no steam usage:

- The dominant energy requirement is the 70 °C (126 °F) temperature rise of the entire water mass.
- The latent-heat component is relatively small.
- Therefore, the time from 0 psig → 100 psig at the same firing rate is on the order of 1.5–2 hours, similar to the warm-up time.

MSG expressions: 65, bytes: 4181, average: 64.3, stdev: 66.8