

Paper-3 — Formula & Concept Guide

Energy Efficiency in Electrical Utilities — all 10 chapters, all 137 formulas (the same list as the Formula & Unit Workbook, so nothing is missing).

For every formula: what each symbol means and its unit, what the formula tells you, a worked example from a real exam question, and the exam trap. Plus 26 photographs of the actual equipment, 16 diagrams, 20 constants, 48 definitions and 23 verified online videos. Values are the 2014 BEE Book-3's.

► **Download the whole guide as one PDF · Numericals drill**

Ch 1 · Electrical Systems (19 formulas)

Ch 2 · Electric Motors (14 formulas)

Ch 3 · Compressed Air System (14 formulas)

Ch 4 · HVAC and Refrigeration System (13 formulas)

Ch 5 · Fans and Blowers (14 formulas)

Ch 6 · Pumps and Pumping System (12 formulas)

Ch 7 · Cooling Tower (12 formulas)

Ch 8 · Lighting System (13 formulas)

Ch 9 · DG Set System (13 formulas)

Ch 10 · Buildings and ECBC (13 formulas)

CONSTANTS TO MEMORISE (USED ALL THROUGH THE PAPER)

1 TR (Ton of Refrigeration) in kcal/hr

3024 kcal/hr

1 TR in kW

3.51 kW

1 TR in BTU/hr

12,000 BTU/hr

1 kW in kcal/hr

860 kcal/hr

1 kWh in kcal

860 kcal

1 BHP in kW

0.746 kW

Acceleration due to gravity, g

9.81 m/s²

Density and specific heat of water

1000 kg/m³ ; Cp = 1 kcal/kg °C

1 kg/cm² pressure as water head

10 m of water column

1 m³/min in cfm

35.31 cfm

Density of air at 0 °C (fans)

1.293 kg/m³

Molecular weight of air

28.92 kg/kg-mole

Maximum luminous efficacy

683 lm/W at 555 nm

Condenser water flow per TR

0.91 m³/hr per TR (4 gpm/TR)

Evaporation per 10,00,000 kcal heat rejected (cooling tower)

1.8 m³

DG exhaust gas: mass per kWh and Cp

8 kg/kWh ; 0.25 kcal/kg °C

Stray load loss of a motor (IS/IEC)

0.5 % of input power

Why 102 in fan efficiency formula

1000 ÷ 9.81 (converts m³/s × mmWC into kW)

Temperature in Kelvin

K = °C + 273

ECBC applies to buildings with

connected load ≥ 100 kW or contract demand ≥ 120 kVA

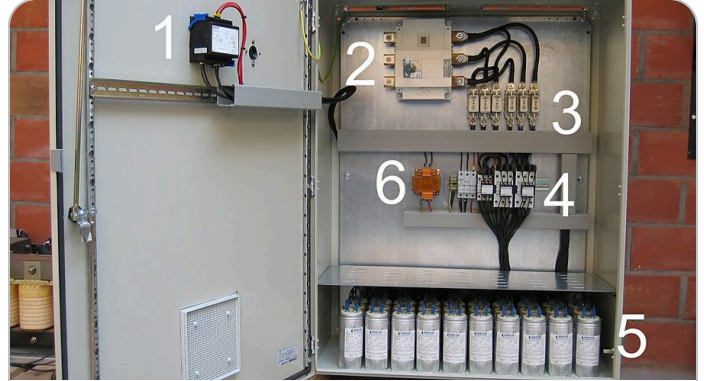
Chapter 1 · Electrical Systems

~23 marks (15 %) — the top chapter with HVAC. PF/kVAr, transformer losses at part load, maximum demand and AT&C losses come every year as numericals.



Distribution transformer — iron loss is constant, copper loss rises with load²

Photo: Cjp24 · CC BY-SA 4.0 · source



Power-factor correction panel: capacitor banks switched in steps by an automatic PF controller

Photo: Beuhri at Dutch Wikipedia · Public domain · source



Three-phase energy meter — records kWh, and kVA maximum demand over 30-minute windows

Photo: Gpkp · CC BY-SA 4.0 · source

Power factor

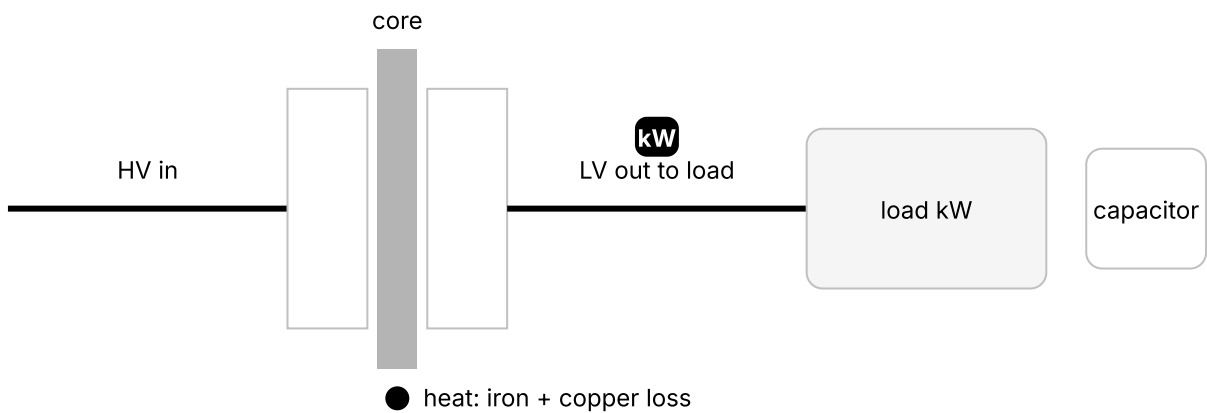
$$PF = \cos \phi = kW \div kVA$$

SYMBOLS · UNITS

Symbols kW = real power, kVA = apparent power

Answer unit no unit (0 to 1)

Book topic Power factor



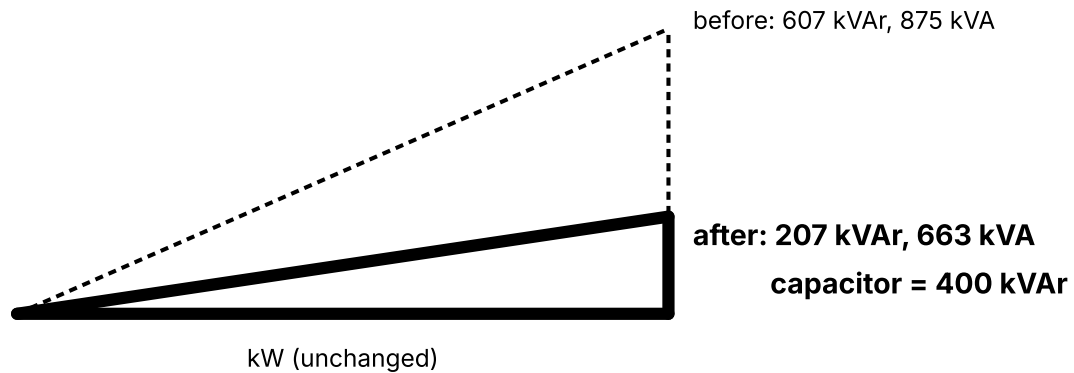
Where each value sits: **kW** → kVA, kVA, kW · **kVA** → kVA, kVA, kW

The diagram shows a power line with a transformer symbol at the top. Below the transformer, a power factor correction capacitor is connected in parallel with the load. Text labels indicate the power factor improvement: $P.F_{old} = 0.8$ and $P.F_{new} = 0.9$. A video player overlay is present at the bottom of the diagram.

► Video: How to Calculate Capacitor kVAR to Improve Power Factor | St

$P = 100 \text{ kW}$
 $P.F = 0.8$
 $Q = ? \text{ kVAR}$

► Try it: Power factor: add capacitor kVAR — watch the triangle shrink



$$630 \times (\tan \cos^{-1}0.72 - \tan \cos^{-1}0.95) = 630 \times (0.964 - 0.329) = \mathbf{400 \text{ kVAr}}$$

WHAT IT MEANS

The fraction of the current that does real work. PF = 1 means every ampere is useful; PF 0.7 means the cables and transformer carry 43 % more current than the work needs.

Worked example. kW 812, kVA 1,160 → PF = 0.70.

Exam trap. PF is a ratio, never a percentage of energy saved.

Apparent power, 3-phase

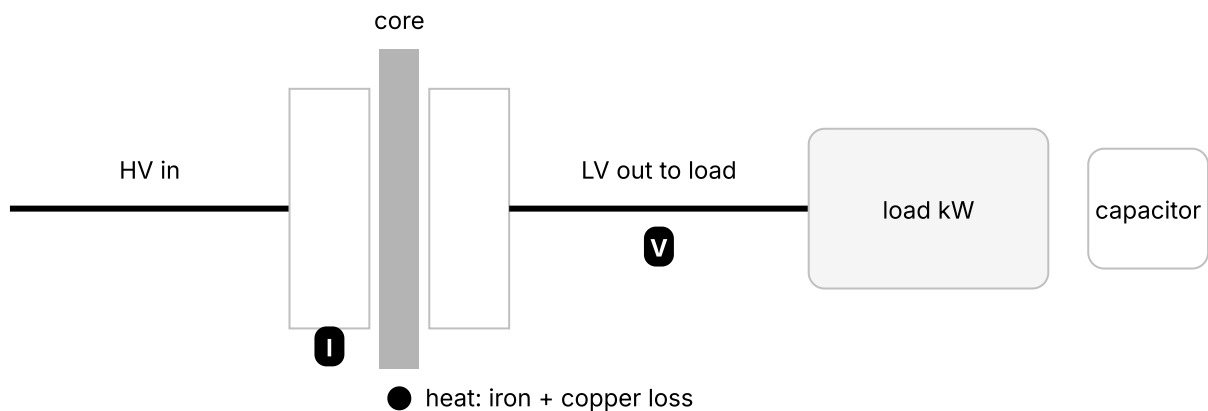
$$\text{kVA} = \sqrt{3} \times V \times I \div 1000$$

SYMBOLS · UNITS

Symbols V = line voltage (V), I = line current (A)

Answer unit **kVA**

Book topic Power triangle



Where each value sits: **V** → receiving-end E_r , $V \cdot I$ → copper / load loss $\propto \text{load}^2$

WHAT IT MEANS

What the supply actually has to deliver — the voltage times the current, before asking how much of it does work. Cables, switchgear and transformers are rated in kVA for this reason.

Worked example. 415 V, 100 A → $\sqrt{3} \times 415 \times 100 \div 1000 = 71.9$ kVA.

Exam trap. Use the line-to-line voltage (415 V), not 230 V, for 3-phase.

Real power, 3-phase

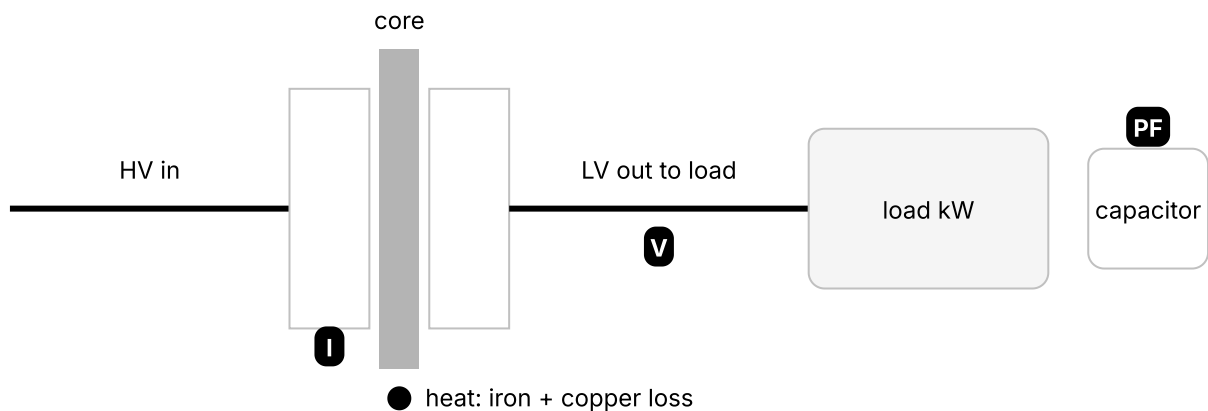
$$\text{kW} = \sqrt{3} \times V \times I \times \text{PF} \div 1000$$

SYMBOLS · UNITS

Symbols V (V), I (A), PF (no unit)

Answer unit kW

Book topic Power triangle



Where each value sits: **V** → receiving-end E_r , $V \cdot I$ → copper / load loss $\propto \text{load}^2$ · **PF** → kVAr, ϕ_1 , ϕ_2 , PF

WHAT IT MEANS

The power that turns into heat, motion or light — what the kWh meter records. It is the apparent power times the power factor.

Worked example. 415 V, 100 A, PF 0.8 → 57.5 kW.

Exam trap. If PF is not given, do not assume 1 — the question usually gives it.

Relation between kW, kVAr and kVA

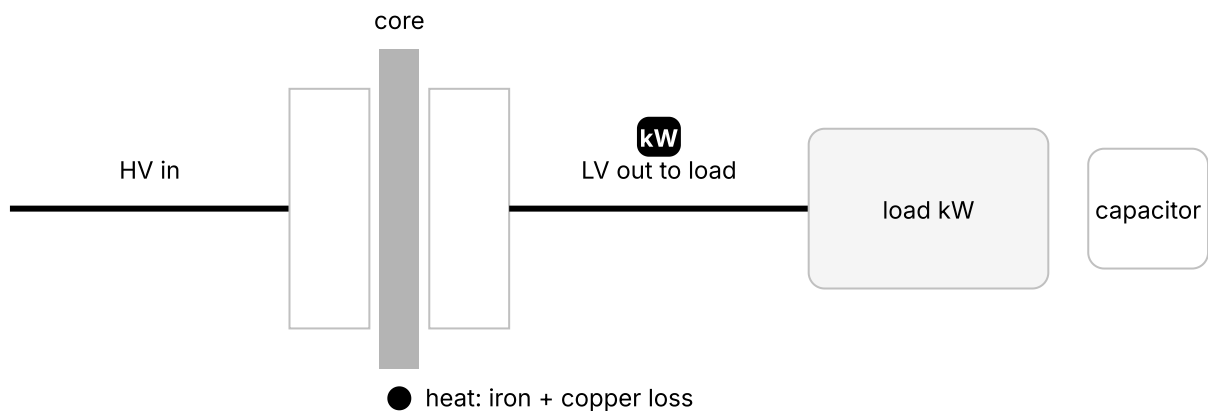
$$\text{kVA}^2 = \text{kW}^2 + \text{kVAr}^2$$

SYMBOLS · UNITS

Symbols kW, kVAr, kVA

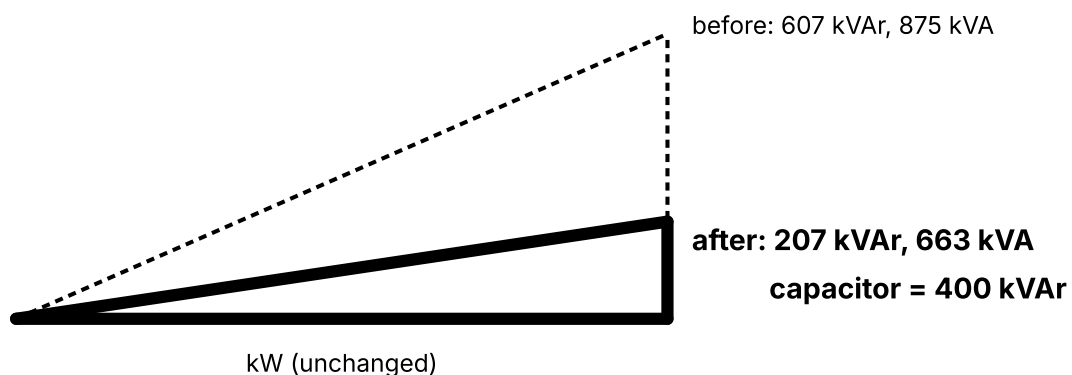
Answer unit **kVA**

Book topic Power triangle



Where each value sits: **kW** → kVA, kVAr, kW · **kVAr** → kVA, kVAr, kW · **kVA** → kVA, kVAr, kW

► Try it: Power factor: add capacitor kVAr — watch the triangle shrink



$$630 \times (\tan \cos^{-1} 0.72 - \tan \cos^{-1} 0.95) = 630 \times (0.964 - 0.329) = \mathbf{400 \text{ kVAr}}$$

WHAT IT MEANS

Pythagoras on the power triangle: kW along the base, kVAr up the side, kVA on the diagonal. Given any two you can find the third.

Worked example. kW 812, kVAr 828 $\rightarrow$ kVA = $\sqrt{(812^2 + 828^2)} = 1,160$.

Exam trap. kVA is NOT kW + kVAr — they add as a triangle, not in a straight line.

Capacitor rating to improve power factor

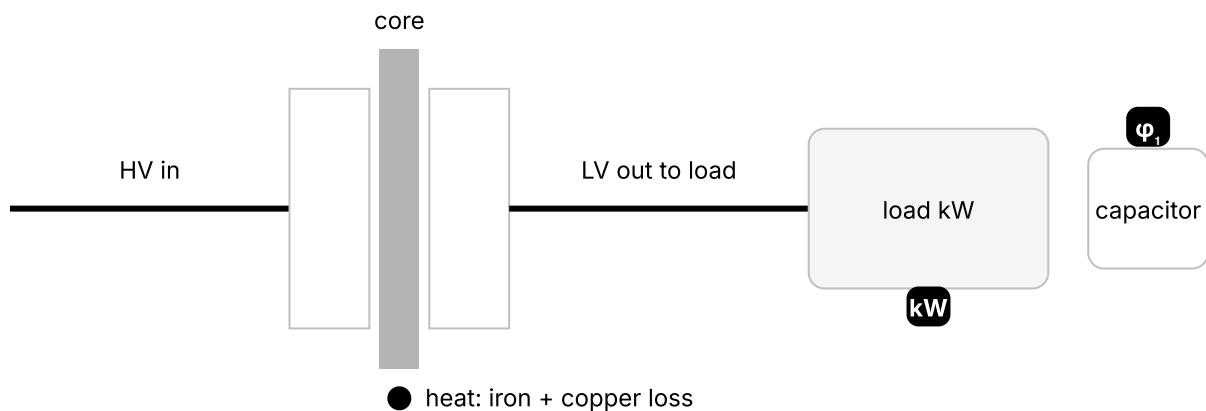
$$\text{kVAr} = \text{kW} \times (\tan \phi_1 - \tan \phi_2)$$

SYMBOLS · UNITS

Symbols kW = average operating load; $\phi_1 = \cos^{-1}$ (existing PF); $\phi_2 = \cos^{-1}$ (improved PF)

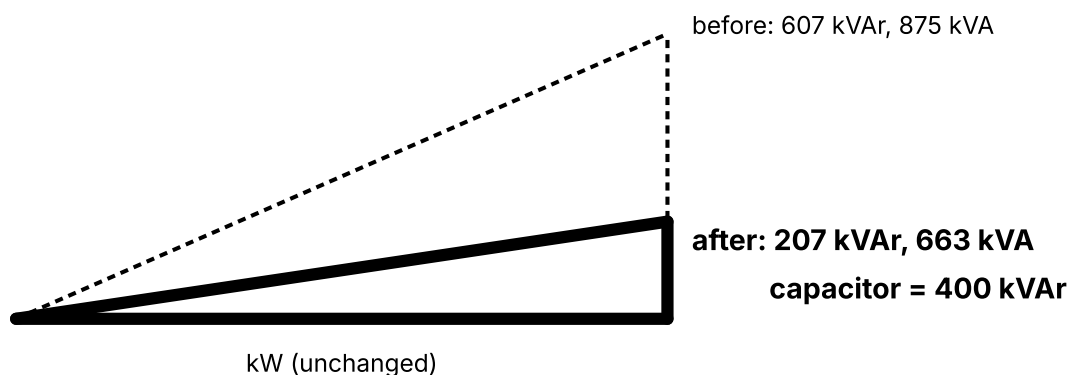
Answer unit kVAr

Book topic PF correction



Where each value sits: **kW** → % load, kVA, kW · **φ₁** → kVAr, φ₁, φ₂, PF · **φ₂** → kVAr, φ₁, φ₂, PF

► Try it: Power factor: add capacitor kVAr — watch the triangle shrink



$$630 \times (\tan \cos^{-1}0.72 - \tan \cos^{-1}0.95) = 630 \times (0.964 - 0.329) = \mathbf{400 \text{ kVAr}}$$

WHAT IT MEANS

How many kVAr of capacitors to add so the existing kW load reaches the target PF. Convert each PF to its angle ($\phi = \cos^{-1}$ PF), take the tangents, multiply the difference

by the kW.

Worked example. 627 kW from PF 0.72 (tan 0.964) to 0.95 (tan 0.329): $627 \times 0.635 = 398$ kVAr (the book's example). Useful tangents: 0.7→1.02, 0.8→0.75, 0.85→0.62, 0.9→0.48, 0.95→0.33, 1→0.

Exam trap. Multiply the OPERATING kW (average load), not the kVA and not the nameplate. A capacitor's kVAr output falls with the square of the voltage: at 400 V a 415 V unit gives $(400/415)^2 = 93\%$.

Line (copper) loss

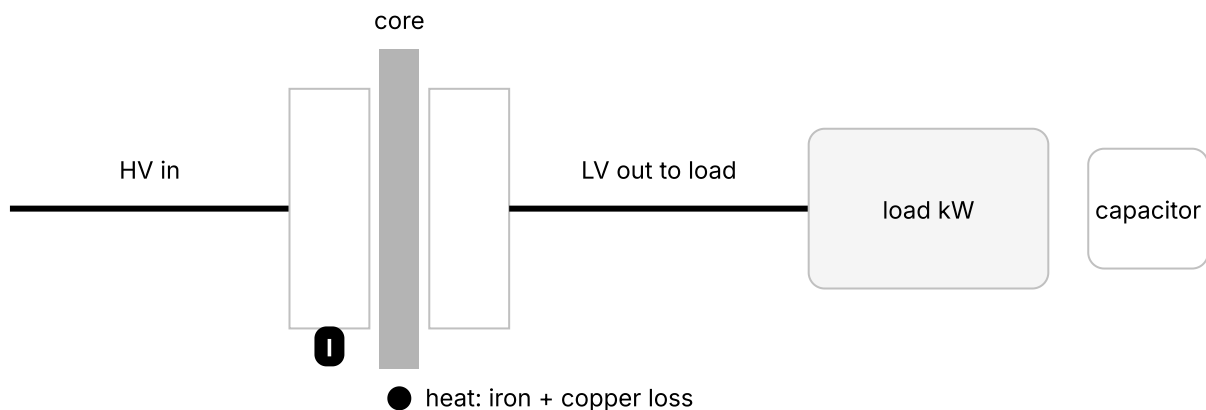
$$P = I^2 \times R$$

SYMBOLS · UNITS

Symbols I = current (A), R = resistance (Ω)

Answer unit **W**

Book topic Distribution losses



Where each value sits: $I \rightarrow$ copper / load loss $\propto \text{load}^2$ · $R \rightarrow$ copper / load loss $\propto \text{load}^2$

WHAT IT MEANS

Heat wasted in a conductor. Because it depends on the SQUARE of the current, halving the current (by raising voltage or improving PF) cuts the loss to a quarter.

Worked example. 100 A through $0.1\ \Omega \rightarrow 1,000$ W; at 50 A $\rightarrow 250$ W.

Exam trap. Loss $\propto I^2$, not $\propto I$.

% reduction in distribution loss when tail-end PF is raised

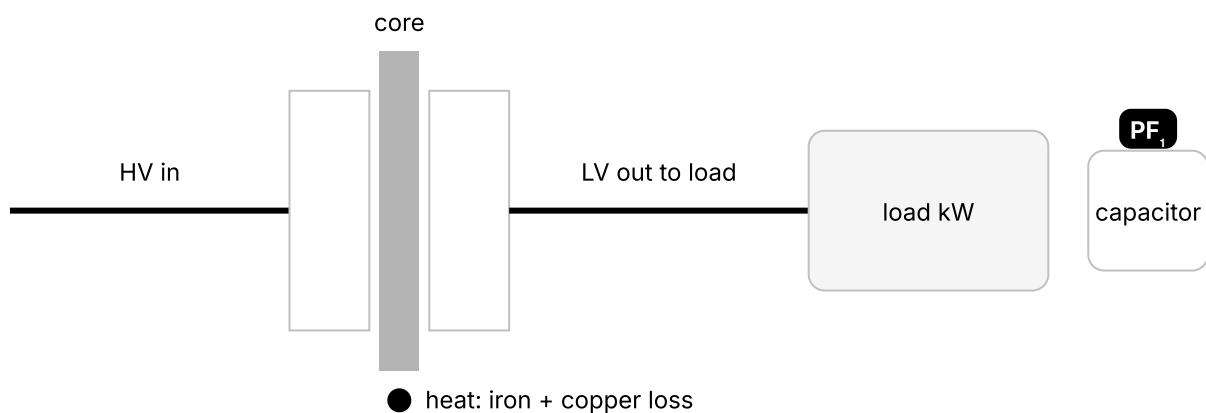
$$[1 - (PF_1 \div PF_2)^2] \times 100$$

SYMBOLS · UNITS

Symbols PF_1 = existing PF, PF_2 = improved PF

Answer unit %

Book topic Location of capacitors



Where each value sits: **PF₁** → kVAr, ϕ_1 , ϕ_2 , PF · **PF₂** → kVAr, ϕ_1 , ϕ_2 , PF

WHAT IT MEANS

Raising the PF at the load end lowers the current for the same kW, so the I^2R loss in the upstream cables falls by $1 - (\text{old PF} \div \text{new PF})^2$.

Worked example. $0.85 \rightarrow 0.95$: $1 - (0.85/0.95)^2 = 1 - 0.80 = 19.9\%$. $0.8 \rightarrow 0.95$: 29 % (2016/2017 objective).

Exam trap. Ratio old $\div$ new, then SQUARE it — then subtract from 1.

Maximum demand registered by MD meter

$$MD = \Sigma(kVA \times \text{minutes}) \div \text{demand interval (30 min)}$$

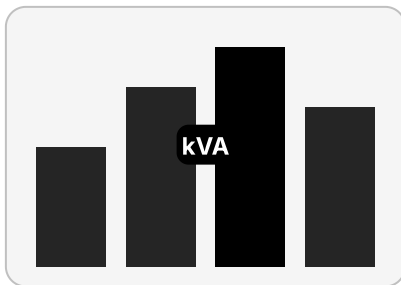
SYMBOLS · UNITS

Symbols kVA of each period; duration in minutes

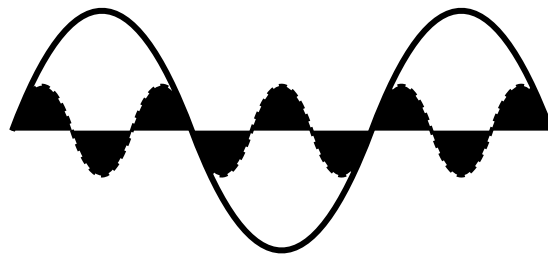
Answer unit kVA

Book topic Maximum demand

MD meter — 30-minute windows



kVA per interval



fundamental 50 Hz + harmonics

Where each value sits: **kVA** → kVA × minutes / 30-min interval · **duration** → kVA × minutes / 30-min interval

WHAT IT MEANS

The meter averages kVA over each 30-minute window and remembers the highest window of the month. You pay demand charges on that peak even if it happened once.

Worked example. $(2,500 \times 4 + 3,600 \times 12 + 4,100 \times 6 + 3,800 \times 8) \div 30 = 3,607$ kVA.

Exam trap. It is the average over the interval, not the instantaneous peak.

Transformer loss at any load (from % load)

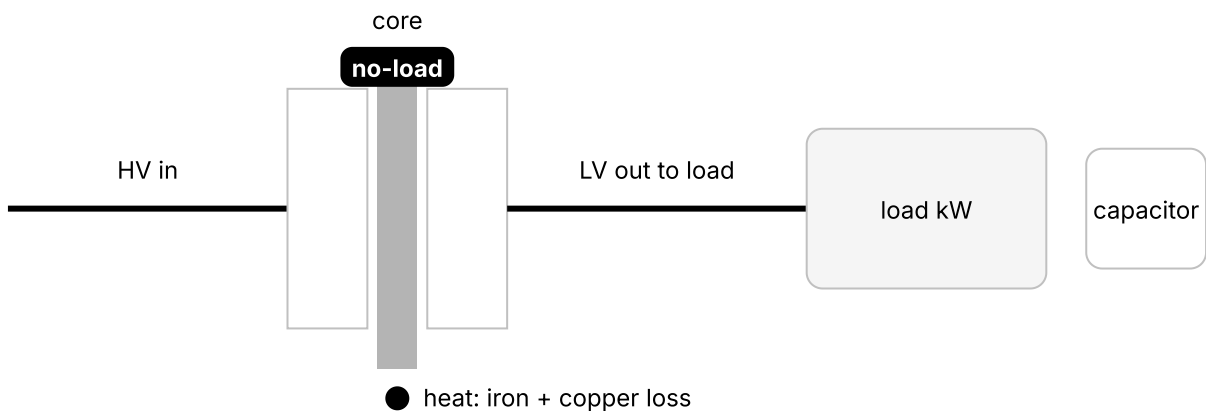
$$P = P_{\text{no-load}} + (\% \text{ load} \div 100)^2 \times P_{\text{full-load load loss}}$$

SYMBOLS · UNITS

Symbols no-load (iron) loss and full-load copper loss in kW or W

Answer unit kW (or W)

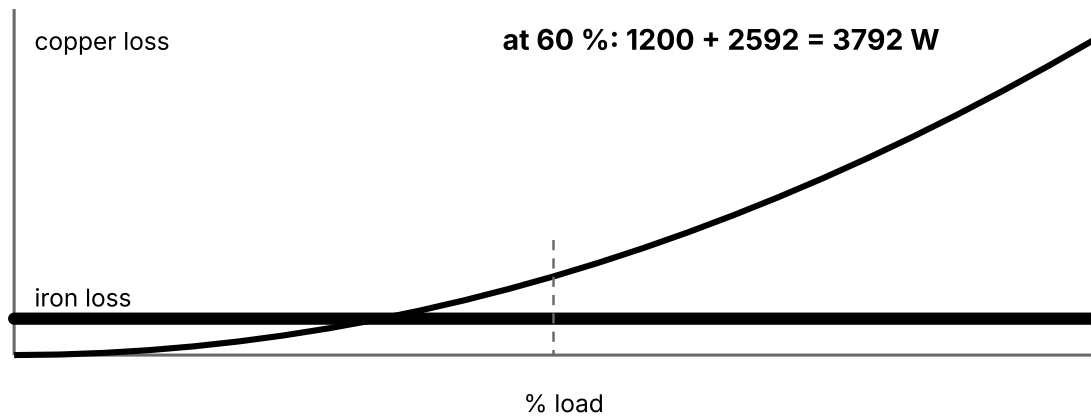
Book topic Transformer losses



Where each value sits: **no-load** → iron / no-load loss (constant)



► Try it: Transformer: load it up — iron loss stays flat, copper loss grows with load²



$$P = 1200 + (60/100)^2 \times 7200 = 1200 + 2592 = \mathbf{3792 \text{ W}}$$

WHAT IT MEANS

Iron (no-load) loss is constant whenever the transformer is energised; copper (load) loss rises with the SQUARE of the load. Efficiency is highest where the two are equal.

Worked example. 750 kVA, 1,200 W no-load, 7,200 W full-load Cu, at 60 %: $1,200 + 0.36 \times 7,200 = 3,792 \text{ W}$ (2025 Q7).

Exam trap. At 60 % load the copper loss is $0.36 \times$ full-load, never $0.6 \times$.

Transformer loss at any load (from kVA)

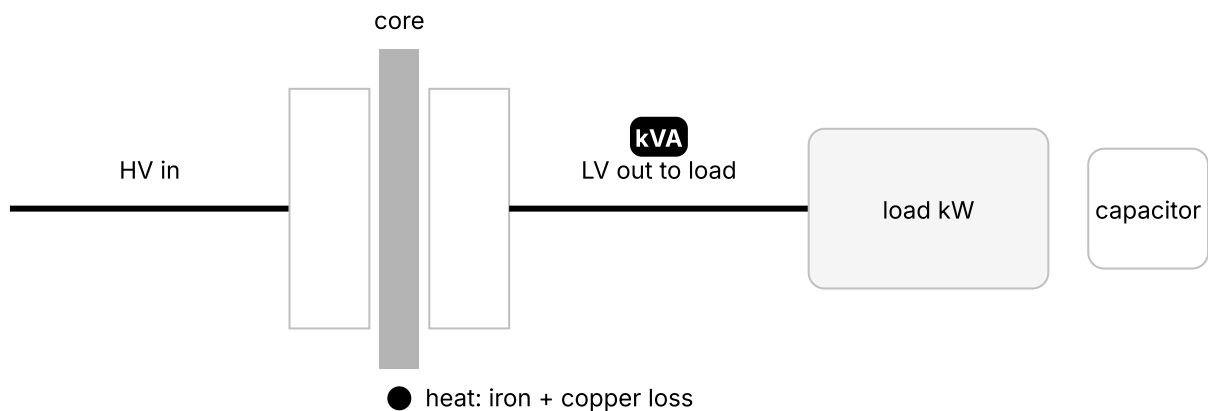
$$= \text{No-load loss} + (\text{actual kVA} \div \text{rated kVA})^2 \times \text{Full-load loss}$$

SYMBOLS · UNITS

Symbols kVA; losses in kW or W

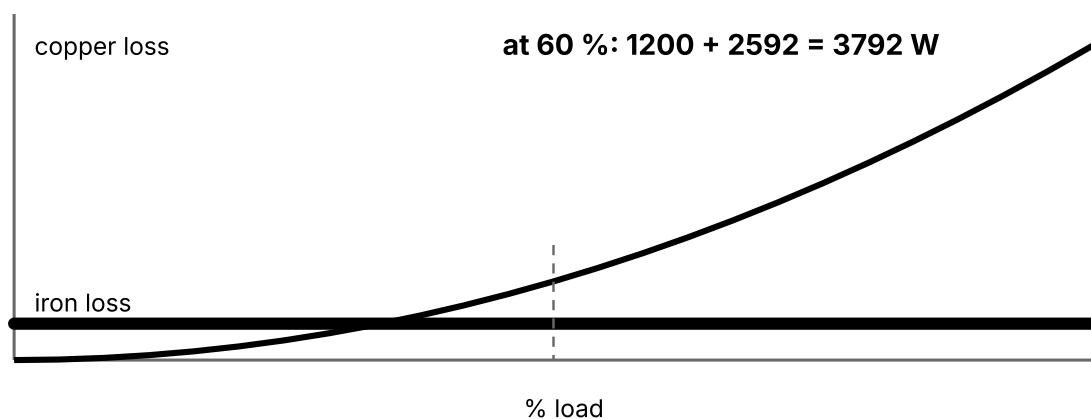
Answer unit kW (or W)

Book topic Transformer losses



Where each value sits: **kVA** → kVA, kVA_r, kW · **losses** → kVA, kVA_r, kW

► Try it: Transformer: load it up — iron loss stays flat, copper loss grows with load²



$$P = 1200 + (60/100)^2 \times 7200 = 1200 + 2592 = \mathbf{3792\ W}$$

WHAT IT MEANS

Same idea using the actual kVA carried: the load fraction is actual ÷ rated kVA.

Worked example. Rated 1,000 kVA carrying 500 kVA → fraction 0.5 → Cu loss = 0.25 × full-load Cu loss.

Exam trap. Load fraction from kVA, not from kW.

Voltage regulation

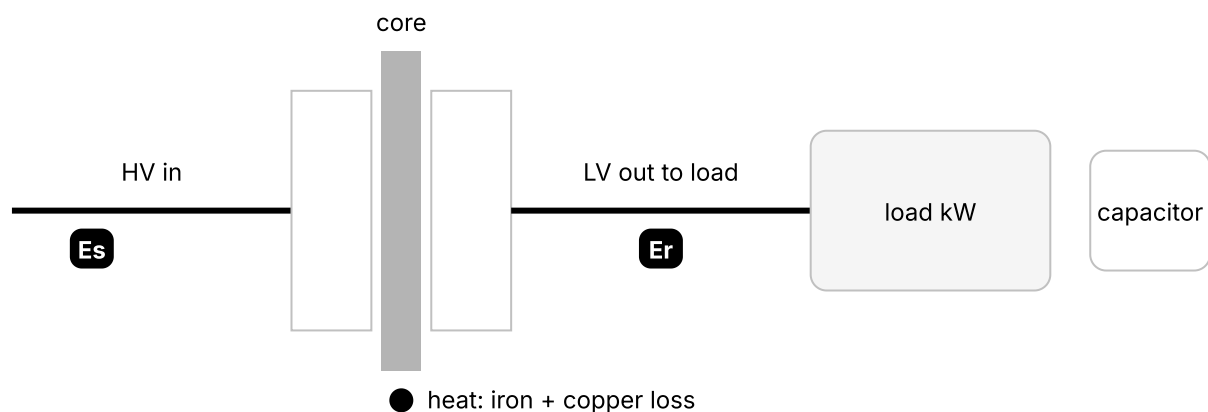
$$\% \text{ Regulation} = (E_s - E_r) \div E_r \times 100$$

SYMBOLS · UNITS

Symbols E_s = sending-end voltage, E_r = receiving-end voltage (V)

Answer unit %

Book topic Voltage regulation



Where each value sits: **E_s** → sending-end E_s · **E_r** → receiving-end E_r , V

WHAT IT MEANS

How much the voltage drops between the sending and receiving end under load, as a percentage of the receiving-end voltage; big drops mean long or overloaded lines.

Worked example. E_s 11.5 kV, E_r 11.0 → 4.5 %.

Exam trap. Divide by the RECEIVING end voltage (book formula).

Input energy of a distribution area

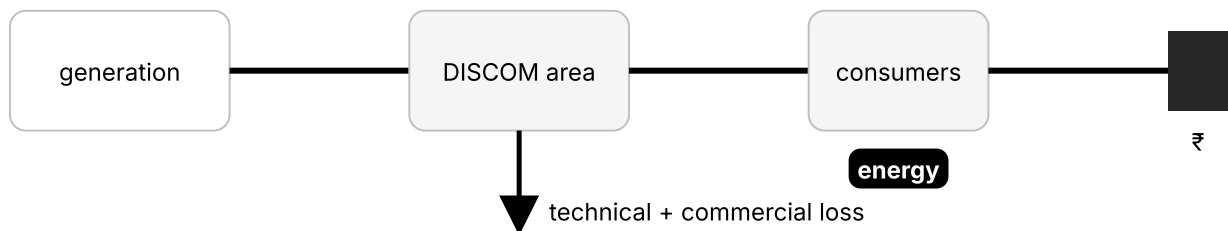
$$E_i = \text{Import} - \text{Export}$$

SYMBOLS · UNITS

Symbols energy in MU (million units)

Answer unit **MU**

Book topic AT&C losses



Where each value sits: **energy** → energy needed at end use

WHAT IT MEANS

The energy a DISCOM area actually receives to sell: what it imports minus what it exports to neighbouring areas.

Worked example. Import 12 MU, export 2 MU → 10 MU.

Exam trap. Measured in million units (MU = 10⁶ kWh).

Billing efficiency

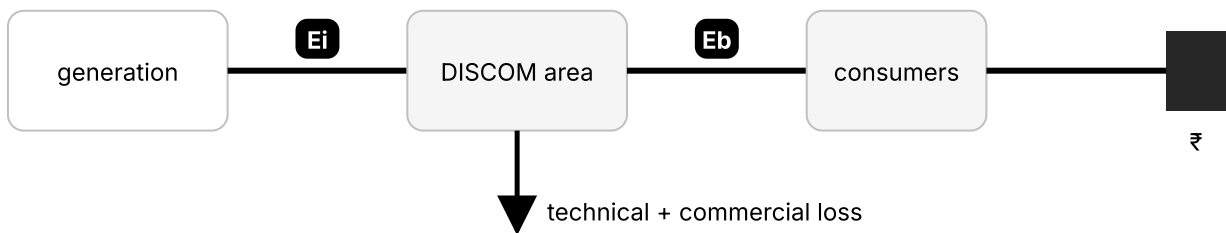
$$BE = E_b \div E_i \times 100$$

SYMBOLS · UNITS

Symbols E_b = total energy billed (MU), E_i = input energy (MU)

Answer unit %

Book topic AT&C losses



Where each value sits: **E_b** → energy billed **E_i** → input energy E_i (import – export)

WHAT IT MEANS

Share of the input energy that was actually billed to consumers (metered + un-metered). The rest is technical loss plus theft/unbilled use.

Worked example. Billed 7 MU of 10 MU input → 70 % (book Table 1.7).

Exam trap. Include un-metered billed energy (flat-rate agricultural) in the billed figure.

Amount collected without arrears

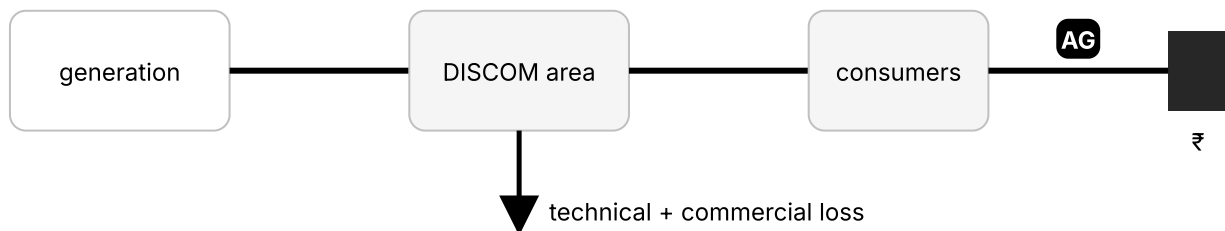
$$Ac = AG - Ar$$

SYMBOLS · UNITS

Symbols AG = gross amount collected, Ar = arrears collected (Rs)

Answer unit Rs

Book topic AT&C losses



Where each value sits: **AG** → amount billed Ab, collected AG, arrears Ar · **Ar** → amount billed Ab, collected AG, arrears Ar

WHAT IT MEANS

Money collected for THIS year's bills only — arrears belong to earlier years and would inflate the collection efficiency.

Worked example. Gross collected 410 lakh, arrears 40 → 370 lakh.

Exam trap. If arrears are not given, assume $Ar = AG - Ab$ (book note).

Collection efficiency

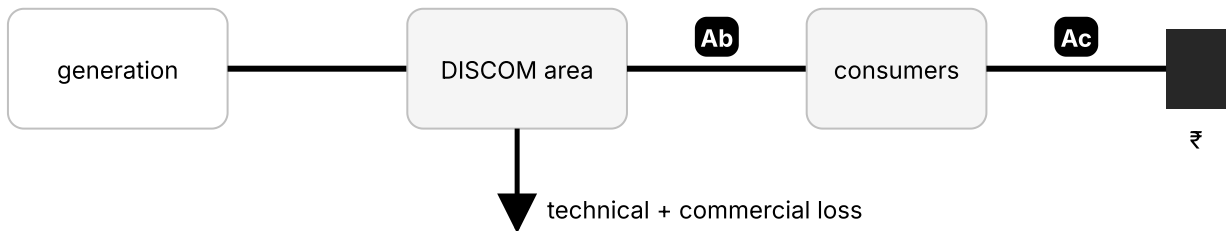
$$CE = Ac \div Ab \times 100$$

SYMBOLS · UNITS

Symbols Ac = amount collected without arrears, Ab = amount billed (Rs)

Answer unit %

Book topic AT&C losses



Where each value sits: **Ac** → amount billed Ab , collected AG , arrears Ar · **Ab** → energy billed Eb

WHAT IT MEANS

Share of the amount billed that was actually paid (this year's bills).

Worked example. $370 \div 400 = 92.5 \% \approx 93 \%$.

Exam trap. Money ratio, not energy.

AT&C (Aggregate Technical & Commercial) loss

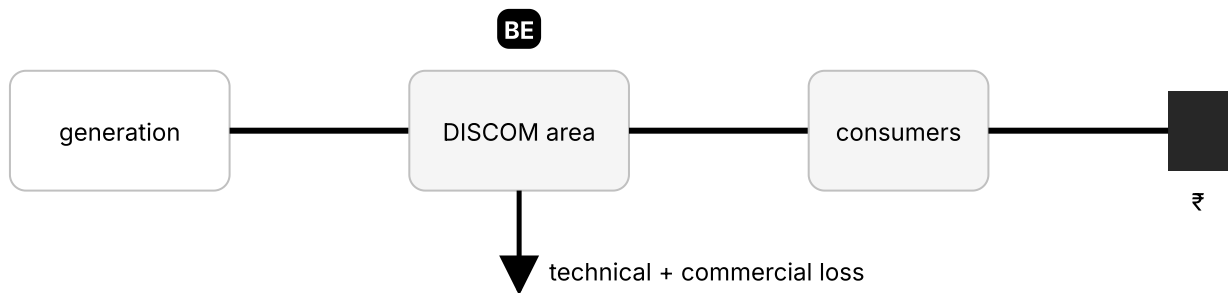
$$\text{AT\&C} = [1 - (\text{BE} \times \text{CE})] \times 100$$

SYMBOLS · UNITS

Symbols BE and CE as fractions

Answer unit %

Book topic AT&C losses



Where each value sits: **BE** → billing efficiency BE

WHAT IT MEANS

The DISCOM's total loss: energy lost technically AND commercially (not billed, not collected) as one number — 1 minus the product of the two efficiencies.

Worked example. BE 0.70 × CE 0.93 = 0.651 → AT&C = 34.9 % ≈ 35 % (book). 2025 S-2 asks exactly this chain.

Exam trap. Multiply the two efficiencies as FRACTIONS, then subtract from 1; do not add the two losses.

Total harmonic distortion of current

$$\text{THD} = \sqrt{(I_3^2 + I_5^2 + I_7^2 + \dots)} \div I_1 \times 100$$

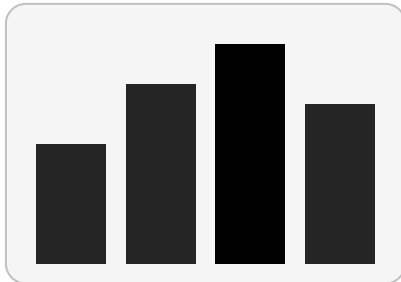
SYMBOLS · UNITS

Symbols I_1 = fundamental current (A); $I_3, I_5, \dots$ = harmonic currents (A)

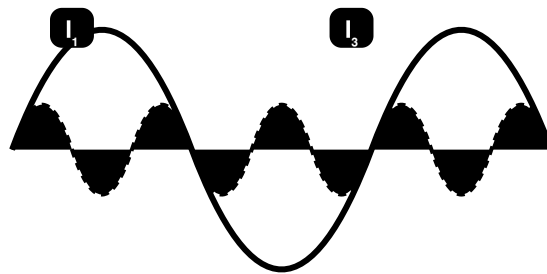
Answer unit %

Book topic Harmonics

MD meter — 30-minute windows



kVA per interval



fundamental 50 Hz + harmonics

Where each value sits: $I_1 \rightarrow I_1$ fundamental · $I_3 \rightarrow I_3, I_5, I_7$ harmonics · $I_5 \dots \rightarrow I_3, I_5, I_7$ harmonics

WHAT IT MEANS

How much the current waveform is polluted by frequencies at multiples of 50 Hz (from VFDs, UPS, rectifiers, CFLs). Root-sum-square of the harmonic currents divided by the fundamental.

Worked example. I_1 250 A, I_3 50, I_5 35 $\rightarrow \sqrt{(2,500 + 1,225)} \div 250 = 24.4\%$ (book example).

Exam trap. Square, add, then root — never a plain sum of the harmonic percentages. Resistive loads (heaters) create no harmonics.

Overall efficiency of an energy chain

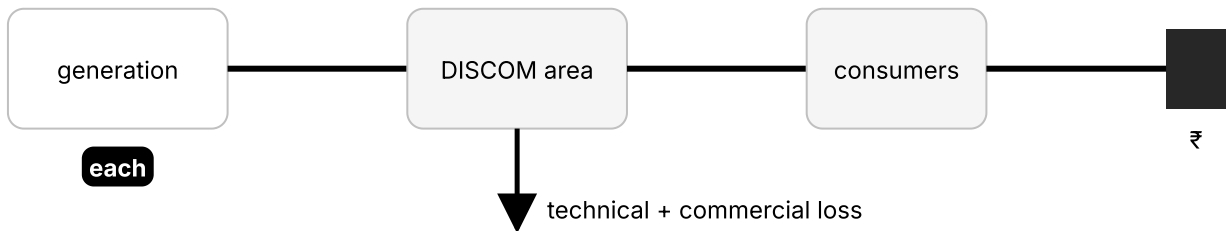
$$\eta_{\text{overall}} = \eta_1 \times \eta_2 \times \eta_3 \times \dots$$

SYMBOLS · UNITS

Symbols each efficiency as a fraction

Answer unit % (or fraction)

Book topic 1 unit saved = 2 units generated



Where each value sits: **each** $\rightarrow \eta_1 \times \eta_2 \times \eta_3$

WHAT IT MEANS

Efficiencies in series multiply. From power station to the motor shaft the book's chain is $0.83 \text{ (generation \& T\&D)} \times 0.95 \times 0.9 \times 0.7 \approx 0.50$.

Worked example. Four stages at 83 %, 95 %, 90 %, 70 % $\rightarrow$ 50 %.

Exam trap. Multiply, do not average.

Energy to be generated for a given end use

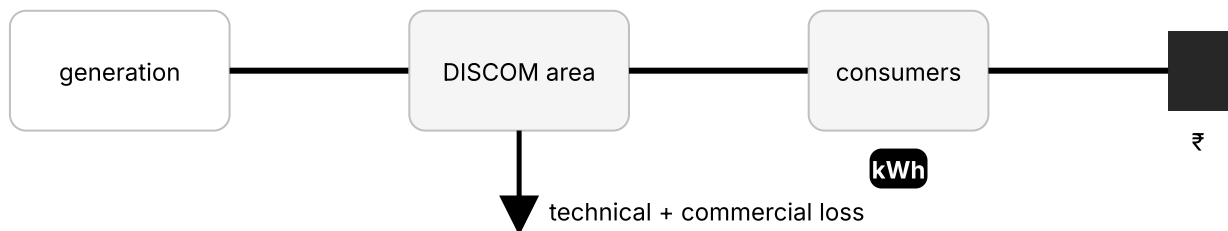
$$= \text{Energy needed at end use} \div \eta_{\text{overall}}$$

SYMBOLS · UNITS

Symbols kWh; η as fraction

Answer unit kWh

Book topic 1 unit saved = 2 units generated



Where each value sits: **kWh** → energy needed at end use · η : η as fraction

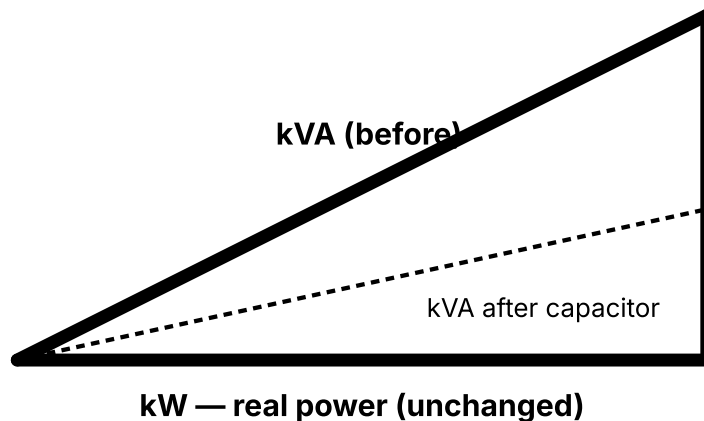
WHAT IT MEANS

Because the chain is only ~50 % efficient, every unit saved at the end use saves about two units at the power station — 'one unit saved = two units generated'.

Worked example. 1 kWh saved at the shaft $\div 0.5 = 2$ kWh of generation avoided.

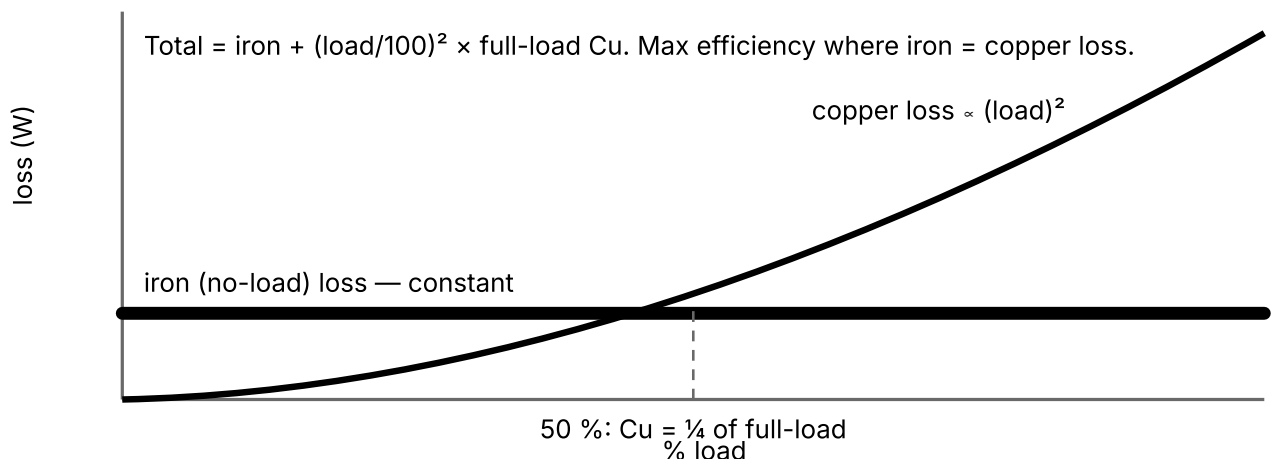
Exam trap. Divide by the efficiency, never multiply.

Power triangle — what a capacitor does



$kVAR = kW (\tan \phi_1 - \tan \phi_2)$
capacitor supplies the
magnetising kVAR locally →
kVA and current fall,
 $PF = kW \div kVA$ rises

Transformer losses vs load



DEFINITIONS THE EXAM ASKS

Maximum demand and load factor

MD is the highest 30-minute average kVA in the month; load factor = average load $\div$ maximum demand. Improving load factor (shifting loads off-peak) cuts demand charges.

TOD tariff

Time-of-day tariff charges more in peak hours and less off-peak, to encourage shifting load.

Harmonics

Currents at multiples of 50 Hz from non-linear loads (VFDs, UPS, rectifiers, CFLs); they heat transformers, trip breakers and distort voltage. Resistive heaters and incandescent lamps create

none.

Automatic PF controller

Switches capacitor steps in and out to hold the target PF as load changes; capacitors at the load end also cut cable losses.

DSM

Demand-side management: the utility shapes customer load — peak clipping, valley filling, load shifting, strategic conservation.

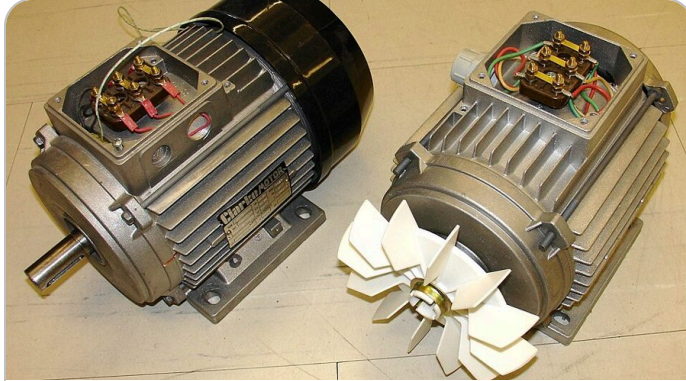
VERIFIED VIDEOS FOR THIS CHAPTER (YOUTUBE)

Power Factor & Capacitor Sizing — How to Calculate Capacitor kVAR to Improve Power Factor | Step-by-Step Guide · Ahmed Hassanin Academy

Transformer Core/Copper Losses — How to Calculate Transformer Efficiency | Core Losses Explained · Kognito Key

Chapter 2 • Electric Motors

~10 marks: many easy objectives (losses, speed, slip, IE classes) plus the loading and replacement-saving numericals.



Squirrel-cage induction motors with the rotor and cooling fan removed

Photo: Zureks · CC BY-SA 3.0 · [source](#)



Variable-frequency drive — changes motor speed by changing supply frequency ($N_s = 120f/P$)

Photo: Suyash.dwivedi · CC BY-SA 4.0 · [source](#)

Synchronous speed

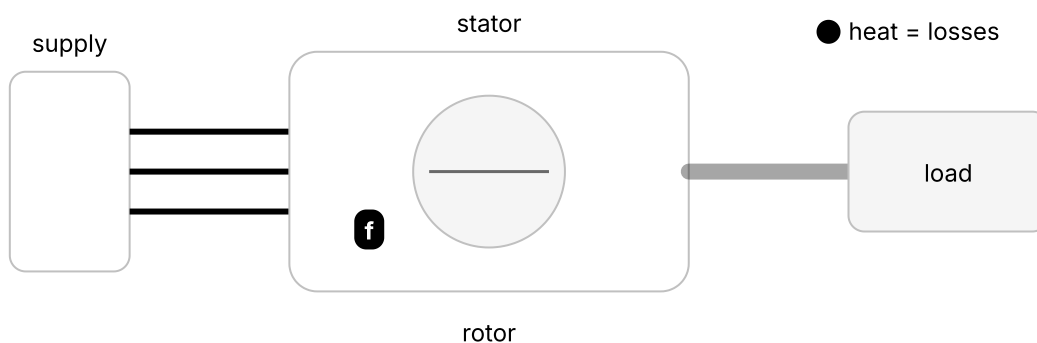
$$N_s = 120 \times f \div P$$

SYMBOLS · UNITS

Symbols f = supply frequency (Hz), P = number of poles

Answer unit rpm

Book topic Motor speed



Where each value sits: **f** → synchronous speed N_s , poles P · **P** → synchronous speed N_s , poles P

First we need to determine the slip, s :

$$s = \frac{n_{sync} - n_m}{n_{sync}}$$

$$= \frac{\left(\frac{120 \times 50}{6}\right) - 960}{\left(\frac{120 \times 50}{6}\right)}$$

$$= 0.04$$

$$n_{sync} = \frac{120}{P} \times f$$

Then R_2/s :

► Video: Tutorial on how to calculate the efficiency of an induction

$$\frac{R_2}{s} = \frac{0.26}{0.04}$$

WHAT IT MEANS

The speed of the rotating magnetic field; the rotor can never quite reach it. Indian 50 Hz speeds: 3,000 / 1,500 / 1,000 / 750 / 600 / 500 rpm for 2 / 4 / 6 / 8 / 10 / 12 poles.

Worked example. 4 poles: $120 \times 50 \div 4 = 1,500$ rpm.

Exam trap. More poles = slower; poles are always an even number.

Slip

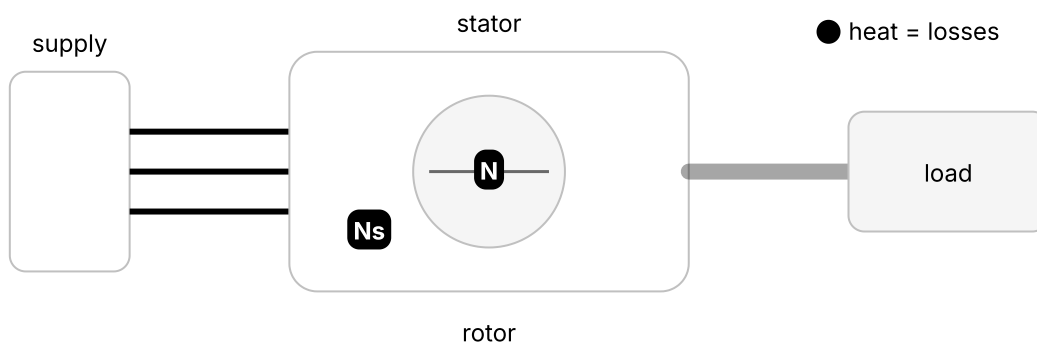
$$\text{Slip \%} = (N_s - N) \div N_s \times 100$$

SYMBOLS · UNITS

Symbols N_s = synchronous speed, N = actual full-load speed (rpm)

Answer unit %

Book topic Motor speed



Where each value sits: **N_s** → synchronous speed N_s , poles P · **N** → rotor speed N , slip

WHAT IT MEANS

How far the rotor lags the field, as a percentage. Full-load slip of a good motor is 2–5 %; slip rises with load and with poor rotor design (rewinding damage).

Worked example. N_s 1,500, N 1,470 → 2 %.

Exam trap. Slip is measured at the rated (full-load) speed on the nameplate.

Motor power factor

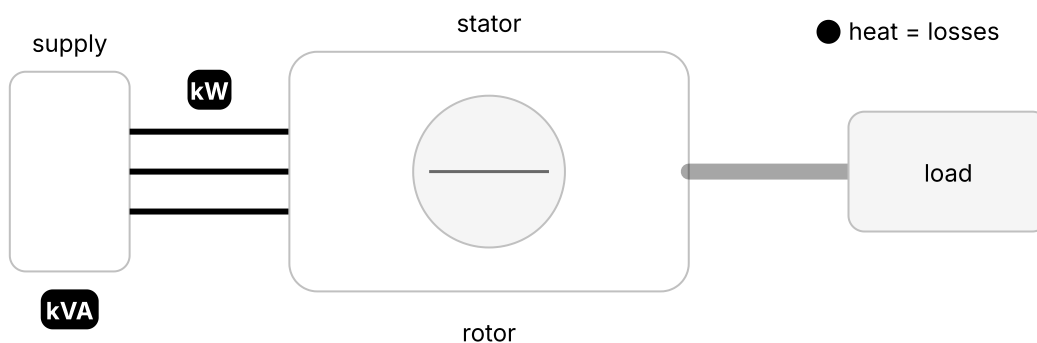
$$PF = \cos \phi = kW \div kVA$$

SYMBOLS · UNITS

Symbols kW, kVA

Answer unit no unit

Book topic Power factor



Where each value sits: **kW** → input kW · **kVA** → V, I, cos ϕ , f

WHAT IT MEANS

As load falls the working current drops but the magnetising current does not, so PF collapses at light load — lightly loaded motors are the main cause of poor plant PF.

Worked example. Full load PF 0.85; at 25 % load perhaps 0.5.

Exam trap. Low PF at light load is normal, not a fault.

Motor efficiency

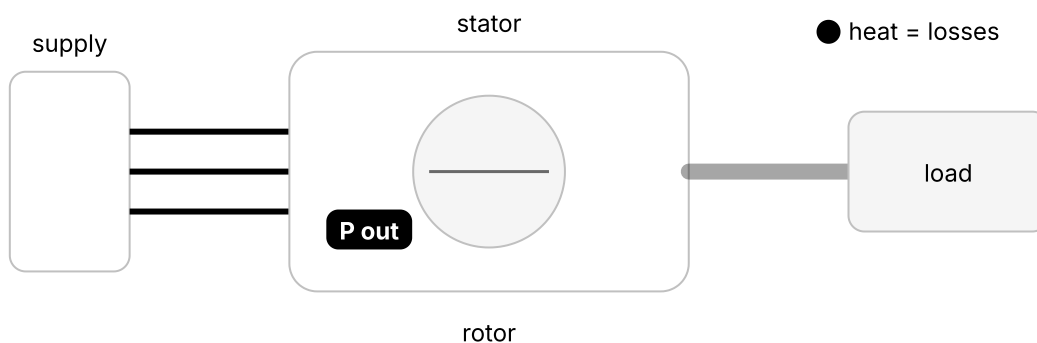
$$\eta = P_{\text{out}} \div P_{\text{in}} = 1 - (P_{\text{loss}} \div P_{\text{in}})$$

SYMBOLS · UNITS

Symbols P_{out} = output, P_{in} = input, P_{loss} = losses (kW)

Answer unit % (or fraction)

Book topic Motor efficiency



Where each value sits: **P out** → synchronous speed N_s , poles P · **P in** → synchronous speed N_s , poles P · **P loss** → synchronous speed N_s , poles P

WHAT IT MEANS

Output at the shaft divided by electrical input; the difference is heat (I^2R in stator and rotor, core, friction & windage, stray). Efficiency is flat from 50–100 % load and falls steeply below 40 %.

Worked example. Input 61.5 kW, output 55 kW → 89.4 % (2023 S-4).

Exam trap. Efficiency is output ÷ input, never input ÷ output.

Input power of a 3-phase motor

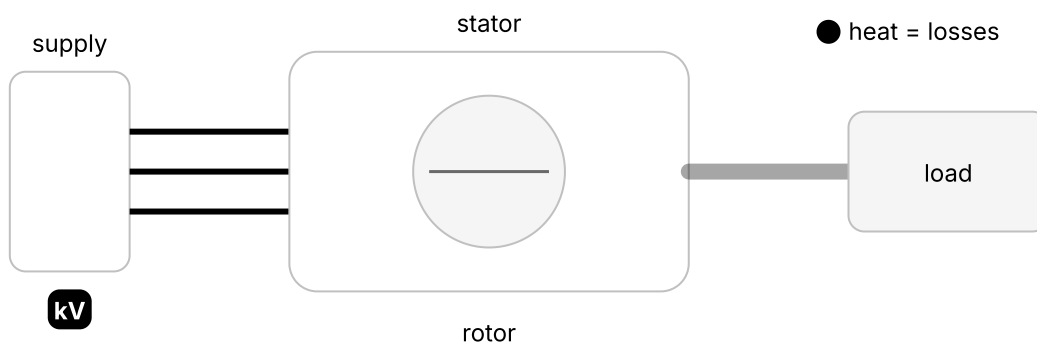
$$P = \sqrt{3} \times kV \times I \times \cos \phi$$

SYMBOLS · UNITS

Symbols kV = line voltage (kV), I = current (A)

Answer unit **kW**

Book topic Motor loading



Where each value sits: **kV** → V, I, cos φ, f · **I** → V, I, cos φ, f

► Try it: Motor: measured volts, amps and PF → loading %



loading = 69 %

input 42.6 kW vs full-load input 61.5 kW

$$\sqrt{3} \times 410 \times 75 \times 0.8 \div 1000 = 42.6 \text{ kW}; \text{ rated input} = 55 \div 0.895 = 61.5 \text{ kW} \rightarrow \text{loading } 69 \%$$

WHAT IT MEANS

The electrical power the motor is drawing right now, from measured volts, amps and PF.

Worked example. 410 V, 75 A, PF 0.8 → $1.732 \times 0.410 \times 75 \times 0.8 = 42.6 \text{ kW}$ (2023).

Exam trap. Voltage in kV in this form of the formula.

Friction & windage + core loss (no-load test)

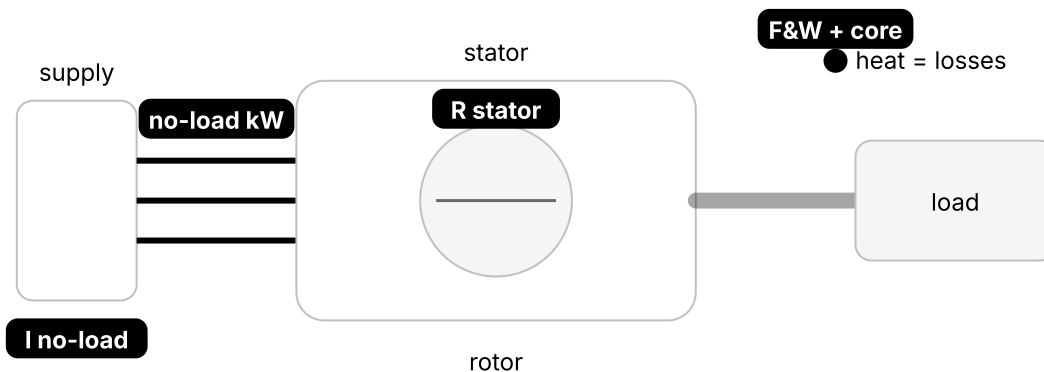
$$= \text{No-load input power} - (\text{No-load current})^2 \times \text{Stator resistance}$$

SYMBOLS · UNITS

Symbols W, A, Ω

Answer unit **W**

Book topic Field tests



Where each value sits: **no-load kW** → input kW · **I no-load** → V, I, $\cos \phi$, f · **R stator** → stator I^2R , resistance R · **F&W + core** → losses, F&W, core, stray

WHAT IT MEANS

Run the motor unloaded: nearly all the input is core loss plus bearing/fan (friction & windage) loss, after subtracting the small stator I^2R at no-load current.

Worked example. No-load 1,064 W, no-load current 10 A, R 0.5 Ω → $1,064 - 100 \times 0.5 = 1,014$ W.

Exam trap. Subtract the stator I^2R at NO-LOAD current, using the per-phase resistance as the book does.

Stator resistance corrected to operating temperature

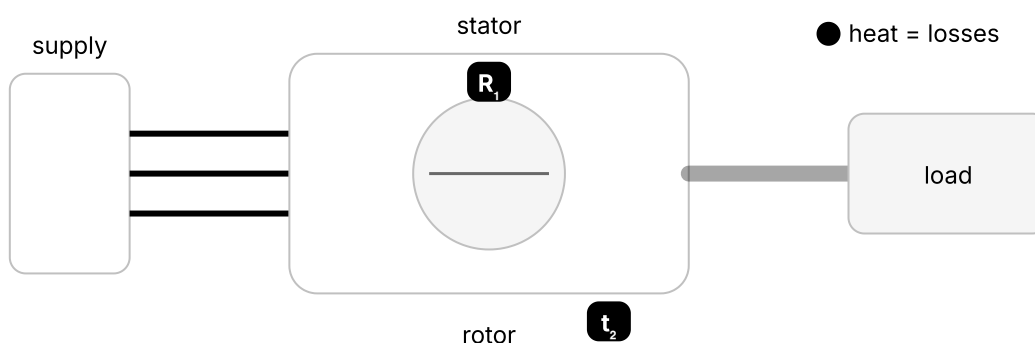
$$R_2 = R_1 \times (235 + t_2) \div (235 + t_1)$$

SYMBOLS · UNITS

Symbols R_1 = resistance at ambient t_1 (°C); t_2 = operating temperature (°C)

Answer unit Ω

Book topic Field tests



Where each value sits: $R_1 \rightarrow$ stator I^2R , resistance R · $t_2 \rightarrow$ temperature t_1, t_2

GUIDING EQUATIONS : THREE PHASE INDUCTION MOTORS

Synchronous speed, $N_s = \frac{120 f}{P}$ — Supply frequency
 Slip speed = $N_s - N_r$ — Rotor speed
 Slip, $s = \frac{N_s - N_r}{N_s}$

Rotor frequency, $f_r = \frac{P}{2\pi} \times \text{relative speed}$

► Video: Simple problems on 3-phase induction motors: Slip, Rotor Fre

The diagram shows a three-phase induction motor with a stator and a rotor. The stator has four poles labeled N, S, N, S. The rotor has four poles labeled N, S, N, S. The slip is indicated as 's'.

WHAT IT MEANS

Copper resistance rises with temperature; the resistance measured cold must be scaled to the running temperature (100–120 °C for modern motors) before calculating I^2R loss.

Worked example. R at 30 °C = 0.5 $\Omega \rightarrow$ at 120 °C: $0.5 \times (235 + 120)/(235 + 30) = 0.67 \Omega$.

Exam trap. The constant 235 belongs to copper; it is added to BOTH temperatures.

Rotor I²R (copper) loss

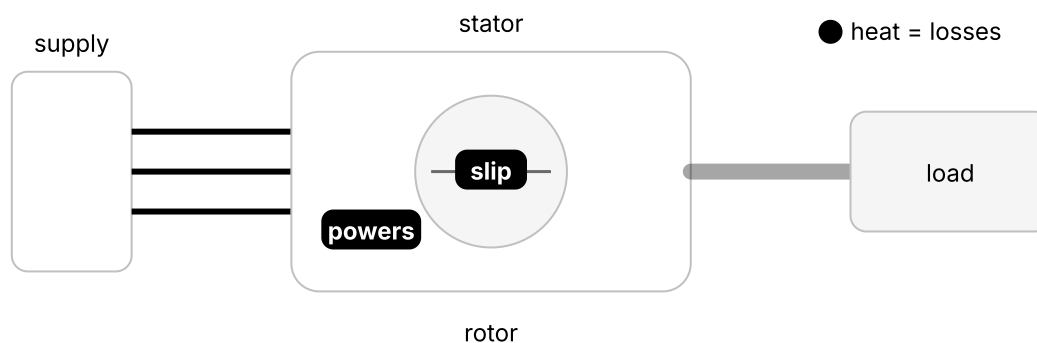
$$= \text{Slip} \times (\text{Stator input} - \text{Stator I}^2\text{R loss} - \text{Core loss})$$

SYMBOLS · UNITS

Symbols slip as a fraction; powers in W

Answer unit **W**

Book topic Field tests



Where each value sits: **slip** → rotor speed N , $\text{slip} \cdot \text{powers}$ → synchronous speed N_s , poles P

WHAT IT MEANS

Rotor loss is the slip fraction of the power crossing the air gap (stator input minus stator losses).

Worked example. Slip $0.03 \times 40,000 \text{ W}$ air-gap power = 1,200 W.

Exam trap. Use slip as a fraction (0.03), not 3.

Stray load loss (IS/IEC method)

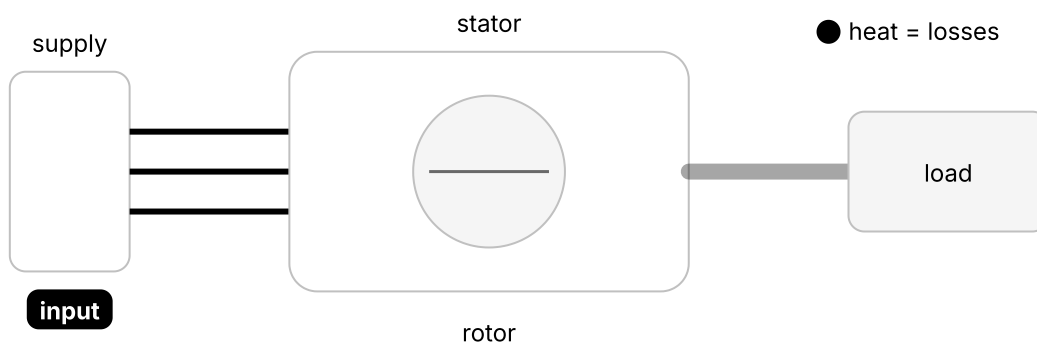
= 0.5 % of input power

SYMBOLS · UNITS

Symbols input power (W)

Answer unit W

Book topic Field tests



Where each value sits: **input** → V, I, cos ϕ , f

WHAT IT MEANS

Losses that cannot be measured directly (leakage flux, harmonics); the Indian/IEC standard simply assumes 0.5 % of input.

Worked example. Input 50 kW → 250 W.

Exam trap. IEEE 112 measures it (and gives lower efficiency); IS/IEC assumes 0.5 %.

Motor % loading (input method)

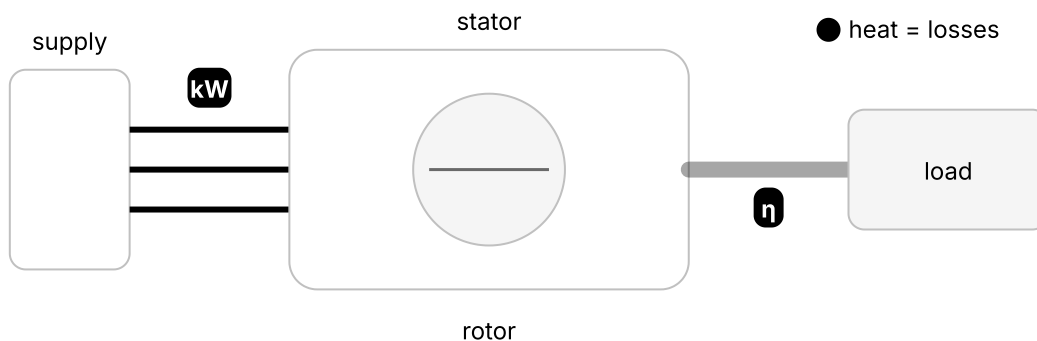
$$= \text{Input kW at existing load} \div (\text{Nameplate kW} \div \text{Nameplate } \eta) \times 100$$

SYMBOLS · UNITS

Symbols kW; η as fraction

Answer unit %

Book topic Motor loading



Where each value sits: **kW** → input kW · **η** → output kW, η

► Try it: Motor: measured volts, amps and PF → loading %



loading = 69 %

input 42.6 kW vs full-load input 61.5 kW

$$\sqrt{3} \times 410 \times 75 \times 0.8 \div 1000 = 42.6 \text{ kW}; \text{ rated input} = 55 \div 0.895 = 61.5 \text{ kW} \rightarrow \text{loading } 69 \%$$

WHAT IT MEANS

Compare measured input with the input the motor would draw at full load (nameplate kW ÷ nameplate efficiency).

Worked example. Input 42.6 kW; rated input $55/0.894 = 61.5 \rightarrow 69 \%$ (2023 S-4).

Exam trap. Never estimate loading from the current ratio alone — current is not proportional to load at low loads.

Motor % loading (output method)

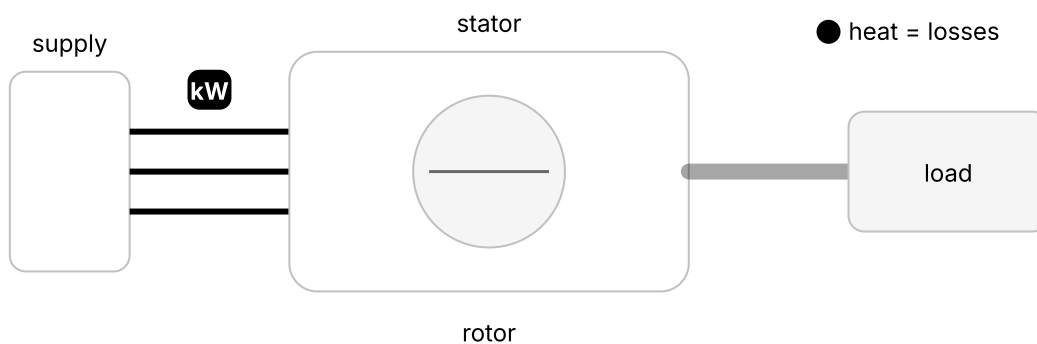
$$= \text{Actual operating load} \div \text{Rated capacity} \times 100$$

SYMBOLS · UNITS

Symbols kW

Answer unit %

Book topic Motor loading



Where each value sits: **kW** → input kW

WHAT IT MEANS

Actual mechanical load divided by rated output — used when the shaft load is known (e.g. from pump duty).

Worked example. Pump needs 30 kW from a 37 kW motor → 81 %.

Exam trap. Same units top and bottom (both kW output).

Saving by replacing with an energy-efficient motor

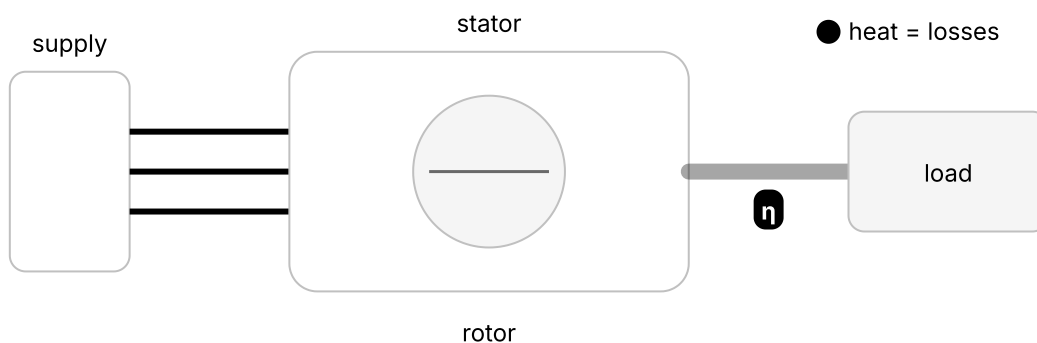
$$\text{kW saving} = \text{kW output} \times (1 \div \eta_{\text{old}} - 1 \div \eta_{\text{new}})$$

SYMBOLS · UNITS

Symbols η old, η new as fractions

Answer unit kW

Book topic High-efficiency motors



Where each value sits: $\eta \rightarrow$ output kW, $\eta \cdot \eta \rightarrow$ output kW, η

WHAT IT MEANS

For the same output, a more efficient motor draws less input; the saving is the difference of the two inputs.

Worked example. 22 kW output, η 0.88 $\rightarrow$ 0.92: $22 \times (1/0.88 - 1/0.92) = 1.09$ kW; $\times 6,000$ h = 6,540 kWh/yr.

Exam trap. Use the OUTPUT kW in the bracket formula; the reciprocals handle the inputs.

Voltage unbalance (NEMA)

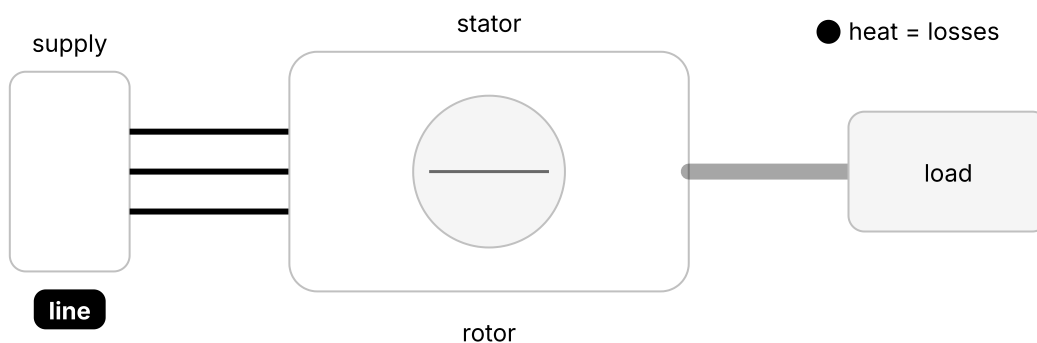
$$\% = \text{Max. deviation from mean of } (V_{ab}, V_{bc}, V_{ca}) \div \text{Mean} \times 100$$

SYMBOLS · UNITS

Symbols line voltages (V)

Answer unit %

Book topic Voltage unbalance



Where each value sits: **line** → V, I, cos φ, f

A single-phase induction motor is rated at 500Vrms, 10HP, 85% efficiency and 0.6pf lagging. Calculate the magnitude of the rms motor current in Amperes.

$$P_{out} = V I \cos \phi \eta$$

$$\eta = \frac{P_{out}}{P_{in}}$$

$$1 \text{ HP} = 746 \text{ W}$$

$$I = \frac{P_{out}}{V \cos \phi \eta} = \frac{10 \text{ HP}}{500 \times 0.6}$$

► Video: Induction Motor--Calculate Current Given HP, Efficiency and P

WHAT IT MEANS

Unequal phase voltages; even 1 % unbalance causes 6–10× that in current unbalance and overheats the motor.

Worked example. 410/417/408 V: mean 411.7, max deviation 5.3 → 1.29 % (book).

Exam trap. Deviation from the MEAN divided by the mean, not the spread between max and min.

Additional temperature rise due to voltage unbalance

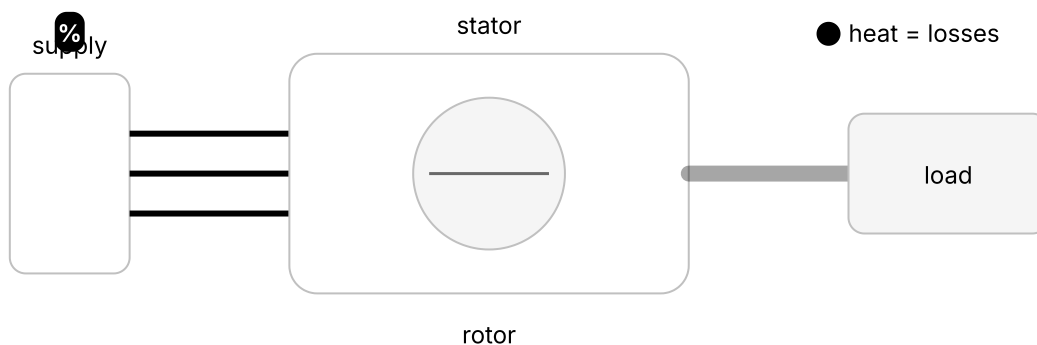
$$\Delta T = 2 \times (\% \text{ voltage unbalance})^2$$

SYMBOLS · UNITS

Symbols % unbalance

Answer unit °C

Book topic Voltage unbalance



Where each value sits: % → Vab, Vbc, Vca

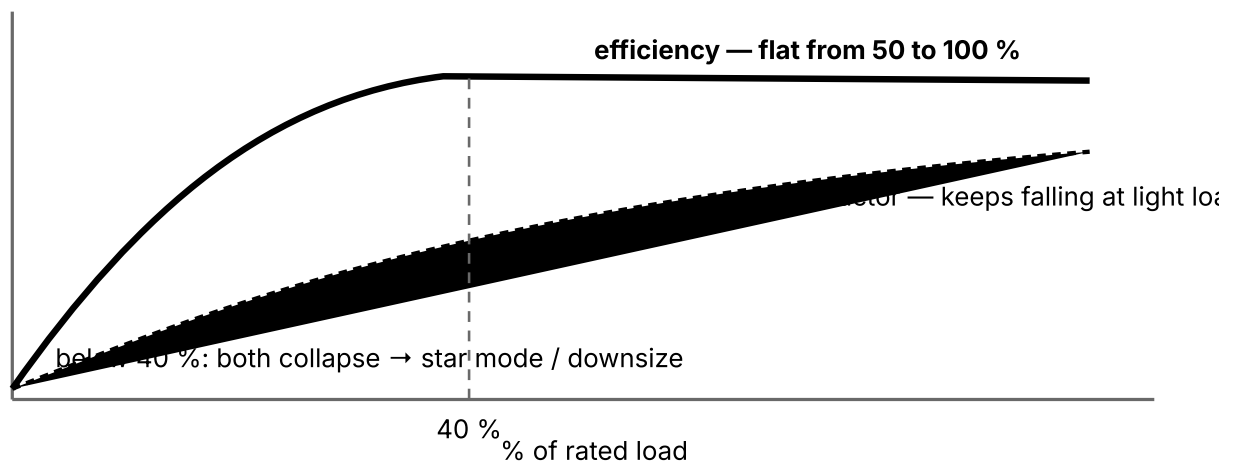
WHAT IT MEANS

Each 10 °C hotter halves insulation life; a 2 % unbalance adds 8 °C.

Worked example. 2 % → $2 \times 4 = 8$ °C.

Exam trap. Square the percentage first, then double.

Motor efficiency and power factor vs load



DEFINITIONS THE EXAM ASKS

Motor losses (book split)

Stator + rotor I^2R 55–60 %, iron/core 20–25 %, friction & windage 8–12 %, stray 4–5 %.

Energy-efficient motors

IE2/IE3 (IS 12615): lower losses through better steel, more copper, better fans; saving = $kW(1/\eta_{old} - 1/\eta_{new})$.

Rewinding

A poorly rewound motor loses 1–2 % efficiency; check no-load current and stator resistance per phase before and after.

Star-delta / star mode

A motor loaded below ~40 % runs better permanently in star ($\sqrt{3}$ lower voltage): higher efficiency and PF, less magnetising current.

Soft starter

Limits inrush current and mechanical shock at start; it does NOT improve running efficiency.

VERIFIED VIDEOS FOR THIS CHAPTER (YOUTUBE)

Motor Loss Split & EEM Standards — Tutorial on how to calculate the efficiency of an induction motor · Marayati Marsadek

Rewinding Effects & Stator Resistance — Simple problems on 3-phase induction motors: Slip, Rotor Frequency(Part-I) · Gargi Basu

Voltage Unbalance & Star Mode — Induction Motor--Calculate Current Given HP, Efficiency and Pf ·
Raiya Academy

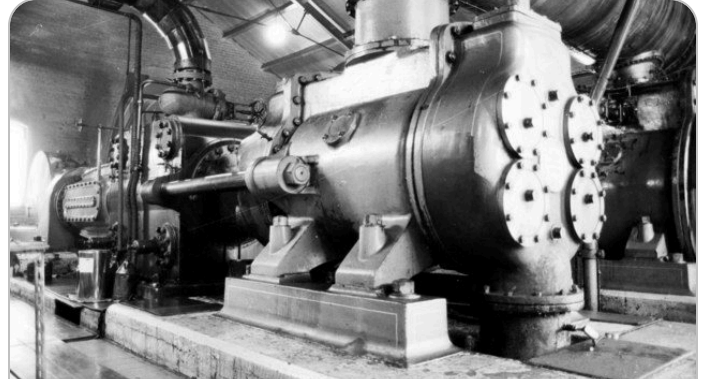
Chapter 3 • Compressed Air System

~20 marks: FAD, leakage, specific power and receiver/pipe sizing numericals; intercooling and dryer theory.



Small reciprocating (piston) air compressor with its receiver

Photo: Sirotmusic · CC BY-SA 4.0 · source



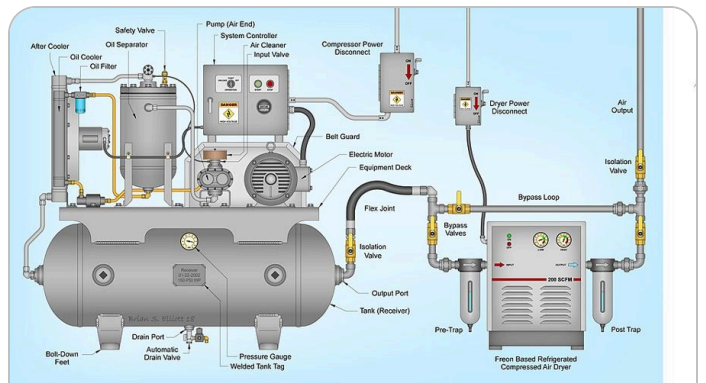
Large two-stage reciprocating compressor — intercooling between stages cuts the work

Photo: Chris Allen · CC BY-SA 2.0 · source



Air receiver — stores air, smooths demand peaks and separates moisture

Photo: P1898 · CC BY 4.0 · source



Compressed-air system layout: compressor, after-cooler, receiver, dryer, distribution

Photo: Brian S. Elliott · CC BY-SA 4.0 · source

Compressor displacement

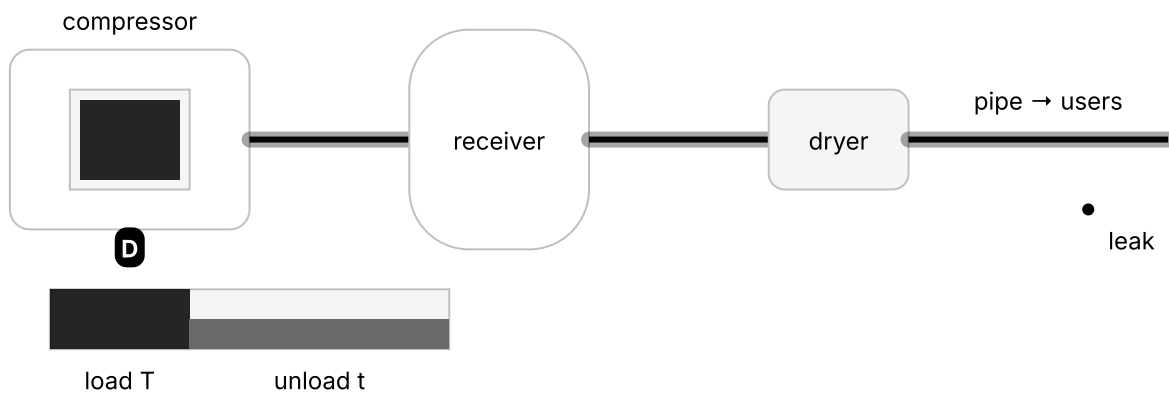
$$= (\pi \div 4) \times D^2 \times L \times S \times X \times n$$

SYMBOLS · UNITS

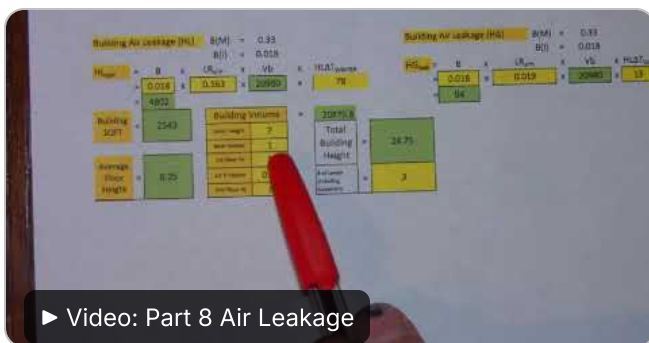
Symbols D = bore (m), L = stroke (m), S = speed (rpm), X = 1 single / 2 double acting, n = no. of cylinders

Answer unit m³/min

Book topic Volumetric efficiency



Where each value sits: **D** → bore D, stroke L, speed S, X, n · **L** → bore D, stroke L, speed S, X, n · **S** → bore D, stroke L, speed S, X, n · **X** → bore D, stroke L, speed S, X, n · **n** → bore D, stroke L, speed S, X, n



WHAT IT MEANS

The volume the pistons sweep per minute — the theoretical maximum the machine could deliver.

Worked example. Bore 0.2 m, stroke 0.15 m, 600 rpm, double-acting (X=2), 2 cylinders → 0.785 × 0.04 × 0.15 × 600 × 2 × 2 = 11.3 m³/min.

Exam trap. X = 2 for double-acting cylinders.

Volumetric efficiency

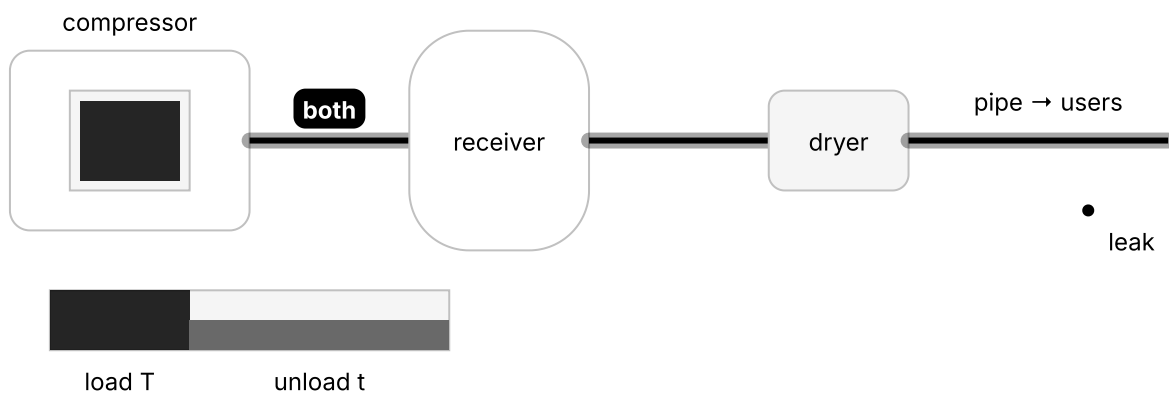
$$= \text{FAD} \div \text{Compressor displacement} \times 100$$

SYMBOLS · UNITS

Symbols both in m^3/min

Answer unit %

Book topic Volumetric efficiency



Where each value sits: **both** → FAD Q, displacement

WHAT IT MEANS

How much of the swept volume actually comes out as free air; clearance volume, leakage and valve losses take the rest (typically 65–85 %).

Worked example. $\text{FAD } 9 \text{ m}^3/\text{min} \div \text{displacement } 11.3 = 80 \text{ \%}$.

Exam trap. No power term in this formula — it is volume ÷ volume.

Isothermal power

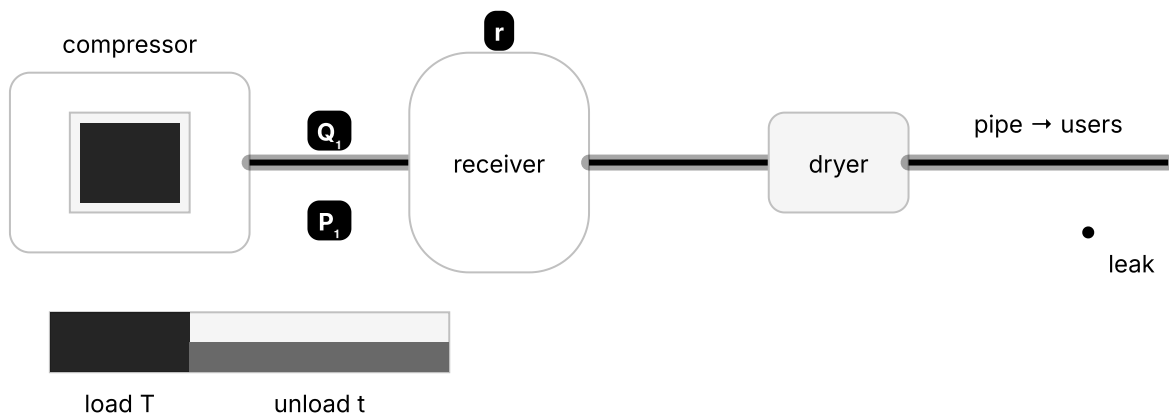
$$= P_1 \times Q_1 \times \log_e r \div 36.7$$

SYMBOLS · UNITS

Symbols P_1 = absolute intake pressure (kg/cm²), Q_1 = FAD (m³/hr), $r = P_2 \div P_1$

Answer unit kW

Book topic Isothermal efficiency



Where each value sits: $P_1 \rightarrow P_1$ intake, P_2 delivery, $r = P_2/P_1$ · $Q_1 \rightarrow$ FAD Q , displacement · $r \rightarrow$ receiver V , $P_1 \rightarrow P_2$, time T

WHAT IT MEANS

The ideal power if the air were compressed at constant temperature — the lowest possible. Uses the natural log of the pressure ratio.

Worked example. P_1 1.03 kg/cm² abs, Q_1 600 m³/hr, $r = 8 \rightarrow 1.03 \times 600 \times 2.08 \div 36.7 = 35$ kW.

Exam trap. Absolute pressures and Q in m³/HOUR in this book formula.

Isothermal efficiency

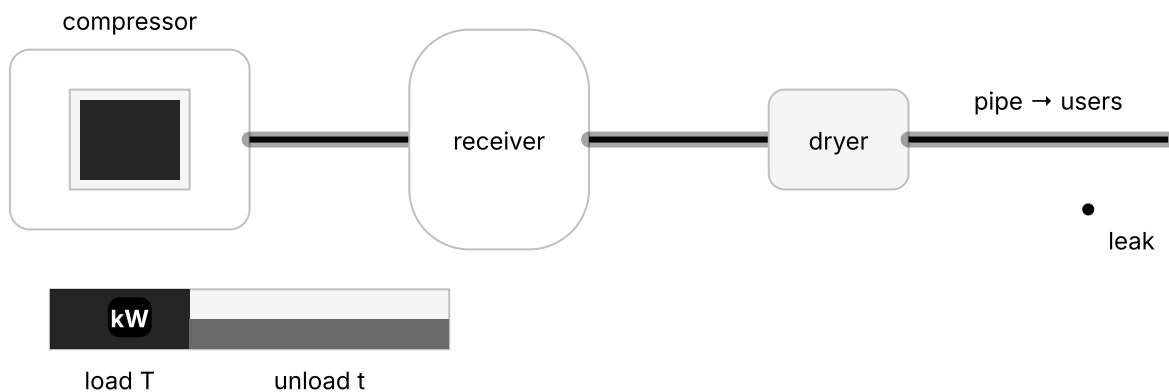
$$= \text{Isothermal power} \div \text{Actual measured input power} \times 100$$

SYMBOLS · UNITS

Symbols kW

Answer unit %

Book topic Isothermal efficiency



Where each value sits: **kW** → input kW, isothermal kW, SPC

WHAT IT MEANS

Ideal power divided by what the compressor and motor actually draw — the reported compressor efficiency (typically 60–70 %).

Worked example. 35 kW ideal ÷ 55 kW actual = 64 %.

Exam trap. It is lower than adiabatic efficiency for the same machine — the book warns about comparing vendors' numbers.

Free air delivery by pump-up test

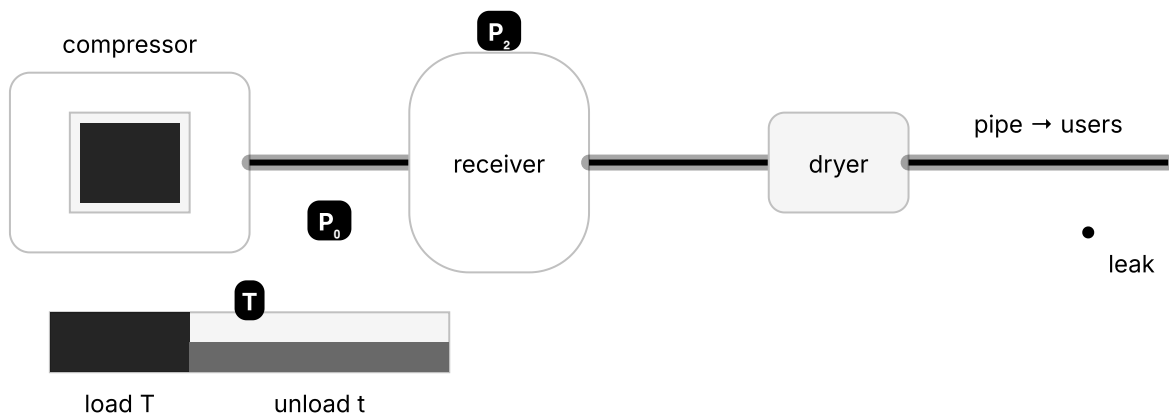
$$Q = [(P_2 - P_1) \div P_0] \times V \div T$$

SYMBOLS · UNITS

Symbols P_2 final, P_1 initial, P_0 atmospheric (kg/cm² abs); V = receiver + pipe volume (m³); T = time (min)

Answer unit m³/min

Book topic Capacity assessment



Where each value sits: $P_2 \rightarrow$ receiver V , $P_1 \rightarrow P_2$, time T · $P_1 \rightarrow$ receiver V , $P_1 \rightarrow P_2$, time T · $P_0 \rightarrow P_1$ intake, P_2 delivery, $r = P_2/P_1$ · $V \rightarrow$ receiver V , $P_1 \rightarrow P_2$, time T · $T \rightarrow T$ load, t unload

WHAT IT MEANS

Shop-floor capacity test: isolate the receiver, time how long the compressor takes to raise its pressure from P_1 to P_2 ; the air delivered is the receiver volume times the pressure rise in atmospheres, per minute.

Worked example. V 5 m³, P_2 8 kg/cm² a, P_1 1 kg/cm² a, P_0 1.03, T 5 min $\rightarrow (7/1.03) \times 5 \div 5 = 6.8$ m³/min.

Exam trap. Use ABSOLUTE pressures and include the pipe volume up to the isolation valve.

Leakage % (load-unload test)

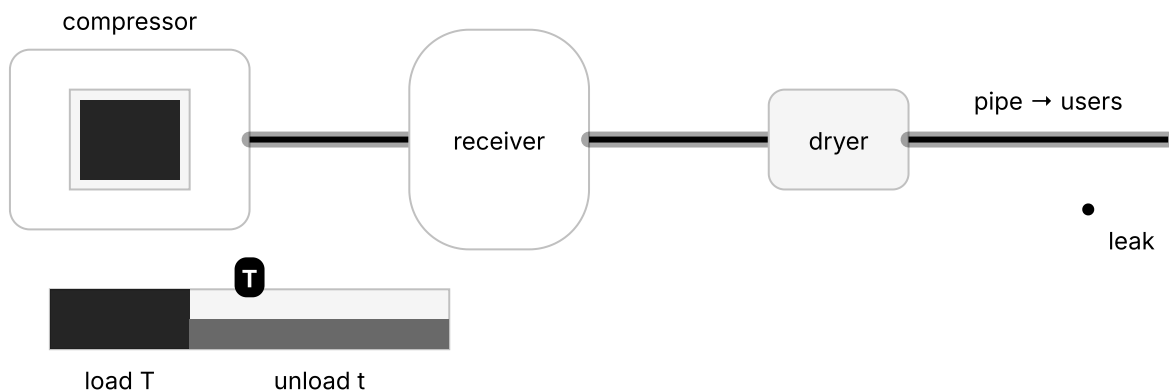
$$= T \div (T + t) \times 100$$

SYMBOLS · UNITS

Symbols T = load (on) time, t = unload (off) time — same units

Answer unit %

Book topic Leakage test



Where each value sits: **T** → T load, t unload · **t** → T load, t unload

► Try it: Compressed air: load and unload times → leakage

$$\text{leakage} = 20 \div (20 + 30) = 40.0 \% \rightarrow 200 \text{ cfm}$$



green = loaded (replacing leaked air) · grey = unloaded

$$\text{Leakage \%} = 20 \div 50 \times 100 = \mathbf{40.0 \%}; \text{ quantity} = 500 \times 0.400 = \mathbf{200 \text{ cfm}}$$

WHAT IT MEANS

With no consumers connected, the compressor still loads periodically to replace leaked air; the fraction of time it spends loaded is the leakage fraction.

Worked example. Load 1.5 min, unload 10.5 min → $1.5/12 = 12.5 \%$. 200 cfm, load 10 s / unload

20 s $\rightarrow$ 67 cfm leakage (2023).

Exam trap. T (load) on top, T + t below.

Leakage quantity

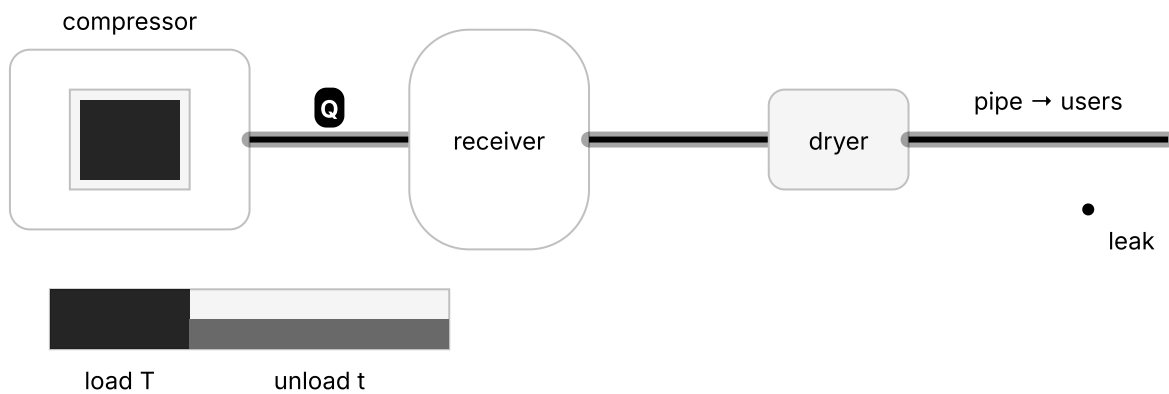
$$q = Q \times T \div (T + t)$$

SYMBOLS · UNITS

Symbols Q = compressor capacity (m³/min)

Answer unit m³/min

Book topic Leakage test



Where each value sits: $Q \rightarrow$ FAD Q , displacement

► Try it: Compressed air: load and unload times → leakage

$$\text{leakage} = 20 \div (20 + 30) = 40.0 \% \rightarrow 200 \text{ cfm}$$



green = loaded (replacing leaked air) · grey = unloaded

$$\text{Leakage \%} = 20 \div 50 \times 100 = \mathbf{40.0 \%}; \text{ quantity} = 500 \times 0.400 = \mathbf{200 \text{ cfm}}$$

WHAT IT MEANS

Leakage in flow units = compressor capacity × leakage fraction.

Worked example. 500 cfm × 0.125 = 62.5 cfm.

Exam trap. Same units as the capacity.

Specific power consumption

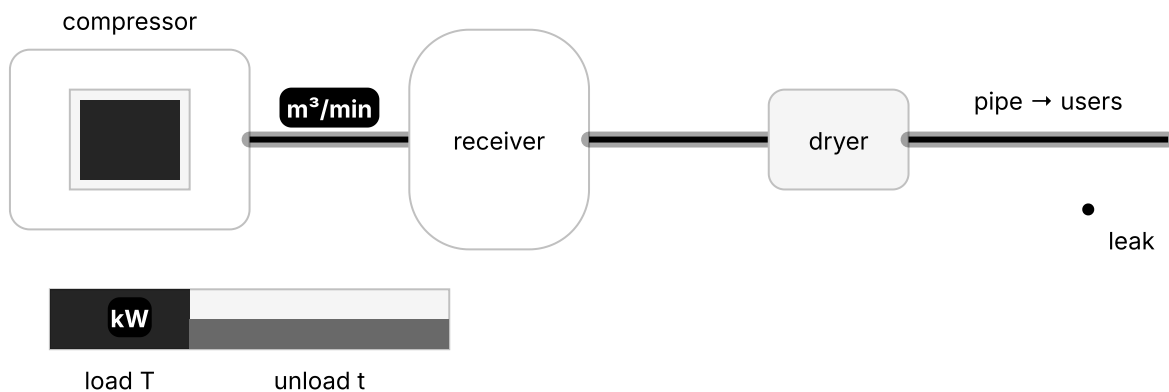
$$= \text{Power (kW)} \div \text{FAD (m}^3/\text{min)}$$

SYMBOLS · UNITS

Symbols kW, m³/min

Answer unit kW per m³/min

Book topic Performance



Where each value sits: **kW** → input kW, isothermal kW, SPC · **m³/min** → FAD Q, displacement

► Try it: Chiller: flow and temperature drop of chilled water → tons of refrigeration



$$\text{kW/TR} = 1.30 \cdot \text{COP} = 2.71$$

$$20,000 \text{ kg/hr} \times 1 \times 7 \text{ °C} \div 3024 = \mathbf{46.3 \text{ TR}}; 60 \text{ kW} \div 46.3 = \mathbf{1.30 \text{ kW/TR}}, \text{COP} = 3.51 \div 1.30 = \mathbf{2.71}$$

WHAT IT MEANS

kW per unit of air delivered — the efficiency benchmark of a compressed-air system (typical 0.15–0.20 kW/cfm... in book units $\approx 6\text{--}8$ kW per m^3/min).

Worked example. $370 \text{ kW} \div 2,392 \text{ m}^3/\text{min} \dots$ (book: $0.155 \text{ kW}/\text{m}^3$).

Exam trap. Keep kW and flow in the same basis (per minute or per hour).

Power wasted in leakage

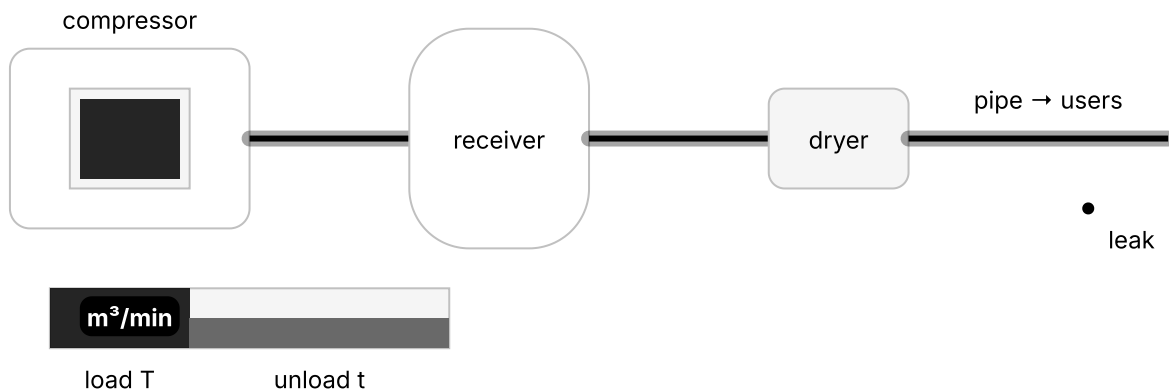
$$= \text{Leakage quantity} \times \text{Specific power consumption}$$

SYMBOLS · UNITS

Symbols $\text{m}^3/\text{min} \times \text{kW per m}^3/\text{min}$

Answer unit **kW**

Book topic Leakage test



Where each value sits: **m³/min** → input kW, isothermal kW, SPC

WHAT IT MEANS

Leaked air cost you the power to compress it: leakage flow $\times$ specific power.

Worked example. $62.5 \text{ cfm} \times 0.18 \text{ kW/cfm} = 11 \text{ kW}, \approx 88,000 \text{ kWh/yr.}$

Exam trap. Every 1 bar over-pressure also costs 6–7 % more power.

Gas law (air expansion / compression)

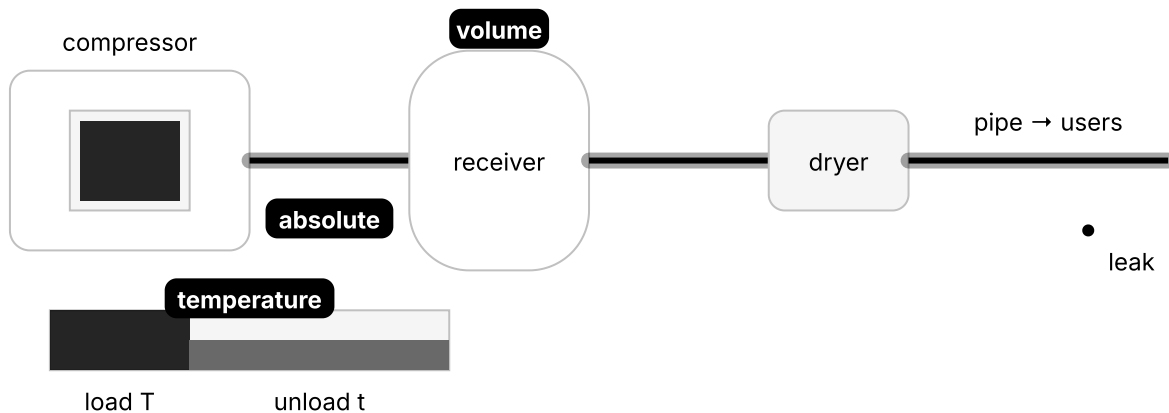
$$P_1 V_1 \div T_1 = P_2 V_2 \div T_2$$

SYMBOLS · UNITS

Symbols absolute pressure; volume; temperature in K

Answer unit —

Book topic Pipe & receiver sizing



Where each value sits: **absolute** → P_1 intake, P_2 delivery, $r = P_2/P_1$ · **volume** → receiver V , $P_1 \rightarrow P_2$, time T · **temperature** → T load, t unload

WHAT IT MEANS

Relates pressure, volume and temperature of the same air at two states — used to convert free air to line-pressure volume for pipe sizing.

Worked example. 6 m³ of free air at 1 atm → at 8 atm abs and same T : 0.75 m³.

Exam trap. Absolute pressure and Kelvin temperature only.

Compressed air pipe diameter

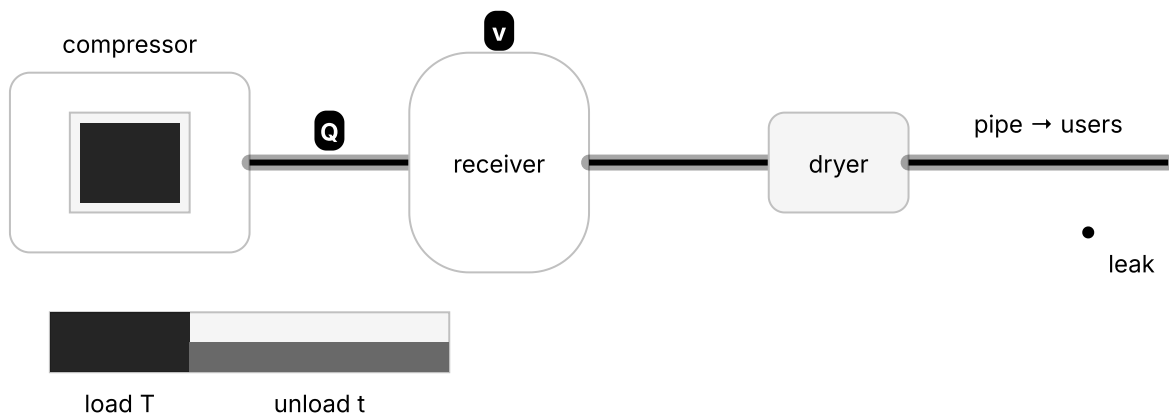
$$Q = (\pi \div 4) \times D^2 \times v \rightarrow D = \sqrt{(4Q \div \pi v)}$$

SYMBOLS · UNITS

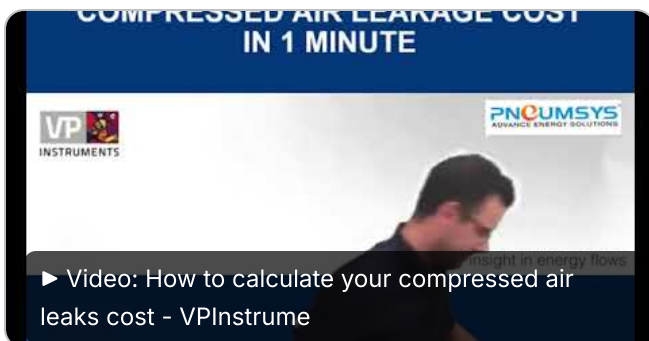
Symbols Q = flow at line pressure (m³/s), v = air velocity (m/s)

Answer unit m

Book topic Pipe sizing



Where each value sits: $Q \rightarrow$ FAD Q , displacement · $v \rightarrow$ receiver V , $P_1 \rightarrow P_2$, time T



WHAT IT MEANS

Choose the pipe so the air (at line pressure) moves at 6–10 m/s; faster means high pressure drop.

Worked example. 500 cfm FAD (0.236 m³/s) at 7 kg/cm² abs $\rightarrow$ 0.034 m³/s at line pressure; at 6 m/s area 0.0056 m² $\rightarrow D \approx 85$ mm (2023 S-5 pattern).

Exam trap. Convert FAD to volume at LINE pressure first ($\div$ pressure ratio).

Air receiver size

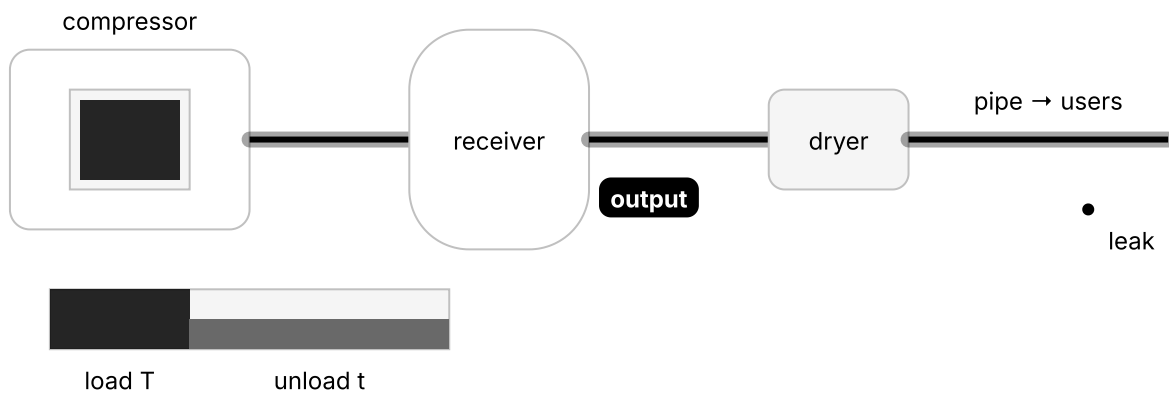
$$V = 1/10 \text{ to } 1/6 \times \text{compressor output}$$

SYMBOLS · UNITS

Symbols output in m^3/min

Answer unit m^3

Book topic Air receivers



Where each value sits: **output** → capacity, rated vs actual

WHAT IT MEANS

Storage that smooths demand peaks and reduces load/unload cycling; IS 7938 rule of thumb.

Worked example. $10 \text{ m}^3/\text{min}$ compressor → $1\text{--}1.7 \text{ m}^3$ receiver.

Exam trap. Bigger is not always better: too large delays pressure recovery.

Capacity shortfall of a compressor

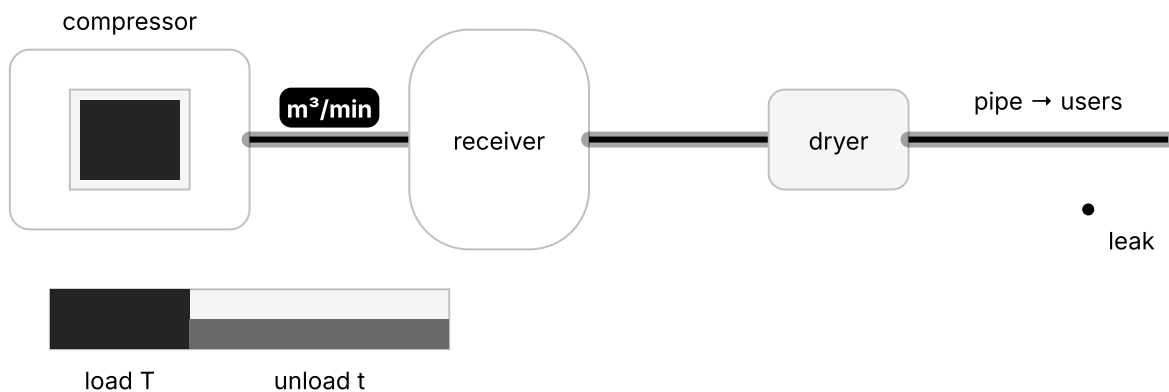
$$= (\text{Rated} - \text{Actual FAD}) \div \text{Rated} \times 100$$

SYMBOLS · UNITS

Symbols m^3/min

Answer unit %

Book topic Capacity assessment



Where each value sits: **m³/min** → FAD Q, displacement

WHAT IT MEANS

Compares tested FAD with the rated value; a shortfall above ~10 % means worn valves, rings or leaks and calls for overhaul.

Worked example. Rated 15, actual 13.2 m^3/min → 12 %.

Exam trap. Compare on the same pressure and temperature basis.

m³/min to cfm

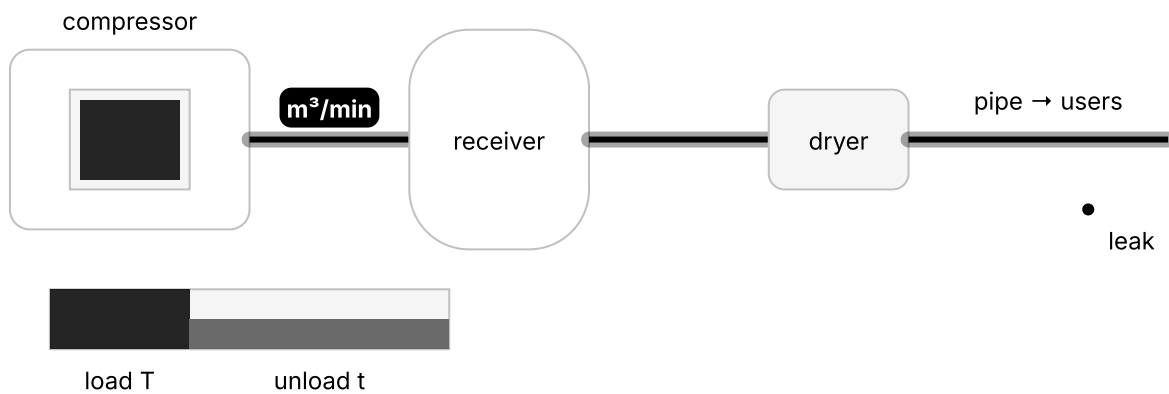
$$\text{cfm} = \text{m}^3/\text{min} \times 35.31$$

SYMBOLS · UNITS

Symbols m³/min

Answer unit cfm

Book topic Units



Where each value sits: **m³/min** → FAD Q, displacement

WHAT IT MEANS

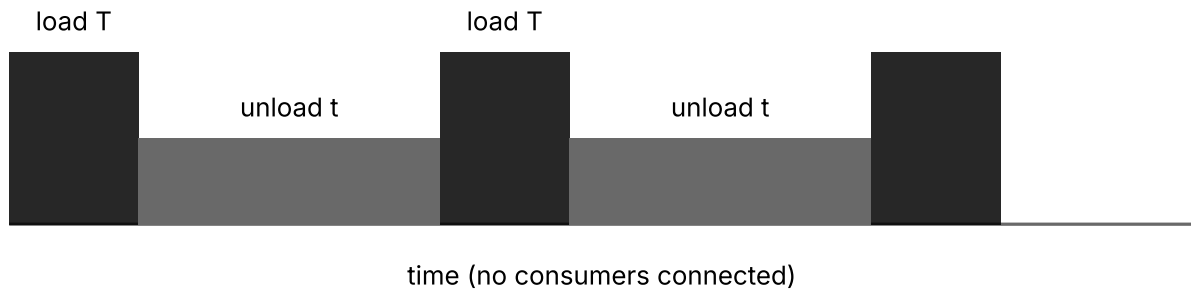
Unit bridge between the book's SI values and nameplates in cfm.

Worked example. 10 m³/min = 353 cfm.

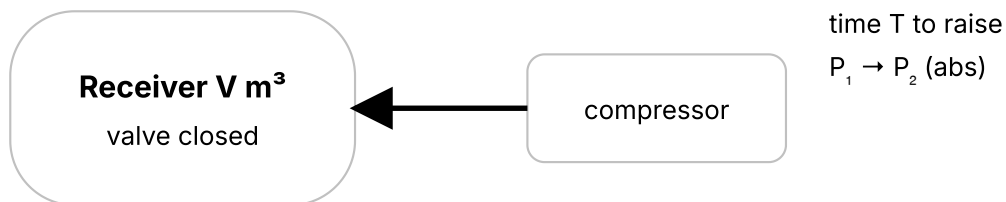
Exam trap. Divide by 35.31 to go the other way.

Leakage test — load/unload timeline

The compressor loads only to replace leaked air → $\text{leakage \%} = T \div (T + t) \times 100$



FAD pump-up test



$$\text{FAD } Q = [(P_2 - P_1) \div P_0] \times V \div T \text{ m}^3/\text{min (all pressures absolute)}$$

DEFINITIONS THE EXAM ASKS

Types of compressors

Positive displacement (reciprocating, screw, vane) and dynamic (centrifugal). Centrifugal machines do not use load/unload capacity control.

Intercooling

Cooling air between stages reduces its volume so the next stage does less work — the main reason multi-stage compression saves power.

Air dryers

Refrigerated (dew point +3 °C, cheapest power), heatless desiccant (uses 15–20 % purge air, highest cost), heat-of-compression (lowest operating cost); adsorption dryers use activated alumina / silica gel / molecular sieve.

Pressure settings

Every 1 bar reduction in delivery pressure saves 6–7 % power; each 4 °C rise in intake temperature costs ~1 %.

Leakage benchmarks

Well-maintained system < 10 % of capacity; badly maintained 20–30 %.

VERIFIED VIDEOS FOR THIS CHAPTER (YOUTUBE)

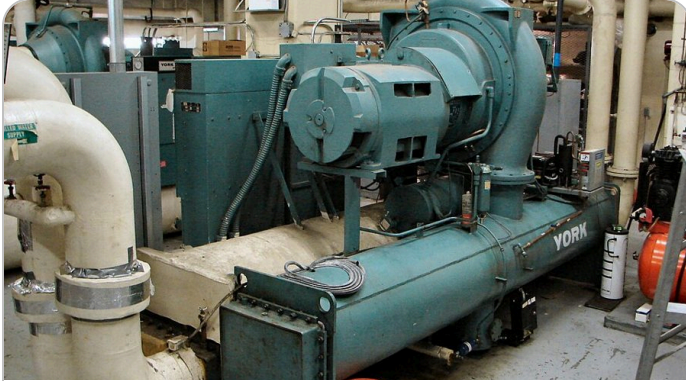
FAD Pump-Up Test Method — Part 8 Air Leakage · Les Druiven

Leakage Quantification Test — How to Check for Air Leaks in Five Simple Steps · Compressed Air Controls

Air Dryers Comparison — How to calculate your compressed air leaks cost - VPIstruments · PNEUMSYS ADVANCE ENERGY SOLUTIONS

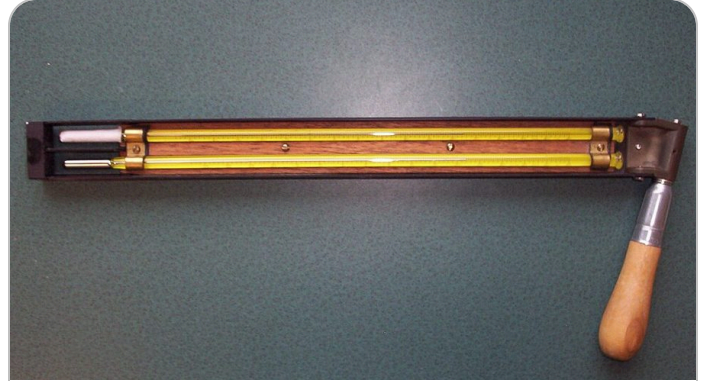
Chapter 4 · HVAC and Refrigeration System

~23 marks (top chapter): TR, COP, kW/TR numericals every year; VCR vs VAM, refrigerants, psychrometry and ventilation.



Water-cooled centrifugal chiller — evaporator and condenser shells with the compressor on top

Photo: P199 · Public domain · [source](#)



Sling psychrometer — wet-bulb and dry-bulb thermometers give relative humidity

Photo: User:CambridgeBayWeather · Public domain · [source](#)

Refrigeration load from chilled water

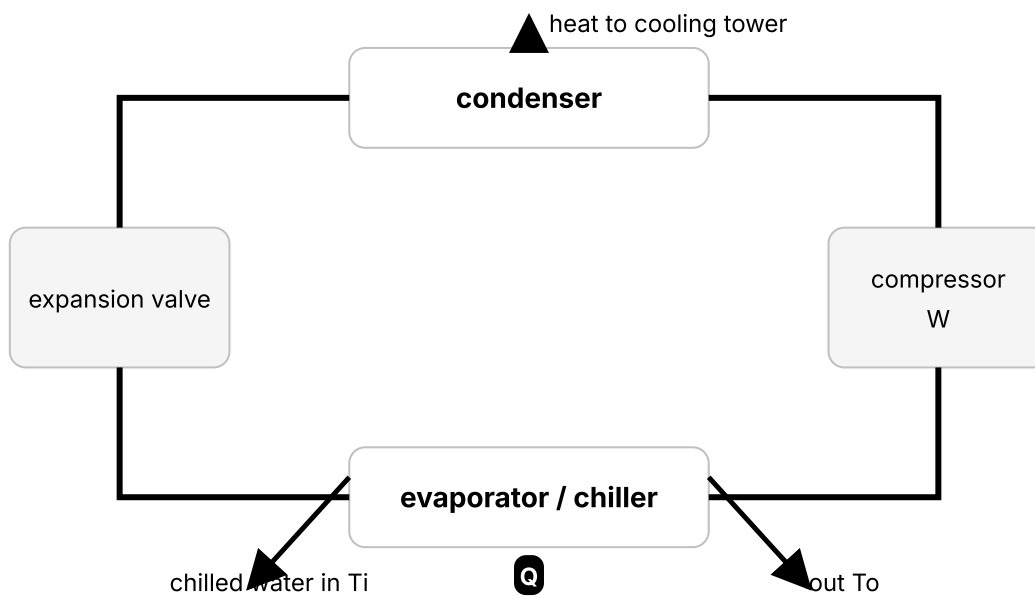
$$TR = Q \times C_p \times (T_i - T_o) \div 3024$$

SYMBOLS · UNITS

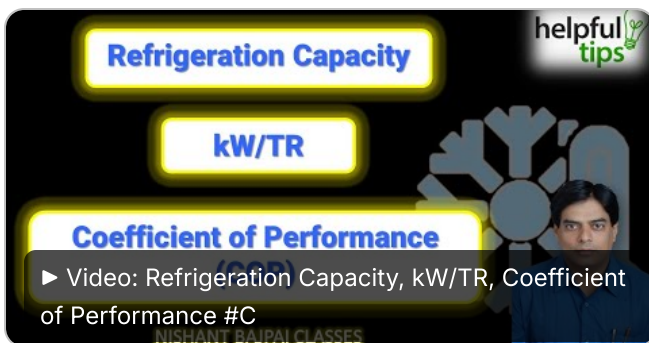
Symbols Q = coolant flow (kg/hr), C_p (kcal/kg °C), T_i , T_o = inlet, outlet temperature (°C)

Answer unit TR

Book topic Performance assessment



Where each value sits: **Q** → Q flow kg/hr, C_p , T_i , T_o → TR · **C_p** → Q flow kg/hr, C_p , T_i , T_o → TR · **T_i** → Q flow kg/hr, C_p , T_i , T_o → TR · **T_o** → Q flow kg/hr, C_p , T_i , T_o → TR · **outlet:** outlet temperature (°C)



► Try it: Chiller: flow and temperature drop of chilled water → tons of refrigeration



$$\text{kW/TR} = 1.30 \cdot \text{COP} = 2.71$$

$20,000 \text{ kg/hr} \times 1 \times 7 \text{ °C} \div 3024 = \mathbf{46.3 \text{ TR}}$; $60 \text{ kW} \div 46.3 = \mathbf{1.30 \text{ kW/TR}}$, $\text{COP} = 3.51 \div 1.30 = \mathbf{2.71}$

WHAT IT MEANS

Heat removed from the chilled water = flow × specific heat × temperature drop; divided by 3,024 to give tons of refrigeration.

Worked example. 20 m³/hr cooled 17 → 10 °C: $20,000 \times 1 \times 7 \div 3,024 = 46.3 \text{ TR}$.

Exam trap. Flow in kg/HOUR (m³/hr × 1000); 3,024 kcal/hr per TR.

Refrigeration load from air side (AHU / FCU)

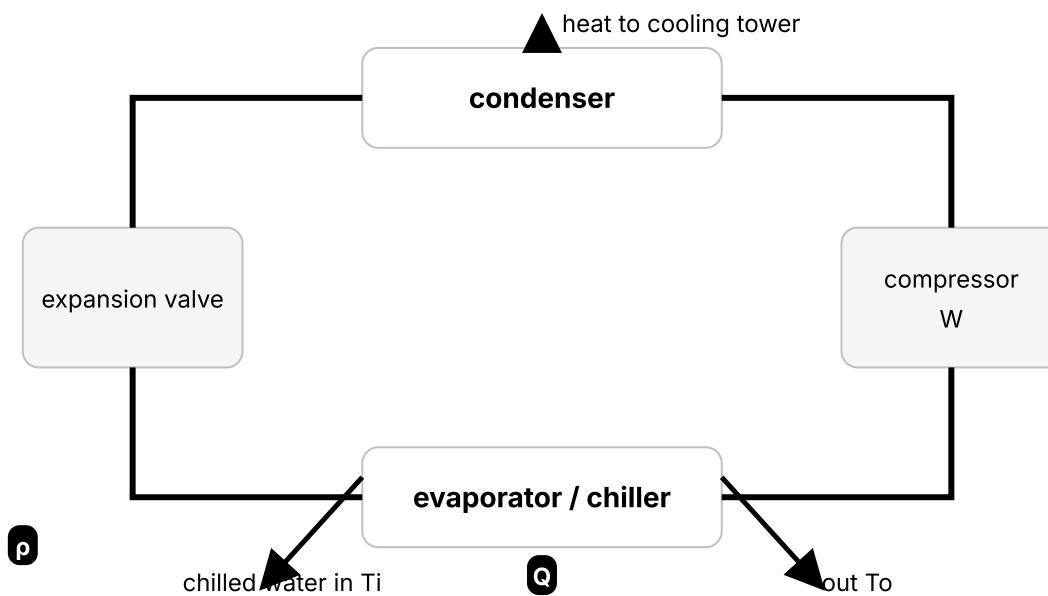
$$TR = Q \times \rho \times (h_{in} - h_{out}) \div 3024$$

SYMBOLS · UNITS

Symbols Q = air flow (m^3/hr), ρ = air density (kg/m^3), h = enthalpy ($kcal/kg$)

Answer unit TR

Book topic Performance assessment



Where each value sits: $Q \rightarrow Q$ flow kg/hr , C_p , T_i , $T_o \rightarrow TR$ · $p \rightarrow$ air flow, ρ , h in/out, ACH, $L \times B \times H$ · $h \rightarrow$ air flow, ρ , h in/out, ACH, $L \times B \times H$

WHAT IT MEANS

Same idea on the air side: air mass flow $\times$ enthalpy drop across the coil, read from the psychrometric chart.

Worked example. $10,800 \text{ m}^3/hr \times 1.2 \text{ kg/m}^3 \times (h_{in} - h_{out}) \div 3,024$.

Exam trap. Use enthalpy (total heat) for air, not just temperature — latent heat of moisture matters.

Specific power consumption

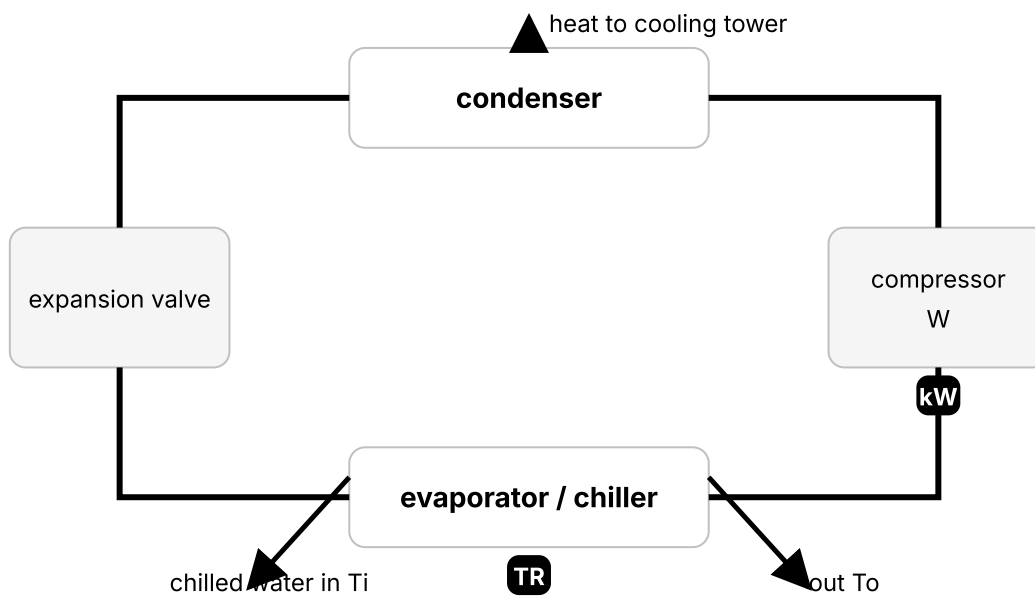
$$\text{kW/TR} = \text{Power input (kW)} \div \text{TR}$$

SYMBOLS · UNITS

Symbols kW, TR

Answer unit kW/TR

Book topic Performance assessment



Where each value sits: **kW** → power input kW, W · **TR** → Q flow kg/hr, Cp, Ti, To → TR

► Try it: Chiller: flow and temperature drop of chilled water → tons of refrigeration



$$\text{kW/TR} = 1.30 \cdot \text{COP} = 2.71$$

$$20,000 \text{ kg/hr} \times 1 \times 7 \text{ °C} \div 3024 = \mathbf{46.3 \text{ TR}}; 60 \text{ kW} \div 46.3 = \mathbf{1.30 \text{ kW/TR}}, \text{COP} = 3.51 \div 1.30 = \mathbf{2.71}$$

WHAT IT MEANS

The benchmark of a refrigeration plant: kW drawn per ton produced. Good centrifugal chillers $\approx 0.6\text{--}0.7$ kW/TR; reciprocating $\approx 1.0\text{--}1.2$.

Worked example. Compressor 10.69 kW for 8.07 TR $\rightarrow 1.32$ kW/TR (book example).

Exam trap. Lower kW/TR is better; it is the inverse of COP ($\times 3.51$).

Overall kW/TR of a chilled-water plant

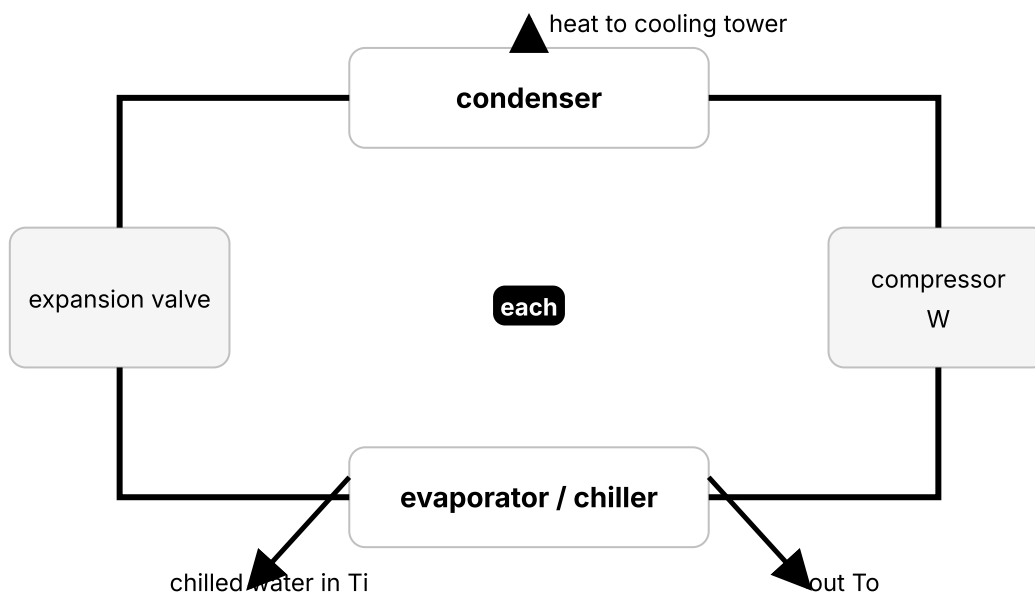
= Compressor + Chilled-water pump + Condenser-water pump + Cooling-tower fan kW/TR

SYMBOLS · UNITS

Symbols each in kW/TR

Answer unit kW/TR

Book topic Performance assessment



Where each value sits: **each** $\rightarrow$ COP, kW/TR, EER

WHAT IT MEANS

Add the pumps and cooling-tower fan to the compressor — the plant benchmark, not just the chiller's.

Worked example. $(10.69 + 4.86 + 0.87) \div 8.07 = 2.03$ kW/TR (book).

Exam trap. The exam sometimes asks for compressor kW/TR only — read which.

Coefficient of performance

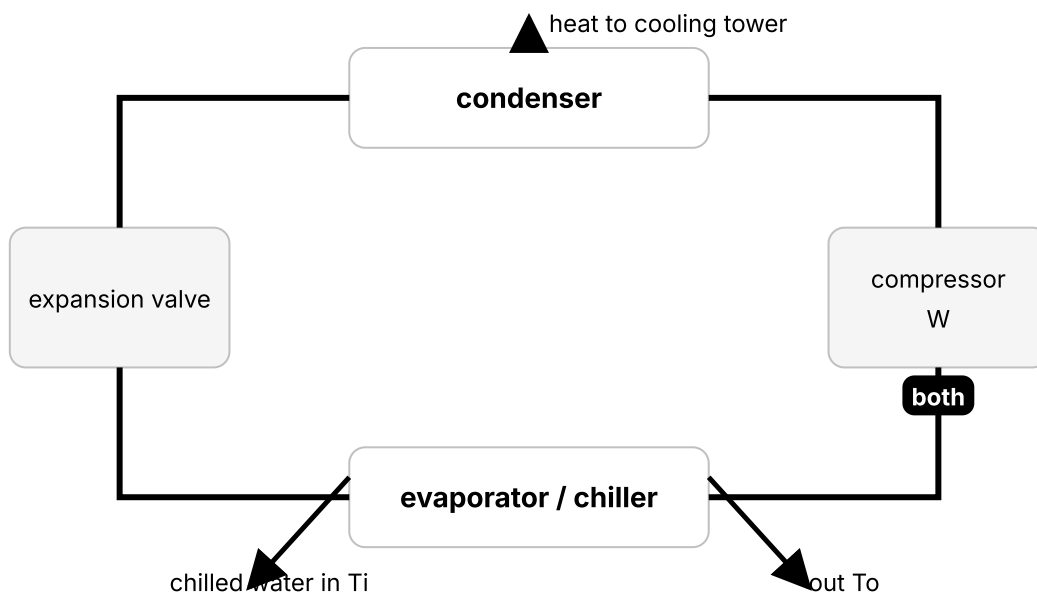
$$\text{COP} = \text{Refrigeration effect} \div \text{Power input}$$

SYMBOLS · UNITS

Symbols both in the same units (kW ÷ kW)

Answer unit no unit

Book topic COP



Where each value sits: **both** → power input kW, W

► Try it: Chiller: flow and temperature drop of chilled water → tons of refrigeration



$$\text{kW/TR} = 1.30 \cdot \text{COP} = 2.71$$

$$20,000 \text{ kg/hr} \times 1 \times 7 \text{ °C} \div 3024 = \mathbf{46.3 \text{ TR}}; 60 \text{ kW} \div 46.3 = \mathbf{1.30 \text{ kW/TR}}, \text{COP} = 3.51 \div 1.30 = \mathbf{2.71}$$

WHAT IT MEANS

Cooling produced per unit of work input, both in the same units. Higher COP = more efficient. Typical VCR 3–5; single-effect VAM $\approx$ 0.65–0.7.

Worked example. Cooling 3.517 kW per TR at 1.7 kW/TR $\rightarrow$ COP 2.07 (2018/2021).

Exam trap. Same units top and bottom (kW $\div$ kW, or kcal $\div$ kcal).

COP from kW/TR

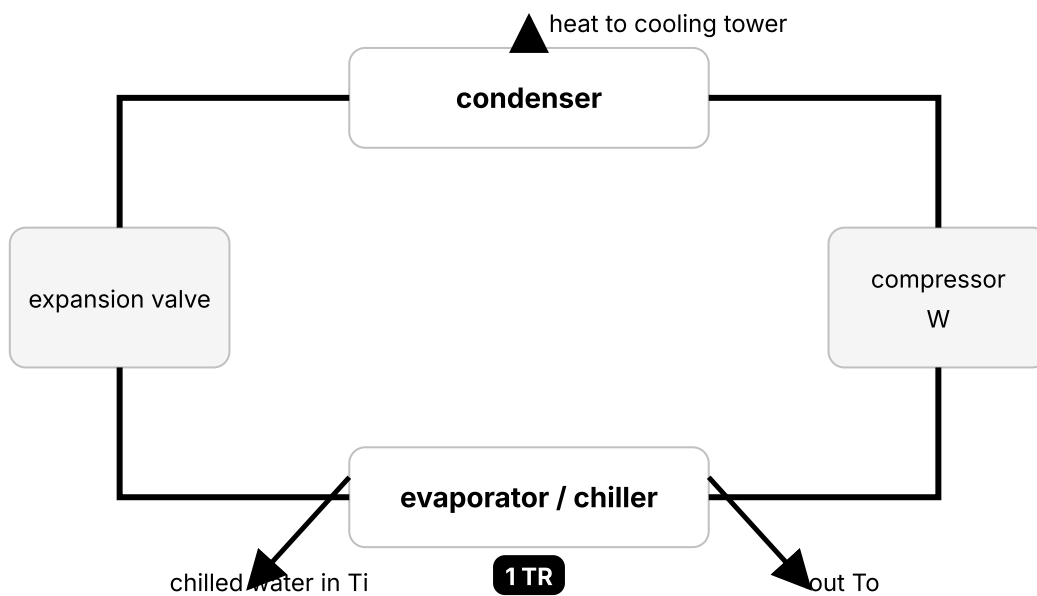
$$\text{COP} = 3.51 \div (\text{kW/TR})$$

SYMBOLS · UNITS

Symbols 1 TR = 3.51 kW

Answer unit no unit

Book topic COP



Where each value sits: **1 TR** → Q flow kg/hr, Cp, Ti, To → TR

► Try it: Chiller: flow and temperature drop of chilled water → tons of refrigeration



$$\text{kW/TR} = 1.30 \cdot \text{COP} = 2.71$$

$20,000 \text{ kg/hr} \times 1 \times 7 \text{ °C} \div 3024 = \mathbf{46.3 \text{ TR}}$; $60 \text{ kW} \div 46.3 = \mathbf{1.30 \text{ kW/TR}}$, $\text{COP} = 3.51 \div 1.30 = \mathbf{2.71}$

WHAT IT MEANS

Because 1 TR = 3.51 kW of cooling, COP is simply 3.51 divided by the kW/TR.

Worked example. 0.7 kW/TR → COP 5.0.

Exam trap. Use 3.51 (kW), not 3,024 (kcal/hr) with kW.

Carnot COP

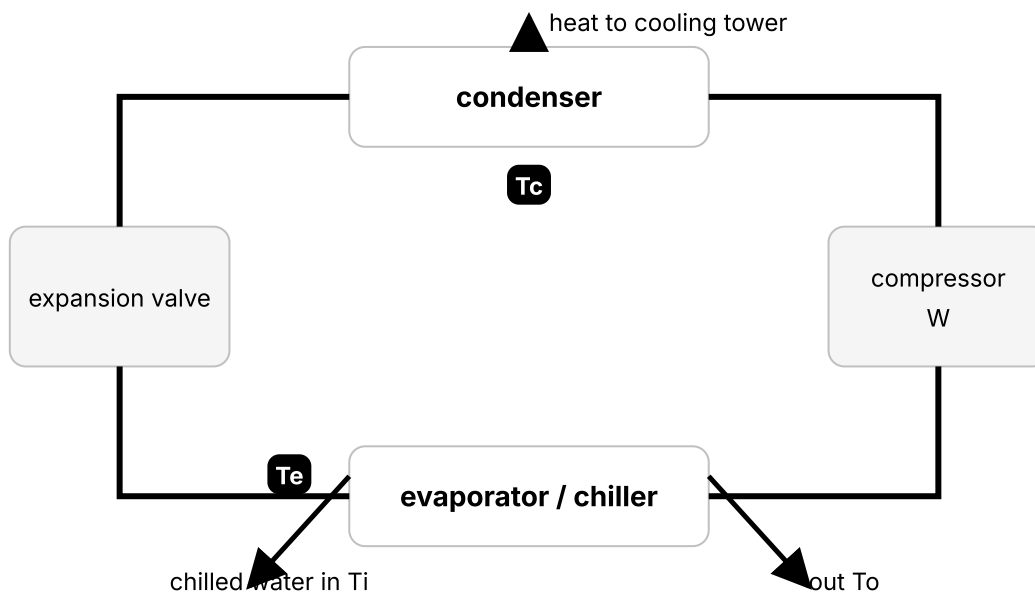
$$\text{COP} = T_e \div (T_c - T_e)$$

SYMBOLS · UNITS

Symbols T_e = evaporator, T_c = condenser temperature ($K = ^\circ C + 273$)

Answer unit no unit

Book topic COP



Where each value sits: $T_e \rightarrow T_e$ evaporator · $T_c \rightarrow$ heat rejected, T_c

WHAT IT MEANS

The theoretical best for the two temperatures; shows why a HIGHER evaporator temperature and LOWER condenser temperature raise efficiency ($\approx 2-3\%$ per $^\circ C$).

Worked example. $T_e 5^\circ C$ (278 K), $T_c 40^\circ C$ (313 K) $\rightarrow 278 \div 35 = 7.9$.

Exam trap. Kelvin — add 273 to both.

Energy efficiency ratio (star label)

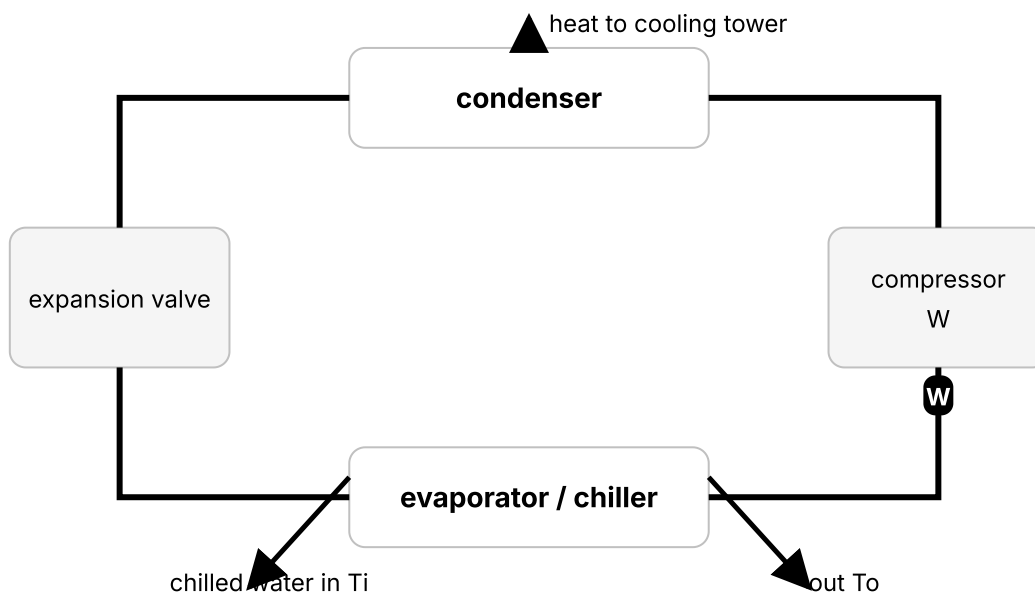
$$\text{EER} = \text{Refrigeration effect (W)} \div \text{Power input (W)}$$

SYMBOLS · UNITS

Symbols W, W

Answer unit W/W

Book topic Room AC labelling



Where each value sits: **W** → power input kW, **W · W** → power input kW, **W**

COP & KW / Ton

How to Calculate COP
& KW per Ton



WHAT IT MEANS

COP expressed in watts of cooling per watt of input (or BTU/hr per W in older labels); the basis of the BEE star rating for room ACs.

Worked example. 5 TR unit delivering 4 TR cooling with EER 2.9... (2018/2021 objective 4.84).

Exam trap. EER and COP are the same ratio when both sides are in watts.

Heat rejected in the condenser

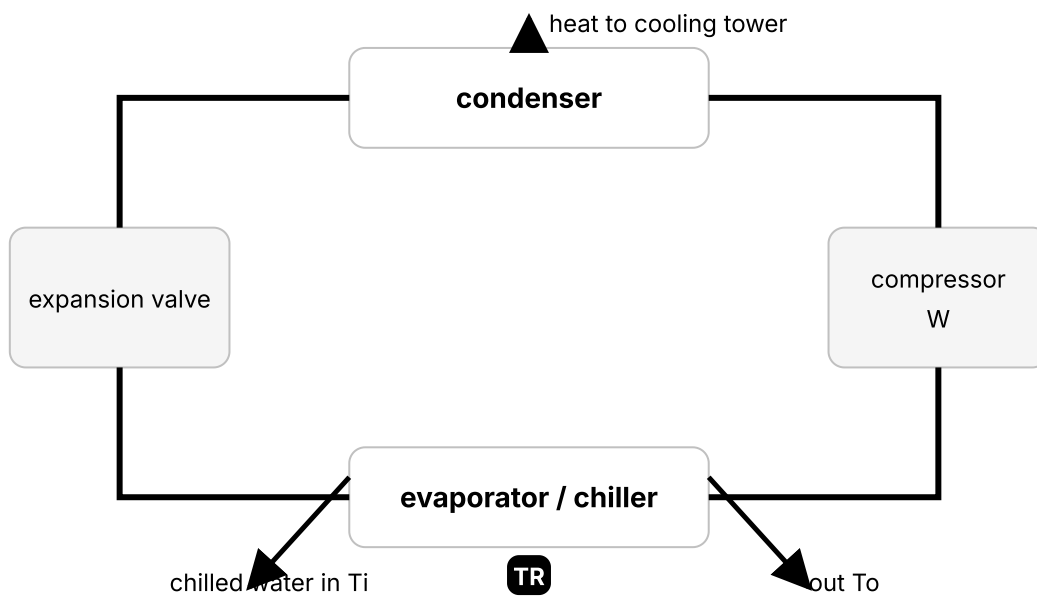
$$= \text{Refrigeration effect} + \text{Compressor work}$$

SYMBOLS · UNITS

Symbols TR × 3024 + kW × 860 (kcal/hr)

Answer unit kcal/hr

Book topic Refrigeration cycle



Where each value sits: **TR** → Q flow kg/hr, Cp, Ti, To → TR

WHAT IT MEANS

The condenser must dump the heat taken from the room PLUS the compressor's work — always more than the cooling effect.

Worked example. 100 TR at COP 4: cooling 302,400 kcal/hr + work 25 kW × 860 = 21,500 → 323,900 kcal/hr to the cooling tower.

Exam trap. Condenser heat > evaporator heat, always.

Heat delivered by a heat pump

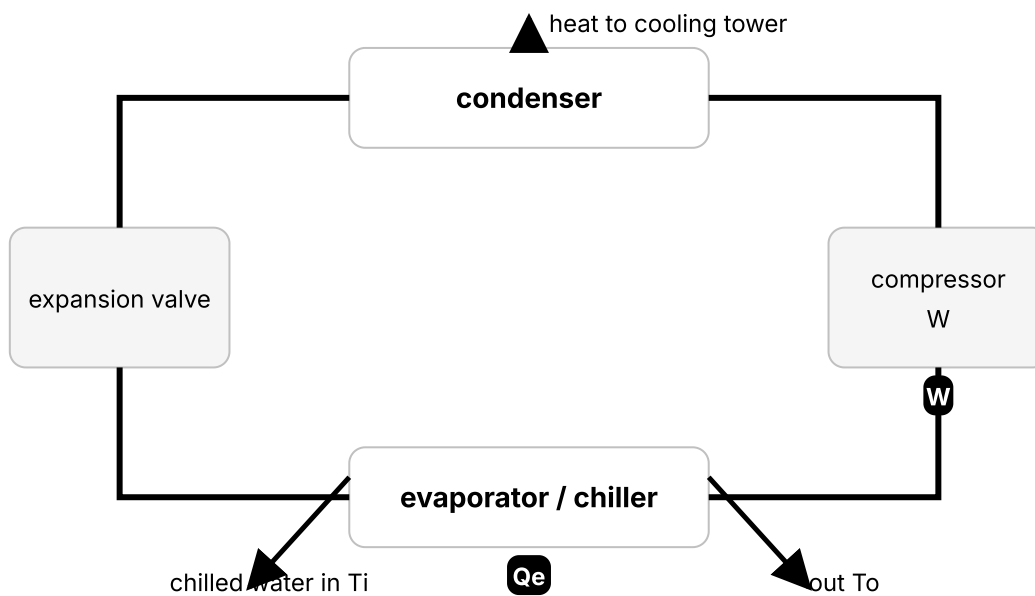
$$= Q_e + W$$

SYMBOLS · UNITS

Symbols Q_e = waste heat taken in (kW), W = compressor work (kW)

Answer unit kW

Book topic Heat pumps



Where each value sits: **Qe** → Q flow kg/hr, Cp, Ti, To → TR · **W** → power input kW, W

WHAT IT MEANS

A heat pump is a refrigerator used for its hot side: it delivers the waste heat it absorbed plus the compressor work, so heating COP is always > 1 .

Worked example. Absorbs 100 kW at 20 kW work → delivers 120 kW (COP 6 heating).

Exam trap. Heating COP = cooling COP + 1.

Ventilation rate

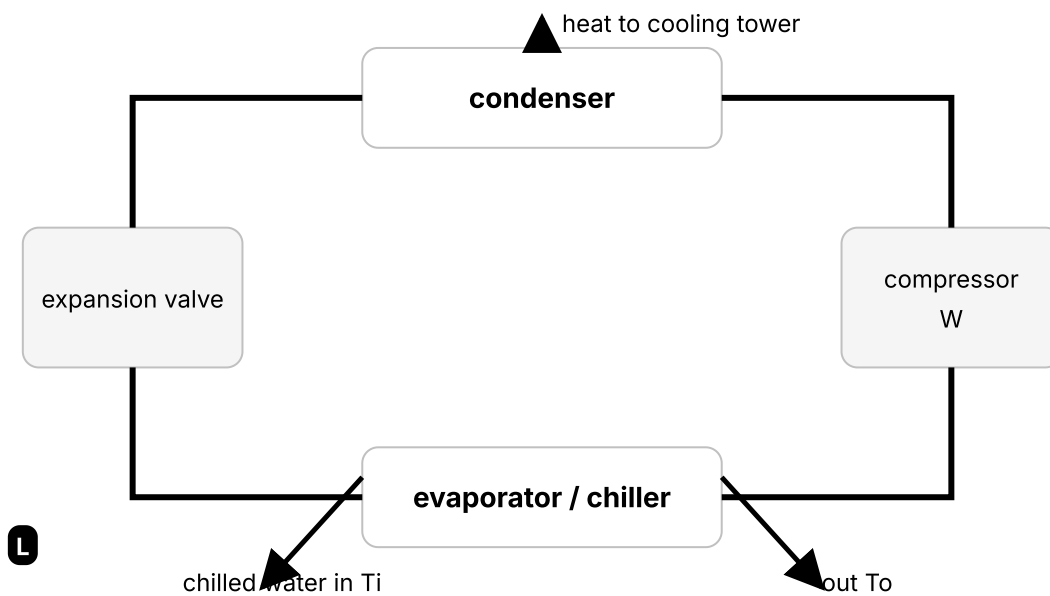
$$Q = L \times B \times H \times \text{ACH}$$

SYMBOLS · UNITS

Symbols L, B, H = room size (m), ACH = air changes per hour

Answer unit m³/hr

Book topic Ventilation



Where each value sits: **L** → air flow, ρ , h in/out, ACH, $L \times B \times H$ · **B** → air flow, ρ , h in/out, ACH, $L \times B \times H$ · **H** → air flow, ρ , h in/out, ACH, $L \times B \times H$ · **ACH** → air flow, ρ , h in/out, ACH, $L \times B \times H$

WHAT IT MEANS

Air changes per hour times the room volume gives the fan duty for ventilating a room (compressor rooms 10–20 ACH, engine rooms 20).

Worked example. $15 \times 10 \times 4$ m room at 10 ACH = 6,000 m³/hr (book); $15 \times 10 \times 4$ at 20 ACH = 12,000 m³/hr (2018/2022 objective).

Exam trap. ACH is per HOUR; divide by 3,600 for m³/s.

Water added in humidification

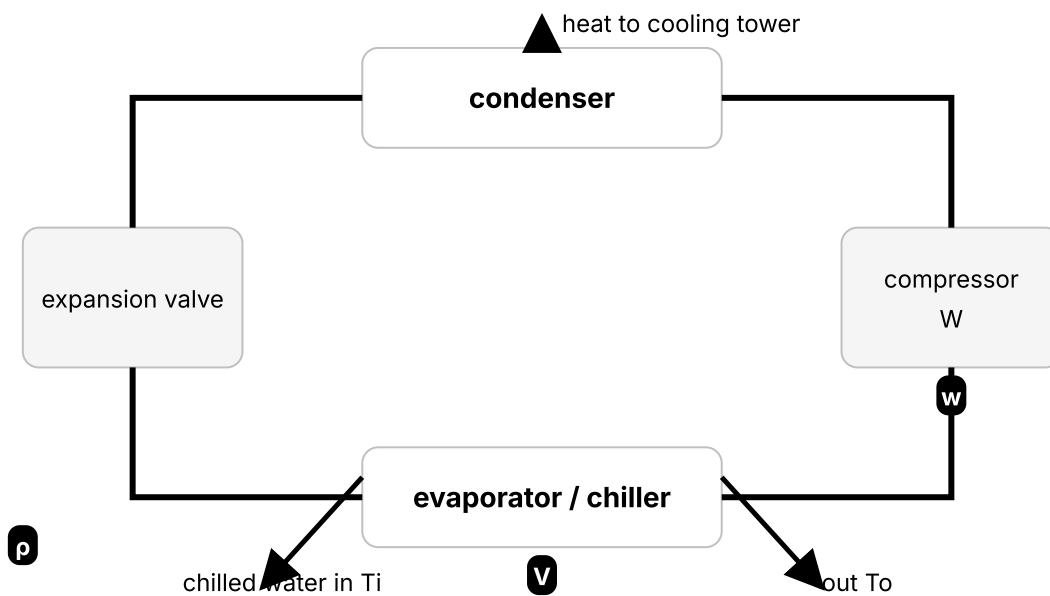
$$m = V \times \rho \times (w_2 - w_1)$$

SYMBOLS · UNITS

Symbols V = air flow (m^3/hr), ρ (kg/m^3), w = specific humidity (kg/kg dry air)

Answer unit kg/hr

Book topic Humidification



Where each value sits: $V \rightarrow Q$ flow kg/hr , C_p , T_i , $T_o \rightarrow TR$ · $p \rightarrow$ air flow, ρ , h in/out, ACH, $L \times B \times H$ · $w \rightarrow$ power input kW, W

WHAT IT MEANS

Spraying water into air raises its moisture content; the water needed is the air mass flow times the rise in specific humidity.

Worked example. $3,000 \text{ m}^3/\text{h} \times 1.2 \times (0.0062 - 0.002) = 15.1 \text{ kg}/\text{h}$ (book textile example).

Exam trap. Humidity is per kg of DRY air; DBT falls during adiabatic humidification.

Condenser water flow norm

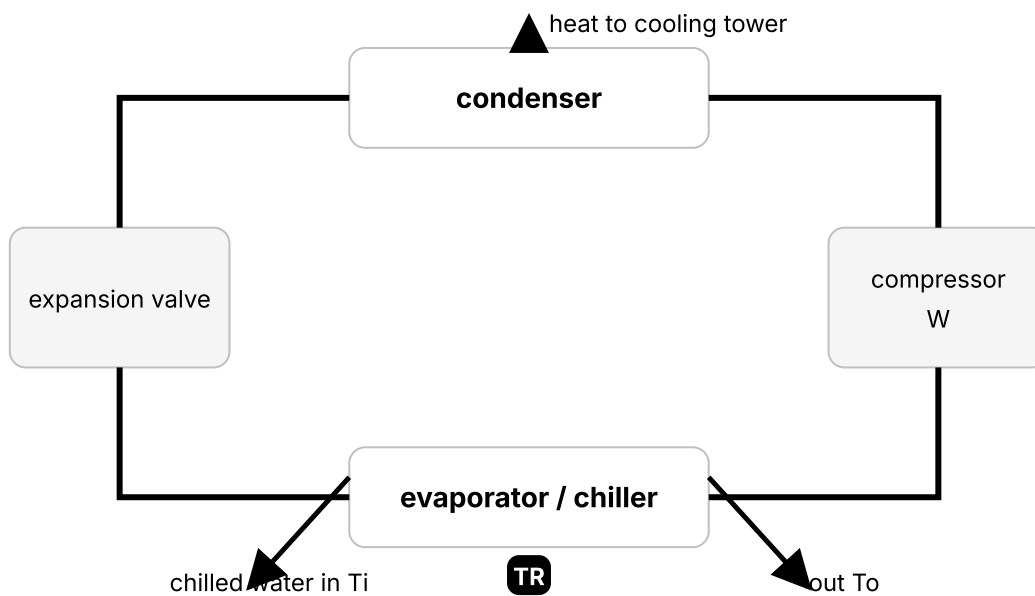
$\approx 0.91 \text{ m}^3/\text{hr}$ per TR (4 gpm per TR)

SYMBOLS · UNITS

Symbols TR

Answer unit m^3/hr per TR

Book topic Performance assessment



Where each value sits: **TR** $\rightarrow$ Q flow kg/hr, Cp, T_i , $T_o \rightarrow$ TR

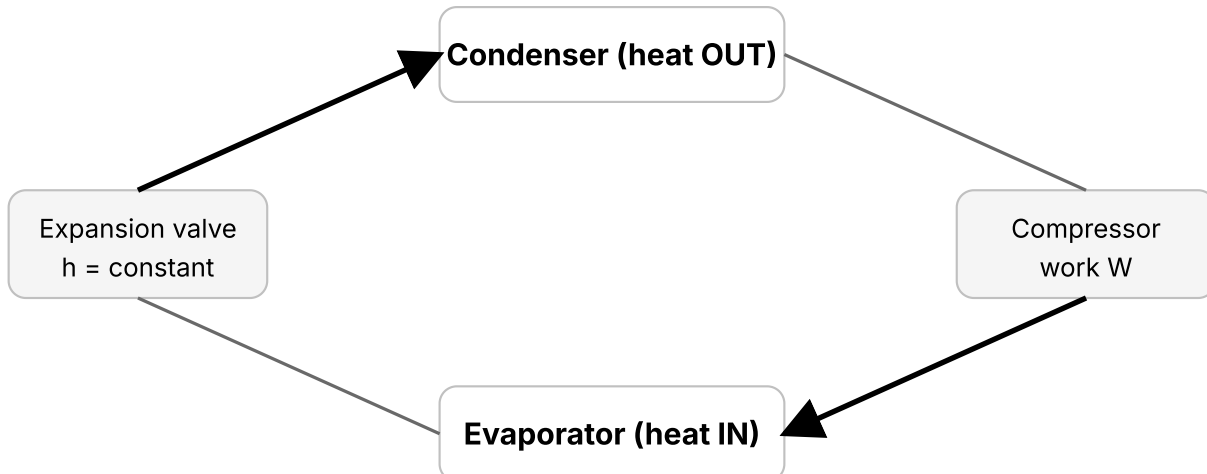
WHAT IT MEANS

Design rule: about $0.91 \text{ m}^3/\text{hr}$ (4 US gpm) of cooling water per ton — used to check whether the condenser is starved of water.

Worked example. 250 TR chiller $\rightarrow \approx 228 \text{ m}^3/\text{hr}$ condenser water.

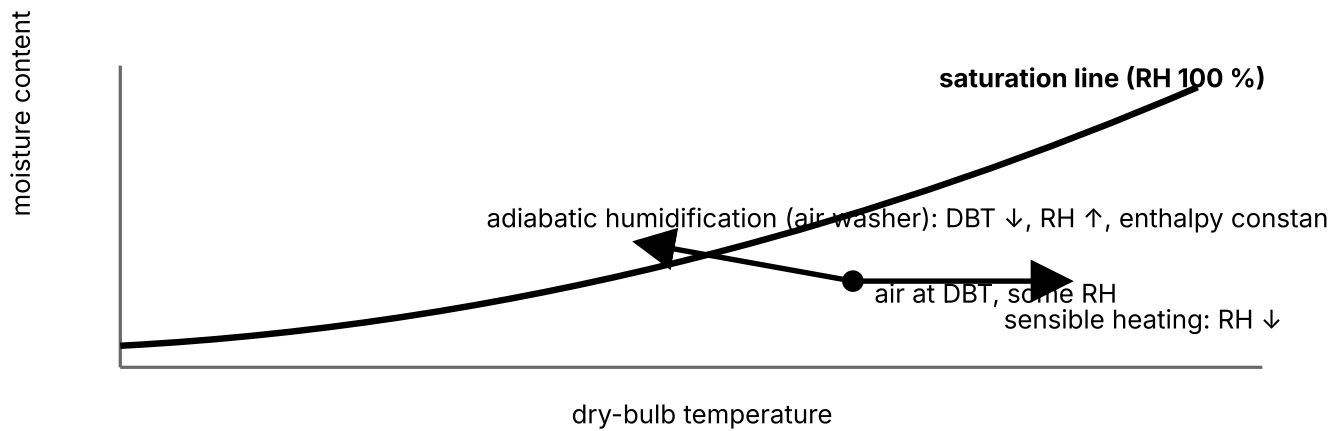
Exam trap. This is a check figure, not a formula to derive.

Vapour-compression cycle



Heat rejected at condenser = cooling effect + compressor work. COP = cooling ÷ W. Enthalpy stays constant

Psychrometric chart basics



DEFINITIONS THE EXAM ASKS

Vapour compression vs absorption

VCR: compressor (electrical) drives the cycle, COP 3–5. VAM: generator (heat) drives it with absorbent LiBr or water-ammonia, COP 0.65–1.2, uses waste heat/steam. Ammonia is the refrigerant common to both; 'generator' is the VAM part that is NOT in VCR; 'absorber' likewise.

Refrigerants

CFCs (R-11, R-12) phased out for ozone; HCFC R-22 being phased out; HFC R-134a; natural: ammonia (R-717), CO₂, hydrocarbons.

Chilled-water temperature

Raising the chilled-water leaving temperature by 1 °C improves compressor efficiency ≈ 3 %; lowering condenser temperature does the same.

Psychrometry terms

DBT, WBT, RH, dew point, specific humidity, enthalpy; when DBT = WBT the air is saturated.

Star labelling of room ACs

Based on EER (W/W) at standard test conditions; higher EER = more stars.

VERIFIED VIDEOS FOR THIS CHAPTER (YOUTUBE)

VCR 4-Stage Cycle vs. VAM — Refrigeration Capacity, kW/TR, Coefficient of Performance #COP · Nishant Bajpai's FinTech Education

Psychrometrics & Air Washers — What is a Refrigeration Ton + CALCULATIONS chiller hvac btu kw · The Engineering Mindset

Chiller Efficiency & Fouling — COP and KW per Ton · VRF Wizard

Chapter 5 • Fans and Blowers

~11 marks: fan laws (power $\propto N^3$) and static-efficiency numericals; fan types, dampers vs VFD, ASME classification.



Industrial centrifugal fan on its motor base

Photo: SAF · CC BY-SA 4.0 · source



Axial-flow fan — air enters and leaves along the shaft with no change of direction

Photo: Bobbie4 (talk) · Public domain · source



Pitot-static tube — measures velocity pressure for duct flow

Photo: Z22 · CC BY-SA 3.0 · source

ASME specific ratio

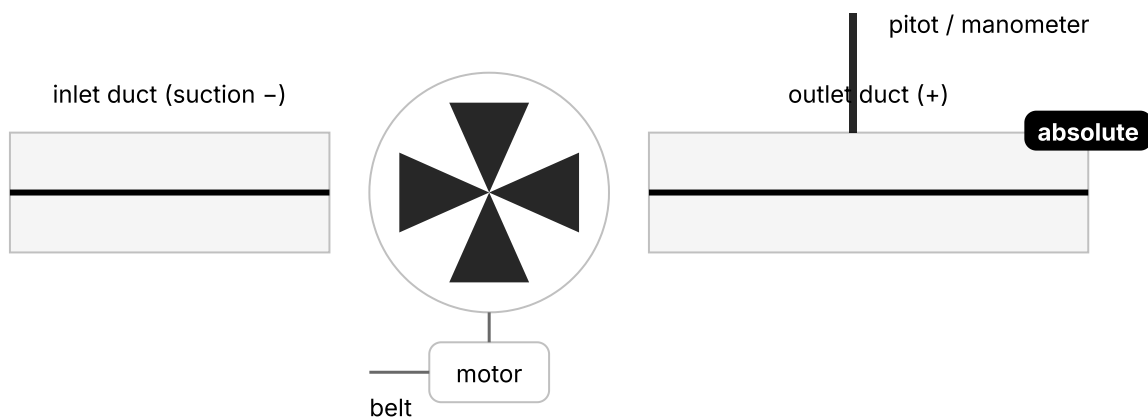
$$SR = \text{Discharge pressure} \div \text{Suction pressure}$$

SYMBOLS · UNITS

Symbols absolute pressures

Answer unit no unit (fan ≤ 1.11 , blower 1.11–1.20, compressor > 1.20)

Book topic Fan / blower / compressor



Where each value sits: **absolute** → duct area A



WHAT IT MEANS

Fans, blowers and compressors are classified by the pressure ratio they develop, not by their construction.

Worked example. Discharge 1.10 bar abs $\div$ suction 1.0 $\rightarrow$ 1.10: a fan.

Exam trap. Fan ≤ 1.11 , blower 1.11–1.20, compressor > 1.20 (2013/2017/2022 objective).

Fan law – flow

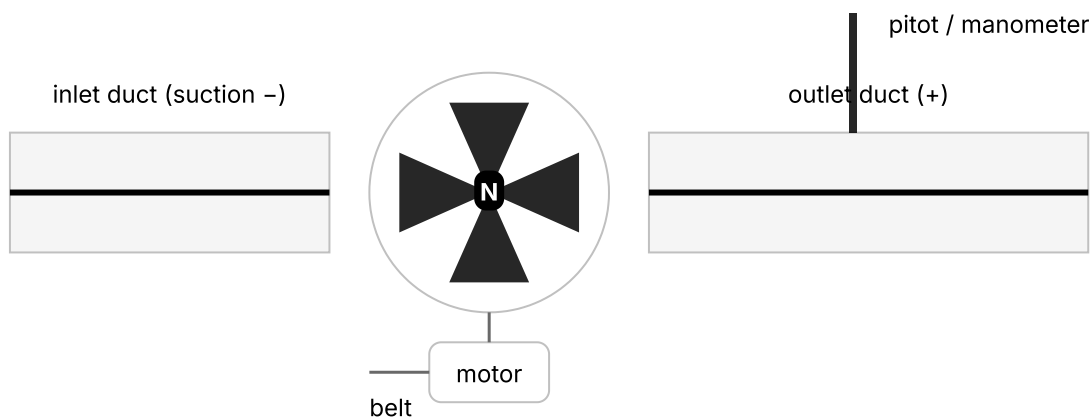
$$Q_2 \div Q_1 = N_2 \div N_1$$

SYMBOLS · UNITS

Symbols N = fan speed (rpm)

Answer unit m³/s (same as Q₁)

Book topic Fan laws



Where each value sits: **N** → speed N

► Try it: Fan laws: slow the fan down — power falls with the CUBE of speed



fan speed N

flow  75 %

pressure  56 %

power  42 %

At 75 % speed: flow 75 %, pressure 56 %, **power 42 %** — e.g. 16 kW → 6.75 kW

WHAT IT MEANS

Flow is directly proportional to speed: 10 % less speed = 10 % less air.

Worked example. 800 → 600 rpm: flow falls to 75 %.

Exam trap. This is the only linear fan law.

Fan law – pressure

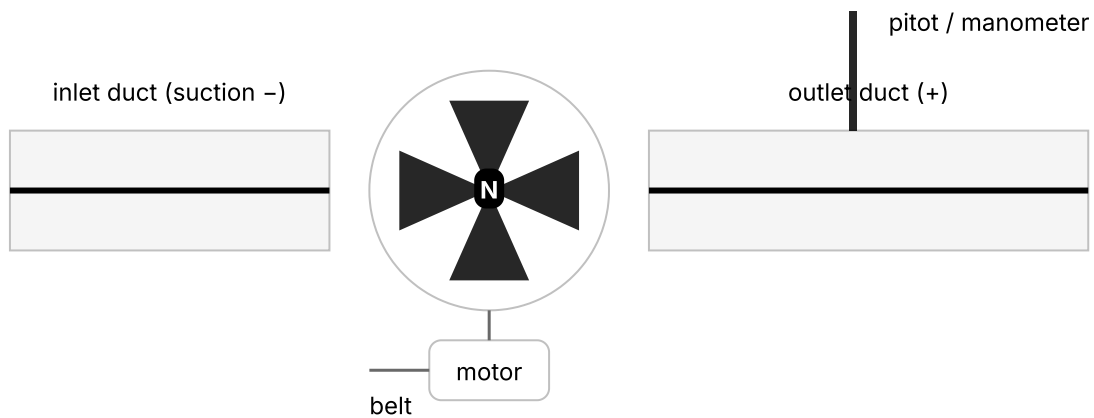
$$SP_2 \div SP_1 = (N_2 \div N_1)^2$$

SYMBOLS · UNITS

Symbols N (rpm)

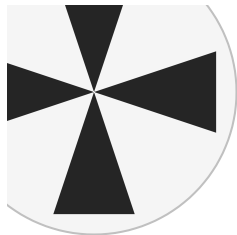
Answer unit mmWC

Book topic Fan laws



Where each value sits: **N** → speed N

► Try it: Fan laws: slow the fan down — power falls with the CUBE of speed



fan speed N

flow  75 %

pressure  56 %

power  42 %

At 75 % speed: flow 75 %, pressure 56 %, **power 42 %** — e.g. 16 kW → 6.75 kW

WHAT IT MEANS

Pressure rises with the square of speed.

Worked example. Speed $\times 1.1 \rightarrow$ pressure $\times 1.21$.

Exam trap. Square, not cube, for pressure.

Fan law – power

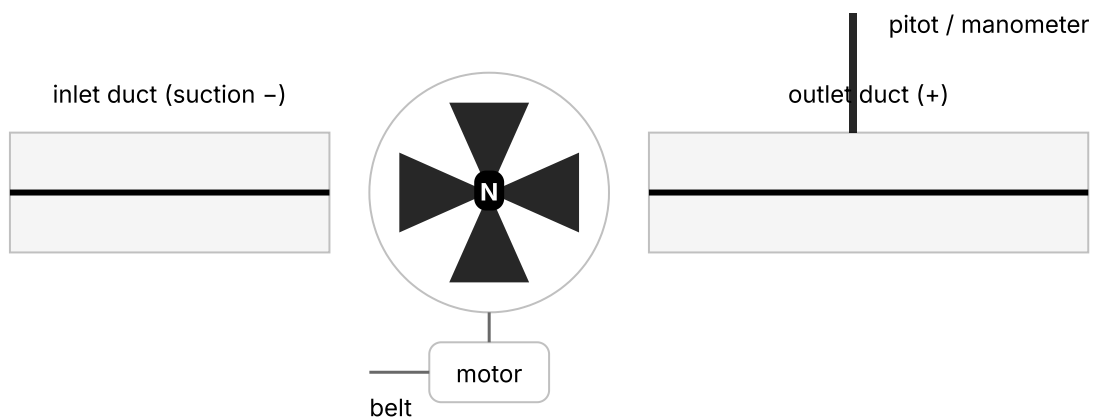
$$kW_2 \div kW_1 = (N_2 \div N_1)^3$$

SYMBOLS · UNITS

Symbols N (rpm)

Answer unit kW

Book topic Fan laws



Where each value sits: **N** → speed N

► Try it: Fan laws: slow the fan down — power falls with the CUBE of speed



fan speed N

flow  75 %

pressure  56 %

power  42 %

At 75 % speed: flow 75 %, pressure 56 %, **power 42 %** — e.g. 16 kW → 6.75 kW

WHAT IT MEANS

Power rises with the CUBE of speed — the whole case for VFDs on fans: 20 % less flow needs only 51 % of the power.

Worked example. 16 kW at 800 rpm → at 600 rpm: $16 \times (600/800)^3 = 6.75$ kW
(2018/2021/2024). 52 kW at 49 Hz → at 47 Hz: $52 \times (47/49)^3 = 45.9$ kW.

Exam trap. Cube the speed RATIO; a damper does not follow this law — only speed change does.

Total pressure

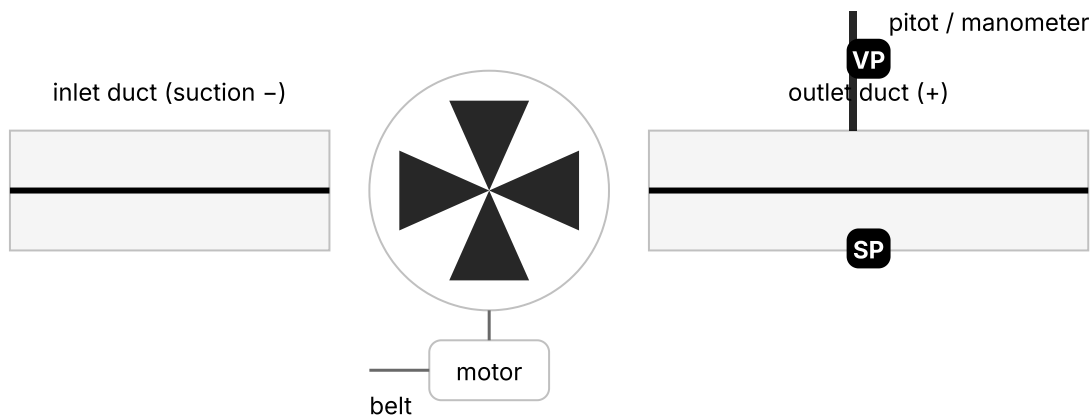
$$TP = SP + VP$$

SYMBOLS · UNITS

Symbols SP = static, VP = velocity pressure (mmWC)

Answer unit mmWC

Book topic Fan performance



Where each value sits: **SP** → static pressure outlet · **VP** → velocity pressure Δp , C_p

WHAT IT MEANS

Total = static (pushes on the duct walls) + velocity (from the moving air).

Worked example. SP 40 mmWC, VP 5 → TP 45.

Exam trap. Velocity pressure is what a pitot tube measures as the difference between total and static ports.

Air velocity from pitot-tube reading

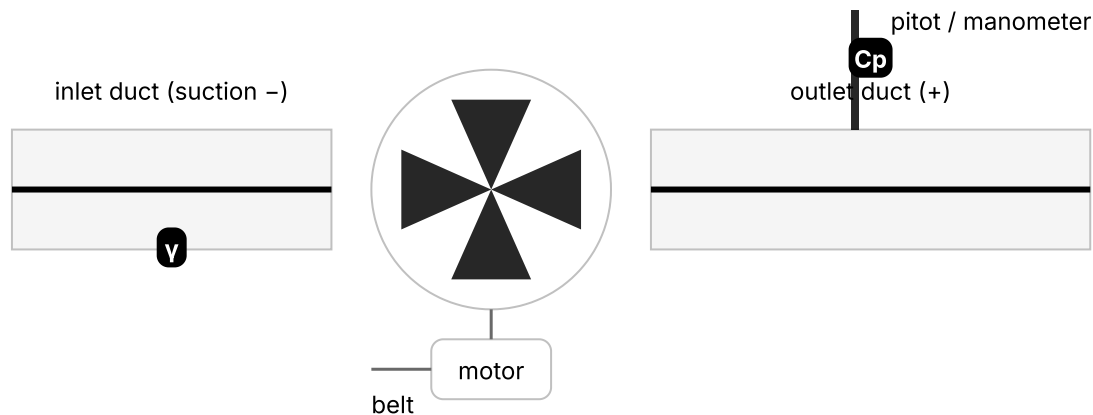
$$v = C_p \times \sqrt{(2 \times 9.81 \times \Delta p \times \gamma) \div \gamma}$$

SYMBOLS · UNITS

Symbols C_p = pitot coefficient (≈ 0.85), Δp = velocity pressure (mmWC), γ = gas density (kg/m^3)

Answer unit **m/s**

Book topic Flow measurement



Where each value sits: **C_p** → velocity pressure Δp , **Δp** → velocity pressure Δp , **γ** → gas density γ , T, M

WHAT IT MEANS

Convert the velocity-pressure reading on a manometer into air speed, corrected for the pitot coefficient and the gas density.

Worked example. C_p 0.9, Δp 47 mmWC, γ 1.135 → $0.9 \times \sqrt{(2 \times 9.81 \times 47 \times 1.135)/1.135} = 25.6$ m/s (book example).

Exam trap. Density at the FLOW temperature, not at 0 °C.

Gas density (ideal gas)

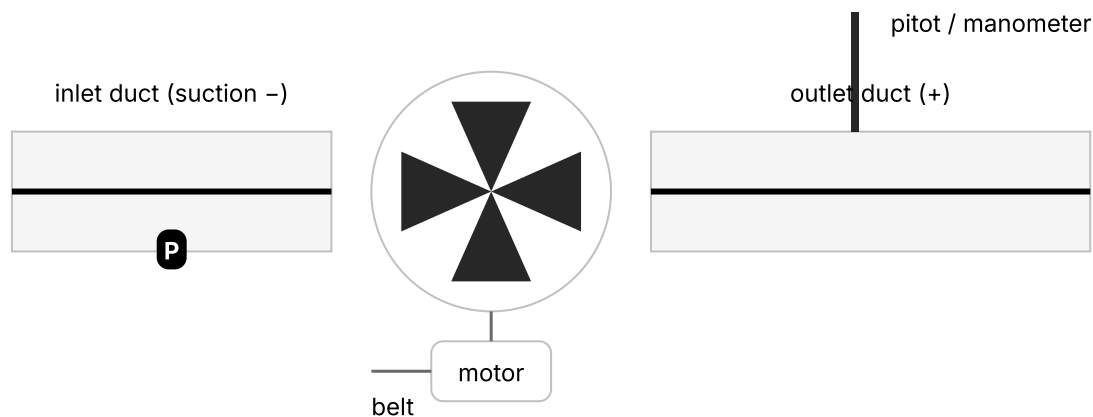
$$\gamma = P \times M \div (R \times T)$$

SYMBOLS · UNITS

Symbols P = absolute pressure (mmWC), M = mol. weight (air 28.92), R = 847.84 mmWC·m³/kg·mole·K, T (K)

Answer unit kg/m³

Book topic Flow measurement



Where each value sits: **P** → gas density γ , T, M · **M** → gas density γ , T, M · **R** → gas density γ , T, M · **m³/kg-mole** → gas density γ , T, M · **K**: K · **T** → gas density γ , T, M

WHAT IT MEANS

Density falls as the gas gets hotter or the pressure drops; needed before velocity and mass-flow calculations for hot flue gas.

Worked example. Air at 10,330 mmWC, 311 K: $10,330 \times 28.92 \div (847.84 \times 311) = 1.133 \text{ kg/m}^3$.

Exam trap. Absolute pressure in mmWC and T in kelvin with R = 847.84.

Air density at t °C

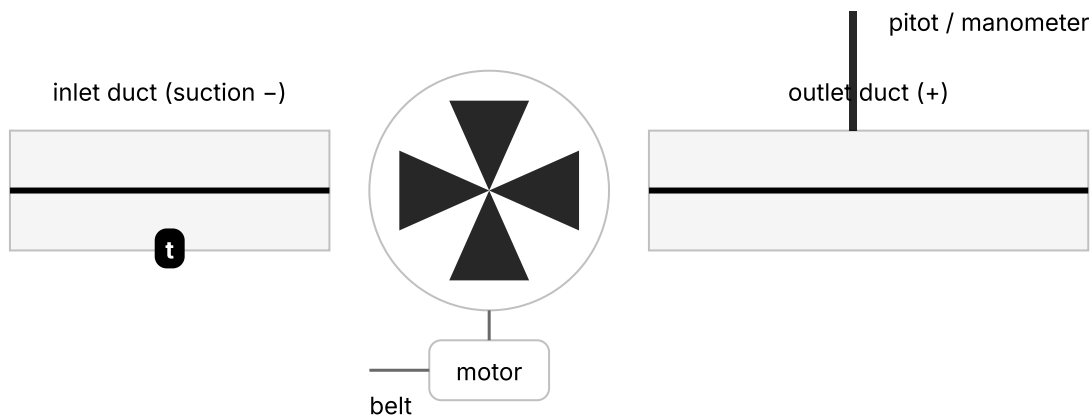
$$\gamma = 1.293 \times 273 \div (273 + t)$$

SYMBOLS · UNITS

Symbols 1.293 kg/m³ at 0 °C; t (°C)

Answer unit kg/m³

Book topic Flow measurement



Where each value sits: **1.293**: 1.293 kg/m³ at 0 °C · **t** → gas density γ , T, M

WHAT IT MEANS

Quick correction from the standard 1.293 kg/m³ at 0 °C.

Worked example. At 38 °C: $1.293 \times 273/311 = 1.135$ kg/m³.

Exam trap. Kelvin ratio, with 273 on top.

Molecular weight of flue gas (dry)

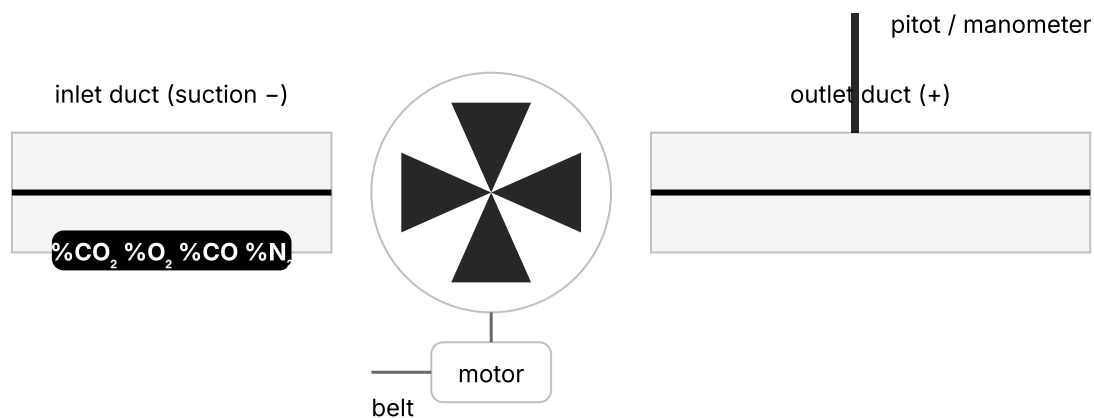
$$M = (\%CO_2 \times 44 + \%O_2 \times 32 + \%CO \times 28 + \%N_2 \times 28) \div 100$$

SYMBOLS · UNITS

Symbols gas analysis in % (dry basis)

Answer unit kg/kg-mole

Book topic Flow measurement



Where each value sits: $\%CO_2$ $\%O_2$ $\%CO$ $\%N_2$ → gas density γ , T, M · **M** → gas density γ , T, M

WHAT IT MEANS

Weighted average of the gases in the flue-gas analysis; used in the density formula for boiler ID/FD fans.

Worked example. 12 % CO_2 , 6 % O_2 , 82 % N_2 → $0.12 \times 44 + 0.06 \times 32 + 0.82 \times 28 = 30.2$.

Exam trap. Dry basis; water vapour is excluded.

Volume flow in a duct

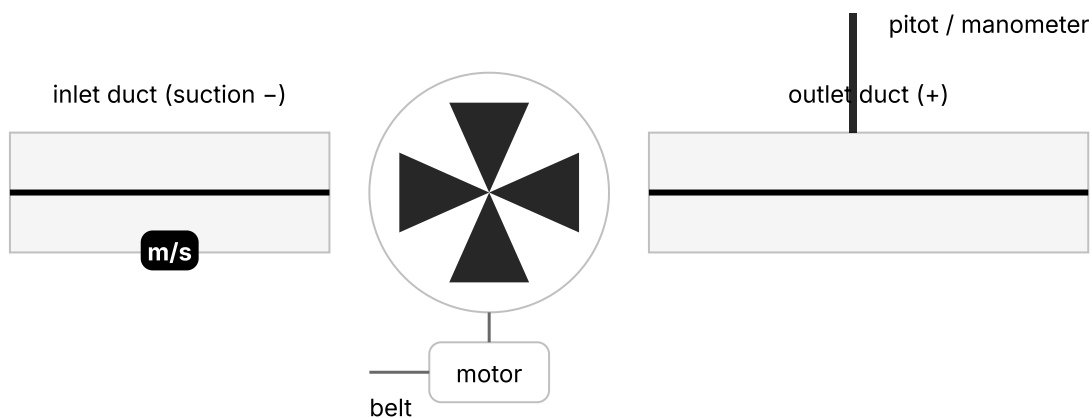
$$Q = \text{Velocity} \times \text{Duct area}$$

SYMBOLS · UNITS

Symbols $\text{m/s} \times \text{m}^2$

Answer unit m^3/s

Book topic Flow measurement



Where each value sits: **m/s** → gas density γ , T, M

WHAT IT MEANS

Average velocity from a pitot traverse times the duct cross-section.

Worked example. $25.6 \text{ m/s} \times 0.5 \text{ m}^2 = 12.8 \text{ m}^3/\text{s}$.

Exam trap. Use the average of several traverse points, not the centre-line reading.

Fan mechanical (total) efficiency

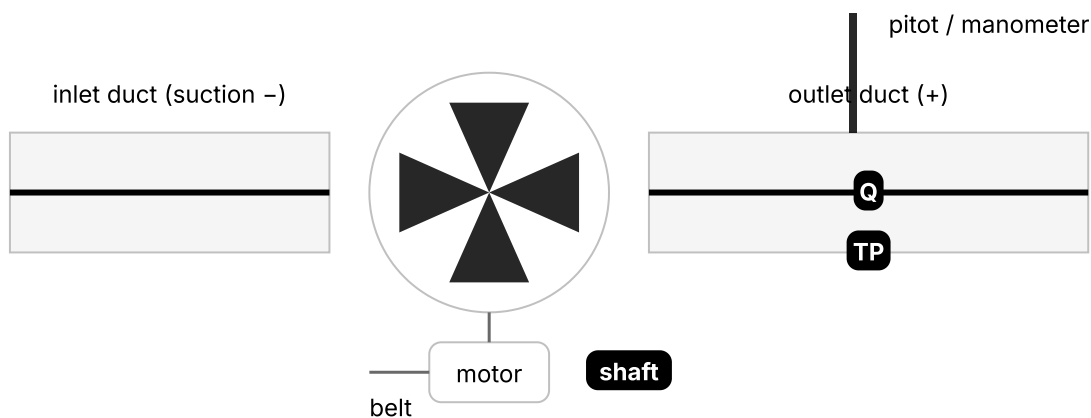
$$\eta = Q \times TP \div (102 \times \text{Shaft kW}) \times 100$$

SYMBOLS · UNITS

Symbols Q (m³/s), TP = total pressure (mmWC), shaft power (kW)

Answer unit %

Book topic Fan efficiency



Where each value sits: **Q** → air flow Q · **TP** → static pressure outlet · **shaft** → motor kW, η motor

WHAT IT MEANS

How well the shaft power becomes air power, counting both static and velocity pressure.

Worked example. $12.65 \text{ m}^3/\text{s} \times 210 \text{ mmWC} \div (102 \times 67.65 \text{ kW}) = 38.5 \%$.

Exam trap. $102 = 1000 \div 9.81$, converting $\text{m}^3/\text{s} \times \text{mmWC}$ to kW.

Fan static efficiency

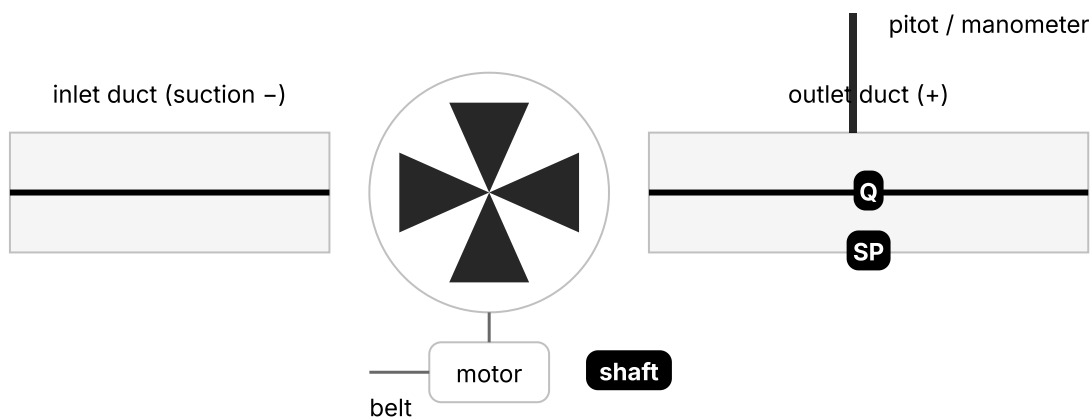
$$\eta = Q \times SP \div (102 \times \text{Shaft kW}) \times 100$$

SYMBOLS · UNITS

Symbols Q (m³/s), SP = static pressure rise (mmWC), shaft power (kW)

Answer unit %

Book topic Fan efficiency



Where each value sits: **Q** → air flow Q · **SP** → static pressure outlet · **shaft** → motor kW, η motor

WHAT IT MEANS

Same, but counting only the static pressure rise — the usual figure quoted, and what the exam asks (2019 L-1, 2021 S-7).

Worked example. $12.65 \times (185 - (-20)) \div (102 \times 67.65) = 37.6 \%$ (book example).

Exam trap. Inlet static pressure is NEGATIVE (suction): $185 - (-20) = 205$.

Power input to fan shaft

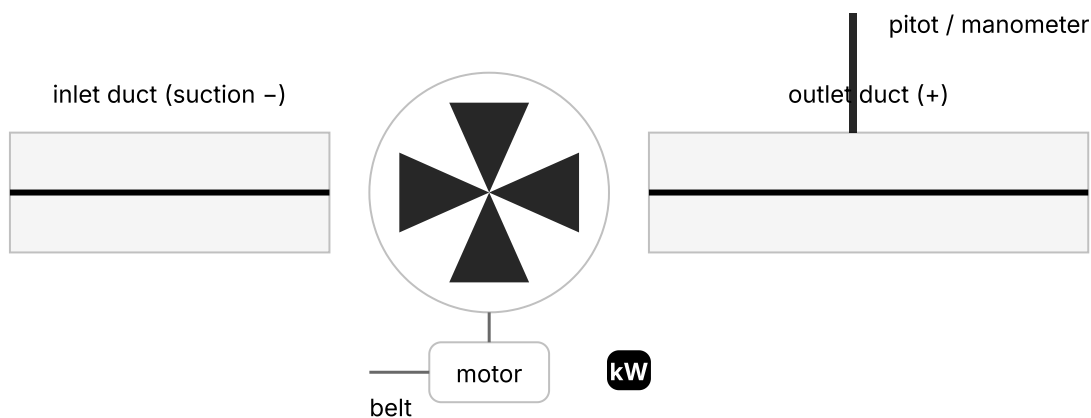
$$= \text{Motor input kW} \times \eta_{\text{motor}} (\times \eta_{\text{belt drive}})$$

SYMBOLS · UNITS

Symbols kW; η as fractions

Answer unit kW

Book topic Fan efficiency



Where each value sits: **kW** → motor kW, η_{motor} · η : η as fractions

WHAT IT MEANS

Motor input kW is not fan input: subtract the motor loss and, for belt drives, the belt loss.

Worked example. 75 kW input $\times$ 0.97 (motor) $\times$ 0.93 (belt) = 67.65 kW (book).

Exam trap. Use shaft power in the efficiency formula, never motor input.

Static pressure rise across the fan

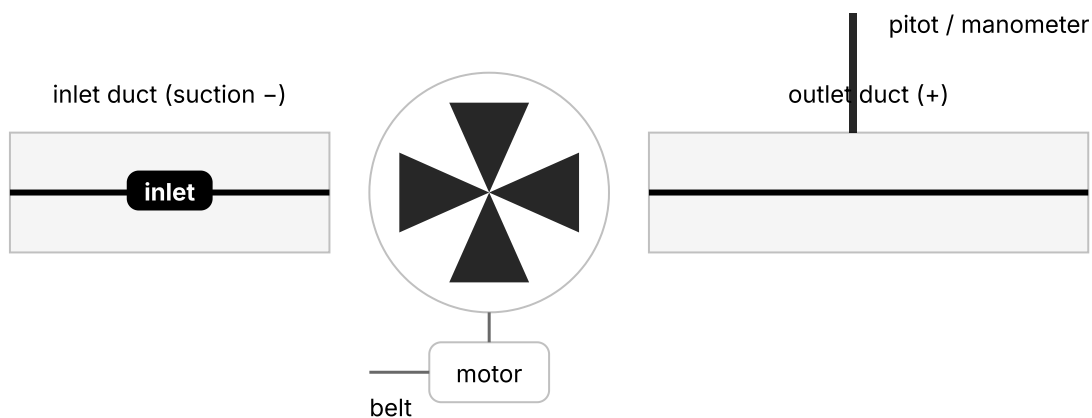
$$= \text{SP outlet} - \text{SP inlet}$$

SYMBOLS · UNITS

Symbols inlet (suction) pressure is negative (mmWC)

Answer unit mmWC

Book topic Fan performance



Where each value sits: **inlet** → static pressure inlet

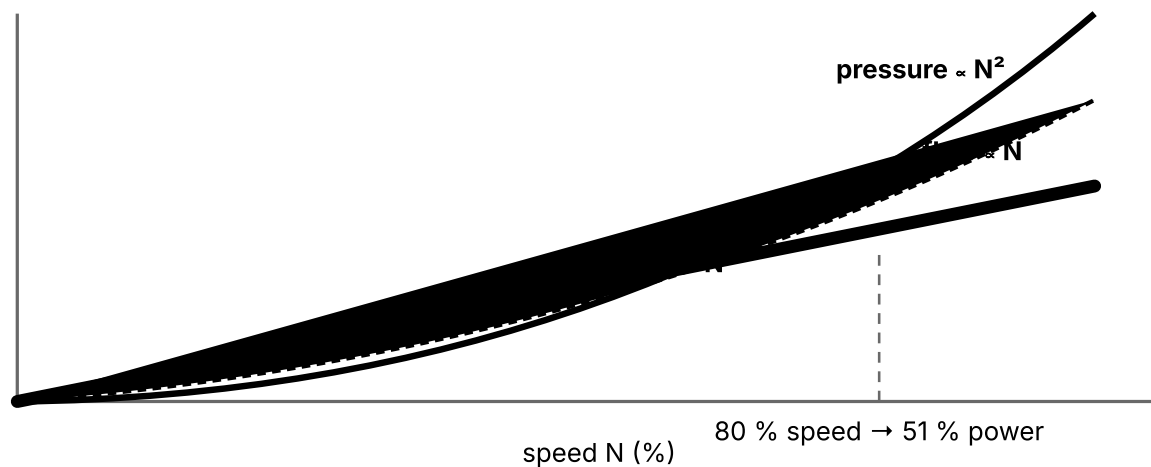
WHAT IT MEANS

The pressure the fan adds: outlet static minus inlet static, remembering the inlet is usually below atmosphere.

Worked example. Outlet +10, inlet -230 → 240 mmWC (book ID fan).

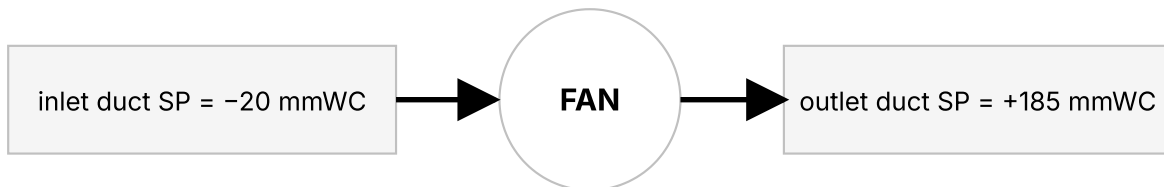
Exam trap. Two negatives: subtracting a negative inlet ADDS.

The three fan laws



Static pressure rise across a fan

Static rise across the fan = $185 - (-20) = 205 \text{ mmWC}$ · $\eta_{\text{static}} = Q \times 205 \div (102 \times \text{shaft } k')$



Total pressure = static + velocity pressure; the pitot tube reads velocity pressure $\rightarrow v = C_p \sqrt{(2 \cdot 9.81 \cdot \Delta p / \gamma)}$

DEFINITIONS THE EXAM ASKS

Fan types

Centrifugal: radial (dust), forward-curved (low pressure, HVAC), backward-curved/inclined (non-overloading, most efficient). Axial: propeller, tube-axial, vane-axial — air does not change direction.

System resistance

Depends on ducts, bends, dampers, pickups; $\propto \text{flow}^2$. Larger ducts and fewer bends lower it.

Flow control

Damper (wastes energy), inlet guide vanes (better, modest range), variable speed (best — power $\propto N^3$), pulley change (cheap, permanent).

Non-overloading fan

Backward-curved fans — power peaks then falls with flow, so the motor cannot be overloaded.

VERIFIED VIDEOS FOR THIS CHAPTER (YOUTUBE)

ASME Specific Ratio & Fan Types — Three Key Fan Laws Explained: Airflow vs. Static Pressure vs. Horsepower · The New York Blower Company

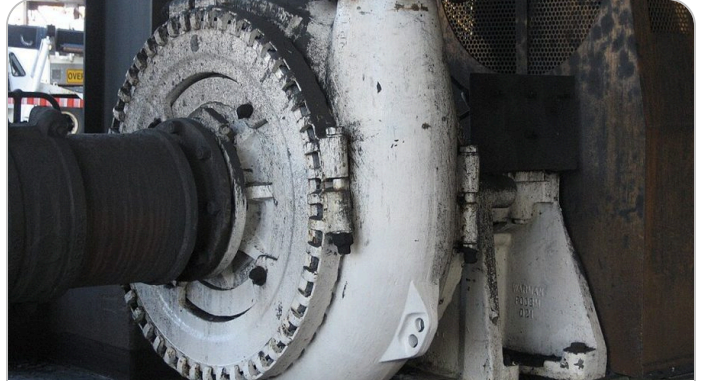
Chapter 6 • Pumps and Pumping System

~18 marks: pump power ($\rho g Q H$), efficiency and affinity/impeller-trimming numericals; throttling vs VFD; NPSH and cavitation.



Close-coupled centrifugal pumps with pressure gauges on suction and discharge

Photo: Saud · CC BY-SA 4.0 · [source](#)



Large centrifugal pump — impeller casing (volute) and suction inlet

Photo: Bernard S. Janse · CC BY 2.5 · [source](#)

Hydraulic power

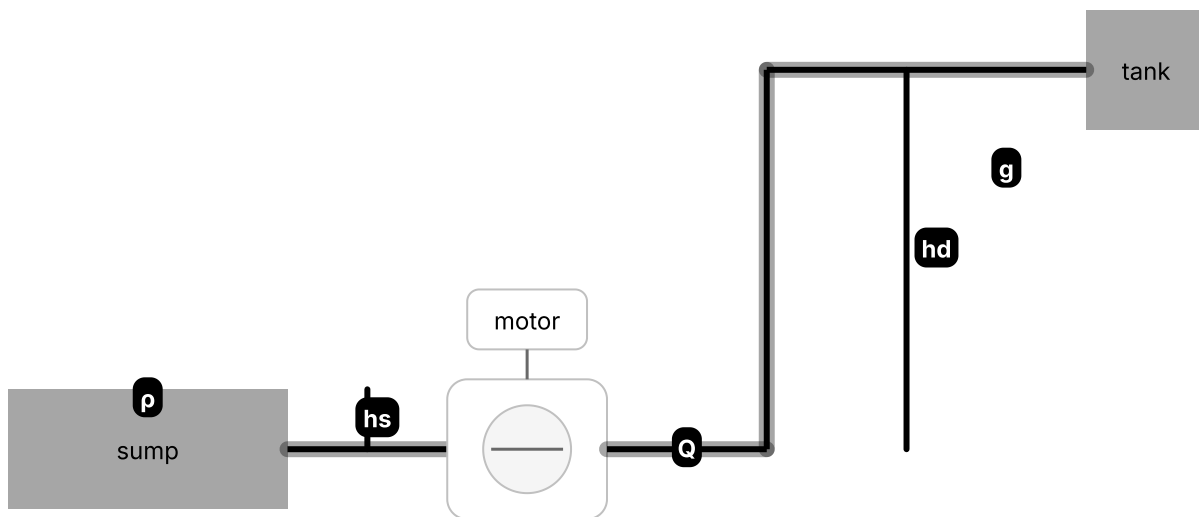
$$P_h = Q \times (h_d - h_s) \times \rho \times g \div 1000$$

SYMBOLS · UNITS

Symbols Q (m³/s), h_d = discharge head, h_s = suction head (m), ρ (kg/m³), $g = 9.81$ m/s²

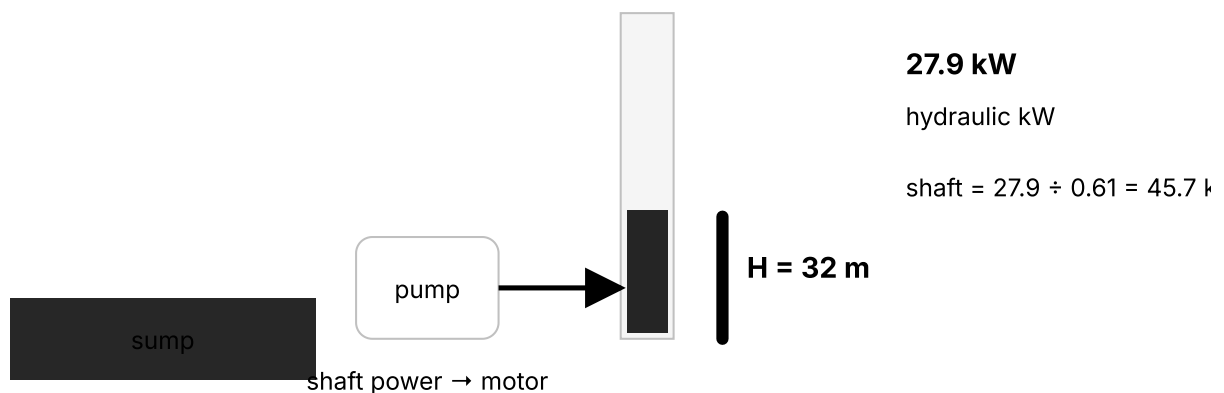
Answer unit **kW**

Book topic Pump power



Where each value sits: **Q** → pipe: flow Q · **hd** → discharge head h_d · **hs** → suction head h_s · **ρ** → liquid ρ · **g** → $g = 9.81$ m/s²

► Try it: Pump: change flow and head — watch the water rise and the power change



Hydraulic power = $0.0889 \text{ m}^3/\text{s} \times 32 \text{ m} \times 1000 \times 9.81 \div 1000 = \mathbf{27.9 \text{ kW}}$; shaft power at 61 %

$$= 45.7 \text{ kW}$$

WHAT IT MEANS

The power actually given to the water: how much flows (Q) times how high it is lifted (head) times the weight of water. This is the useful output of the pump.

Worked example. Q $0.0888 \text{ m}^3/\text{s}$, H 32 m, water: $0.0888 \times 32 \times 1000 \times 9.81 \div 1000 = 27.9 \text{ kW}$ (book example).

Exam trap. Q in m^3/SECOND ($\text{m}^3/\text{hr} \div 3600$); head in metres of the liquid pumped.

Pump shaft power

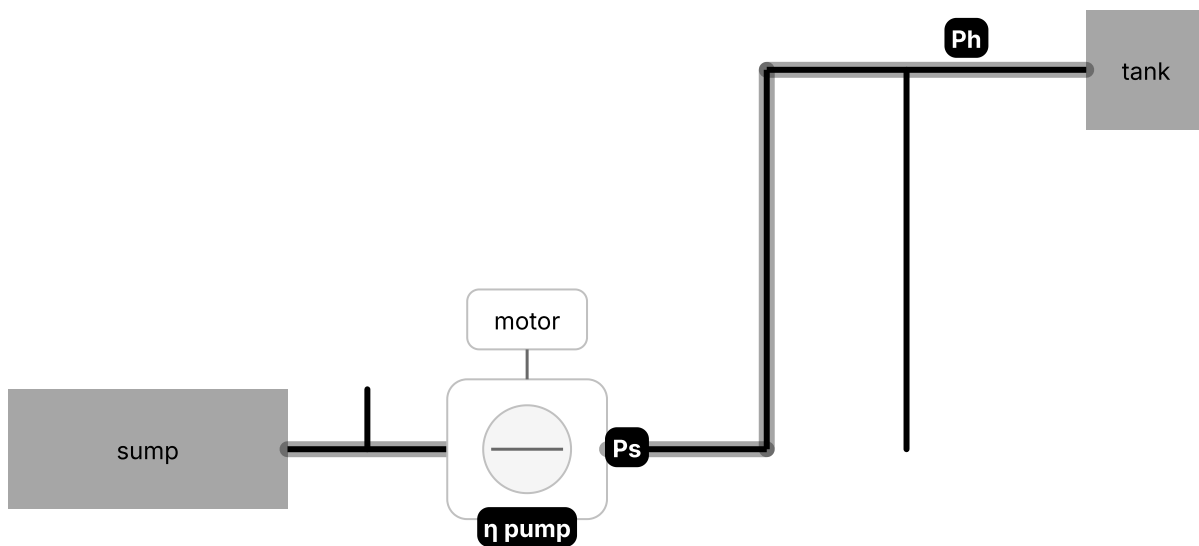
$$P_s = P_h \div \eta_{\text{pump}}$$

SYMBOLS · UNITS

Symbols kW; η as fraction

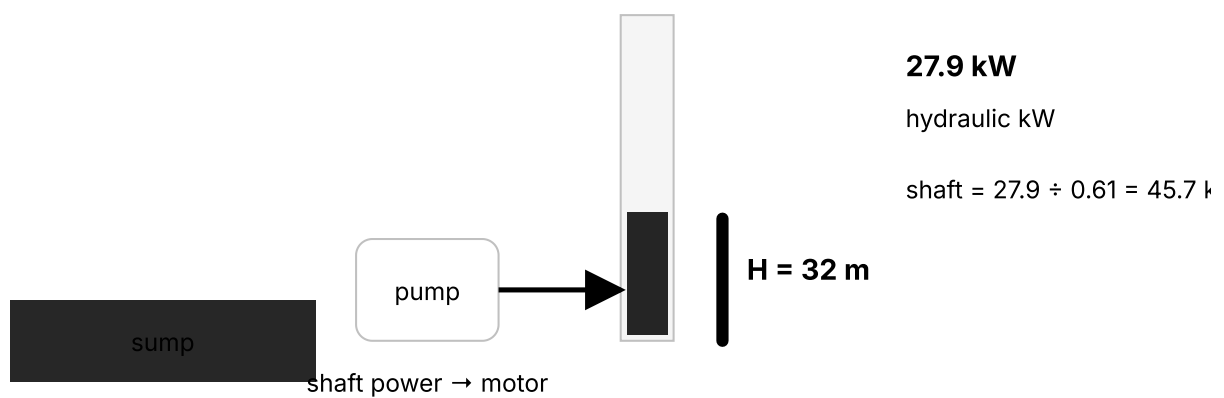
Answer unit **kW**

Book topic Pump power



Where each value sits: **P_h** → hydraulic power **η_{pump}** → pump η · **P_s** → shaft power P_s

► Try it: Pump: change flow and head — watch the water rise and the power change



Hydraulic power = $0.0889 \text{ m}^3/\text{s} \times 32 \text{ m} \times 1000 \times 9.81 \div 1000 = \mathbf{27.9 \text{ kW}}$; shaft power at 61 % = **45.7 kW**

WHAT IT MEANS

What the pump needs at its shaft; larger than hydraulic power because of the pump's own losses.

Worked example. $27.9 \text{ kW} \div 0.61 = 45.7 \text{ kW}$.

Exam trap. Divide by efficiency (a fraction), do not multiply.

Motor input power

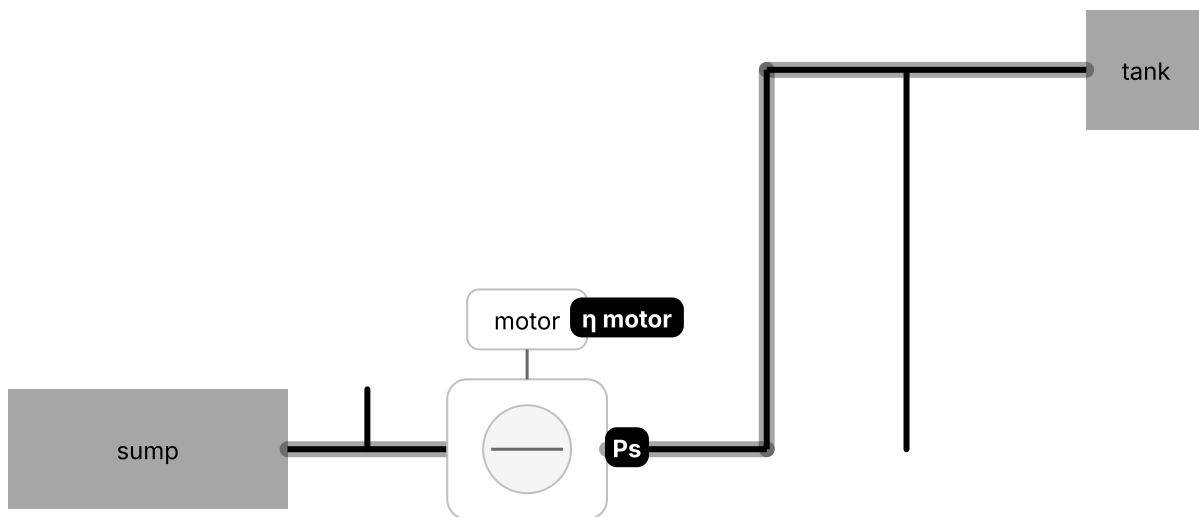
$$= P_s \div \eta_{\text{motor}}$$

SYMBOLS · UNITS

Symbols kW; η as fraction

Answer unit kW

Book topic Pump power



Where each value sits: **Ps** → shaft power P_s · **η_{motor}** → motor η , input kW · **input kW** → motor η , input kW

WHAT IT MEANS

What the electricity meter sees: shaft power plus the motor's losses.

Worked example. $45.7 \div 0.9 = 50.7$ kW.

Exam trap. Two efficiencies in series: hydraulic $\div \eta_{\text{pump}} \div \eta_{\text{motor}}$.

Pump efficiency

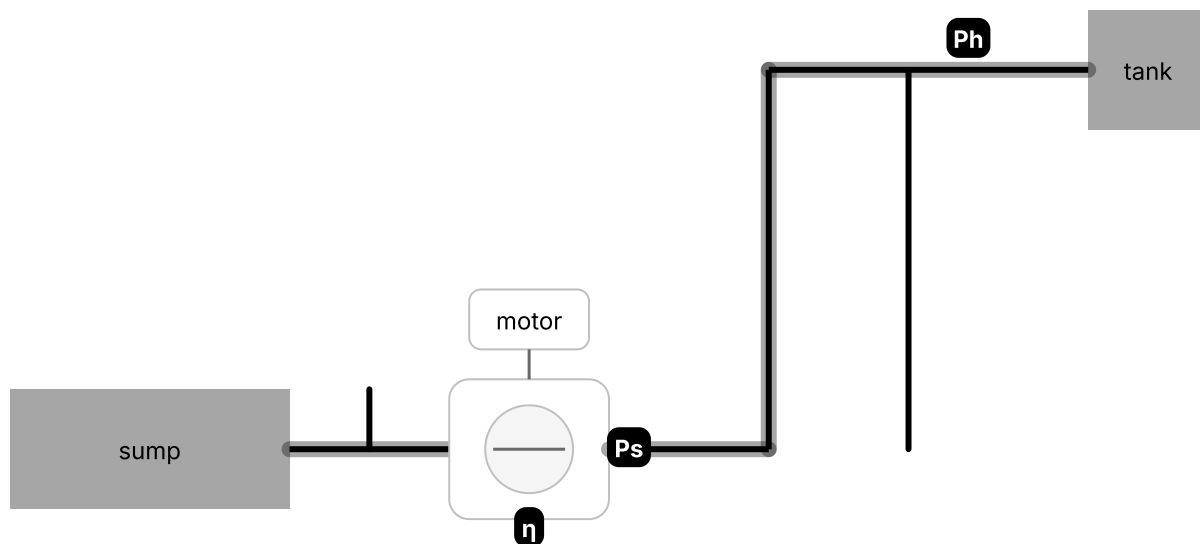
$$\eta_{\text{pump}} = P_h \div P_s \times 100$$

SYMBOLS · UNITS

Symbols kW

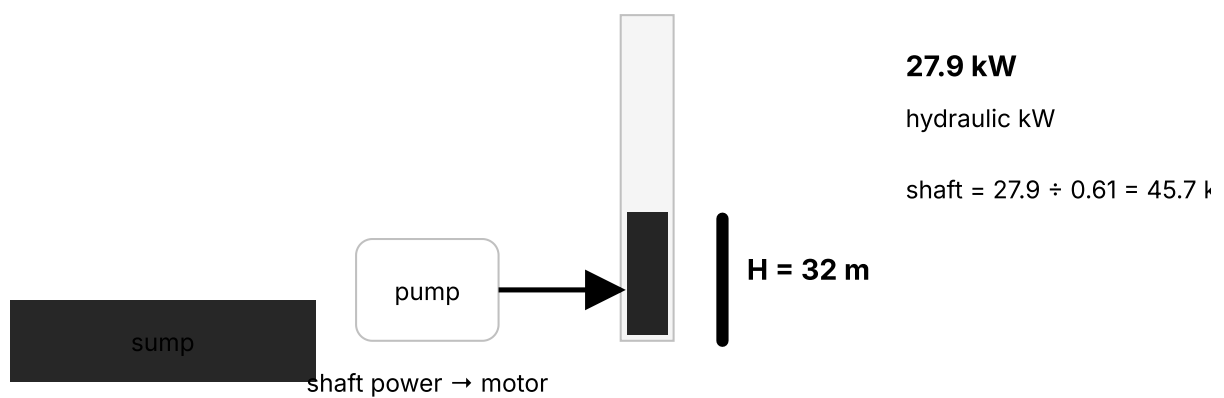
Answer unit %

Book topic Pump power



Where each value sits: **P_h** → hydraulic power **P_s** → shaft power **η** → pump η

► Try it: Pump: change flow and head — watch the water rise and the power change



Hydraulic power = $0.0889 \text{ m}^3/\text{s} \times 32 \text{ m} \times 1000 \times 9.81 \div 1000 = \mathbf{27.9 \text{ kW}}$; shaft power at 61 % = **45.7 kW**

WHAT IT MEANS

Useful water power divided by the shaft power; measured in an audit from flow, head and motor kW ($\times$ motor efficiency).

Worked example. Hydraulic 27.9 kW; motor 50.7 kW at 90 % $\rightarrow$ shaft 45.6 $\rightarrow \eta = 61 \%$ (book).

2024 S-6: 5 m suction + 30 m discharge, 150 m³/hr, 18 kW motor at 85 % $\rightarrow$ 15.3 kW shaft $\rightarrow \eta \approx 93 \%$... check numbers in the paper.

Exam trap. Use SHAFT power (motor kW $\times$ motor η), not motor input, or you understate efficiency.

Head from a pressure-gauge reading (water)

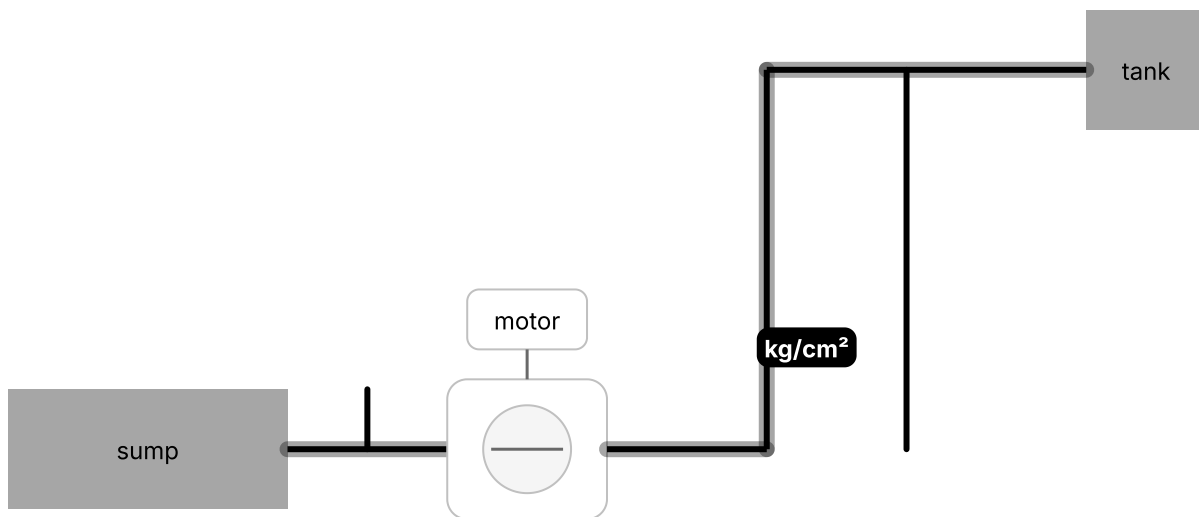
$$\text{Head (m)} = \text{Pressure (kg/cm}^2\text{)} \times 10$$

SYMBOLS · UNITS

Symbols kg/cm^2

Answer unit **m**

Book topic Pump head



Where each value sits: $\text{kg/cm}^2 \rightarrow$ pressure gauge kg/cm^2

WHAT IT MEANS

A pressure gauge in kg/cm^2 converts to metres of water column at about 10 m per kg/cm^2 ; add suction lift (or subtract positive suction head) to get total head.

Worked example. Discharge $2.6 \text{ kg/cm}^2 = 26 \text{ m}$; water 4 m BELOW pump centreline $\rightarrow$ total head 30 m (2013 exam). 3.0 kg/cm^2 with +5 m positive suction $\rightarrow 30 - 5 = 25 \text{ m}$ (2024).

Exam trap. Suction lift ADDS to head; positive suction head SUBTRACTS.

Affinity law – flow and speed

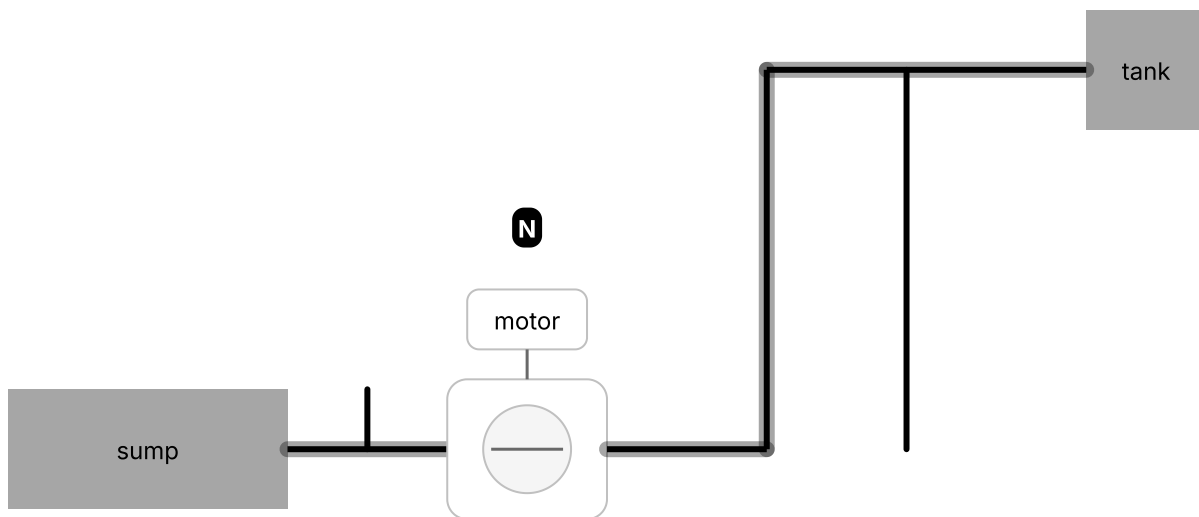
$$Q_1 \div Q_2 = N_1 \div N_2$$

SYMBOLS · UNITS

Symbols N = speed (rpm)

Answer unit m^3/hr

Book topic Affinity laws



Where each value sits: **N** → speed N , impeller D

WHAT IT MEANS

Flow moves in step with speed.

Worked example. $3000 \rightarrow 1500$ rpm: $100 \text{ m}^3/\text{hr} \rightarrow 50$ (book).

Exam trap. Linear — the only one.

Affinity law – head and speed

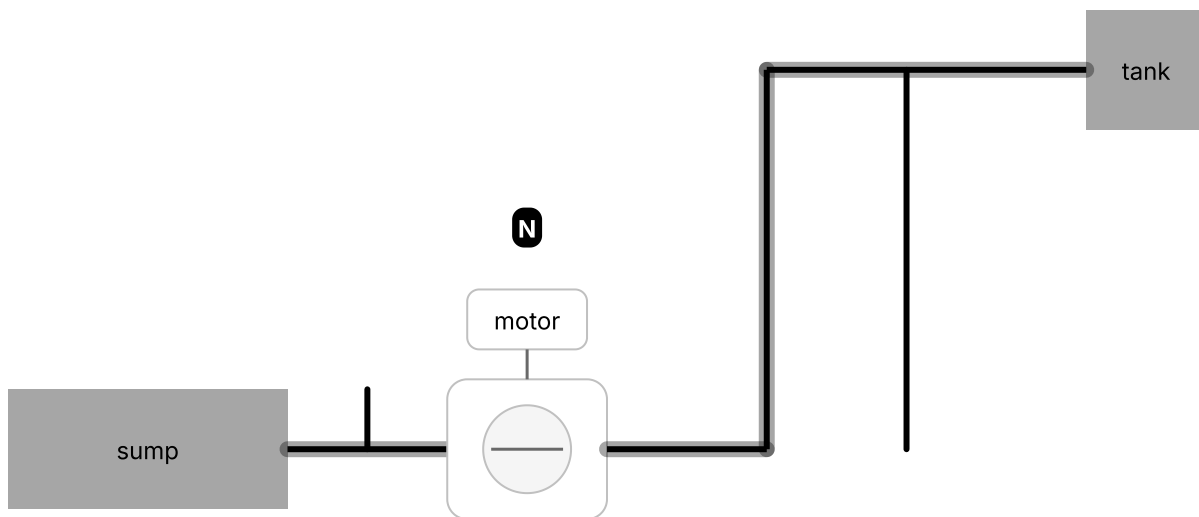
$$H_1 \div H_2 = (N_1 \div N_2)^2$$

SYMBOLS · UNITS

Symbols N (rpm)

Answer unit **m**

Book topic Affinity laws



Where each value sits: **N** → speed N , impeller D

WHAT IT MEANS

Head varies with the square of speed.

Worked example. Speed halved → head 100 m → 25 m (book).

Exam trap. Square.

Affinity law – power and speed

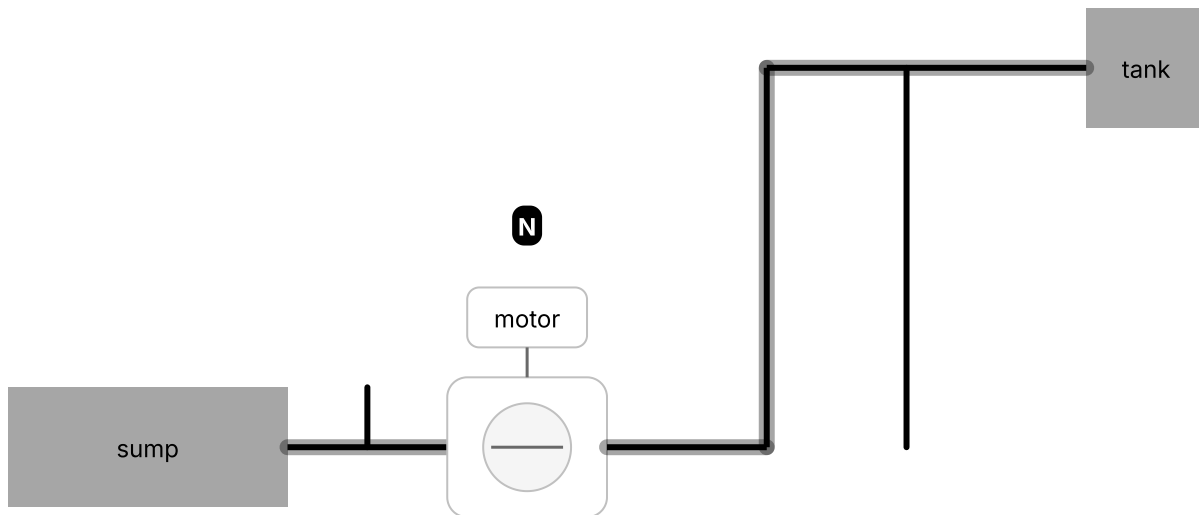
$$kW_1 \div kW_2 = (N_1 \div N_2)^3$$

SYMBOLS · UNITS

Symbols N (rpm)

Answer unit kW

Book topic Affinity laws



Where each value sits: **N** → speed N, impeller D

► Try it: Fan laws: slow the fan down — power falls with the CUBE of speed



fan speed N

flow  75 %

pressure  56 %

power  42 %

At 75 % speed: flow 75 %, pressure 56 %, **power 42 %** — e.g. 16 kW → 6.75 kW

WHAT IT MEANS

Power varies with the CUBE of speed — halving speed needs one-eighth of the power; two-thirds speed $\approx 30\%$.

Worked example. 40 kW at 3000 rpm $\rightarrow$ 5 kW at 1500 rpm (book).

Exam trap. Cube the ratio of speeds, not the ratio of flows squared.

Impeller trimming – flow

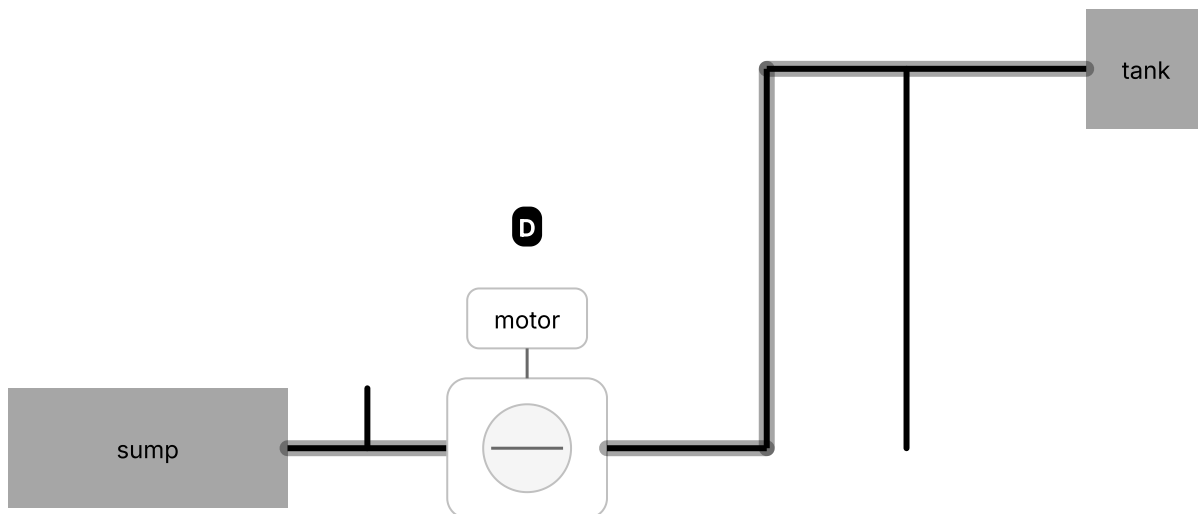
$$Q_1 \div Q_2 = D_1 \div D_2$$

SYMBOLS · UNITS

Symbols D = impeller diameter (mm)

Answer unit m^3/hr

Book topic Impeller trimming



Where each value sits: **D** $\rightarrow$ speed N, impeller D

WHAT IT MEANS

Trimming the impeller diameter reduces flow in proportion — a one-time, cheap fix for an oversized pump that is throttled.

Worked example. Flow 150 $\rightarrow$ 110 m^3/hr needs $D = 230 \times 110/150 = 169$ mm (2018/2024 objective).

Exam trap. Trim only down to $\sim 75\%$ of the original diameter; beyond that efficiency collapses.

Impeller trimming – head

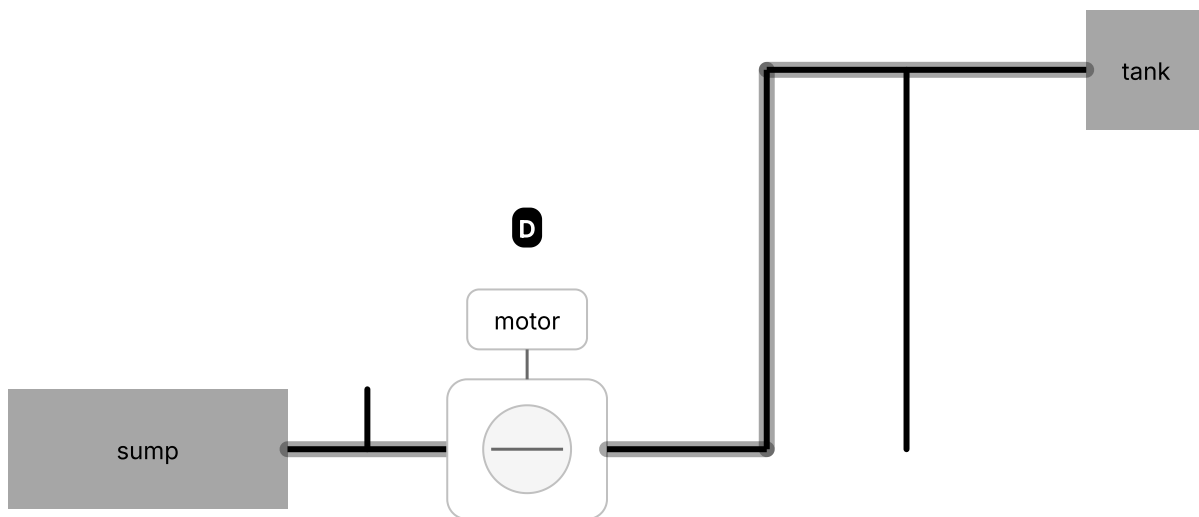
$$H_1 \div H_2 = (D_1 \div D_2)^2$$

SYMBOLS · UNITS

Symbols D (mm)

Answer unit m

Book topic Impeller trimming



Where each value sits: **D** → speed N, impeller D

WHAT IT MEANS

Head falls with the square of the diameter ratio.

Worked example. D ratio 0.9 → head 81 %.

Exam trap. Square.

Impeller trimming – power

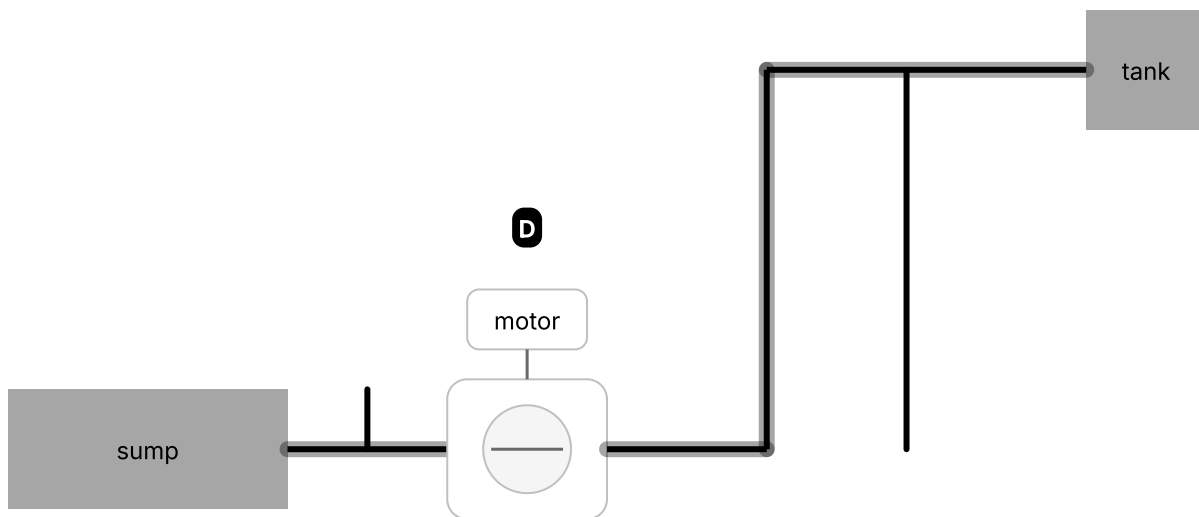
$$P_1 \div P_2 = (D_1 \div D_2)^3$$

SYMBOLS · UNITS

Symbols D (mm)

Answer unit kW

Book topic Impeller trimming



Where each value sits: **D** → speed N, impeller D

WHAT IT MEANS

Power falls with the cube of the diameter ratio — the saving from trimming.

Worked example. D ratio 0.9 → power 73 %.

Exam trap. Cube.

Friction head at a new flow

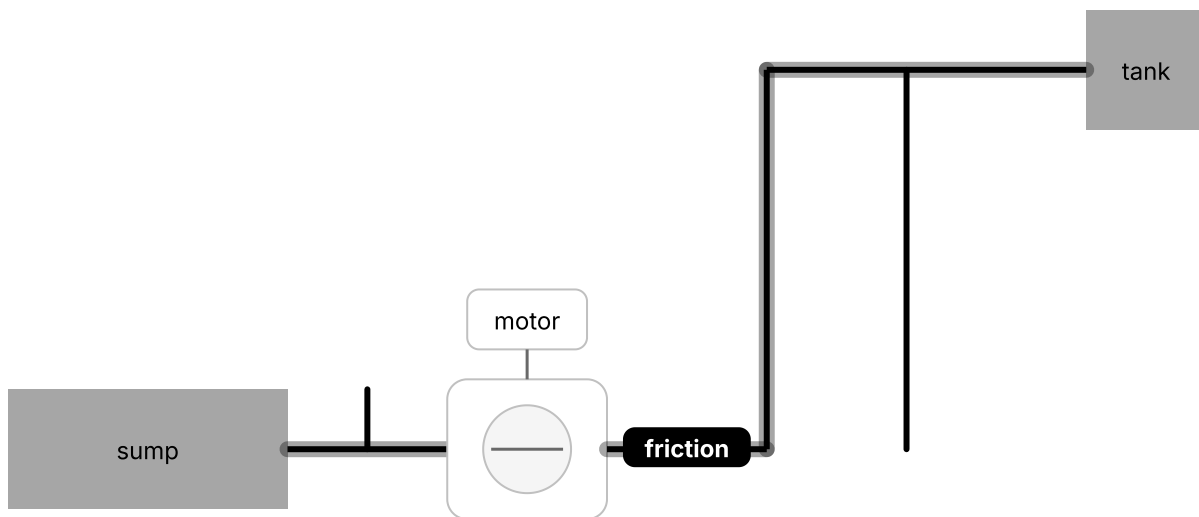
$$h_2 = h_1 \times (Q_2 \div Q_1)^2$$

SYMBOLS · UNITS

Symbols friction head (m) varies with the square of flow

Answer unit m

Book topic System curve



Where each value sits: **friction** → pipe: flow Q

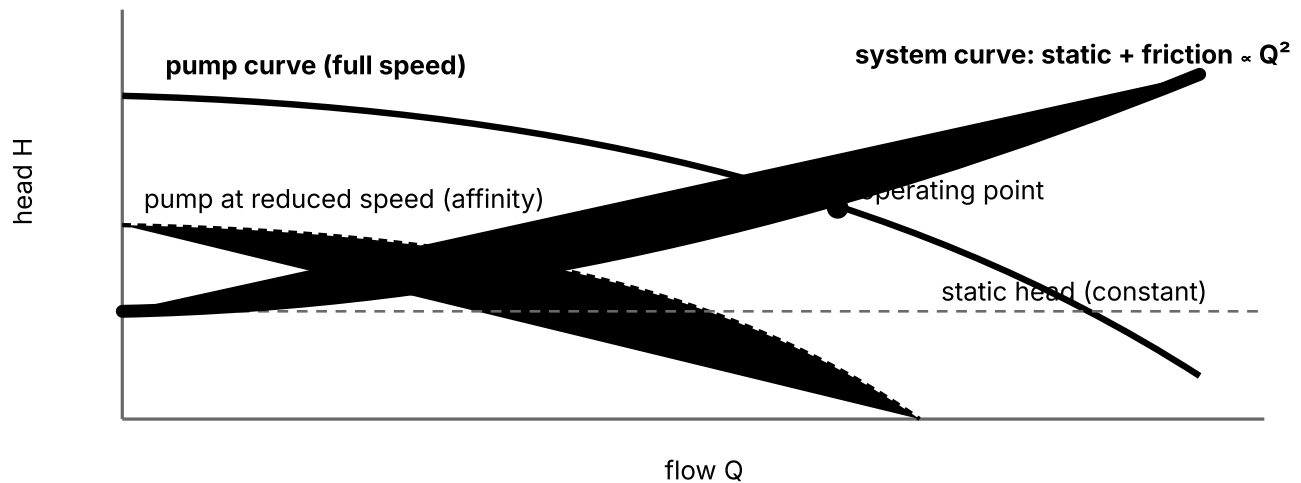
WHAT IT MEANS

Pipe friction losses rise with the square of flow; static head (the lift) does not change. This is why the system curve is a parabola sitting on the static head.

Worked example. Friction 15 m at 100 m³/hr → at 80 m³/hr: 15 × 0.64 = 9.6 m; static 10 m stays 10 m (2011 objective).

Exam trap. Static head is constant; ONLY the friction part scales with Q².

Pump curve, system curve and speed control



DEFINITIONS THE EXAM ASKS

System curve

Static head (constant) plus friction head ($\propto Q^2$); the pump runs where its curve meets the system curve.

Throttling vs speed control

A throttled valve adds resistance and wastes the head; reducing speed moves the pump curve down — power falls with N^3 . Throttled > 30 % → trim impeller or fit a VFD.

NPSH and cavitation

Net positive suction head available must exceed the pump's required NPSH; otherwise vapour bubbles form and collapse (cavitation). Larger suction pipe, lower liquid temperature and lower suction lift raise NPSHa.

Pumps in series / parallel

Series adds head (shut-off head doubles for two identical pumps); parallel adds flow (shut-off head unchanged).

By-pass lines

Small by-pass lines protect the pump against overheating at very low or zero flow.

Chapter 7 • Cooling Tower

~13 marks: range/approach/effectiveness, evaporation, COC and blowdown numericals recur; L/G ratio and fill types.



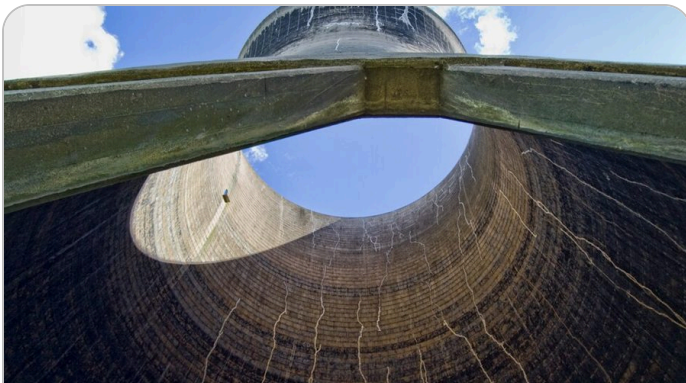
Induced-draft cooling tower cells with fans on top

Photo: Cenk Endustri • CC BY-SA 3.0 • [source](#)



Fill media inside a cooling tower — where water film meets the air

Photo: SAF • CC BY-SA 4.0 • [source](#)



Natural-draft (hyperbolic) cooling tower seen from inside

Photo: TJBlackwell • CC BY 3.0 • [source](#)

Range

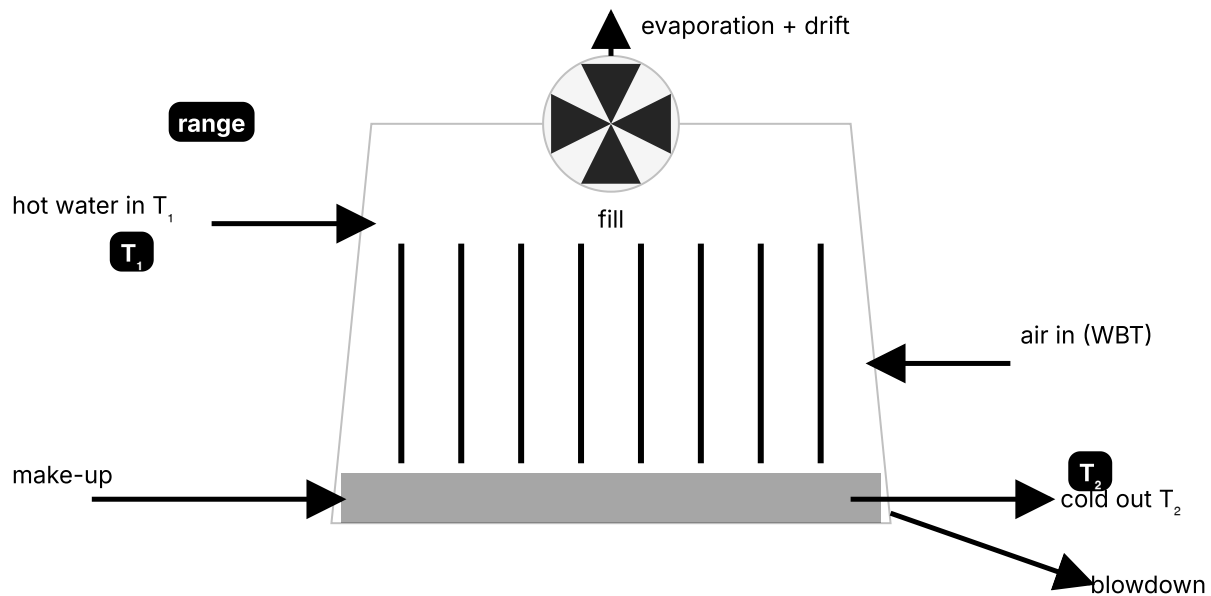
$$= T_1 - T_2 \text{ (CW inlet hot - CW outlet cold)}$$

SYMBOLS · UNITS

Symbols water temperatures (°C)

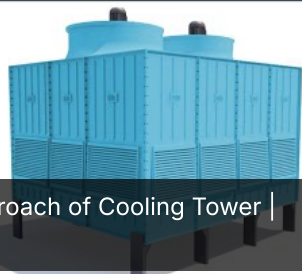
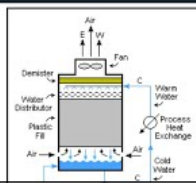
Answer unit °C

Book topic Performance



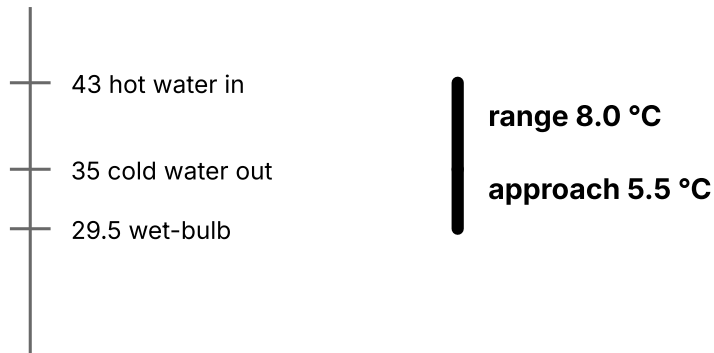
Where each value sits: $T_1 \rightarrow T_1$ hot water in · $T_2 \rightarrow T_2$ cold water out · **range** $\rightarrow$ range = $T_1 - T_2$

Range & Approach of Cooling Tower



► Video: Range and Approach of Cooling Tower |
Cooling Tower Factors:

► Try it: Cooling tower: move the temperatures — range, approach and effectiveness



$$\text{effectiveness} = 8.0 \div (8.0 + 5.5) = 59 \%$$

Range **8.0 °C**, approach **5.5 °C**, effectiveness **59 %**

WHAT IT MEANS

How much the tower cools the water — set by the PROCESS heat load and flow, not by the tower.

Worked example. Hot 43 °C in, 35 °C out → range 8 °C.

Exam trap. Range is water-to-water.

Approach

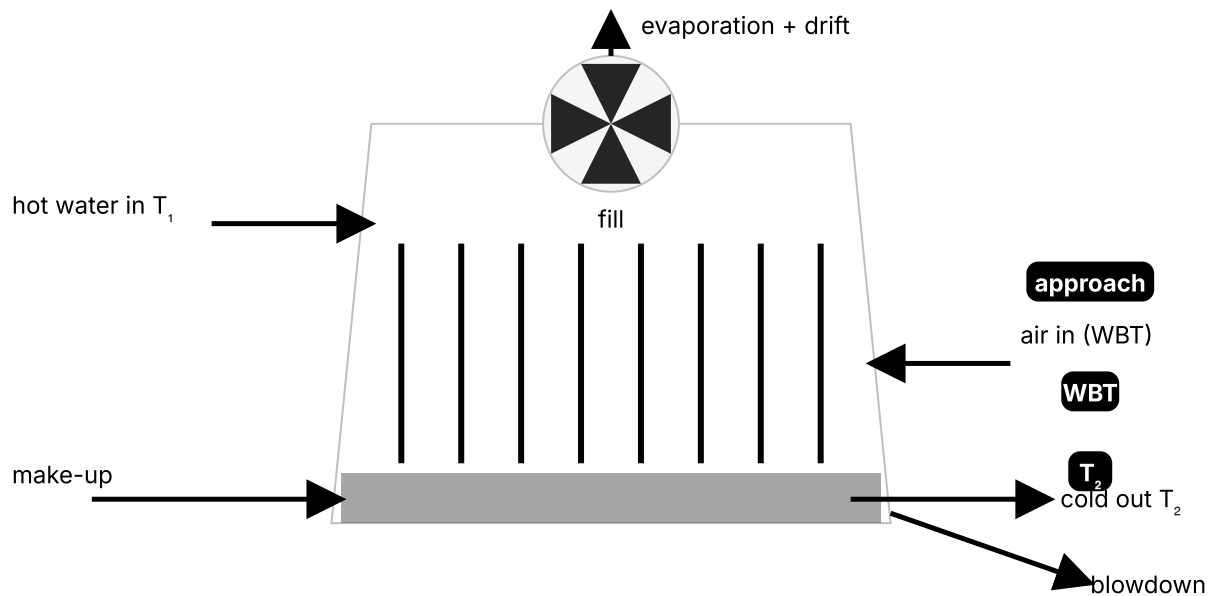
= CW outlet (cold) temperature – Ambient wet-bulb temperature

SYMBOLS · UNITS

Symbols °C

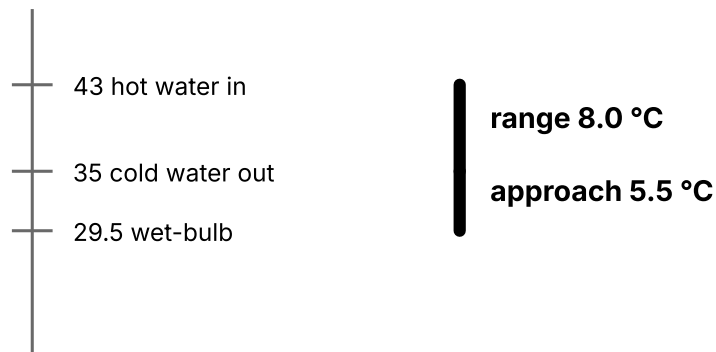
Answer unit °C

Book topic Performance



Where each value sits: $T_2 \rightarrow T_2$ cold water out · WB T $\rightarrow$ wet-bulb temperature · approach $\rightarrow$ approach = $T_2 -$ WB T

► Try it: Cooling tower: move the temperatures — range, approach and effectiveness



effectiveness = $8.0 \div (8.0 + 5.5) = 59 \%$

Range **8.0 °C**, approach **5.5 °C**, effectiveness **59 %**

WHAT IT MEANS

How close the cold water gets to the air's wet-bulb temperature — the true measure of tower performance; lower approach = better (and bigger, costlier) tower.

Worked example. Cold water 32.2 °C, WBT 26.7 → approach 5.5 °C (book).

Exam trap. Approach uses the WET-bulb of the ambient air, not the dry-bulb, and not the inlet water.

Cooling tower effectiveness

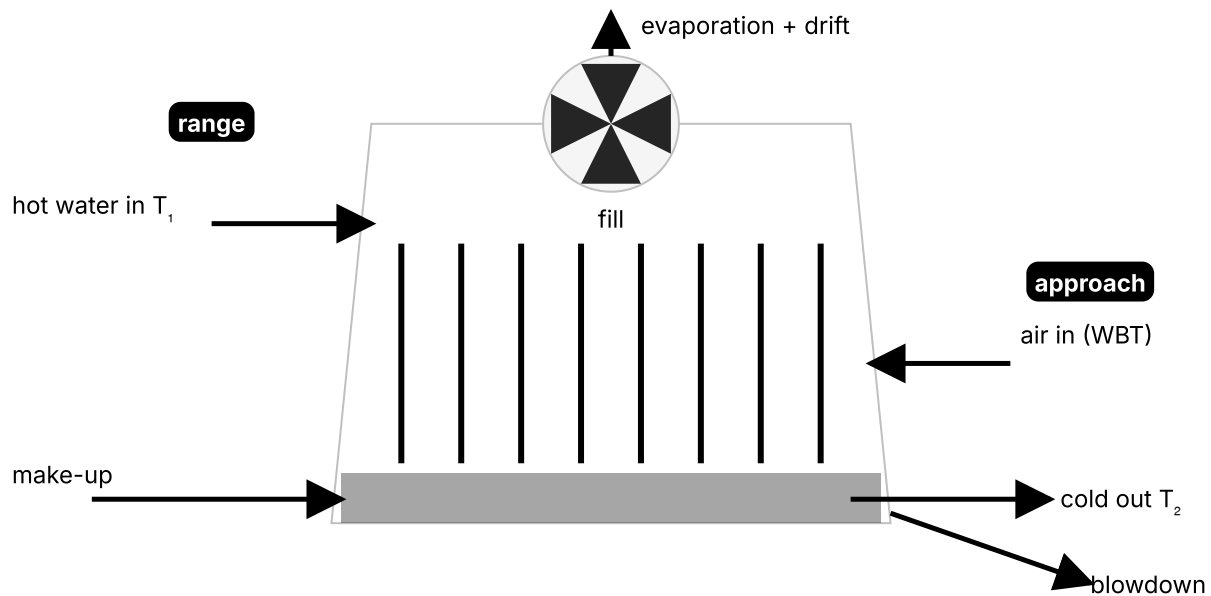
$$= \text{Range} \div (\text{Range} + \text{Approach}) \times 100$$

SYMBOLS · UNITS

Symbols °C

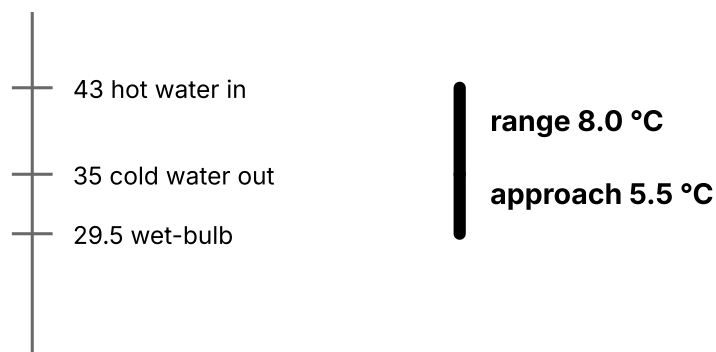
Answer unit %

Book topic Performance



Where each value sits: **range** → $\text{range} = T_1 - T_2$ · **approach** → $\text{approach} = T_2 - \text{WBT}$

► Try it: Cooling tower: move the temperatures — range, approach and effectiveness



$$\text{effectiveness} = 8.0 \div (8.0 + 5.5) = 59 \%$$

Range **8.0 °C**, approach **5.5 °C**, effectiveness **59 %**

WHAT IT MEANS

Range as a share of the ideal range (hot water to wet-bulb); 100 % would mean the water reached the wet-bulb.

Worked example. Range 8, approach 5.5 $\rightarrow 8 \div 13.5 = 59 \%$.

Exam trap. Denominator is range PLUS approach.

Cooling capacity (heat rejected)

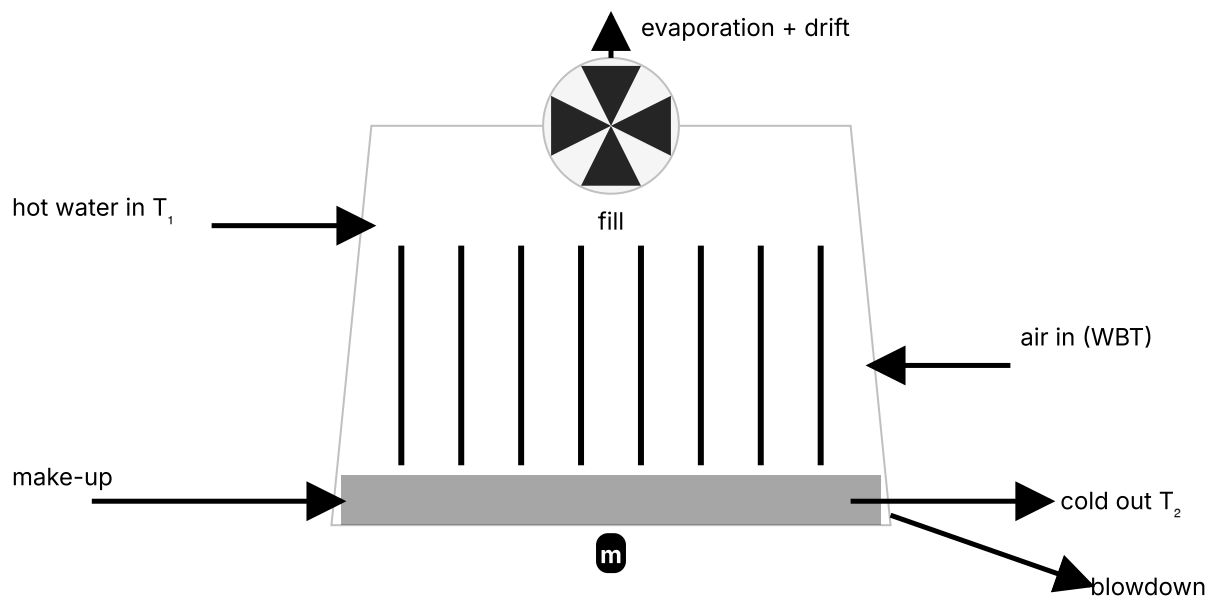
$$= m \times C_p \times (T_1 - T_2)$$

SYMBOLS · UNITS

Symbols m = water flow (kg/hr = $m^3/\text{hr} \times 1000$), $C_p = 1 \text{ kcal/kg } ^\circ\text{C}$

Answer unit kcal/hr ($\div 3024 = \text{TR}$)

Book topic Performance



Where each value sits: $m \rightarrow$ circulation rate m^3/hr , m , $C_p \cdot C_p \rightarrow$ circulation rate m^3/hr , m , C_p

WHAT IT MEANS

The heat the tower throws away = water flow $\times 1 \text{ kcal/kg } ^\circ\text{C} \times$ range; divide by 3,024 for TR.

Worked example. $3,000 \text{ m}^3/\text{hr} \times 1000 \times (41 - 31) = 30 \text{ million kcal/hr (book)} \approx 9,920 \text{ TR}$. $2 \text{ m}^3/\text{min}, 43 \rightarrow 35 ^\circ\text{C}: 120,000 \text{ kg/hr} \times 8 \div 3,024 = 317 \text{ TR (2013 S-5)}$.

Exam trap. $m^3/\text{hr} \times 1000 = \text{kg/hr}$; C_p of water = 1.

Range from heat load

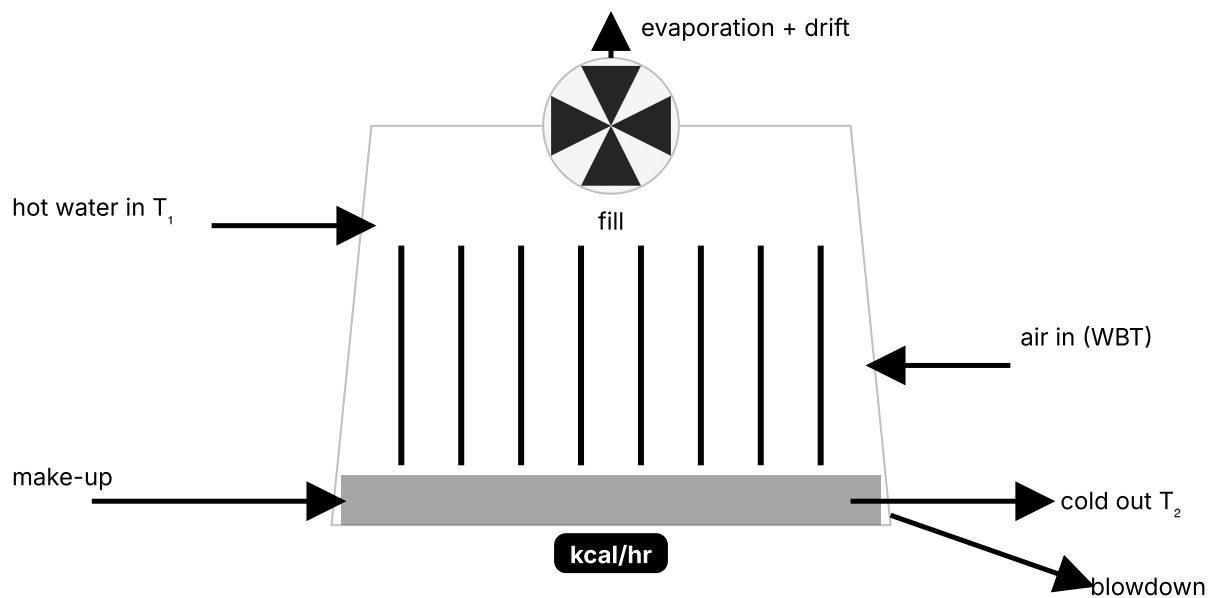
$$= \text{Heat load (kcal/hr)} \div \text{Water circulation rate (litres/hr)}$$

SYMBOLS · UNITS

Symbols kcal/hr, LPH

Answer unit °C

Book topic Range



Where each value sits: **kcal/hr** → circulation rate m³/hr, m, Cp · **LPH** → circulation rate m³/hr, m, Cp

WHAT IT MEANS

If you know the heat load and the circulation rate, the range follows — the tower cannot change it.

Worked example. 6,000,000 kcal/hr ÷ 1,000,000 L/hr = 6 °C.

Exam trap. Litres per hour in the denominator (= kg/hr for water).

Evaporation loss

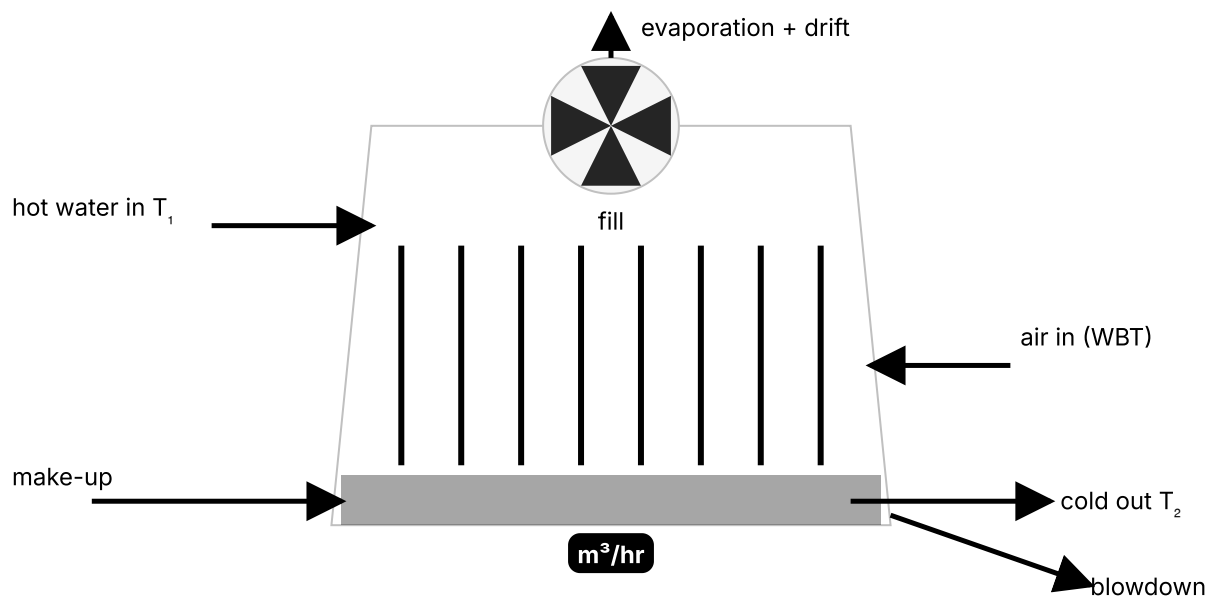
$$= 0.00085 \times 1.8 \times \text{Circulation rate (m}^3/\text{hr)} \times (T_1 - T_2)$$

SYMBOLS · UNITS

Symbols m^3/hr , $^{\circ}\text{C}$

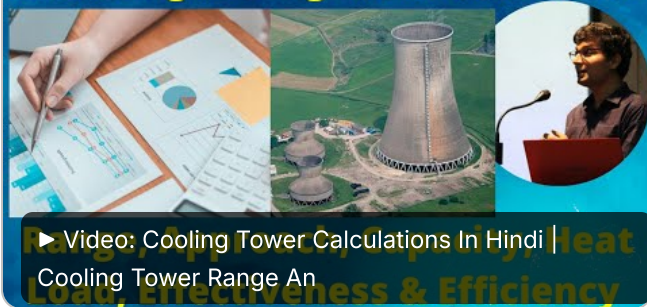
Answer unit m^3/hr

Book topic Water losses



Where each value sits: $\text{m}^3/\text{hr} \rightarrow$ circulation rate m^3/hr , m , $C_p \cdot ^{\circ}\text{C}$: $^{\circ}\text{C}$

Mastering Cooling Tower Calculation



► Try it: Cooling tower water: raise the cycles of concentration — blowdown falls

evaporation



12.2 m³/hr

blowdown



6.1 m³/hr

make-up



20.4 m³/hr

Evaporation = $0.00085 \times 1.8 \times 1000 \times 8 = \mathbf{12.2}$; blowdown = $12.2 \div (3 - 1) = \mathbf{6.1}$; make-up = E + B + drift = $\mathbf{20.4 \text{ m}^3/\text{hr}}$

WHAT IT MEANS

Cooling happens mainly by evaporating about 1 % of the water for every 5.5–6 °C of range; this water is lost and must be made up.

Worked example. 1,000 m³/hr, range 8: $0.00085 \times 1.8 \times 1,000 \times 8 = 12.2 \text{ m}^3/\text{hr}$ ($\approx 1.2 \%$).

Exam trap. Multiply by BOTH constants 0.00085 and 1.8 (book form).

Because only pure water evaporates, dissolved solids build up; COC says how many times more concentrated the circulating water is than the make-up. Higher COC = less blowdown = less water, until scaling limits it.

Worked example. Circulating TDS 1,500 ppm, make-up 500 → COC 3.

Exam trap. Also = make-up ÷ blowdown = conductivity ratio.

Blowdown

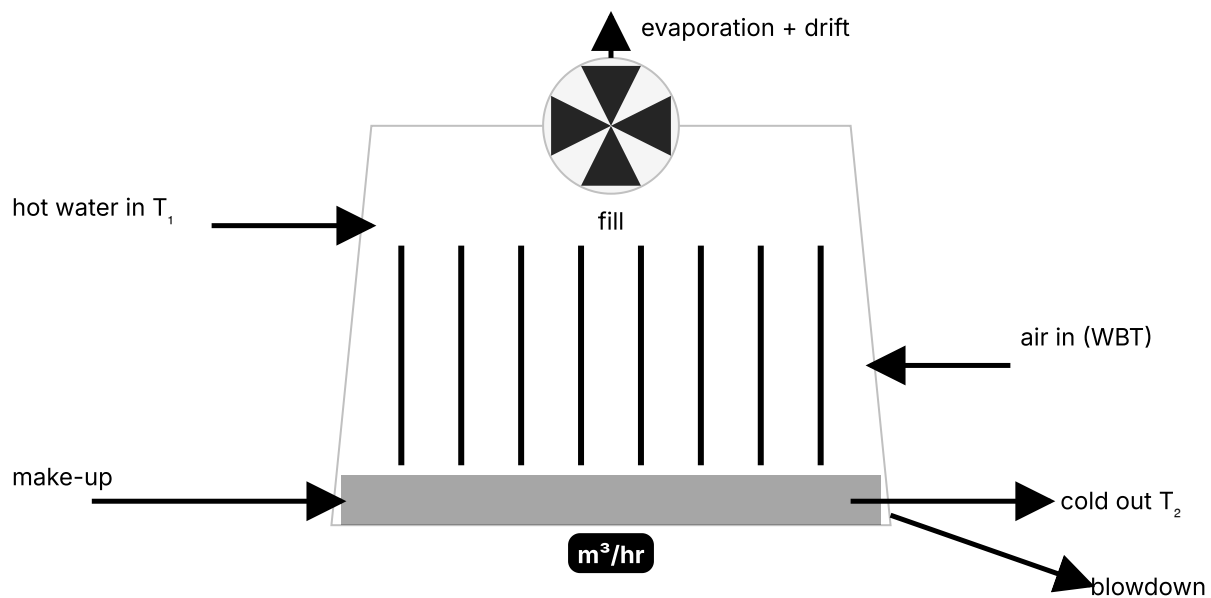
$$= \text{Evaporation loss} \div (\text{COC} - 1)$$

SYMBOLS · UNITS

Symbols m^3/hr

Answer unit m^3/hr

Book topic	Water losses
-------------------	--------------



Where each value sits: $\text{m}^3/\text{hr} \rightarrow$ circulation rate m^3/hr , m , C_p

► **Try it: Cooling tower water: raise the cycles of concentration — blowdown falls**

evaporation	12.2 m ³ /hr
-------------	-------------------------

blowdown 6.1 m³/hr

make-up		20.4 m ³ /t
---------	--	------------------------

Evaporation = $0.00085 \times 1.8 \times 1000 \times 8 = \mathbf{12.2}$; blowdown = $12.2 \div (3 - 1) = \mathbf{6.1}$; make-up =
E + B + drift = $\mathbf{20.4 \text{ m}^3/\text{hr}}$

WHAT IT MEANS

Water deliberately drained to keep TDS at the chosen COC. Raising COC from 3 to 5 halves blowdown ($\div 2$ vs $\div 4$).

Worked example. Evaporation $12.2 \text{ m}^3/\text{hr}$, COC 3 $\rightarrow 12.2 \div 2 = 6.1 \text{ m}^3/\text{hr}$; at COC 5 $\rightarrow 3.05$.

Exam trap. Denominator is (COC - 1), not COC — and increasing COC DECREASES blowdown (2009/2018 objective).

Worked example. $12.2 + 6.1 + 1.0 = 19.3 \text{ m}^3/\text{hr}$.

Exam trap. Drift is small but the exam expects it in the sum.

Liquid-to-gas (L/G) ratio

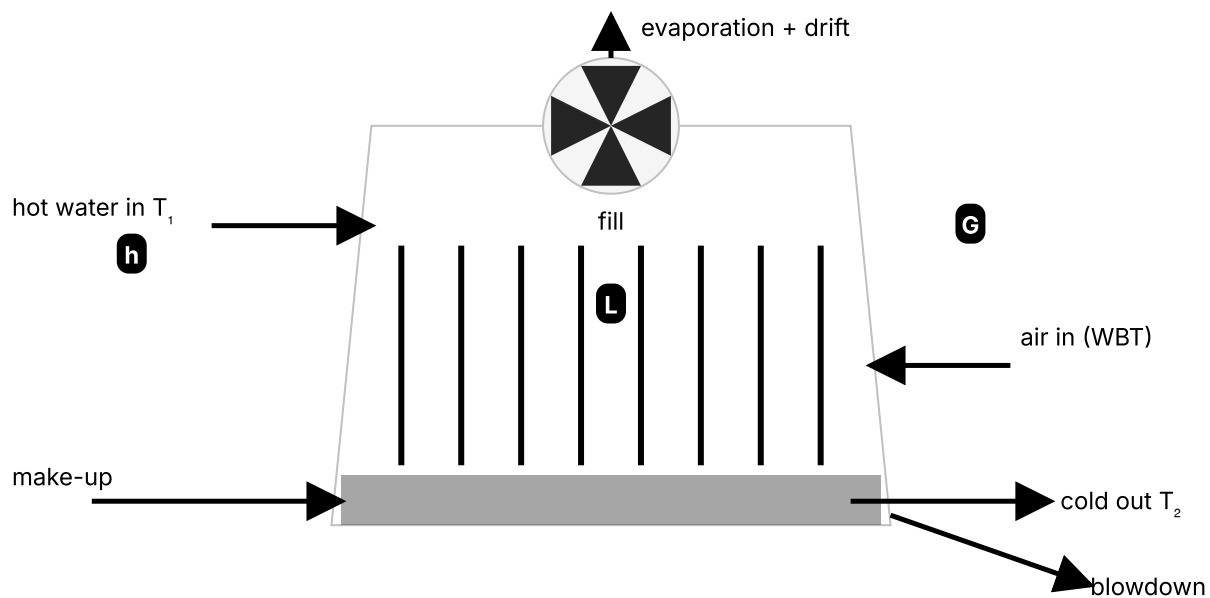
$$L \times (T_1 - T_2) = G \times (h_2 - h_1) \rightarrow L/G = (h_2 - h_1) \div (T_1 - T_2)$$

SYMBOLS · UNITS

Symbols L, G = water, air mass flow (kg/hr); h = air enthalpy at exit / inlet wet bulb

Answer unit kg/kg

Book topic L/G ratio



Where each value sits: **L** → L/G = water ÷ air mass · **G** → air G, density, enthalpy h_1 h_2 · **air** → air G, density, enthalpy h_1 h_2 · **h** → T_1 hot water in



WHAT IT MEANS

Mass of water per mass of air through the tower; the heat lost by the water equals the heat gained by the air, so $L/G = \text{enthalpy rise of air} \div \text{temperature drop of water}$.

Typical 0.75–1.5.

Worked example. Air enthalpy in 20, out 30 kcal/kg; water 43 → 35: $L/G = 10 \div 8 = 1.25$.

Exam trap. It is MASS flow of water ÷ MASS flow of air (2015/2018 objective), not volume.

Air mass flow

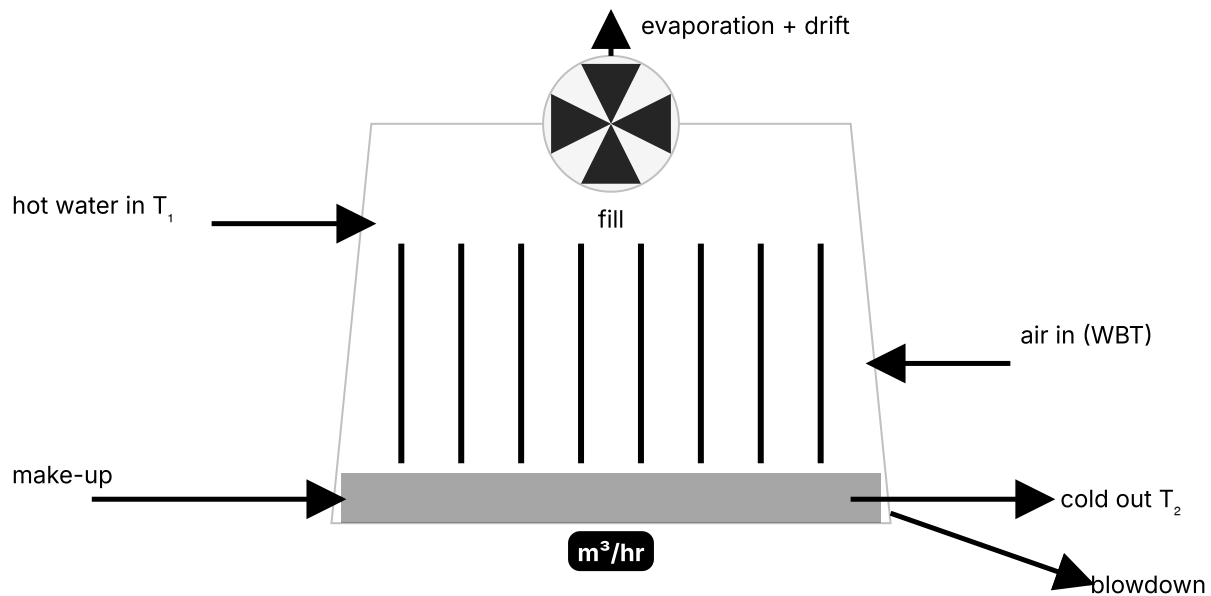
$$= \text{Air volume flow} \times \text{Air density}$$

SYMBOLS · UNITS

Symbols $\text{m}^3/\text{hr} \times \text{kg}/\text{m}^3$

Answer unit **kg/hr**

Book topic L/G ratio



Where each value sits: $\text{m}^3/\text{hr} \rightarrow$ circulation rate m^3/hr , m , C_p

WHAT IT MEANS

Fan air volume $\times$ air density; needed to compute L/G.

Worked example. $989,544 \text{ m}^3/\text{hr} \times 1.08 \text{ kg}/\text{m}^3 = 1,068,700 \text{ kg}/\text{hr}$ (book trial).

Exam trap. Density of hot humid air ≈ 1.08 , not 1.2.

% evaporation loss

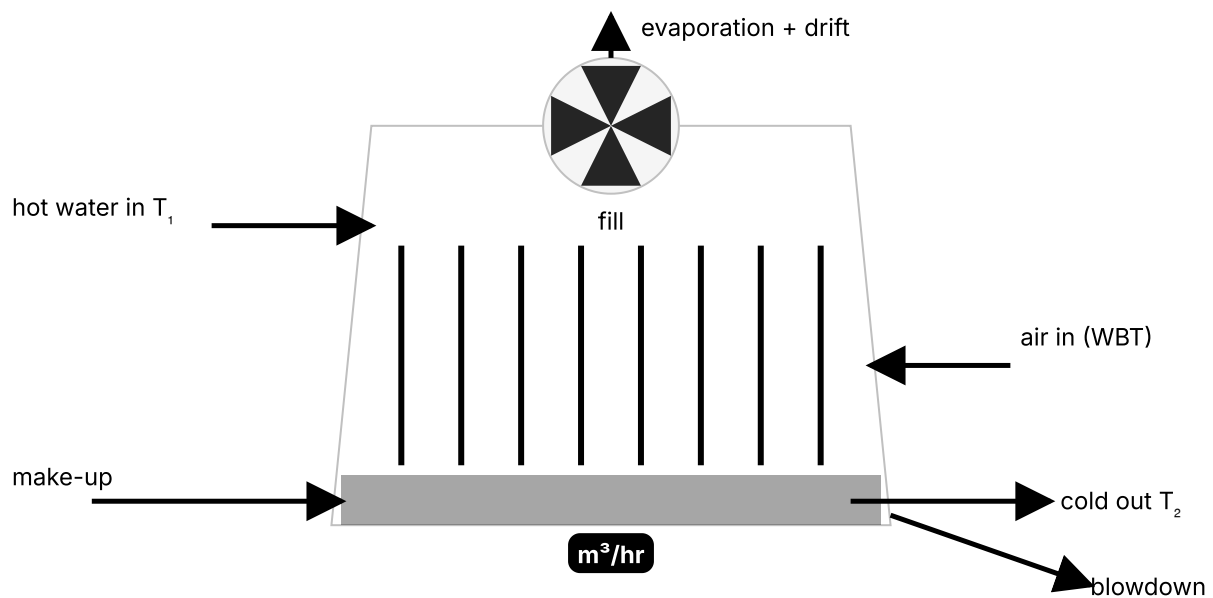
$$= \text{Evaporation} \div \text{Circulation rate} \times 100$$

SYMBOLS · UNITS

Symbols m^3/hr

Answer unit %

Book topic Water losses



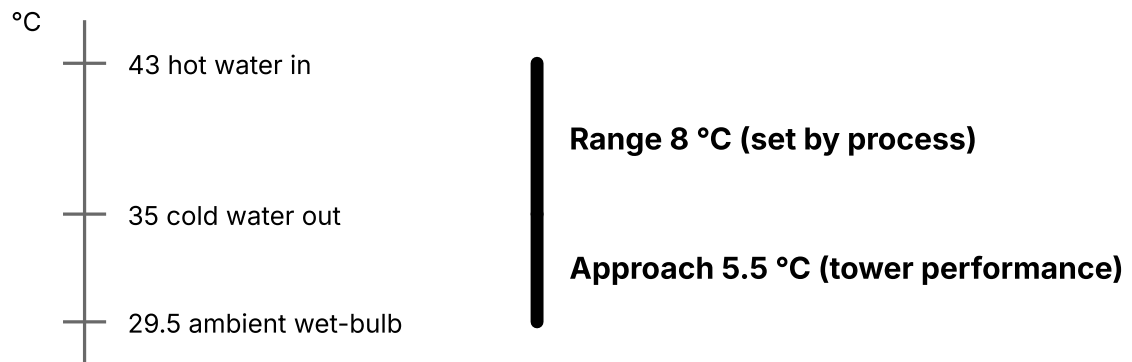
Where each value sits: $\text{m}^3/\text{hr} \rightarrow$ circulation rate m^3/hr , m , C_p

WHAT IT MEANS

Evaporation as a share of circulation — a sanity check (about 1 % per 6 °C of range).

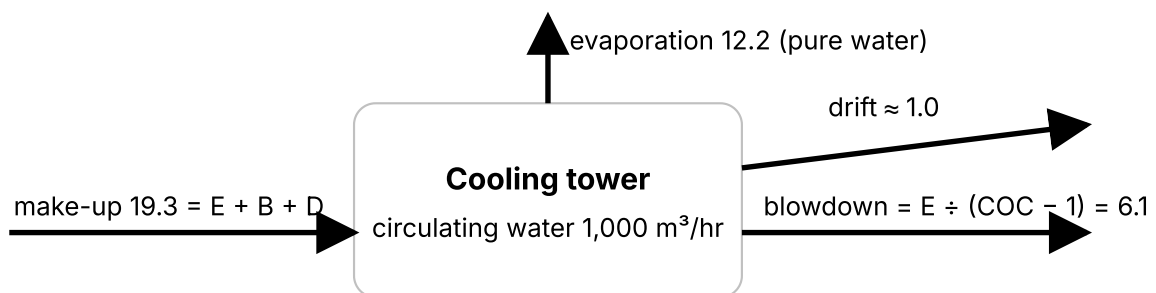
Worked example. $12.2 \div 1,000 = 1.2 \%$.

Range, approach and effectiveness



Effectiveness = $\text{Range} \div (\text{Range} + \text{Approach}) = 8 \div 13.5 = 59\%$. Lower approach = better (and bigger) tower

Cooling-tower water balance



Only pure water evaporates, so TDS rises: $\text{COC} = \text{TDS circulating} \div \text{TDS make-up}$. Higher COC → less blowdown

DEFINITIONS THE EXAM ASKS

Tower types

Natural draft (hyperbolic, power plants) and mechanical draft — forced (fan at inlet) or induced (fan at top, most common in industry); counter-flow vs cross-flow.

Fill

Splash fill (droplets, 30–45 m²/m³) and film fill (thin film over sheets, 150 m²/m³, more efficient but fouls).

Drift eliminator

Captures water droplets carried out in the air stream leaving the tower.

Factors affecting performance

Wet-bulb temperature, range, approach, heat load, L/G ratio, fill condition, water distribution. If heat load, range and WBT are fixed, a smaller approach needs a bigger tower.

Book performance norms

Approach 2.8–5.5 °C typical; % evaporation $\approx 1\%$ per 6 °C range.

VERIFIED VIDEOS FOR THIS CHAPTER (YOUTUBE)

Range, Approach & Effectiveness — Range and Approach of Cooling Tower | Cooling Tower Factors: Range & Approach | Wet Bulb Temperature · Core Engineering

Water Balance, Evaporation & Blowdown — Cooling Tower Calculations In Hindi | Cooling Tower Range And Approach | Efficiency Calculation · Sandeep Academy [IITR, GATE AIR 1]

L/G Ratio & Fill Media — COOLING TOWER PERFORMANCE || How to check cooling tower performance in 10 minutes || · Power Plant Discussion

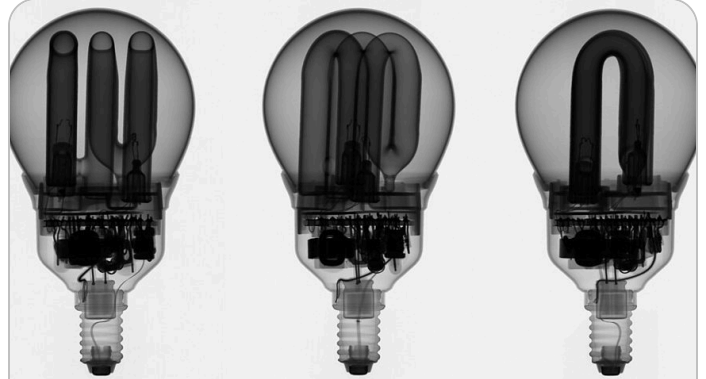
Chapter 8 • Lighting System

~7 marks, mostly easy objectives: lux/lumen, efficacy ranking, lamp types, T-numbers, CRI; one lumen-method numerical.



Street-light luminaire (HPSV/LED) — luminaire distributes and controls the lamp's light

Photo: Bidgee · CC BY 3.0 · source



Compact fluorescent lamps

Photo: SecretDisc · CC BY-SA 3.0 · source



Tubular lamps — T-number gives the tube diameter in eighths of an inch

Photo: Dmitry G · CC BY-SA 3.0 · source

Illuminance – inverse square law

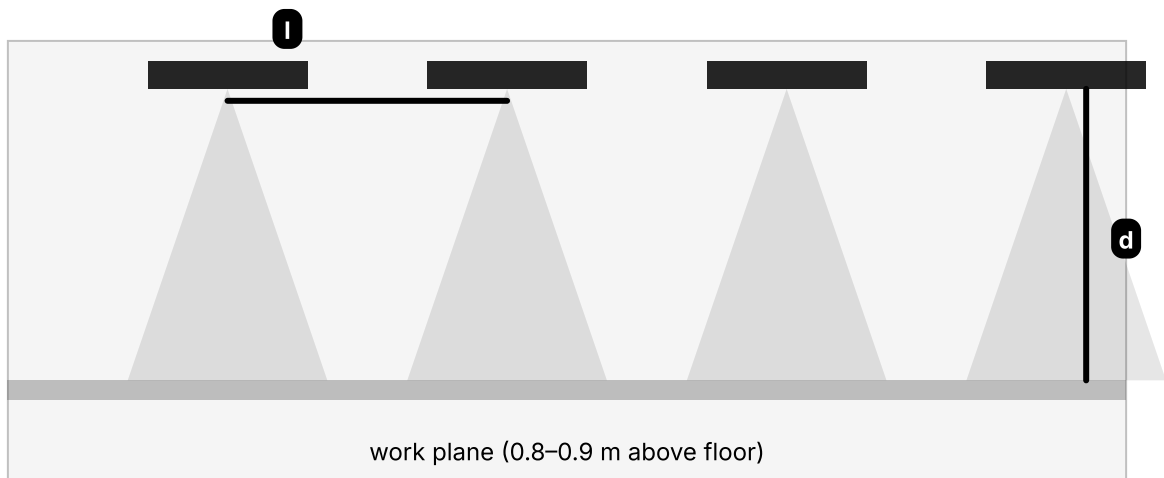
$$E = I \div d^2$$

SYMBOLS · UNITS

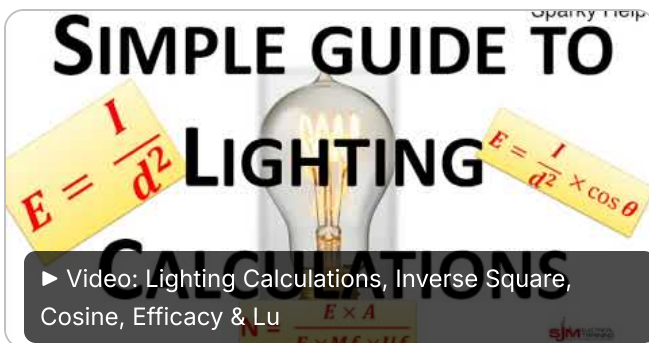
Symbols I = luminous intensity of the source (book writes it in lumens), d = distance (m)

Answer unit lux (lm/m^2)

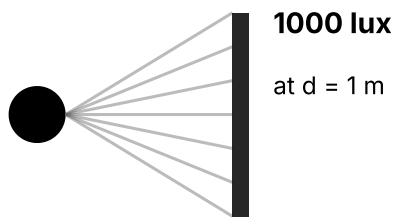
Book topic Basic terms



Where each value sits: **I** → lamp: lumens F , watts, efficacy lm/W · **d** → mounting height H_m , distance d



► Try it: Lighting: move the lamp away — illuminance falls with distance²



$$E = 1000 \div 1^2 = \mathbf{1000 \text{ lux}}$$

WHAT IT MEANS

Light spreads out: doubling the distance from a small source quarters the illuminance on the surface.

Worked example. 10 lux at 1 m $\rightarrow$ 2.5 lux at 2 m.

Exam trap. Divide by distance SQUARED.

Inverse square law – two distances

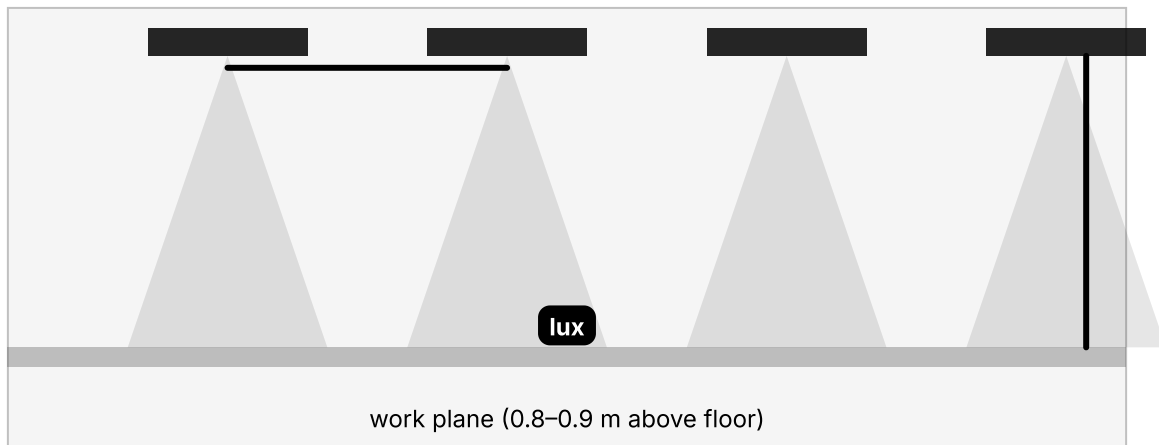
$$E_1 \times d_1^2 = E_2 \times d_2^2$$

SYMBOLS · UNITS

Symbols lux, m

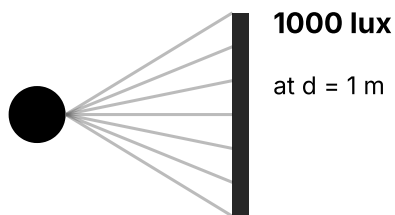
Answer unit lux

Book topic Basic terms



Where each value sits: **lux** → illuminance E lux, area A · **m**: m

► Try it: Lighting: move the lamp away — illuminance falls with distance²



$$E = 1000 \div 1^2 = 1000 \text{ lux}$$

WHAT IT MEANS

Same law rearranged to compare two distances.

Worked example. $E_1 = (d_2/d_1)^2 \times E_2 = (1.0/0.5)^2 \times 10 = 40 \text{ lux (book).}$

Exam trap. Square the ratio of distances.

Lux (definition)

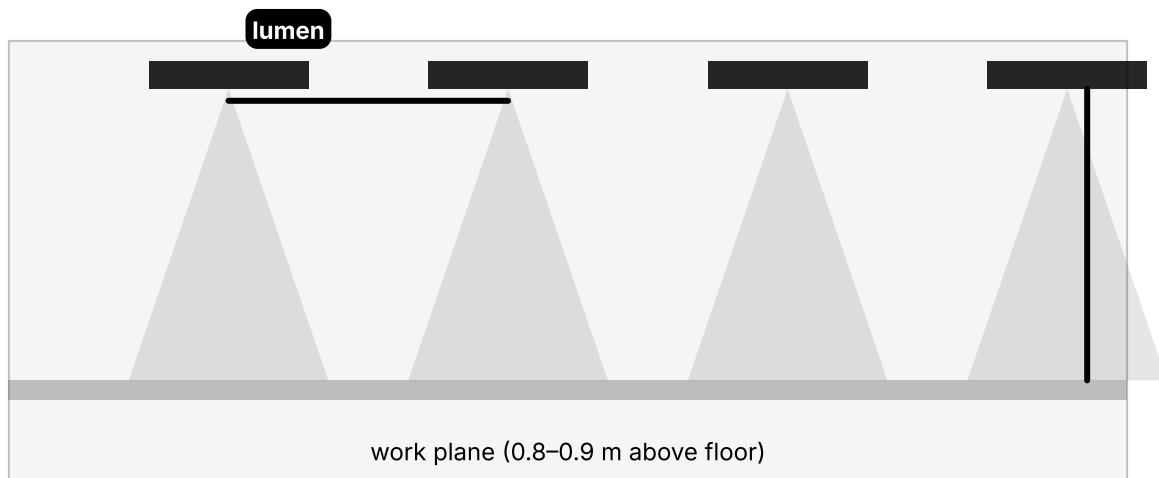
$$1 \text{ lux} = 1 \text{ lumen} \div 1 \text{ m}^2$$

SYMBOLS · UNITS

Symbols lumen, m²

Answer unit lm/m²

Book topic Basic terms



Where each value sits: **lumen** → lamp: lumens F, watts, efficacy lm/W · **m²**: m²

WHAT IT MEANS

One lumen of light spread over one square metre. Offices need ~300–500 lux, corridors ~100, precision work 1,000+.

Worked example. 300 lux on 216 m² needs 64,800 lumens (2025 S-1).

Exam trap. Lux is per m²; lumen is the total light output.

Luminous efficacy

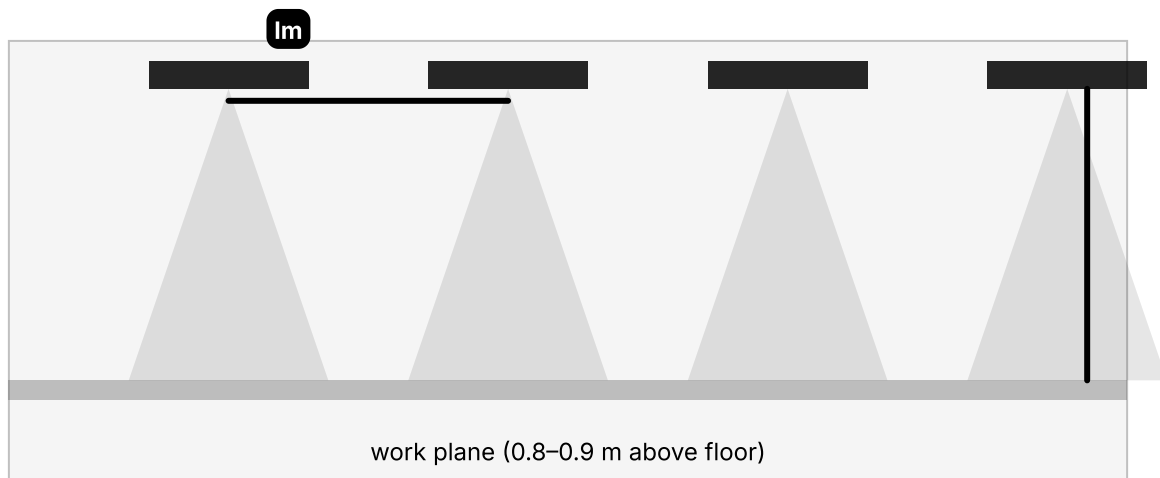
$$= \text{Luminous flux (lm)} \div \text{Lamp power (W)}$$

SYMBOLS · UNITS

Symbols lm, W

Answer unit lm/W

Book topic Basic terms



Where each value sits: **lm** → lamp: lumens F, watts, efficacy lm/W · **W** → lamp: lumens F, watts, efficacy lm/W

WHAT IT MEANS

Lumens of light per watt of electricity — the efficiency of a lamp. Ranking: LPSV > HPSV ≈ LED > metal halide > CFL > FTL > HPMV > halogen > incandescent.

Worked example. 18 W LED tube giving 1,800 lm → 100 lm/W.

Exam trap. Efficacy is a property of the LAMP; circuit efficacy includes the ballast/driver.

Maximum possible luminous efficacy

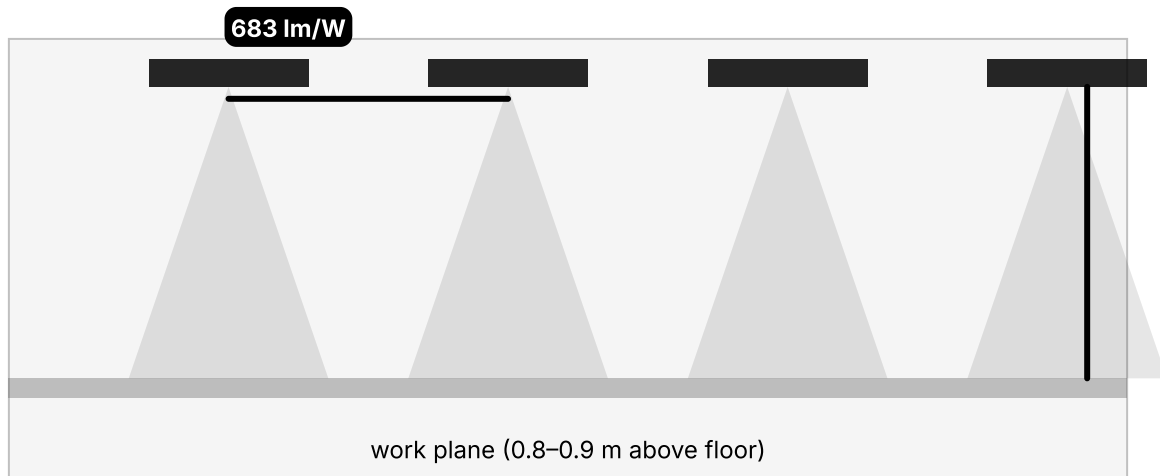
1 W = 683 lm at 555 nm

SYMBOLS · UNITS

Symbols —

Answer unit lm/W

Book topic Basic terms



Where each value sits: **683 lm/W** → lamp: lumens F, watts, efficacy lm/W · **555 nm** → lamp: lumens F, watts, efficacy lm/W

WHAT IT MEANS

If every watt became visible green light at 555 nm (the eye's peak sensitivity) you would get 683 lm — the physical ceiling.

Worked example. A 100 lm/W lamp is 15 % of the maximum.

Exam trap. 683 lm/W at 555 nm, not white light.

Installed load efficacy (ILE)

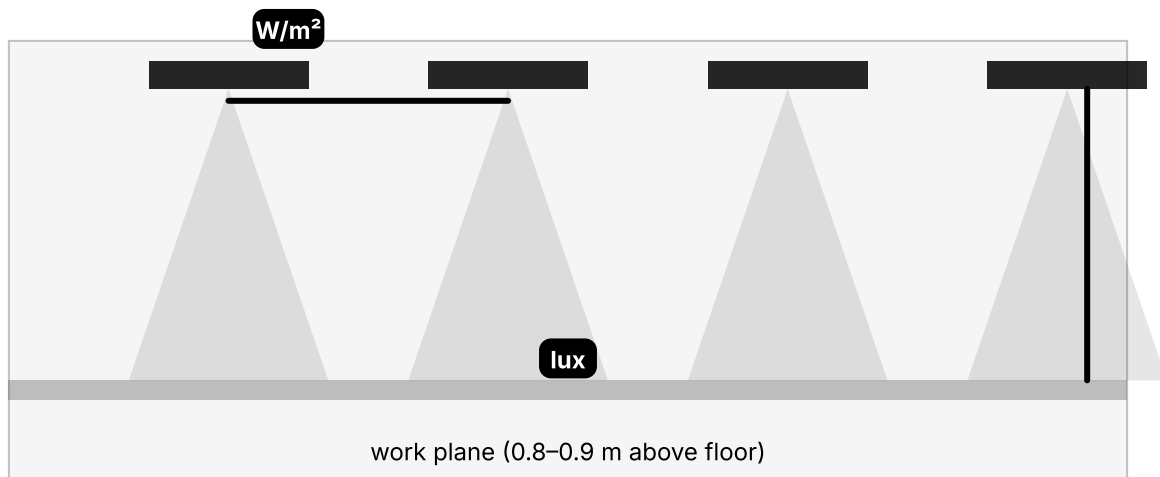
= Average maintained illuminance (lux) ÷ Installed power density (W/m^2)

SYMBOLS · UNITS

Symbols lux, W/m^2

Answer unit lux/ W/m^2

Book topic Basic terms



Where each value sits: **lux** → illuminance E lux, area A · **W/m^2** → lamp: lumens F, watts, efficacy lm/W

WHAT IT MEANS

How much illuminance you get per watt per square metre — judges the whole installation (lamps + luminaires + layout), not just the lamp.

Worked example. 300 lux at $12 \text{ W}/\text{m}^2 \rightarrow 25 \text{ lux per W}/\text{m}^2$.

Exam trap. Higher ILE = better installation.

Installed power density (lighting power density)

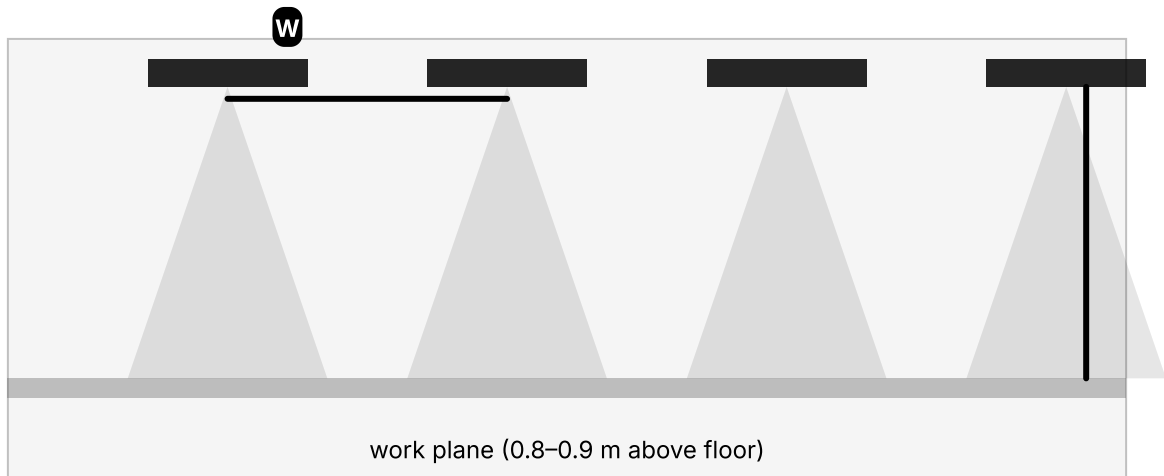
$$= \text{Total lighting load (W)} \div \text{Floor area (m}^2\text{)}$$

SYMBOLS · UNITS

Symbols W, m²

Answer unit W/m² (book: per 100 lux)

Book topic Basic terms



Where each value sits: **W** → lamp: lumens F, watts, efficacy lm/W · **m²**: m²

WHAT IT MEANS

Watts of lighting per square metre of floor; ECBC limits it (e.g. offices $\approx 10.8 \text{ W/m}^2$, Ch10).

Worked example. 2.1 kW over 200 m² = 10.5 W/m².

Exam trap. The book also quotes it 'per 100 lux' for comparison between spaces.

Room index

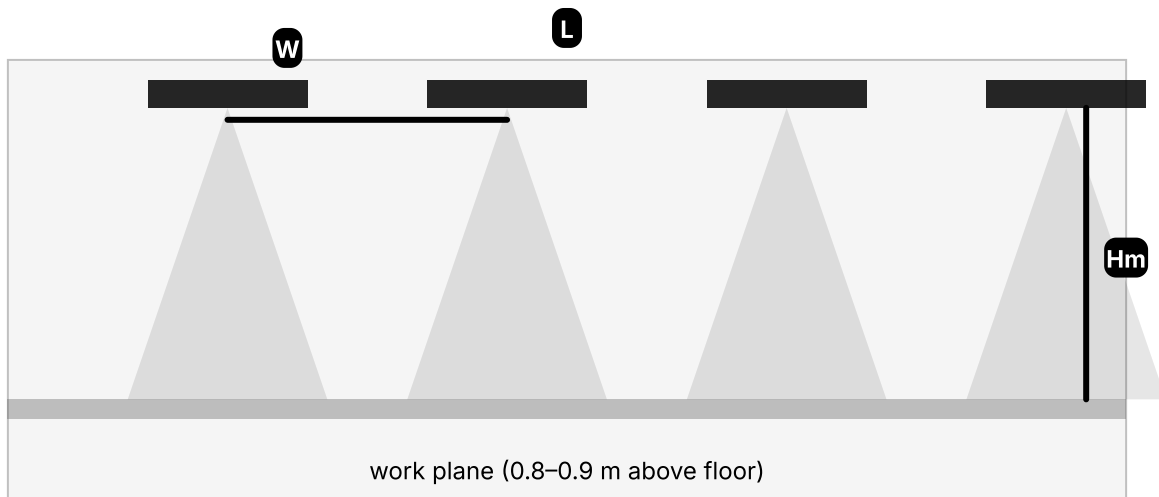
$$RI = (L \times W) \div [Hm \times (L + W)]$$

SYMBOLS · UNITS

Symbols L, W = room length, width (m), Hm = mounting height (m)

Answer unit no unit

Book topic Lighting design



Where each value sits: **L** → room L × W, room index, UF, LLF · **W** → lamp: lumens F, watts, efficacy lm/W · **width** → lamp: lumens F, watts, efficacy lm/W · **Hm** → mounting height Hm, distance d



WHAT IT MEANS

A shape factor: big low rooms have a high index (light reaches the work plane easily); tall narrow rooms a low one. It is looked up against the luminaire's utilisation factor table.

Worked example. 10 × 10 m room, mounting height 2.0 m → $100 \div (2 \times 20) = 2.5$ (book).

Exam trap. Mounting height is luminaire height ABOVE THE WORK PLANE, not above the floor.

Mounting height

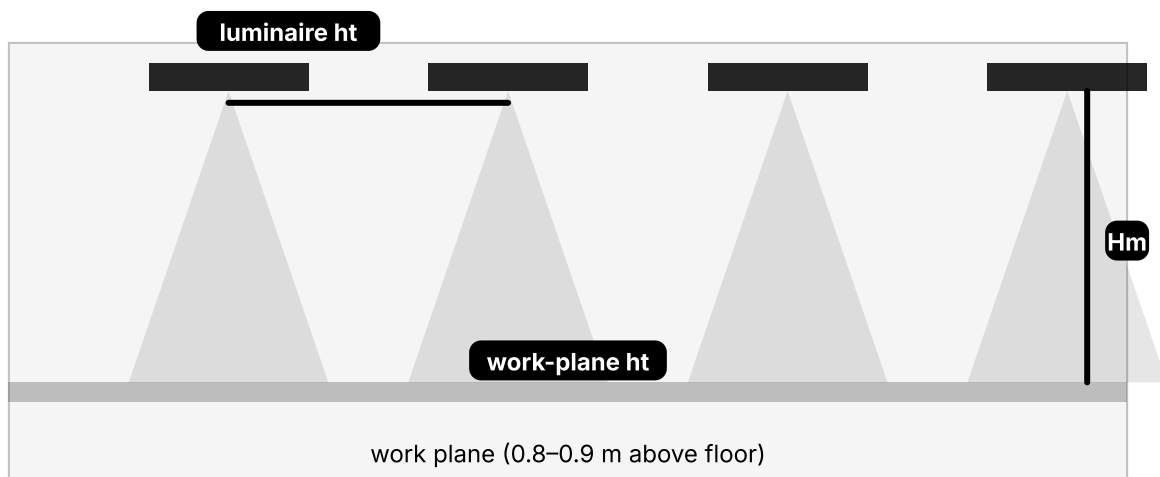
$$H_m = \text{Luminaire height} - \text{Work-plane height}$$

SYMBOLS · UNITS

Symbols m

Answer unit m

Book topic Lighting design



Where each value sits: **luminaire ht** → lamp: lumens F, watts, efficacy lm/W · **work-plane ht** → illuminance E lux, area A · **Hm** → mounting height Hm, distance d

WHAT IT MEANS

Distance from the luminaire down to the work plane (desk height ≈ 0.8–0.9 m).

Worked example. Luminaire at 2.9 m, work plane 0.9 m → 2.0 m (book).

Exam trap. Subtract the work-plane height.

Light loss factor

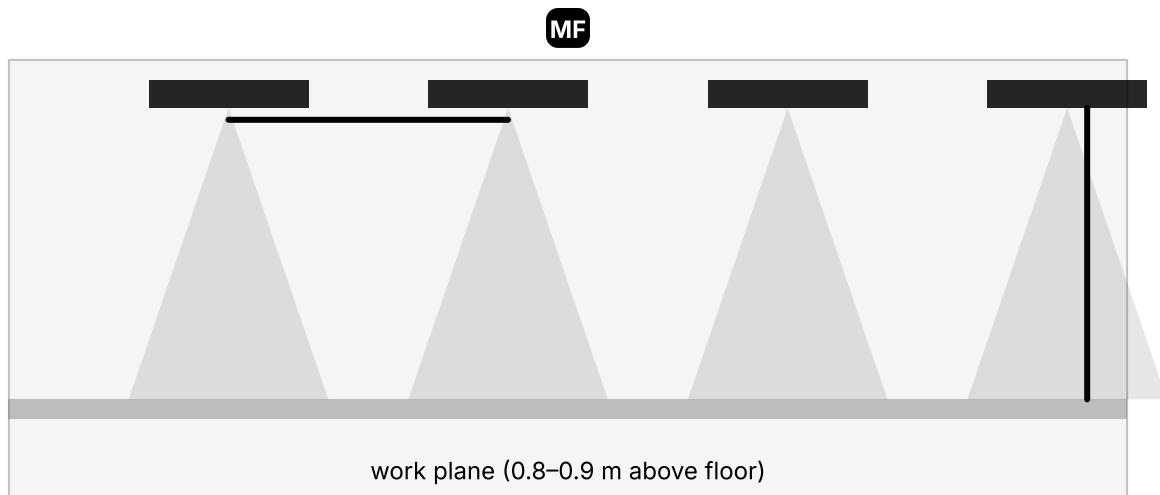
$$\text{LLF} = \text{Lamp lumen MF} \times \text{Luminaire MF} \times \text{Room surface MF}$$

SYMBOLS · UNITS

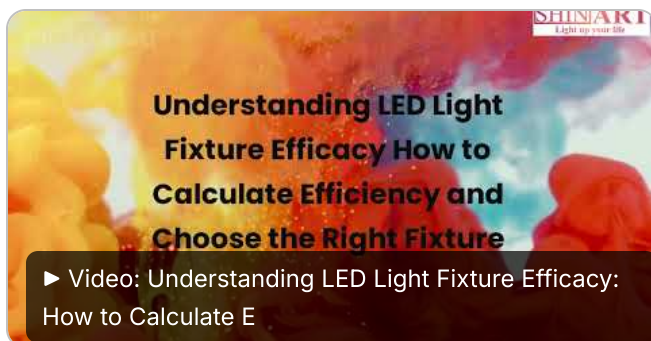
Symbols MF = maintenance factor (no unit)

Answer unit no unit

Book topic Lighting design



Where each value sits: **MF** → room L × W, room index, UF, LLF



WHAT IT MEANS

Lamps dim with age, luminaires and room surfaces get dirty; LLF ($\approx 0.7\text{--}0.8$) allows for this so the design still meets the lux at maintenance time.

Worked example. $0.9 \times 0.9 \times 0.9 = 0.73$.

Exam trap. Multiply the three maintenance factors.

Number of fittings required

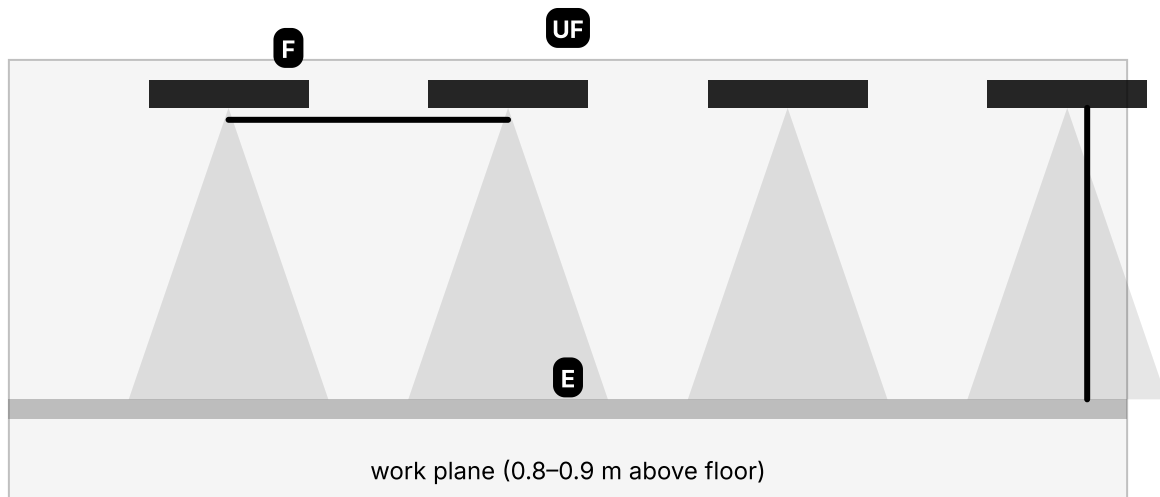
$$N = (E \times A) \div (F \times UF \times LLF)$$

SYMBOLS · UNITS

Symbols E = required lux, A = area (m^2), F = lumens per fitting, UF = utilisation factor

Answer unit **number**

Book topic Lighting design



Where each value sits: **E** → illuminance E lux, area A · **A** → illuminance E lux, area A · **F** → lamp: lumens F, watts, efficacy lm/W · **UF** → room L × W, room index, UF, LLF

WHAT IT MEANS

The lumen method: total lumens needed ÷ lumens each fitting actually delivers to the work plane.

Worked example. 216 m^2 at 300 lux, 18 W LED tubes of 1,800 lm, UF 0.5, LLF 0.8: $N = 64,800 \div (1,800 \times 0.5 \times 0.8) = 90$ tubes (2025 S-1 pattern).

Exam trap. F is lumens per FITTING (twin-tube = 2 lamps); round UP.

Space-to-height ratio

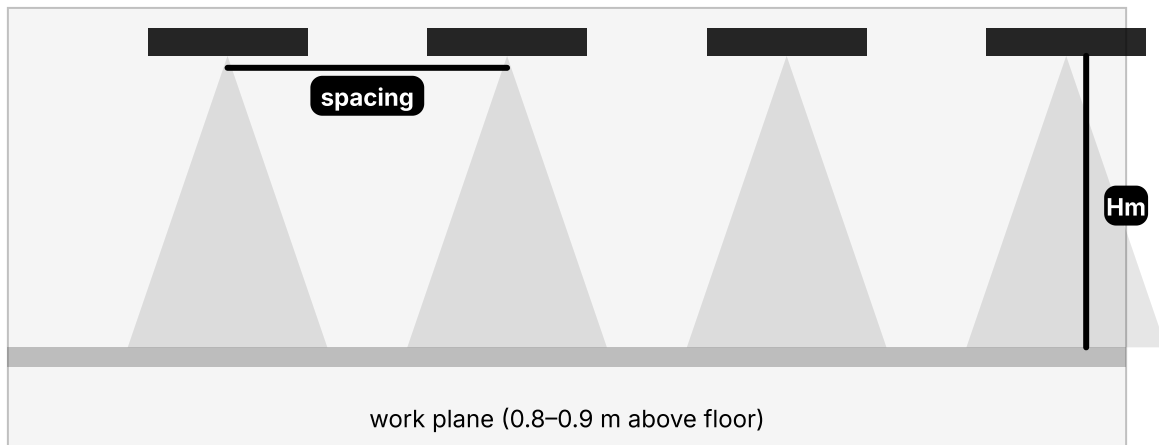
$$\text{SHR} = \text{Spacing between luminaires} \div \text{Mounting height}$$

SYMBOLS · UNITS

Symbols m ÷ m

Answer unit no unit

Book topic Lighting design



Where each value sits: **spacing** → spacing, SHR · **Hm** → mounting height Hm, distance d

WHAT IT MEANS

Spacing between luminaires divided by mounting height; keep at or below the luminaire's recommended value (≈ 1.5) for uniform light.

Worked example. Spacing 3 m, height 2 m → 1.5.

Exam trap. Exceeding it gives dark patches between fittings.

Uniformity ratio

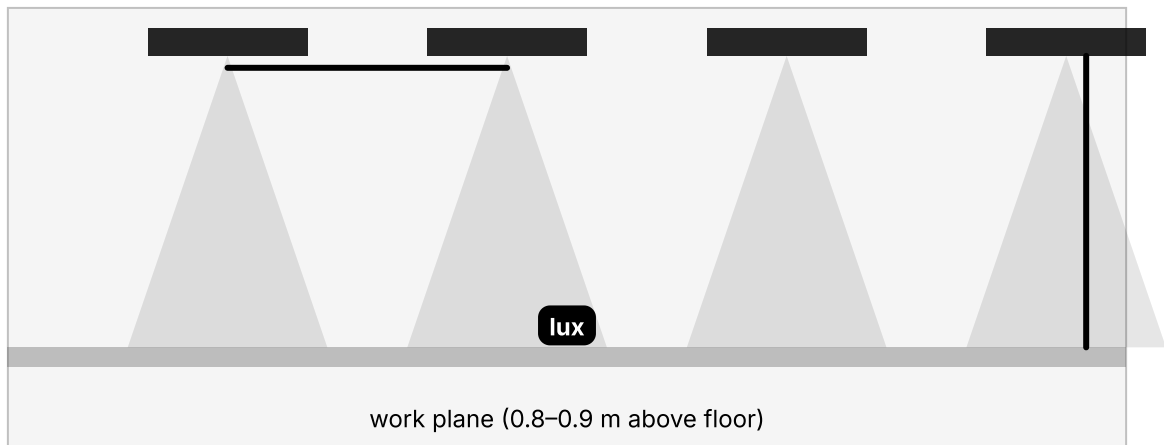
= Minimum illuminance ÷ Average illuminance

SYMBOLS · UNITS

Symbols lux

Answer unit no unit

Book topic Lighting design



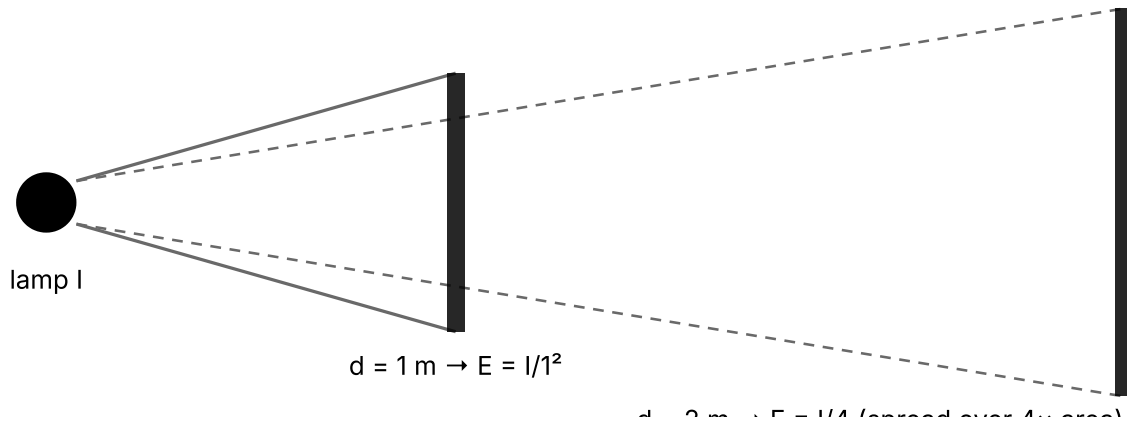
Where each value sits: **lux** → illuminance E lux, area A

WHAT IT MEANS

Minimum lux ÷ average lux on the work plane; aim ≥ 0.7 .

Worked example. Min 210, average 300 → 0.7.

Inverse-square law



Lumen method of lighting design

room $18 \times 12 \text{ m} = 216 \text{ m}^2$, target 300 lux $\rightarrow 64,800 \text{ lm}$ needed

$$N = E \times A \div (F \times UF \times LLF)$$

F = lumens per fitting · UF = utilisation factor (from room index) · LLF = light loss factor (≈ 0.8)

Room index = $L \times W \div [Hm \times (L + W)]$, Hm = luminaire height above the work plane

Efficacy (lm/W) ranking: LPSV > HPSV $\approx$ LED > metal halide > CFL > FTL > HPMV > halogen > incandesce

DEFINITIONS THE EXAM ASKS

Lamp families

Incandescent (efficacy 10–15 lm/W, CRI 100), halogen, FTL (T12 38 mm, T8 26 mm, T5 16 mm), CFL, HPMV, metal halide, HPSV ($\sim 120 \text{ lm/W}$, CRI 20–30), LPSV (highest efficacy $\sim 180 \text{ lm/W}$, CRI 10, monochromatic), LED.

Colour rendering index

How true colours look under the lamp, 0–100; incandescent/halogen = 100 (best for colour-critical work), LPSV = 10.

Ballasts

Electromagnetic ballasts lose 10–15 W per tube; electronic ballasts save 20–30 %, run at high frequency, no flicker.

Controls

Occupancy sensors (infrared, ultrasonic, microwave), daylight-linked dimming, timers, task lighting.

VERIFIED VIDEOS FOR THIS CHAPTER (YOUTUBE)

Lux, Inverse Square Law & Efficacy — Lighting Calculations, Inverse Square, Cosine, Efficacy & Lumen Method for Design Explained · Sparky Help

Lamp Efficacy Hierarchy & T-Diameters — Understanding LED Light Fixture Efficacy: How to Calculate Efficiency and Choose the Right Fixture · ShainART

Lumen Method & Room Index Design — How Much Light Does My Room Need? Lighting Design | Lighting Calculation Formula · Surviving Architecture

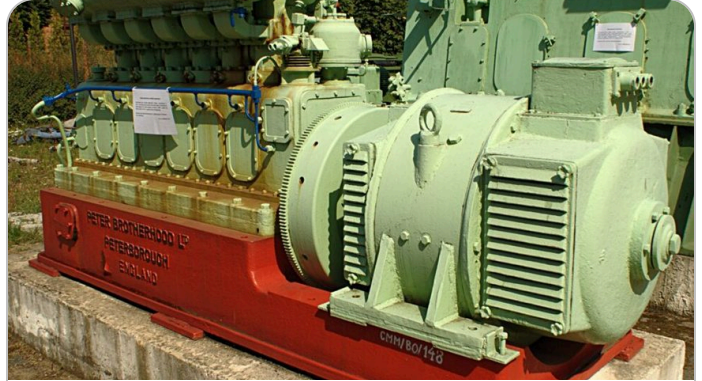
Chapter 9 • DG Set System

~11 marks: SFC and efficiency numericals, loss split (exhaust largest), waste-heat recovery, sizing with diversity factor.



Packaged diesel generator set in an acoustic enclosure

Photo: Gregseditis · CC BY-SA 3.0 · [source](#)



Diesel engine coupled to its alternator

Photo: Wikimedia Commons · CC BY-SA 3.0 · [source](#)

Real power of a DG set

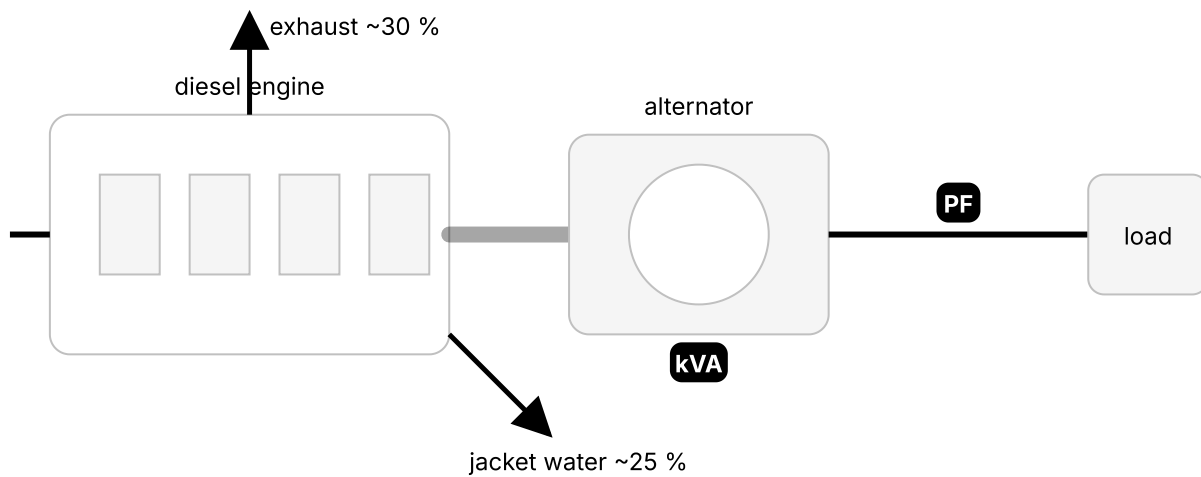
$$\text{kW} = \text{kVA} \times \text{PF}$$

SYMBOLS · UNITS

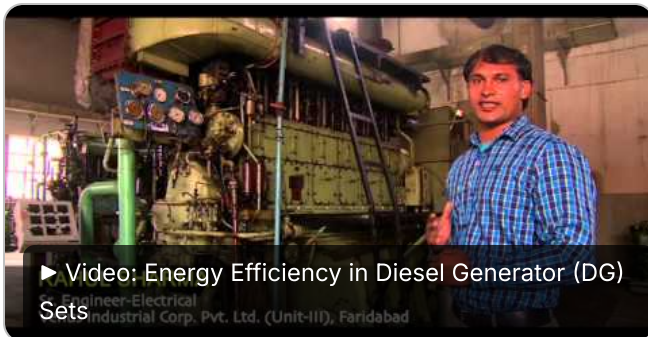
Symbols kVA, PF

Answer unit **kW**

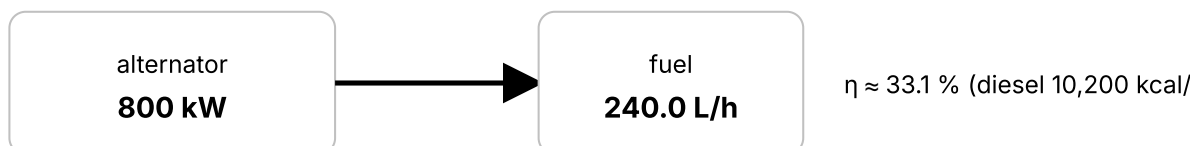
Book topic DG basics



Where each value sits: **kVA** → kVA rating, $\text{BHP} \times 0.746 \cdot \text{PF} \rightarrow \text{kW} = \text{kVA} \times \text{PF}$, units generated



► Try it: DG set: load, PF and specific fuel consumption → litres per hour and efficiency



$1000 \text{ kVA} \times 0.8 = 800 \text{ kW} \times 0.3 \text{ L/kWh} = \mathbf{240.0 \text{ litres/hour}}$; efficiency = $(1/0.3 \times 860) \div (0.85 \times 10,200) = \mathbf{33.1 \%}$

WHAT IT MEANS

A genset is rated in kVA at 0.8 PF; the kW it can deliver is the kVA times the power factor of the load.

Worked example. 1,000 kVA at 0.8 → 800 kW.

Exam trap. Higher-PF loads let you use more of the kVA as kW, but the ENGINE kW limits it.

Apparent power, 3-phase

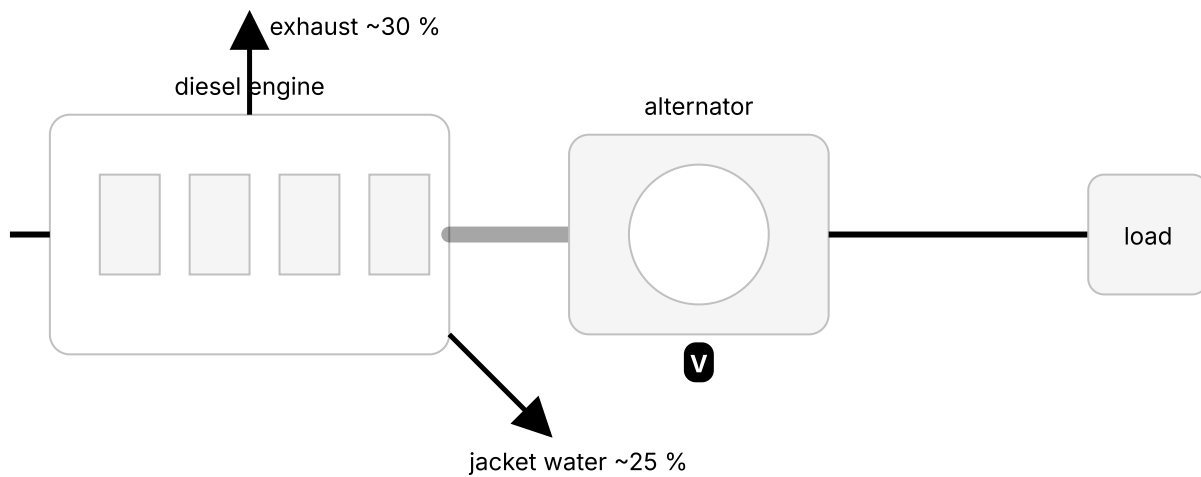
$$\text{kVA} = \sqrt{3} \times V \times I \div 1000$$

SYMBOLS · UNITS

Symbols V (V), I (A)

Answer unit **kVA**

Book topic DG basics



Where each value sits: **V** → kVA rating, BHP × 0.746 · **I** → kVA rating, BHP × 0.746

WHAT IT MEANS

Alternator output from measured line volts and amps.

Worked example. 420 V, 100 A → 72.7 kVA; at PF 0.9 → 65.5 kW (2009/2022).

Exam trap. Line voltage × $\sqrt{3}$.

Engine power from BHP

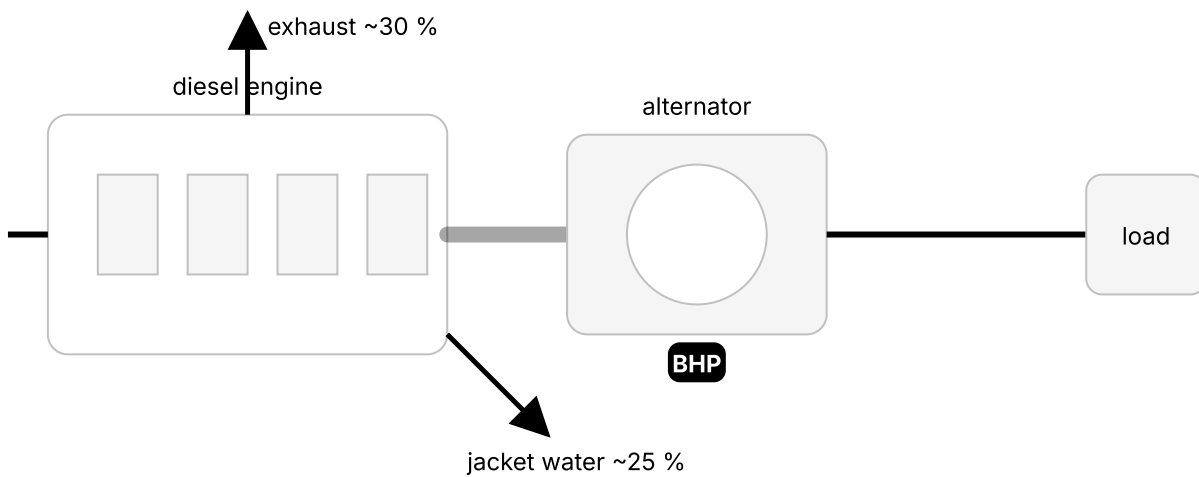
$$\text{kW} = \text{BHP} \times 0.746$$

SYMBOLS · UNITS

Symbols BHP

Answer unit kW

Book topic DG basics



Where each value sits: **BHP** → kVA rating, $\text{BHP} \times 0.746$

WHAT IT MEANS

Engines are rated in brake horsepower; multiply by 0.746 for kW.

Worked example. 250 BHP → 186.5 kW.

Exam trap. 1 HP = 0.746 kW (not 0.735).

Fuel consumption

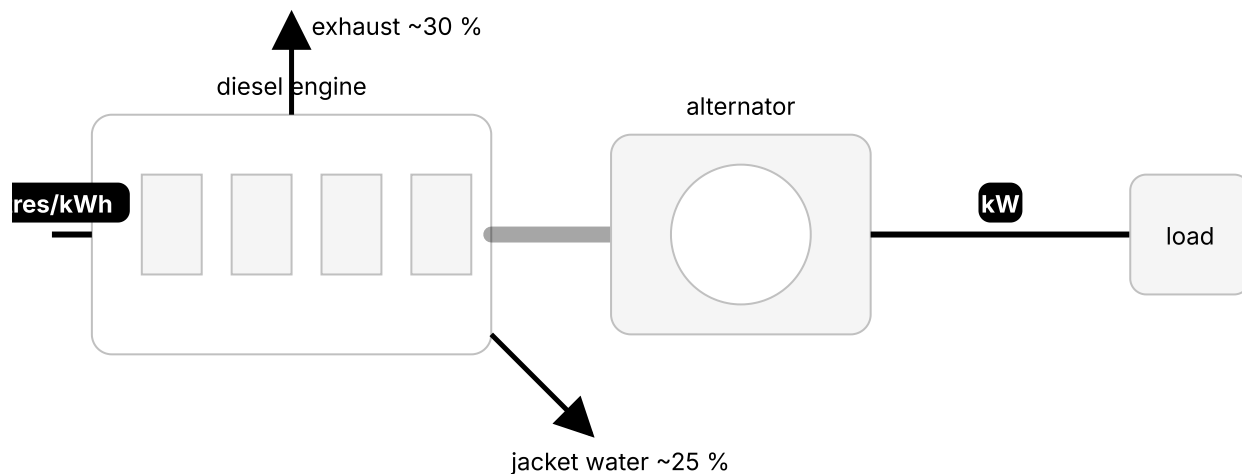
$$\text{Fuel (litres/hr)} = \text{kW generated} \times \text{SFC (litres/kWh)}$$

SYMBOLS · UNITS

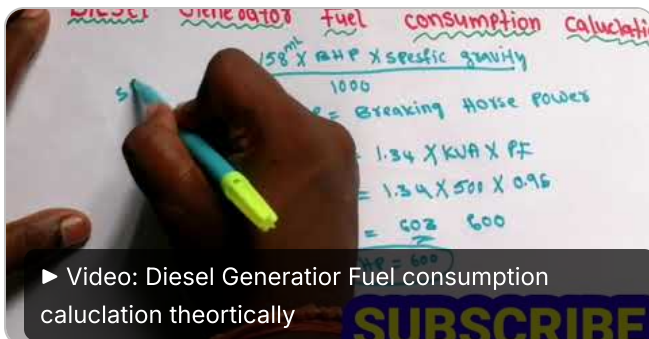
Symbols kW, litres/kWh

Answer unit litres/hr

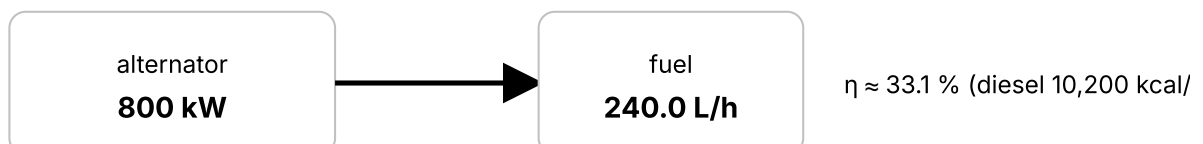
Book topic Performance



Where each value sits: **kW** → kW = kVA × PF, units generated · **litres/kWh** → fuel L/h, SFC, GCV, density



► Try it: DG set: load, PF and specific fuel consumption → litres per hour and efficiency



$1000 \text{ kVA} \times 0.8 = 800 \text{ kW} \times 0.3 \text{ L/kWh} = \mathbf{240.0 \text{ litres/hour}}$; efficiency = $(1/0.3 \times 860) \div (0.85 \times 10,200) = \mathbf{33.1 \%}$

WHAT IT MEANS

Litres of diesel per hour = kW generated $\times$ litres per kWh (the SFC). A DG set at a lower PF generates fewer kW for the same kVA, so burns less fuel.

Worked example. $65.5 \text{ kW} \times 0.3 \text{ L/kWh} = 19.64 \text{ L/h}$ (2009/2022 objective). $70 \text{ L/h} \div 0.33 \text{ L/kWh} = 212 \text{ kW} \rightarrow \div 0.8 = 265 \text{ kVA}$ (2021).

Exam trap. SFC in litres per kWh in this form; specific generation (kWh/L) is its inverse.

Specific energy generation

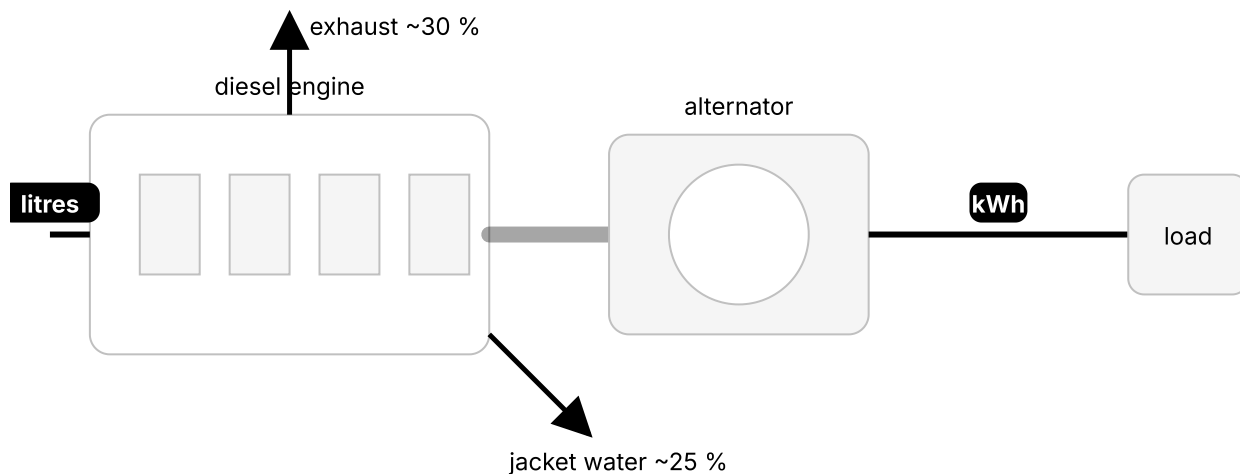
$$= \text{kWh generated} \div \text{Litres of fuel used}$$

SYMBOLS · UNITS

Symbols kWh, litres

Answer unit kWh/litre

Book topic Performance



Where each value sits: **kWh** → kW = kVA × PF, units generated · **litres** → fuel L/h, SFC, GCV, density

WHAT IT MEANS

Units per litre of diesel — the everyday DG benchmark (3–4 kWh/L for a healthy set; falls at low load).

Worked example. 1,500 kWh in a 2-h trial burning 400 L → 3.75 kWh/L.

Exam trap. Inverse of SFC.

DG overall efficiency

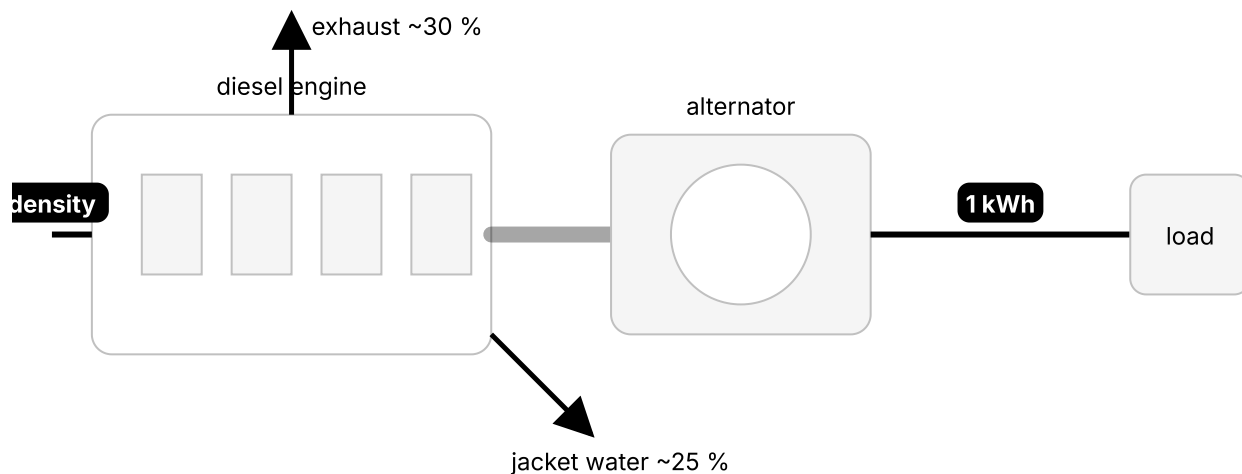
$$\eta = (\text{kWh} \times 860) \div (\text{Fuel litres} \times \text{Density} \times \text{GCV}) \times 100$$

SYMBOLS · UNITS

Symbols 1 kWh = 860 kcal; density (kg/litre); GCV (kcal/kg)

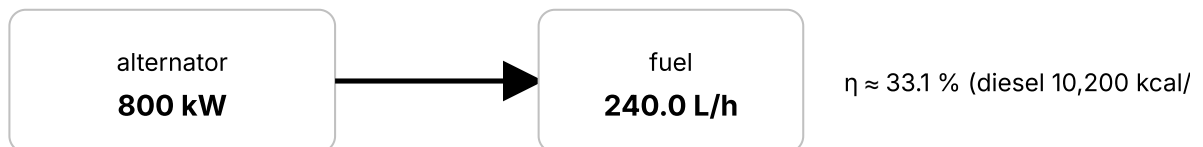
Answer unit %

Book topic Performance



Where each value sits: **1 kWh** → kW = kVA × PF, units generated · **density** → fuel L/h, SFC, GCV, density · **GCV** → fuel L/h, SFC, GCV, density

► Try it: DG set: load, PF and specific fuel consumption → litres per hour and efficiency



$1000 \text{ kVA} \times 0.8 = 800 \text{ kW} \times 0.3 \text{ L/kWh} = \mathbf{240.0 \text{ litres/hour}}$; efficiency = $(1/0.3 \times 860) \div (0.85 \times 10,200) = \mathbf{33.1 \%}$

WHAT IT MEANS

Electrical energy out ÷ fuel energy in: units × 860 kcal, over litres × density (0.85 kg/L) × GCV.

Worked example. 3.5 kWh/L: $3.5 \times 860 \div (0.85 \times 10,200) = 34.7 \%$ (2013 exam; 2025 L-5 gives 34.2 %).

Exam trap. Convert litres to kg with the density before applying GCV.

Waste heat recoverable from exhaust

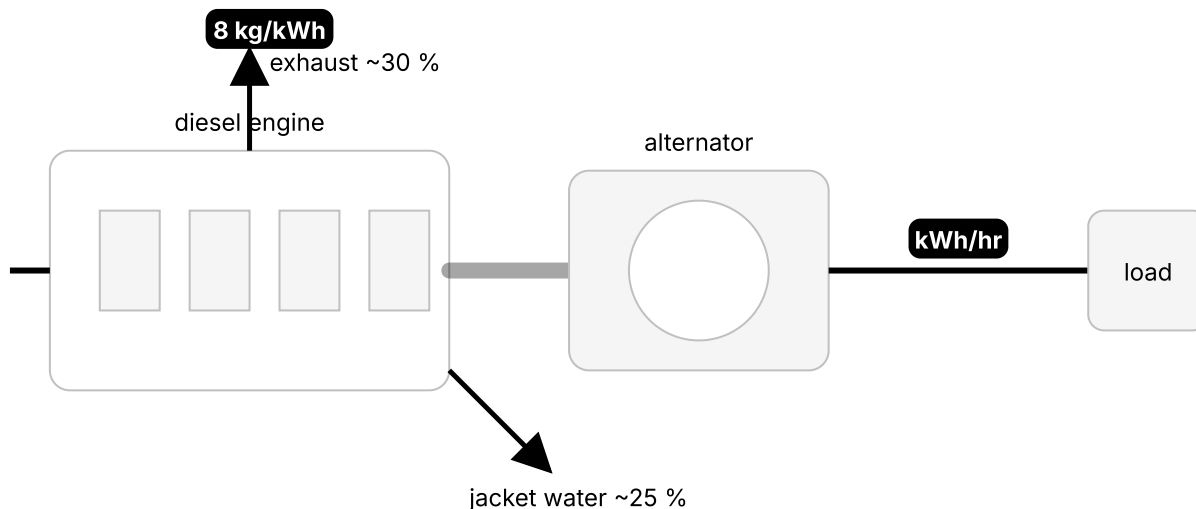
$$= \text{kWh/hr} \times 8 \text{ kg gas/kWh} \times 0.25 \text{ kcal/kg } ^\circ\text{C} \times (T \text{ exhaust} - T \text{ out})$$

SYMBOLS · UNITS

Symbols temperatures ($^\circ\text{C}$)

Answer unit kcal/hr

Book topic Waste heat recovery



Where each value sits: **kWh/hr** → kW = kVA × PF, units generated · **8 kg/kWh** → exhaust: 8 kg/kWh, Cp 0.25, T in/out · **0.25** → exhaust: 8 kg/kWh, Cp 0.25, T in/out · **T exhaust – T out** → exhaust: 8 kg/kWh, Cp 0.25, T in/out

WHAT IT MEANS

Exhaust gas (≈ 8 kg per kWh at ≈ 450 $^\circ\text{C}$) can heat water or make steam down to about 180 $^\circ\text{C}$; the recoverable heat is mass × Cp × temperature drop.

Worked example. $600 \text{ kWh/h} \times 8 \times 0.25 \times (450 - 230) = 264,000 \text{ kcal/hr}$ (book).

Exam trap. Cp of exhaust gas $0.25 \text{ kcal/kg } ^\circ\text{C}$, and do not cool below the stated outlet temperature.

Steam generated from waste heat

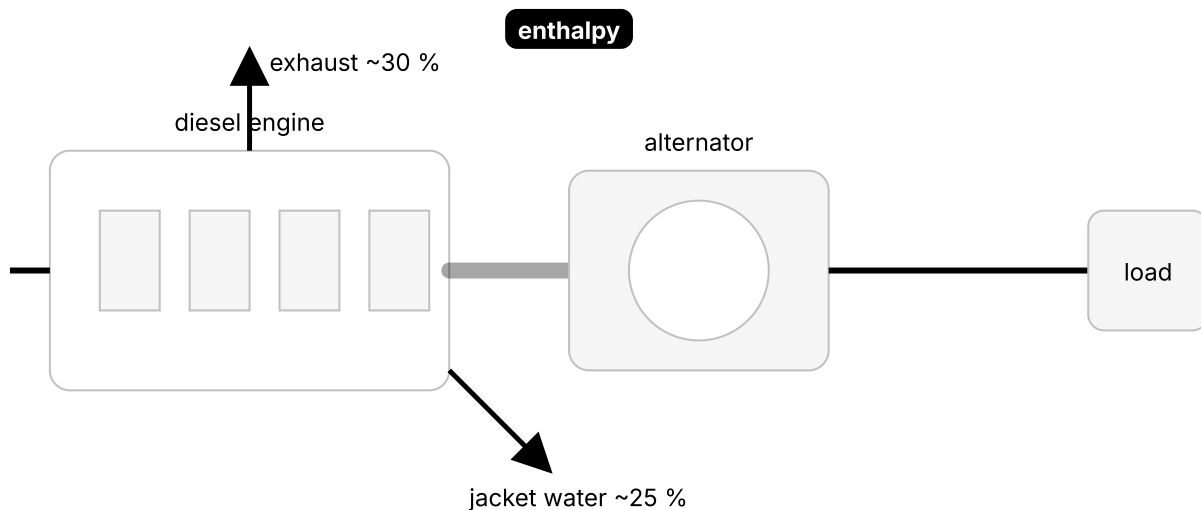
$$= \text{Waste heat (kcal/hr)} \div (\text{Steam enthalpy} - \text{Feed-water enthalpy})$$

SYMBOLS · UNITS

Symbols enthalpy (kcal/kg)

Answer unit kg/hr

Book topic Waste heat recovery



Where each value sits: **enthalpy** → steam kg/hr, enthalpy

WHAT IT MEANS

Recoverable heat divided by the heat needed per kg of steam (steam enthalpy minus feed-water enthalpy).

Worked example. $264,000 \div (650.57 - 80) = 462.7 \text{ kg/h (book).}$

Exam trap. Feed-water enthalpy $\approx$ its temperature in $^{\circ}\text{C}$ (kcal/kg).

Heat lost to jacket cooling water

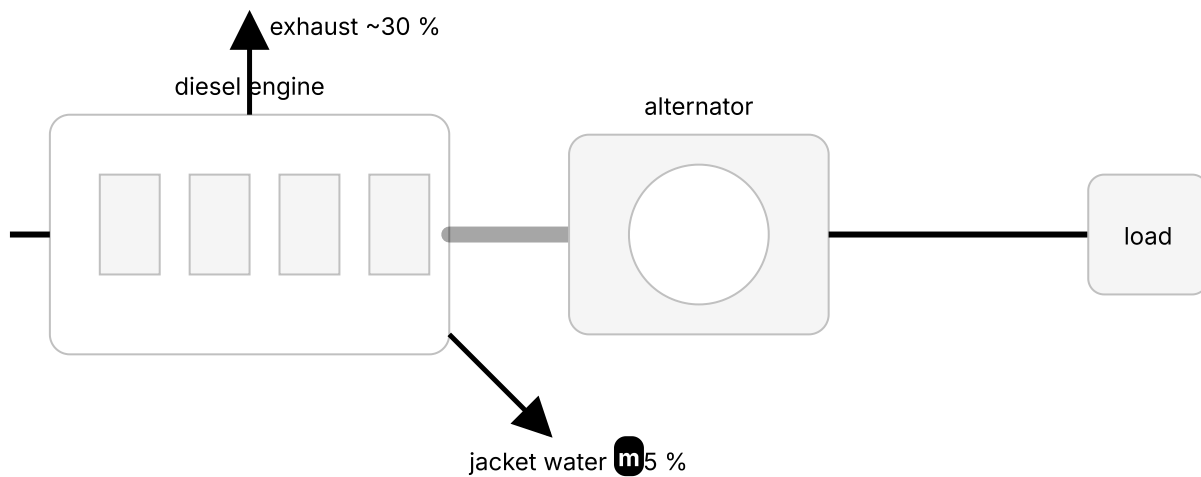
$$Q = m \times C_p \times \Delta T ; \quad kW = Q \div 860$$

SYMBOLS · UNITS

Symbols m (kg/hr), $C_p = 1$ kcal/kg °C, ΔT (°C)

Answer unit **kcal/hr (and kW)**

Book topic Heat balance



Where each value sits: **m** → m , C_p , ΔT jacket water · **Cp** → m , C_p , ΔT jacket water · **ΔT** → m , C_p , ΔT jacket water

WHAT IT MEANS

Engine cooling water carries away ~25–30 % of fuel energy; from its flow and temperature rise.

Worked example. $12.9 \text{ m}^3/\text{hr} \times 1000 \times 1 \times 10 \text{ °C} = 129,000 \text{ kcal/hr} \div 860 = 150 \text{ kW}$ (book / 2014).

Exam trap. Divide by 860 to get kW.

Maximum demand from connected load

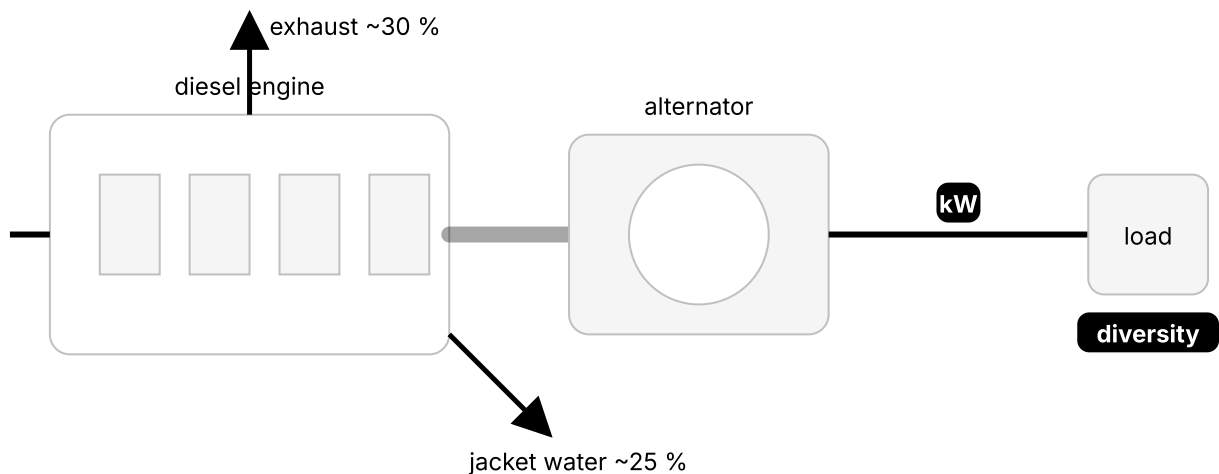
$$= \text{Connected load} \times \text{Diversity factor}$$

SYMBOLS · UNITS

Symbols kW; diversity factor as fraction

Answer unit kW

Book topic Sizing



Where each value sits: **kW** → kW = kVA × PF, units generated · **diversity** → connected load, diversity, load factor, %

WHAT IT MEANS

Not all loads run at once; the diversity factor gives the realistic peak the DG must carry.

Worked example. 650 kW connected × 0.54 = 351 kW (book). When the factor is quoted as a number > 1, DIVIDE: 650 ÷ 1.8.

Exam trap. Read whether the diversity factor is a fraction (< 1, multiply) or a ratio (> 1, divide).

DG set rating

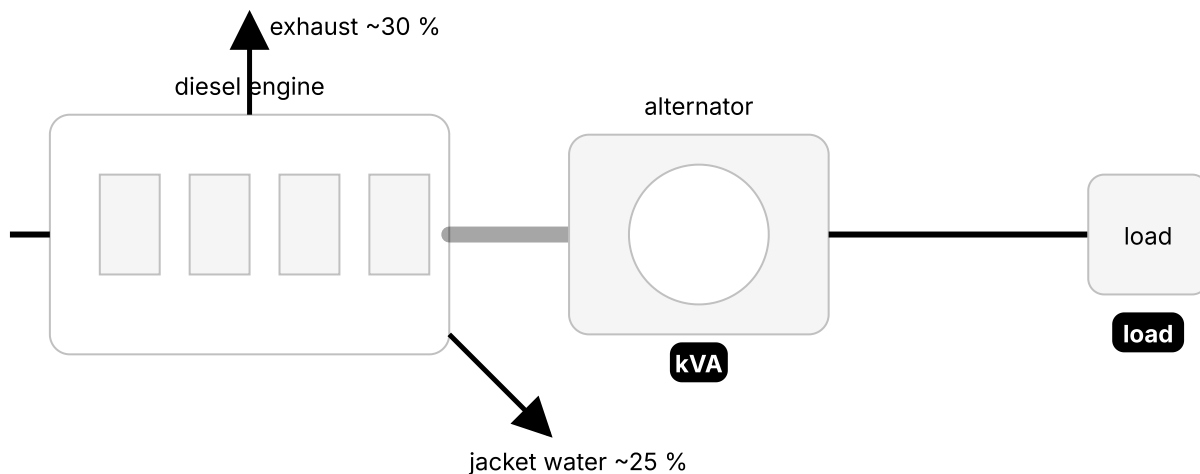
$$= \text{kVA required} \div \text{Load factor}$$

SYMBOLS · UNITS

Symbols kVA; load factor as fraction

Answer unit kVA

Book topic Sizing



Where each value sits: **kVA** → kVA rating, $\text{BHP} \times 0.746$ · **load** → connected load, diversity, load factor, %

WHAT IT MEANS

Size the set so the peak demand is a comfortable load (70–80 %) — running lightly loaded wastes fuel and causes glazing.

Worked example. $351 \text{ kW} \div 0.8 \text{ PF} = 439 \text{ kVA} \div 0.8 \text{ load factor} \rightarrow 550 \text{ kVA}$.

Exam trap. kW → kVA ($\div$ PF) BEFORE applying the load factor.

Load factor

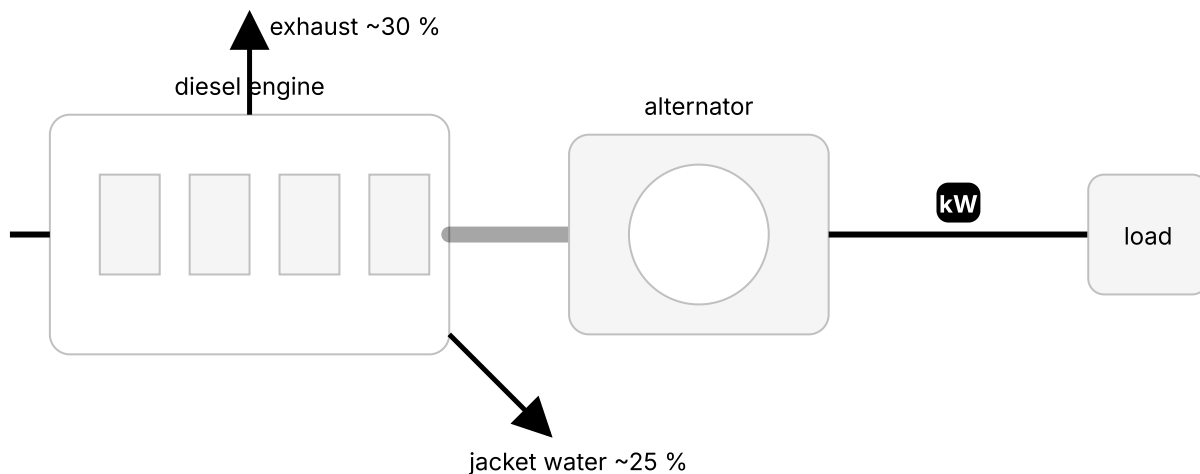
$$= \text{Average load} \div \text{Maximum (rated) load}$$

SYMBOLS · UNITS

Symbols kW or kVA

Answer unit % (or fraction)

Book topic Sizing



Where each value sits: **kW** → kW = kVA × PF, units generated

WHAT IT MEANS

Average load ÷ peak load over the period; a low load factor means a big set idling most of the time.

Worked example. Average 300 kW, peak 500 → 60 %.

Cost of generation

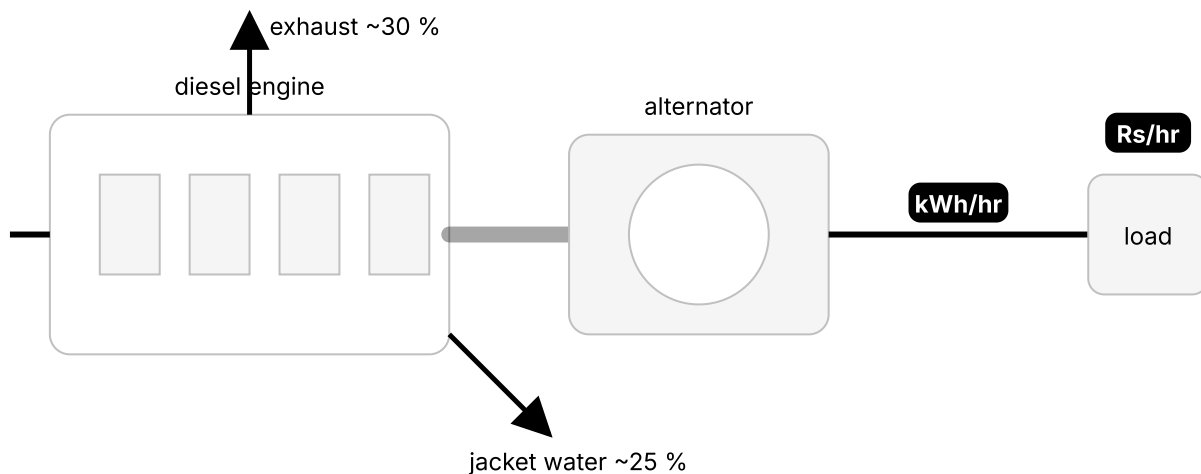
$$= \text{Fuel cost per hour (Rs/hr)} \div \text{kWh generated per hour}$$

SYMBOLS · UNITS

Symbols Rs/hr, kWh/hr

Answer unit Rs/kWh

Book topic Economics



Where each value sits: **Rs/hr** → ₹/L, ₹/kWh · **kWh/hr** → kW = kVA × PF, units generated

WHAT IT MEANS

Fuel cost per unit generated; compare with the grid tariff to decide when to run the set.

Worked example. 19.6 L/h × ₹90 ÷ 65.5 kWh = ₹27/kWh.

Exam trap. Add lubricant and maintenance for the full cost.

Sankey diagram of a diesel generator



DEFINITIONS THE EXAM ASKS

DG basics

4-stroke diesel engine + alternator at 1,500 rpm (4-pole, 50 Hz); rated kVA at 0.8 PF; efficiency $\approx 35 \%$.

Losses

Exhaust gas $\approx 30 \%$ (largest), jacket water $\approx 25 \%$, radiation $\approx 10 \%$ — recover exhaust heat for steam/hot water, jacket water for absorption chillers.

Loading

Run at 70–80 % load; light loading wastes fuel and glazes cylinders. Max PF usable = $(\text{engine kW} - \text{losses}) \div \text{kVA}$.

Derating

Output falls with altitude and ambient temperature (book Tables 9.3/9.4).

Parameters to monitor

Voltage and frequency (plus current and PF) on the generator panel.

VERIFIED VIDEOS FOR THIS CHAPTER (YOUTUBE)

4-Stroke Principles & Sizing — Energy Efficiency in Diesel Generator (DG) Sets · bhavesh swami

Heat Balance & Exhaust WHR — Diesel Generator Fuel consumption calculation theoretically practically in electrical explanations · Electrical Explanations

Chapter 10 • Buildings and ECBC

~15 marks: ECBC applicability, envelope terms (WWR, EA, SHGC, U-factor), EPI/star rating, LPD — the 2025 long question was a full EPI/LPD/diversity calculation.



Office façade — window-wall ratio, SHGC and VLT of the glazing decide the cooling load and daylight
Photo: Calderoliver • CC BY-SA 3.0 • source



Building envelope: glazing and shading
Photo: Jon Rawlinson • CC BY 2.0 • source

Energy Performance Index

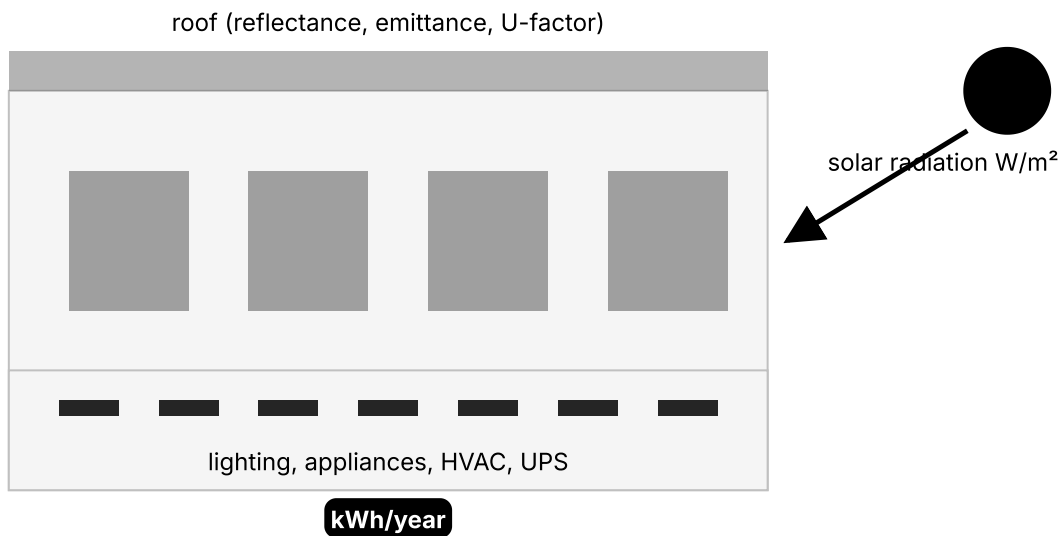
$$\text{EPI} = \text{Annual energy consumption} \div \text{Built-up area}$$

SYMBOLS · UNITS

Symbols kWh/year, m²

Answer unit kWh/m²/year

Book topic Star rating of buildings



Where each value sits: **kWh/year** → annual kWh, built-up area m² → EPI · m²: m²

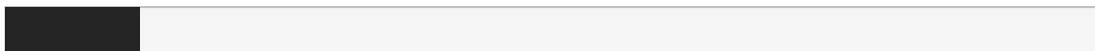
TAKKAR 10 MCQs
DAILY PT SERIES-2024
CLASS- 113
10th Nov. 2023

Energy Conservation

► Video: Energy Conservation Building Code (ECBC)
| Class 113 | Anish

Dr. Anish Kumar Singh

► Try it: Building: annual energy and built-up area → EPI and star rating



EPI scale for offices (book bands, composite climate): ≤ 90 → 5★ ... ≥ 190 → 1★

EPI = 31 kWh/m²/yr → ★★★★★

$110,000 \text{ kWh} \div 3,600 \text{ m}^2 = 31 \text{ kWh/m}^2/\text{year} \rightarrow \text{about } 5 \text{ stars}$ (lower EPI = more stars)

WHAT IT MEANS

The building's annual energy per square metre of built-up area — the number used for BEE star rating of offices (lower EPI = MORE stars).

Worked example. $107,889 \text{ kWh} \div 3,592 \text{ m}^2 = 30 \text{ kWh/m}^2/\text{yr} \rightarrow 5\text{-star}$ (2025 L-5). Bands for offices ≈ 190 (1★) down to 90 (5★) in the book's climate table.

Exam trap. Built-up area, not carpet area; and LOWER EPI is BETTER (2013/2018 objective).

AAhEPI (BPO star rating)

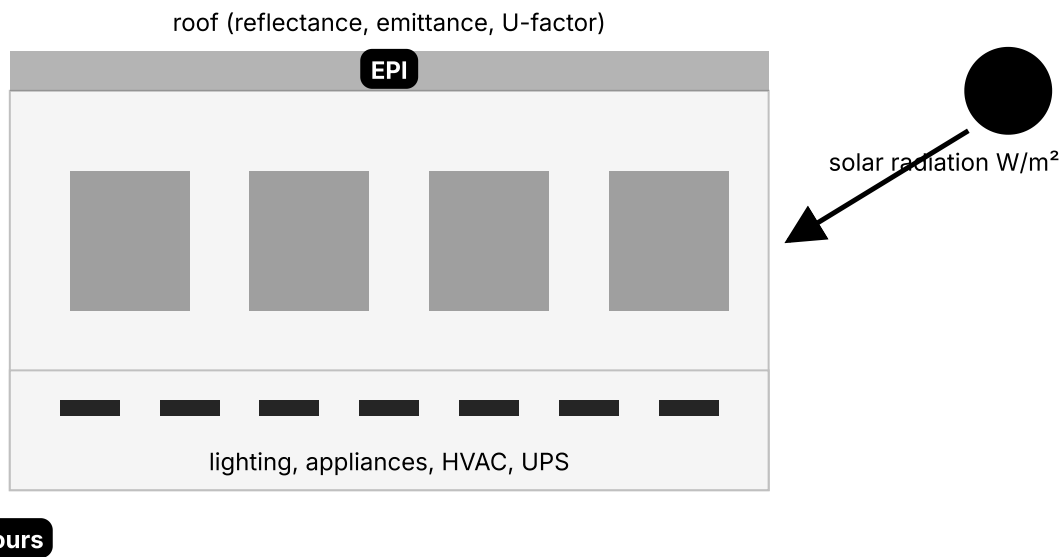
$$= \text{EPI} \times 1000 \div \text{Annual operating hours (hours/day} \times \text{days/week} \times 52)$$

SYMBOLS · UNITS

Symbols EPI (kWh/m²/yr), hours

Answer unit (Wh/m²)/hr

Book topic Star rating of buildings



Where each value sits: **EPI** → reflectance + absorptance = 1, emissivity ϵ · **hours** → hours/day × days/week × 52 → AAhEPI

WHAT IT MEANS

BPOs run round the clock, so their EPI is normalised by operating hours: watt-hours per m² per operating hour.

Worked example. EPI 250 kWh/m²/yr, 24 h × 7 d × 52 = 8,736 h → 250 × 1000 ÷ 8,736 = 28.6 (Wh/m²)/hr.

Exam trap. Unit is (Wh/sqm)/hr (book Q9).

Window-wall ratio

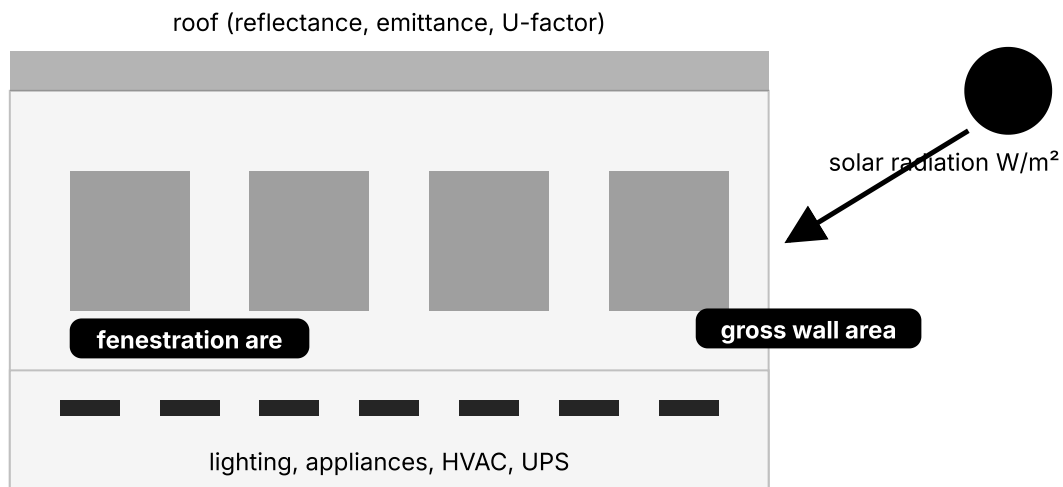
$$\text{WWR} = \text{Vertical fenestration area} \div \text{Gross exterior wall area}$$

SYMBOLS · UNITS

Symbols m^2, m^2

Answer unit **no unit (or %)**

Book topic Building envelope



Where each value sits: **fenestration area** → fenestration area, WWR, VLT, SHGC, U · **gross wall area** → gross exterior wall area · **WWR** → fenestration area, WWR, VLT, SHGC, U

WHAT IT MEANS

How much of the outside wall is glass; more glass = more daylight but more solar heat gain.

Worked example. 60 m^2 window in 150 m^2 wall → 0.40.

Exam trap. Gross exterior wall area in the denominator (2022 objective).

Effective aperture

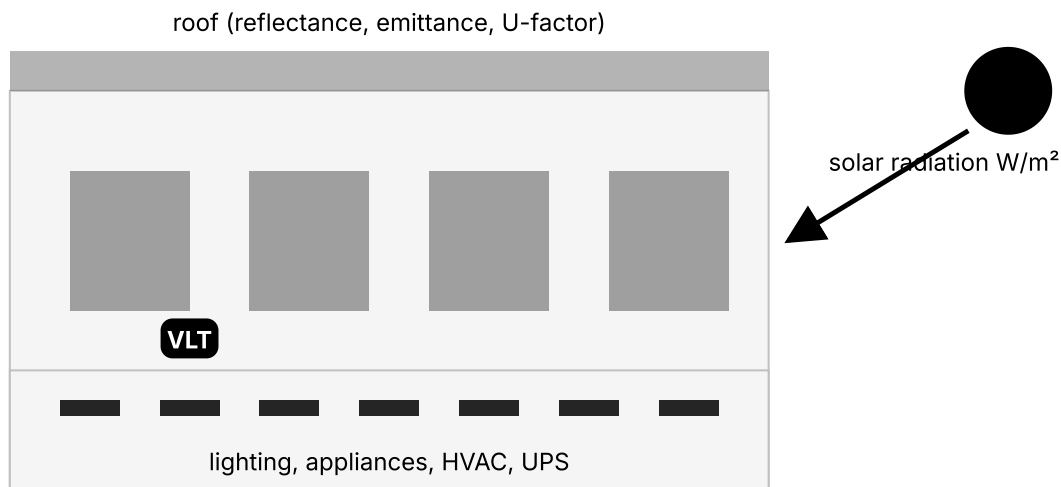
$$EA = VLT \times WWR$$

SYMBOLS · UNITS

Symbols no units

Answer unit no unit (complies if $EA \geq 0.1$)

Book topic Building envelope



Where each value sits: **VLT** → fenestration area, WWR, VLT, SHGC, U · **WWR** → fenestration area, WWR, VLT, SHGC, U · **EA ≥ 0.1** → fenestration area, WWR, VLT, SHGC, U

WHAT IT MEANS

Daylight potential = how much wall is glass × how much light the glass passes; ECBC wants $EA \geq 0.1$ so daylight can replace lighting.

Worked example. $WWR 0.4 \times VLT 0.26 = 0.104 \rightarrow$ complies; $0.6 \times 0.15 = 0.09 \rightarrow$ does not (book cases, 2023 S-3).

Exam trap. Both factors are fractions; compare with 0.1.

Visible light transmittance

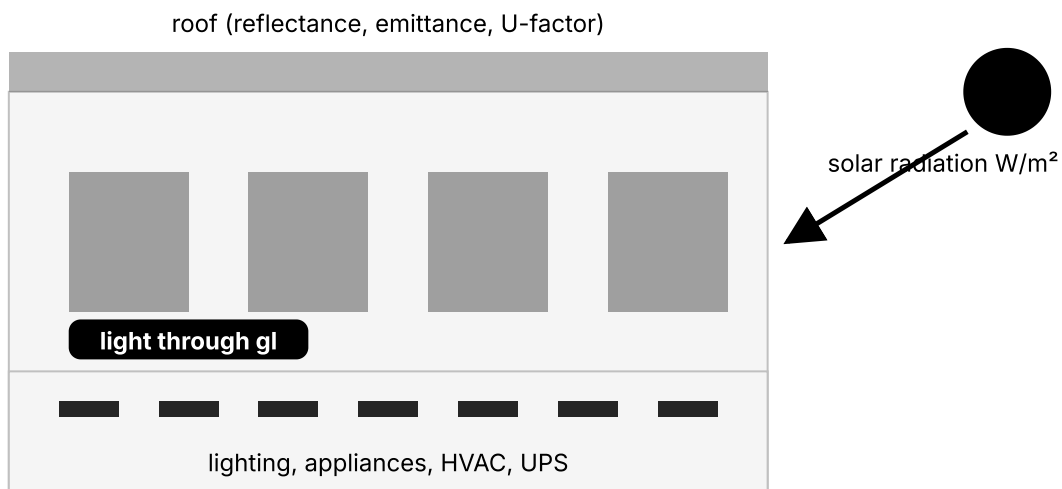
$$\text{VLT} = \text{Light through glazing} \div \text{Light through perfectly transmissive glazing}$$

SYMBOLS · UNITS

Symbols —

Answer unit no unit (0 to 1)

Book topic Building envelope



Where each value sits: **light through glazing** → fenestration area, WWR, VLT, SHGC, U · **VLT** → fenestration area, WWR, VLT, SHGC, U

WHAT IT MEANS

Share of visible light the glazing lets through (clear glass ≈ 0.8 , tinted 0.2–0.5).

Worked example. VLT 0.5 passes half the daylight.

Exam trap. Not the same as SHGC — VLT is light, SHGC is heat.

Solar heat gain coefficient

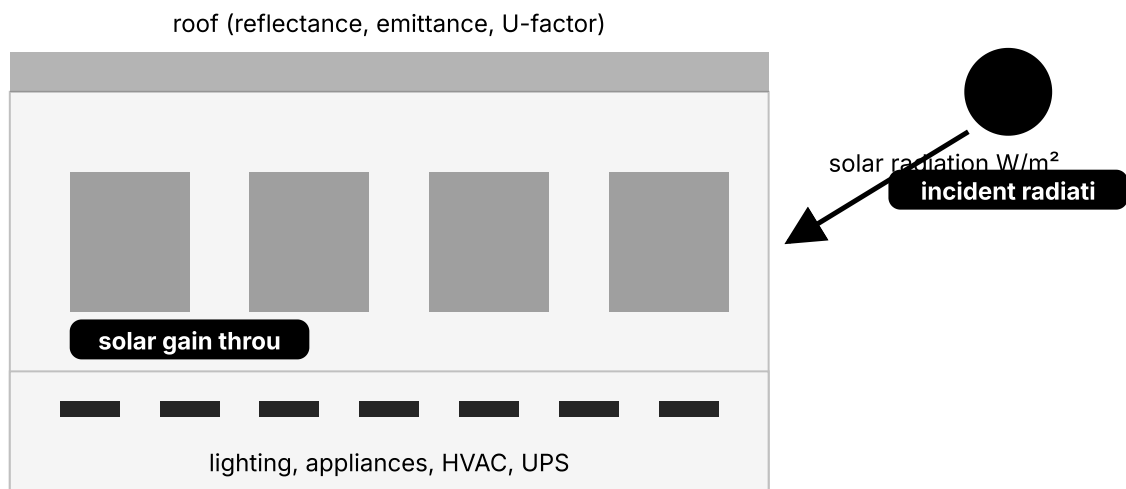
$\text{SHGC} = \text{Solar heat gain through fenestration} \div \text{Incident solar radiation}$

SYMBOLS · UNITS

Symbols —

Answer unit no unit (0 to 1)

Book topic Building envelope



Where each value sits: **solar gain through glass** → fenestration area, WWR, VLT, SHGC, U · **incident radiation** → incident solar radiation, gain W/m² · **SHGC** → fenestration area, WWR, VLT, SHGC, U

WHAT IT MEANS

Share of the sun's heat that gets through the window (directly plus re-radiated). SHGC 0.30 means 30 % of incident solar heat enters; the rest is reflected or re-emitted outside.

Worked example. SHGC 0.30 → 'the window allows 30 % of the sun's heat into the interior' (2018/2021/2022 objective).

Exam trap. Lower SHGC = less cooling load; it is NOT '70 % reflected' (some is absorbed and re-emitted).

Solar heat gain through glass

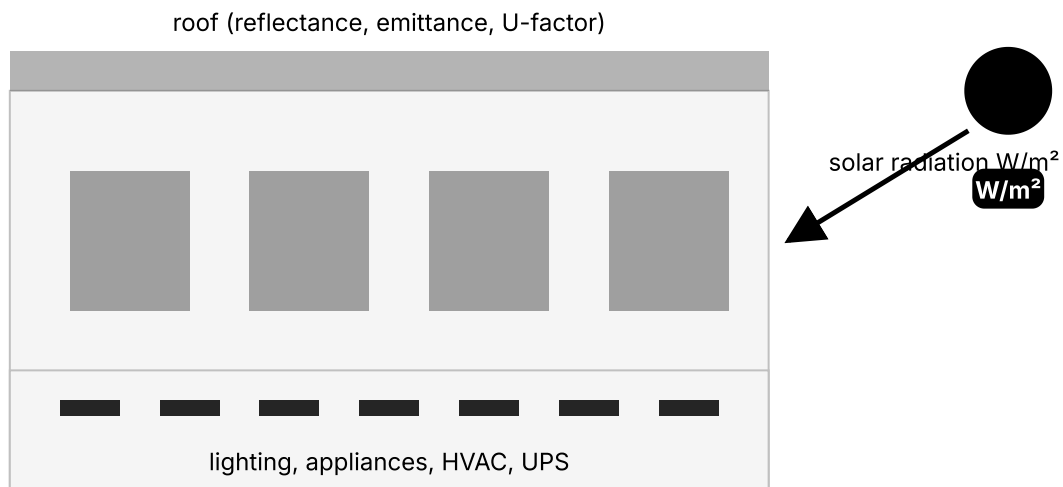
$$= \text{SHGC} \times \text{Incident solar radiation}$$

SYMBOLS · UNITS

Symbols W/m^2

Answer unit W/m^2

Book topic Building envelope



Where each value sits: $\text{W/m}^2 \rightarrow$ incident solar radiation, gain W/m^2

WHAT IT MEANS

Incident solar radiation times the SHGC.

Worked example. $600 \text{ W/m}^2 \times 0.25 = 150 \text{ W/m}^2$ (2024 L-3); $700 \times 0.30 = 210 \text{ W/m}^2$.

Exam trap. Per m^2 of glass; multiply by the glass area for total watts.

Heat flow through a wall or window

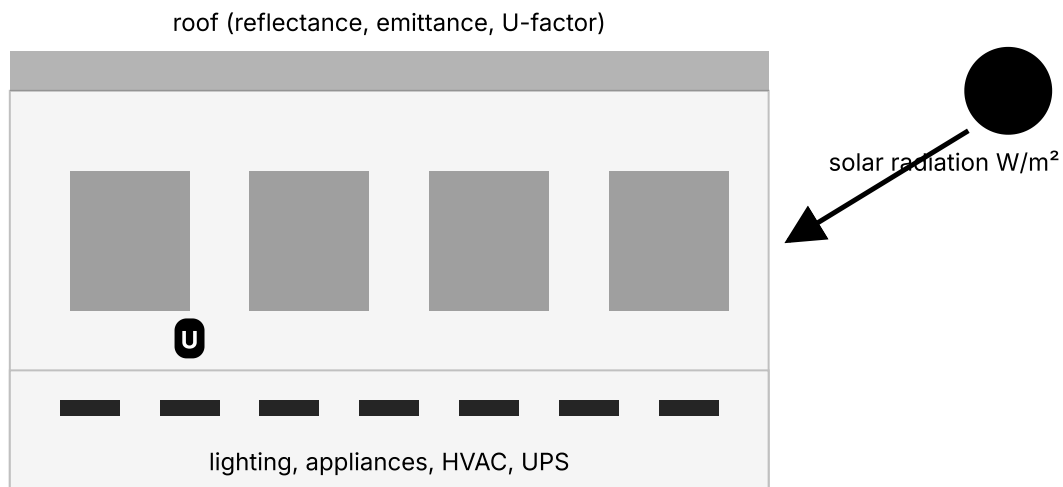
$$Q = U \times A \times \Delta T$$

SYMBOLS · UNITS

Symbols U = U-factor ($\text{W}/\text{m}^2 \text{ } ^\circ\text{C}$), A = area (m^2), ΔT ($^\circ\text{C}$)

Answer unit **W**

Book topic U-factor



Where each value sits: **U** → fenestration area, WWR, VLT, SHGC, **U · A** → fenestration area, WWR, VLT, SHGC, **U · ΔT** → fenestration area, WWR, VLT, SHGC, **U**

WHAT IT MEANS

The U-factor is the heat that passes through 1 m^2 for each degree of temperature difference; lower U = better insulation. ECBC max for vertical fenestration $\approx 3.3 \text{ W}/\text{m}^2 \cdot ^\circ\text{C}$ (most zones).

Worked example. $U \ 3.3$, 20 m^2 , $\Delta T \ 10 \text{ } ^\circ\text{C} \rightarrow 660 \text{ W}$.

Exam trap. U-factor in $\text{W}/\text{m}^2 \cdot ^\circ\text{C}$; R-value is its inverse.

Reflectance and absorptance (opaque surface)

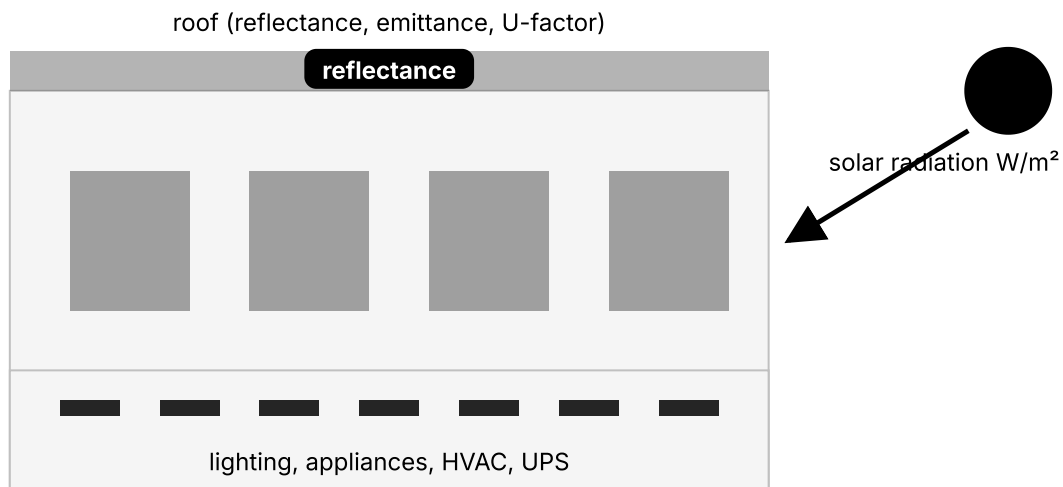
$$\text{Reflectance} + \text{Absorptance} = 1$$

SYMBOLS · UNITS

Symbols —

Answer unit no unit

Book topic Cool roofs



Where each value sits: **reflectance** → reflectance + absorptance = 1, emissivity e · **absorptance** → reflectance + absorptance = 1, emissivity e

WHAT IT MEANS

Whatever sunlight a roof does not reflect, it absorbs; a cool roof has high reflectance (≥ 0.7) AND high emittance (≥ 0.75) so it also radiates the heat away at night.

Worked example. Reflectance 0.7 → absorptance 0.3.

Exam trap. A cool roof REFLECTS heat (book EOC Q5).

Emissivity (thermal emittance)

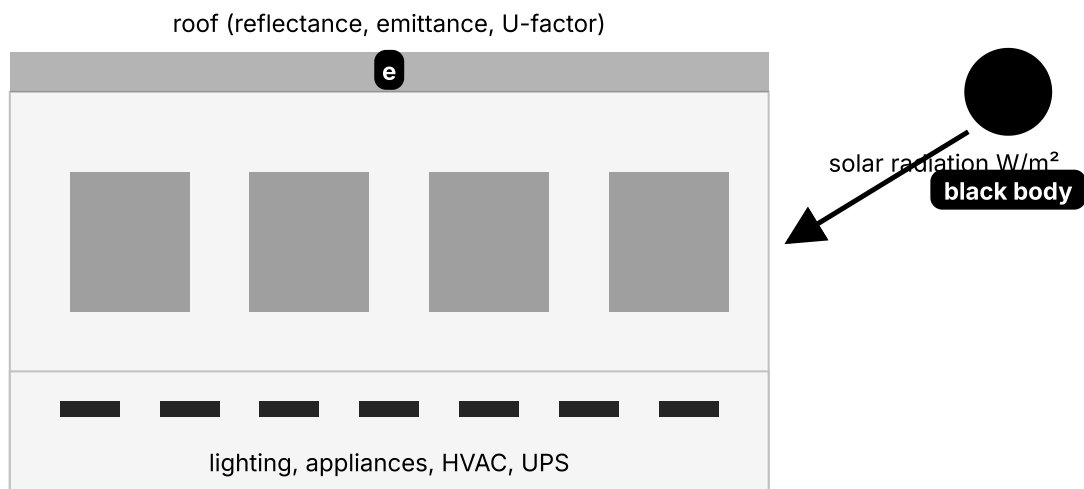
$e = \text{Energy radiated by the material} \div \text{Energy radiated by a black body at same temperature}$

SYMBOLS · UNITS

Symbols —

Answer unit no unit (black body = 1)

Book topic Cool roofs



Where each value sits: $e \rightarrow$ reflectance + absorptance = 1, emissivity e · **black body** $\rightarrow$ incident solar radiation, gain W/m^2

WHAT IT MEANS

How well a surface radiates heat compared with a perfect black body ($e = 1$); cool roofs need high emittance.

Worked example. e 0.9 radiates 90 % of the black-body rate.

Exam trap. Dimensionless, 0–1.

Interior lighting power allowance (building area method)

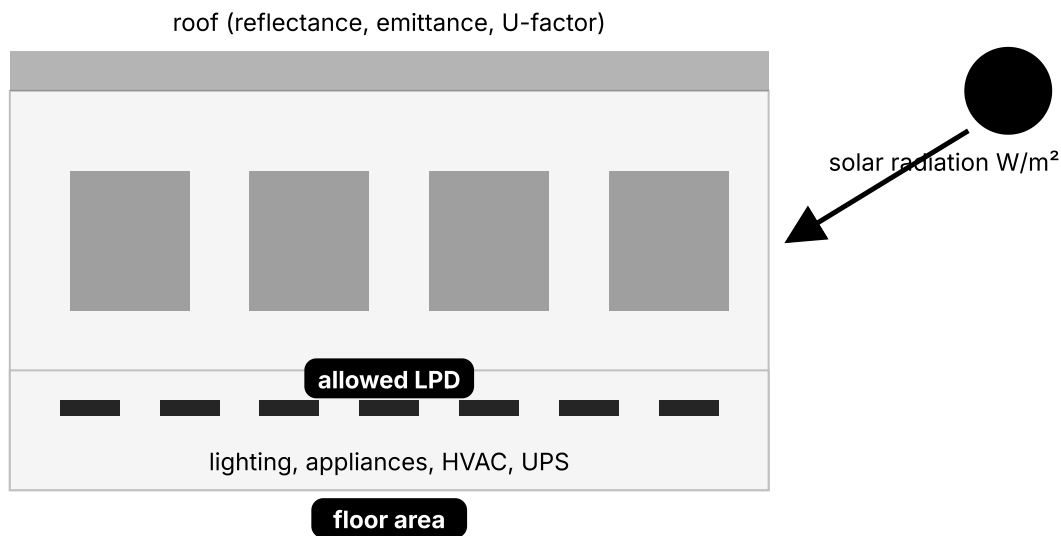
$$= \text{Gross lighted floor area} \times \text{Allowed LPD}$$

SYMBOLS · UNITS

Symbols $\text{m}^2 \times \text{W}/\text{m}^2$

Answer unit **W**

Book topic ECBC lighting



Where each value sits: **floor area** → annual kWh, built-up area m^2 → EPI · **allowed LPD** → lighting W, LPD W/m^2 , floor area · **W** → lighting W, LPD W/m^2 , floor area

WHAT IT MEANS

ECBC cap on total lighting watts for a building type = floor area $\times$ allowed LPD.

Worked example. Hotel $4 \times 1,000 \text{ m}^2$ at $10.8 \text{ W}/\text{m}^2 \rightarrow 43,200 \text{ W}$ (book; 2011/2015/2021/2023/2024 objective).

Exam trap. Use the whole lighted floor area (all floors).

Lighting power density

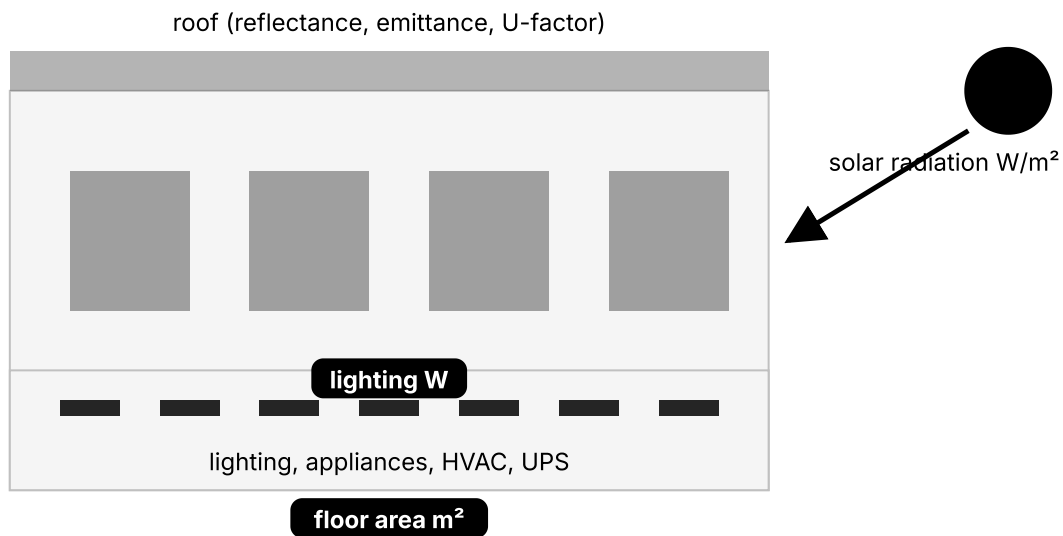
$$\text{LPD} = \text{Lighting power (W)} \div \text{Area (m}^2\text{)}$$

SYMBOLS · UNITS

Symbols W, m²

Answer unit W/m²

Book topic ECBC lighting



Where each value sits: **lighting W** → lighting W, LPD W/m², floor area · **floor area m²** → annual kWh, built-up area m² → EPI · **LPD** → lighting W, LPD W/m², floor area

WHAT IT MEANS

Watts per square metre — compare the actual installed lighting with the ECBC allowance.

Worked example. 8.11 kW ÷ 3,592 m² = 2.25 W/m² (2025 L-5).

Exam trap. kW × 1000 before dividing.

UPS efficiency

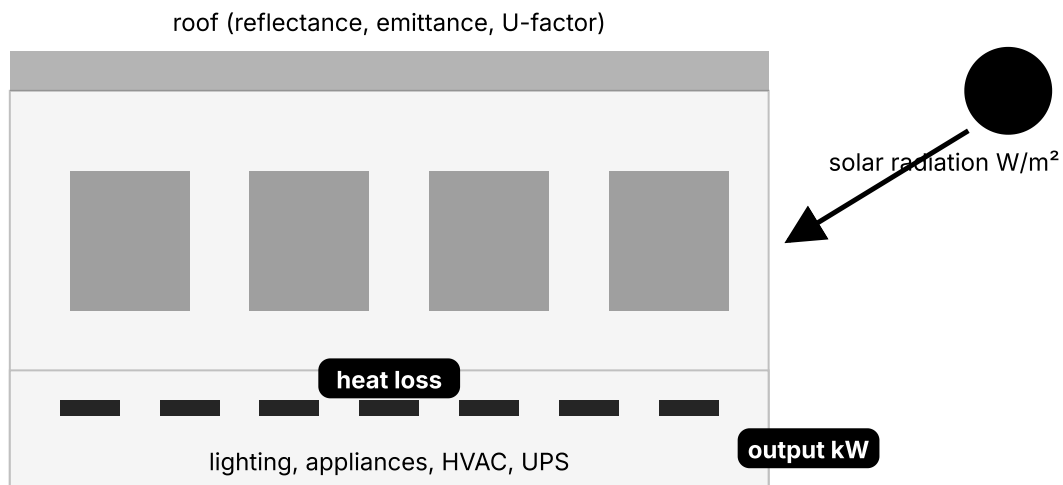
$$\eta = \text{Output power} \div \text{Input power} \times 100$$

SYMBOLS · UNITS

Symbols kW

Answer unit %

Book topic UPS



Where each value sits: **output kW** → UPS in / out kW · **input kW** → UPS in / out kW · **heat loss** → lighting W, LPD W/m², floor area

WHAT IT MEANS

Output ÷ input; losses become heat that the AC must then remove — double penalty.

Worked example. 100 kW in, 90 kW out → 90 %; 10 kW of heat to the room.

Exam trap. In a UPS the inverter converts DC → AC (book EOC Q10).

Building envelope terms



ECBC applies at ≥ 100 kW connected load or ≥ 120 kVA contract demand.

$$\text{WWR} = \text{window} \div \text{wall} = 0.28$$

$$\text{EA} = \text{VLT} \times \text{WWR} (\geq 0.1 \text{ complies})$$

$$\text{SHGC} \times \text{incident W/m}^2 = \text{heat gain}$$

$$\text{U-factor W/m}^2 \cdot ^\circ\text{C}: \text{lower} = \text{better}$$

$$\text{EPI} = \text{kWh/yr} \div \text{built-up m}^2$$

DEFINITIONS THE EXAM ASKS

ECBC

Energy Conservation Building Code (2007) for commercial buildings ≥ 100 kW / 120 kVA: envelope, HVAC, lighting, service hot water, electrical power; five climate zones — hot-dry, warm-humid, composite, moderate, cold (NOT 'cold-humid').

Compliance routes

Prescriptive (meet each limit), envelope trade-off (EPF — envelope performance factor), whole-building performance (simulation of the entire building).

Fenestration

Windows, skylights (slope $< 60^\circ$ from horizontal), glass doors, ventilators — not valves.

Star rating of buildings

BEE rates offices, BPOs, hotels, hospitals by EPI bands per climate zone; lower EPI $\rightarrow$ more stars.

BEMS / BMS

Building management system: central control of HVAC, lighting, pumps, with monitoring and scheduling.

VERIFIED VIDEOS FOR THIS CHAPTER (YOUTUBE)

ECBC Scope, Climate Zones & EPI — Energy Conservation Building Code (ECBC) | Class 113 | Anish Kumar Singh | Lukmaan IAS · Lukmaan IAS

Building Envelope: SHGC, WWR & Cool Roofs — ECBC- Energy Conservation Building Code | Corporate Film | Raasta Studios · Raasta Studios

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