POWER AND ENERGY

A Companion to Book "B"

INTRODUCTION

The ability of electric and magnetic fields to do work is one of its most widespread applications.

Power and energy are separate, but closely linked quantities.

There are many different types of energy, but energy can neither be created nor destroyed. Energy can only be transformed from one kind to another.

ENERGY - JOULE

The SI unit of energy is the *Joule*, or **J**.

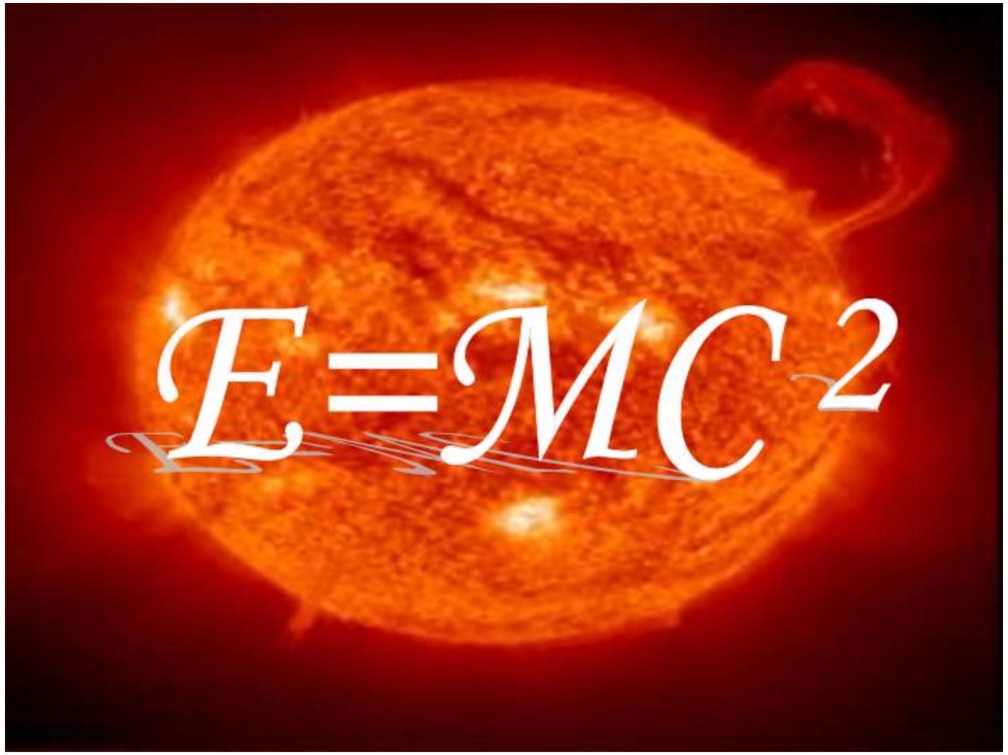
The unit is based on mass multiplied by speed of light squared.

$1\ J = 1\ kg\ m^2\ s^{-2}$.

Note that there is no amps in energy! Electricity still deals with energy, but the electrical parts cancel themselves out.

As an example, a heater consuming 1000 watts releases 1000 joules of heat energy every second.

A joule may also be referred to as a watt-second, as 1 J = 1 Ws.



ENERGY TYPE EXAMPLES

Energy can be stored and used in many different forms.

Kinetic Energy – the energy in moving items that have mass.

Chemical Energy – the energy in chemical bonds.

Heat Energy – the energy in moving atoms and molecules.

Magnetic Energy – the energy in a magnetic field.

Electrical Energy – electricity that has the ability to do work on a load.

Light Energy – the energy in light photons and waves.

Gravitational Energy – the energy stored in an object with mass that can fall under influence of gravity.

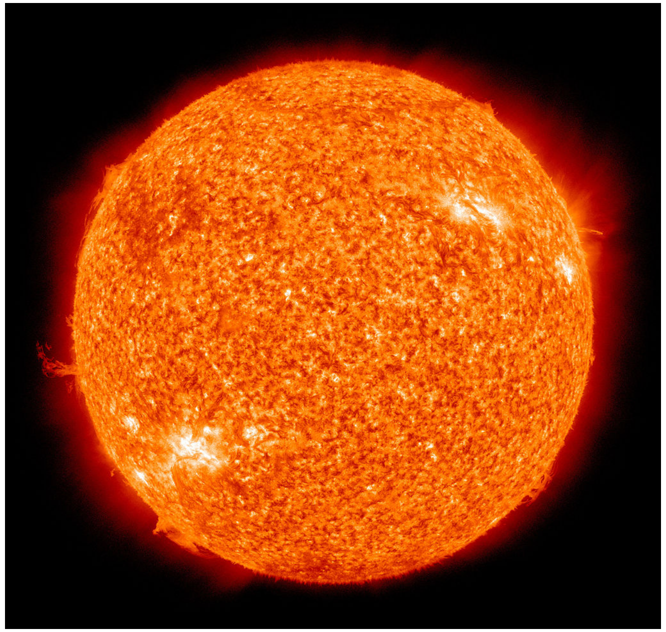
Nuclear Energy – the energy stored in the nucleus of an atom.

Some of these forms can be used to store energy, and some processes transform energy from one form to another e.g. a hydroelectric dam that supplies a heater.

TRANSFORMING ENERGY

Energy is often transferred through a chain to get it from one form to another e.g. hydroelectricity powering a light.

Nuclear (sun) → Electromagnetic (sunlight) → Heat (warm water) → Gravitational (hydro lakes at altitude) → Kinetic (falling water) → Electrical → Light



ENERGY – WATT-HOUR

1 joule, or 1 watt-second is quite a small amount of electrical energy.

Electrical energy is often measured in watt-hours, or kilowatt-hours.

1 Wh = 3600 J

1 kWh = 3600000 J

Electricity to the home consumer is sold in units of kilowatt-hours.

POWER - WATT

The SI unit of energy is the *Watt*, or **W**.

The unit is based on energy per unit time.

$1\ \mathrm{W} = 1\ \mathrm{J\ s^{-1}} = 1\ \mathrm{kg\ m^2\ s^{-3}}$.

POWER – HORSEPOWER

James Watt devised the *horsepower* (**hp**) to compare the output of his steam engines to a horse.

1 hp = 746 W

Many electric motors (especially older motors) are rated in horsepower of mechanical work output.

The picture on the right shows a 7.5 hp motor. The SI output power is 5.6 kW.

ELECTRICAL POWER AND EFFICIENCY

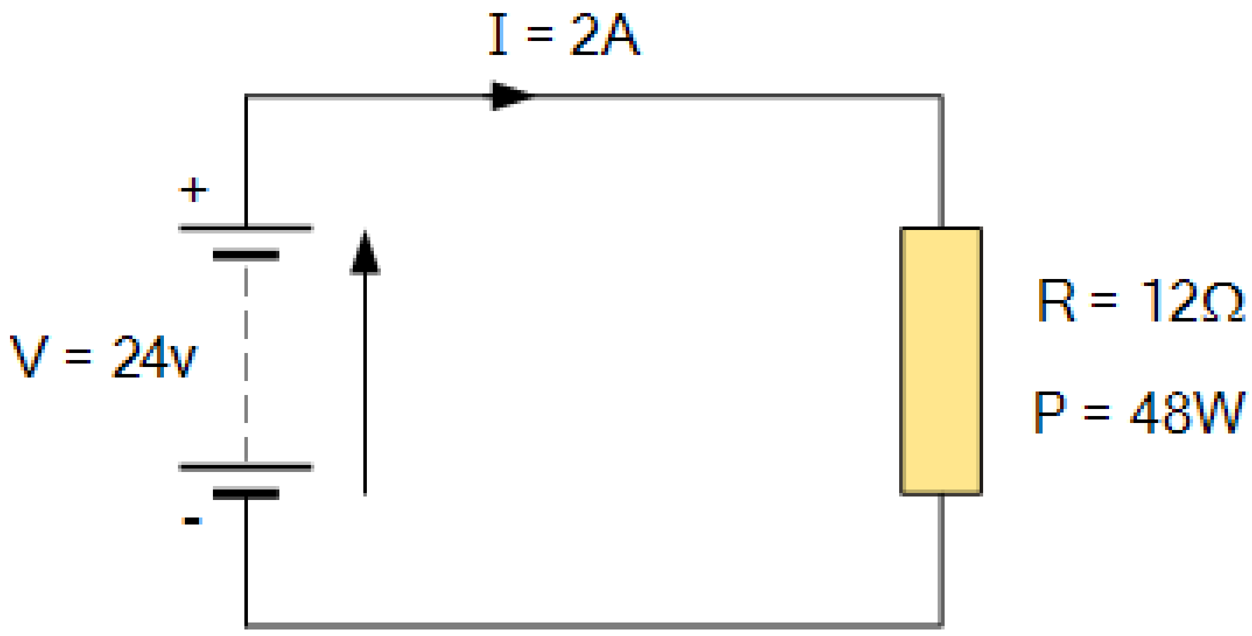
ELECTRICAL POWER

For DC circuits, and AC circuits with resistive loads, the *real power* (the power that results in energy leaving the electrical system) is the product of voltage and current.

$P = VI$

Every load that dissipates power this way may be modelled as a resistor.

Heat dissipated by resistance may also be referred to as *Joule heating* or I^2R *heating*.



ELECTRICAL POWER

There are two more formulas for power that come from Ohm's Law.

Use Ohm's Law to change V to IR. Then we get…

$P = I^2R$

This means that only current and resistance need to be known to get the power dissipated.

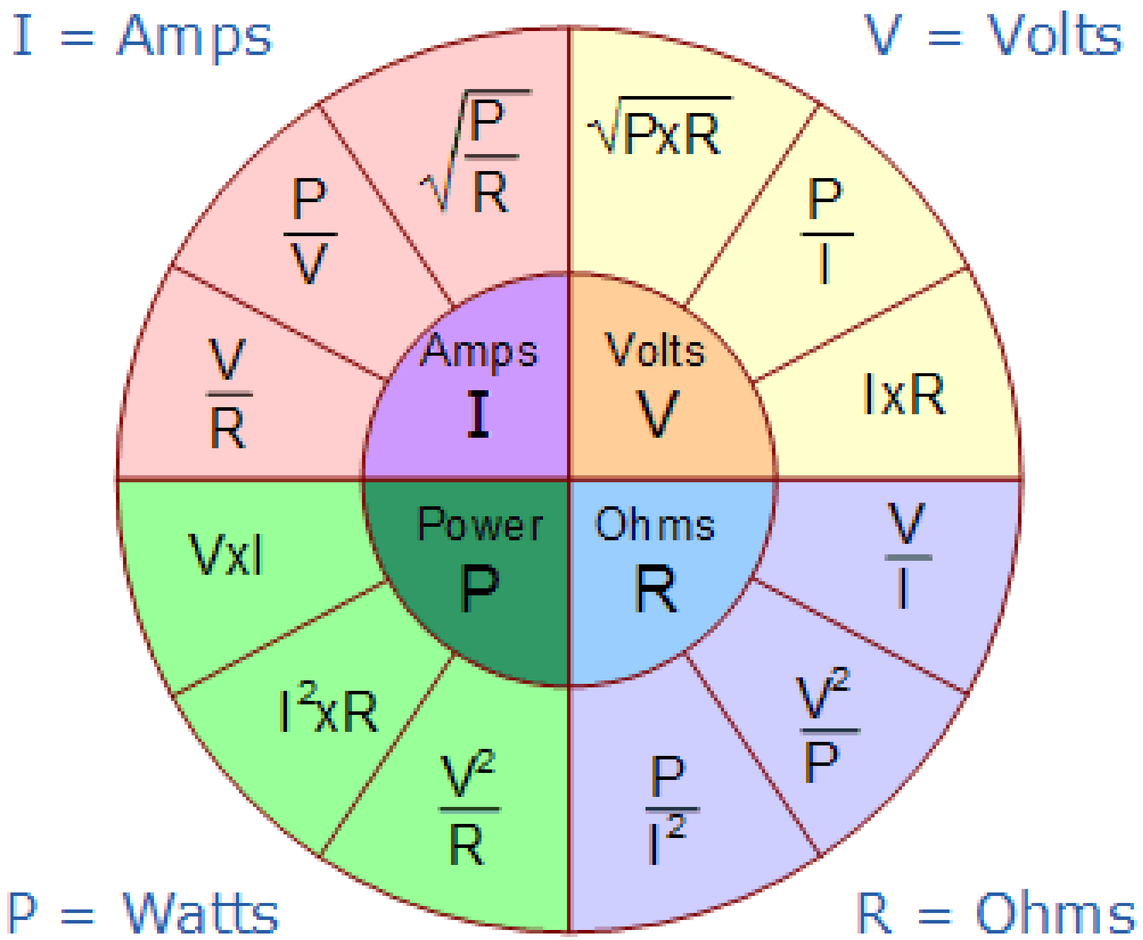
Use Ohm's Law to change I to V/R. Then we get…

$P = V^2/R$

This means that only voltage and resistance need to be known to get the power dissipated.

THE POWER AND OHM'S LAW WHEEL

The power wheel shows all the formulas linking voltage, current, resistance and power.

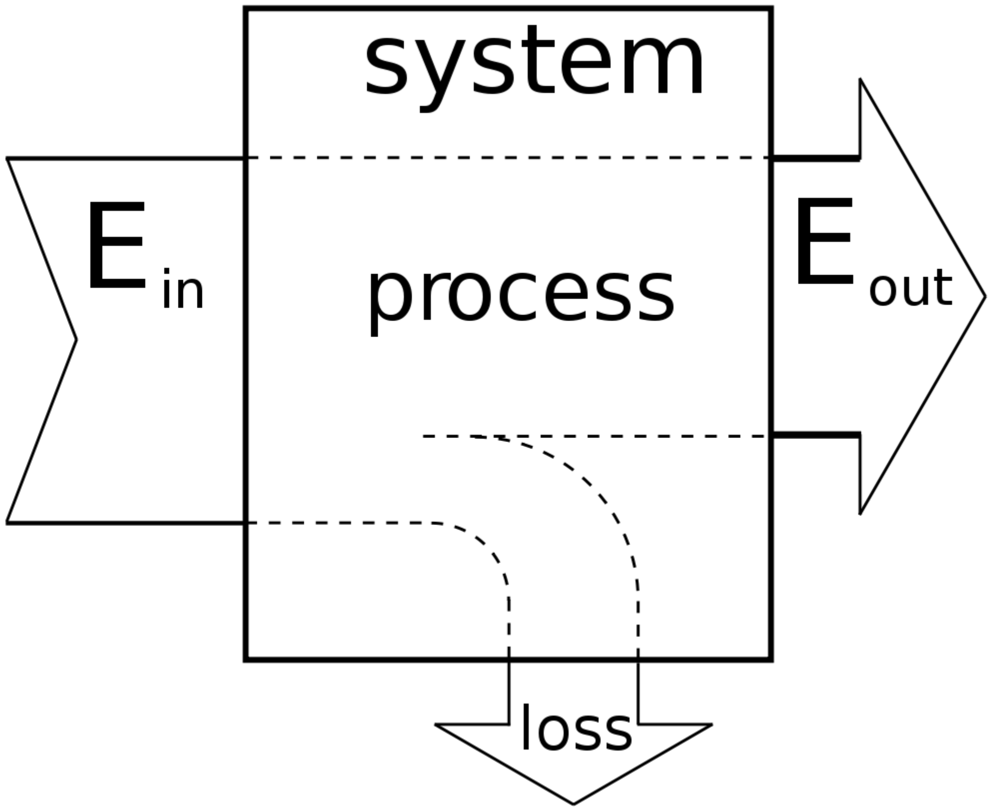


EFFICIENCY

No process of turning one form of energy into another form is perfect – there is always some loss.

The efficiency quantifies how much useful output energy you get for your input energy.

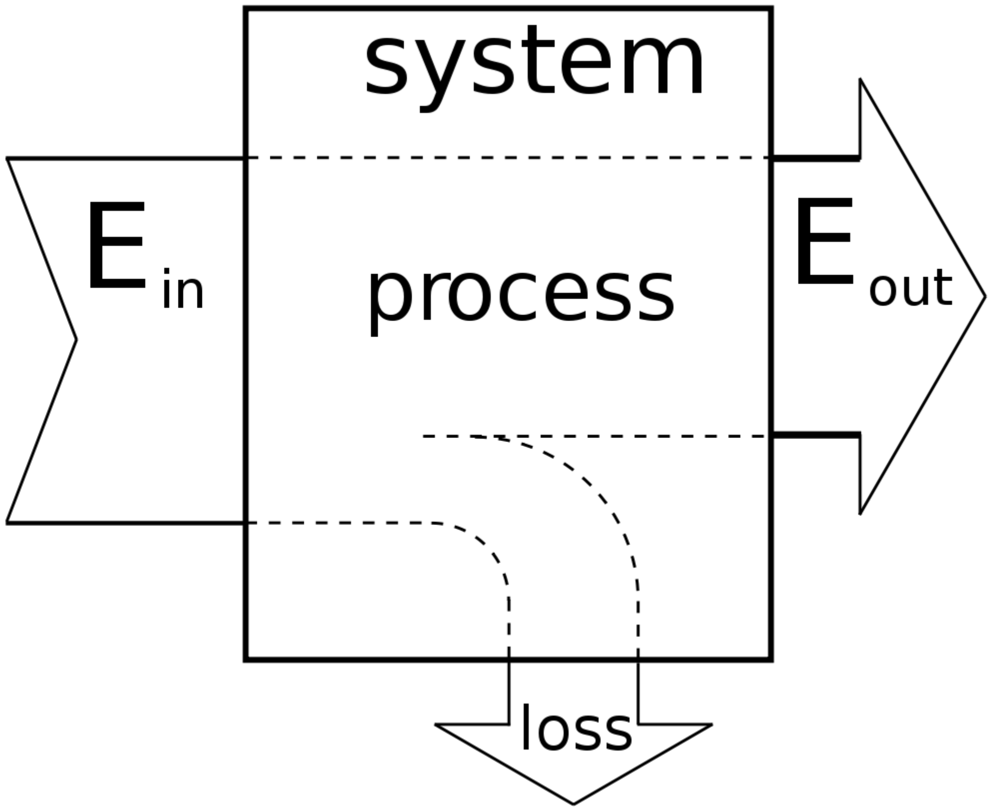
Efficiency is important because you pay for the input energy, even though you only get the output energy as useful work output.



EFFICIENCY

The concept of energy efficiency also works for power.

Most of the time, the energy is lost as heat.



SOURCES OF ENERGY LOSSES

Different electrical devices have different types of losses. All forms of losses produce heat unless otherwise stated.

I^2R losses (Joule Heating): Resistance in wires and wiring.

Iron Losses: Relevant to transformers and magnetic ballasts.

Heat: Some appliances (e.g. incandescent lamps) generate heat as a by-product of their operation.

Windage: Losses due to air movement around motors.

Sound: AC devices lose energy to sound.

Heat Losses: Hot water cylinders and ovens losing heat to the surroundings.

Engine Losses: Heat energy loss through exhaust.

Battery Losses: Non-Recovery of Charging Energy, Discharge Losses.

Friction: Bearing losses.

EFFICIENCY AS A RATIO

The definition of efficiency is:

$$\eta = \frac{\text{Useful Output Power or Energy}}{\text{Total Input Power or Energy}}$$

Where η (Greek letter 'eta') is the efficiency, and the inputs and outputs are quantities in the same units (i.e. comparing energies or powers to each other).

The efficiency is always less than 100%.

The efficiency is often expressed as a percentage. You can get this by multiplying the above equation by 100.

Efficiency has no unit (i.e. it's 'dimensionless'). Note that for efficiency to work you must work solely with power or energy. Don't mix power and energy when calculating efficiency.

EFFICIENCY AS A RATIO

Another useful expression if you know the total input and losses is…

$$\eta = \frac{\text{Total Input} - \text{Losses}}{\text{Total Input}}$$

Or, if you know the useful output and losses…

$$\eta = \frac{\text{Useful Output}}{\text{Useful Output} + \text{Losses}}$$

Whatever the expression, the efficiency is never greater than 100%.

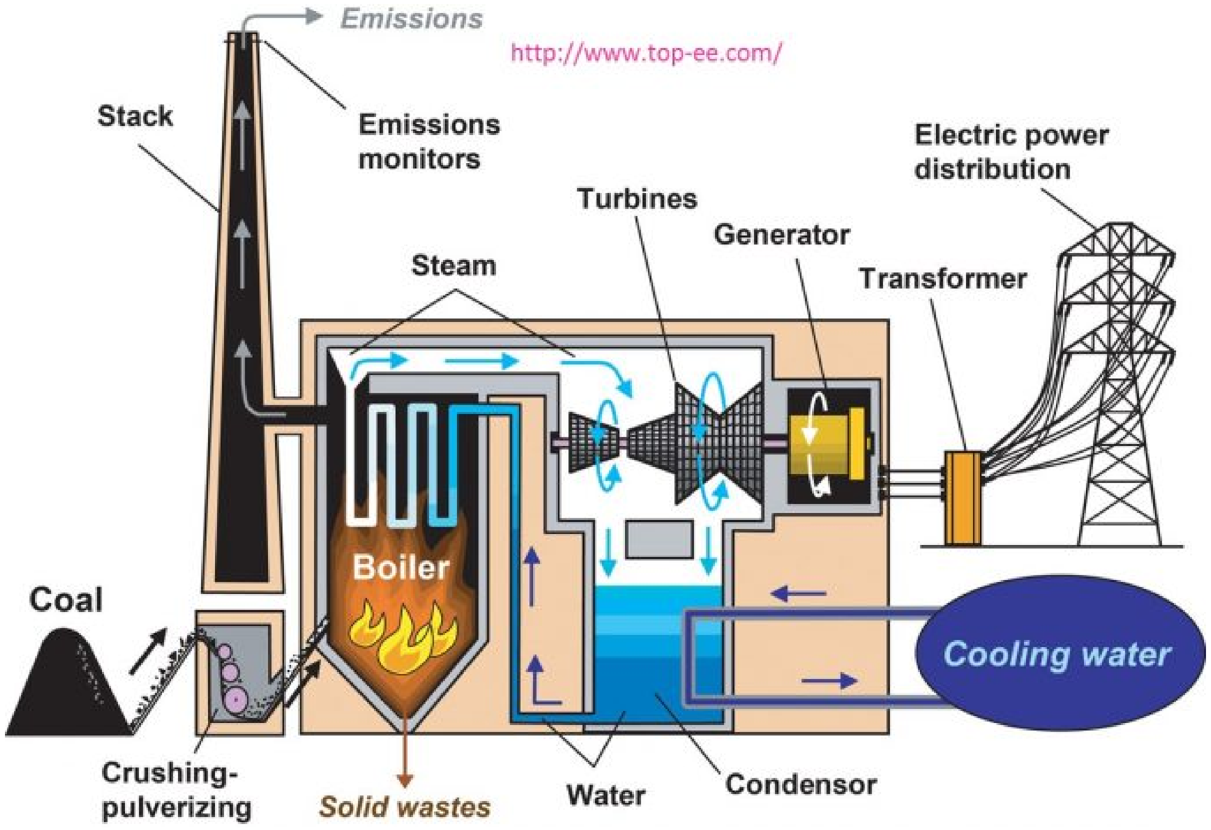
EFFICIENCY OF CASCADED SYSTEMS

Sometimes, a device uses several systems to go from an electrical input to a useful output.

For example, a coal power plant converts heat from burning coal to generate steam which drives a turbine which drives a generator.

The efficiency of a cascaded system such as this is the *product* of the efficiencies of each sub-system.

$\eta_{total} = \eta_1 \times \eta_2 \times \eta_3 \times (\ldots)$



EFFICIENCY OF CASCADED SYSTEMS

Example:

An AC motor with an efficiency of 83.3% drives a gearbox with an efficiency of 93%. What is the combined efficiency of the motor and gearbox system?

$\eta_{total} = 0.833\ldots \times 0.93$

$\eta_{total} = 0.775$ or 77.5%

So for every joule of electrical energy that is supplied to the motor, you will get 0.775 joules of useful work from the gearbox output.

EFFICIENCY – DC MOTOR

A DC motor requires 125 volts and 27 amps to output 4.0 hp. What is the efficiency?

The input power: $125 \times 27 = 3375$ W

The output power: $4 \times 746 = 2984$ W

$\eta = 2984 / 3375 = 0.8841$ or 88.4%

So the motor is 88.4% efficient.

This motor has losses of 391 W when operating at full load.

EFFICIENCY – AC MOTOR

An AC motor has a rated output of 1.5 kW, and losses of 300 W. What is the efficiency at rated output?

The total input power is 1800 W (1500 + 300).

η = 1500 / (1500 + 300) = 0.8333 or 83.3%

EFFICIENCY - JUG

It takes 5 minutes for a 2400 W electric jug to boil 2 litres of water from a starting temperature of 20°C. The water requires 669 kJ of energy to reach boiling point. The jug consumes 720 kJ. What is it's efficiency?

η = 669000 / 720000 = 0.9292 or 92.9%

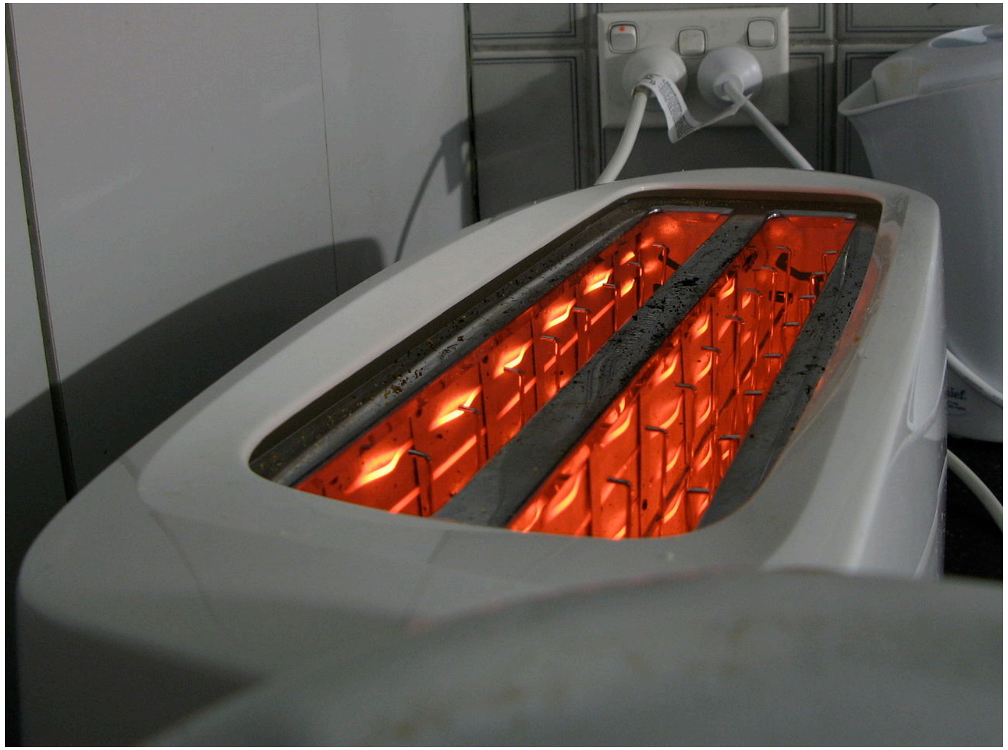
POWER, ENERGY AND RUNNING COSTS

INTRODUCTION

When you're pay a power bill, you're actually paying for energy.

Electricity is sold to home consumers as a price (or tariff) per kWh (or 'unit'). A typical price in Wellington is $0.25/kWh.

The electricity bill you get reflects the number of kWh that have been used.



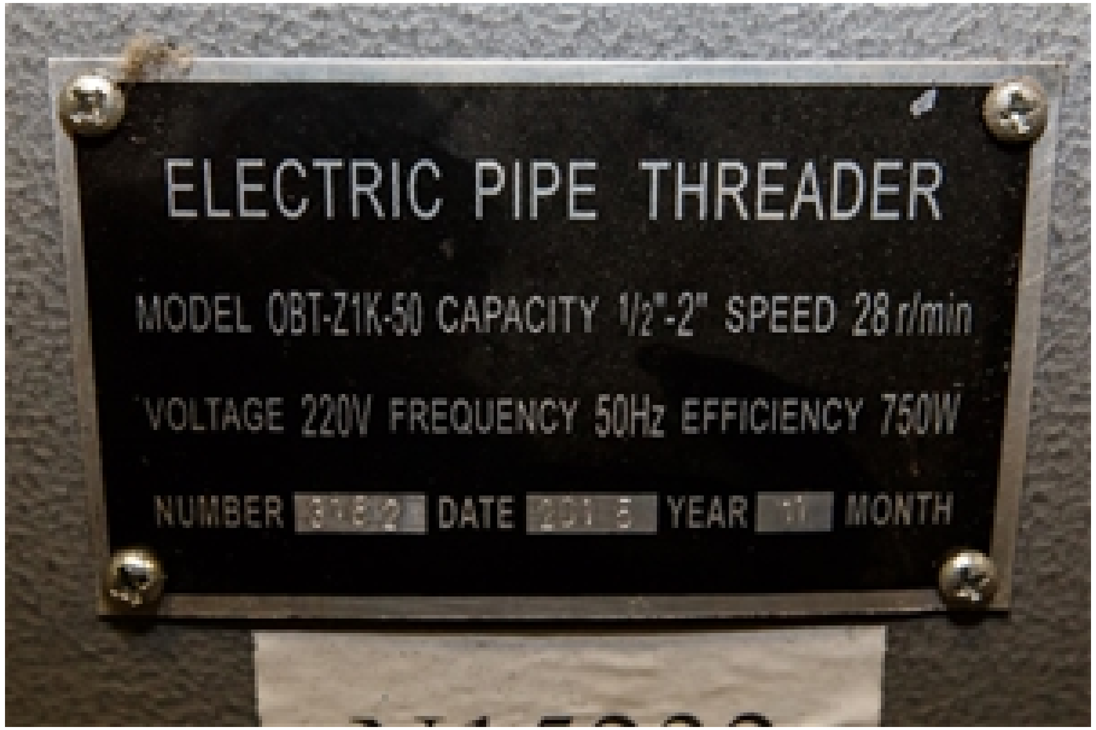
ELECTRICAL POWER

Every appliance has a name plate, specifying the voltage, frequency and power.

Voltage is generally specified as a value or range e.g. 230V or 220-240V.

Frequency may be specified with a Hz value, or with a ~ symbol after the voltage to say it's AC e.g. 230V~.

Any one or more of wattage or current may be specified. In the case of the nameplate on the right, the wattage is specified.



ELECTRICAL POWER

In normal use, the pipe threader would be expected to draw some current. The current is calculated using:

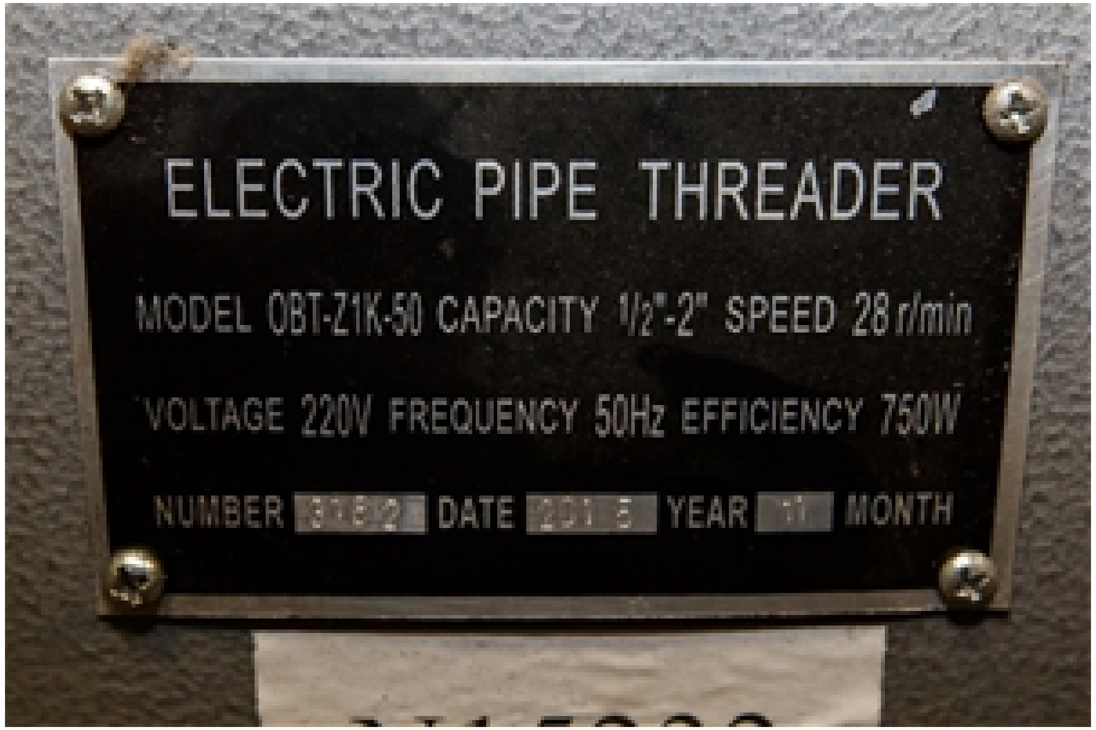
$I = P \,/\, V$

For this appliance, V = 220 V, and
P = 750 W. Therefore the current is…

$I = 750 \,/\, 220$

I = 3.41 A

Despite the name plate saying "efficiency", the efficiency of this appliance is not known. You can only get the efficiency by comparison.



CALCULATION OF RUNNING COSTS

The general formula for running costs is

$C = E\,r$

Where C is the total cost, *E* is the energy used, and *r* is the tariff for each unit of that energy.

E may be directly measurable, but in other cases it is possible to use the properties of the load to get *E*.

Make sure all your units are consistent.

Don’t mix energy in joules with energy tariffs per kilowatt-hour.

RUNNING COSTS – POWER LOADS

Some loads have a known power consumption and are on for a certain amount of time each day. We can use this to estimate the running costs.

$E = P\ t$

Where E is the energy consumed, P is the power, and t is the time.

Note that P should be converted to kilowatts, and t to hours so that E is in kilowatt-hours.

So, a 500 W lighting system running for 8 hours a day should be treated as a 0.5 kW system running for 8 hours a day.

RUNNING COSTS – WATER HEATING

Water heating is just that – the energy required to heat water. The energy required to heat water is

$Q = m\ c\ \Delta T$

where Q is the energy required (J);
m is the mass of water to be heated (kg)
c is the specific heat of water ($J.kg^{-1}.K^{-1}$)
ΔT is the temperature rise (K or °C)

The mass of water may be taken as being equal to the volume in litres.

c is 4184 $J.kg^{-1}.K^{-1}$ for water

Normally, the amount of energy is given in kWh, and we deal with water by volume, so the formula can also be used as…

$Q = (4184/3600000)\ V\ \Delta T$

where Q is the energy in kWh, V is the volume of water in litres, and ΔT is the temperature rise as before.

The (4184/3600000) can also be expressed as 0.00116222…

RUNNING COSTS – MIXED LOADS

Most installations have a number of loads, all drawing different amounts of power for different times.

The total running costs can be calculated by adding up the running cost for each individual load.

EXAMPLE - JUG

An electric jug uses electricity to heat water.

Suppose we wish to boil 2 litres of water from 20°C.

The temperature rise (ΔT) is 80°C, as water boils at 100°C.

The volume (V) is 2 litres.

Plugging this in…

$Q = 0.00116222 \times 2 \times 80 = 0.18596$ kWh

If the jug is 100% efficient, the jug will consume 0.186 kWh.

At 25c per kWh, it will cost 4.65c to boil the jug.

EXAMPLE – HEATING SYSTEM

A ventilation system has a rating of 15000 W, and operates 8 hours a day. What is the yearly running cost of this system if the tariff is \$0.18/kWh?

The ventilation system is rated 15 kW, and runs 8 hours a day, i.e. daily consumption is 120 kWh (15×8).

We will assume a 365 day year, so the annual consumption is 43800 $kWh.yr^{-1}$ (12×365).

The cost of electricity is \$0.18/kWh. The total yearly running cost is therefore \$7884 (43800×0.18).

VALUE VARIATIONS

INTRODUCTION

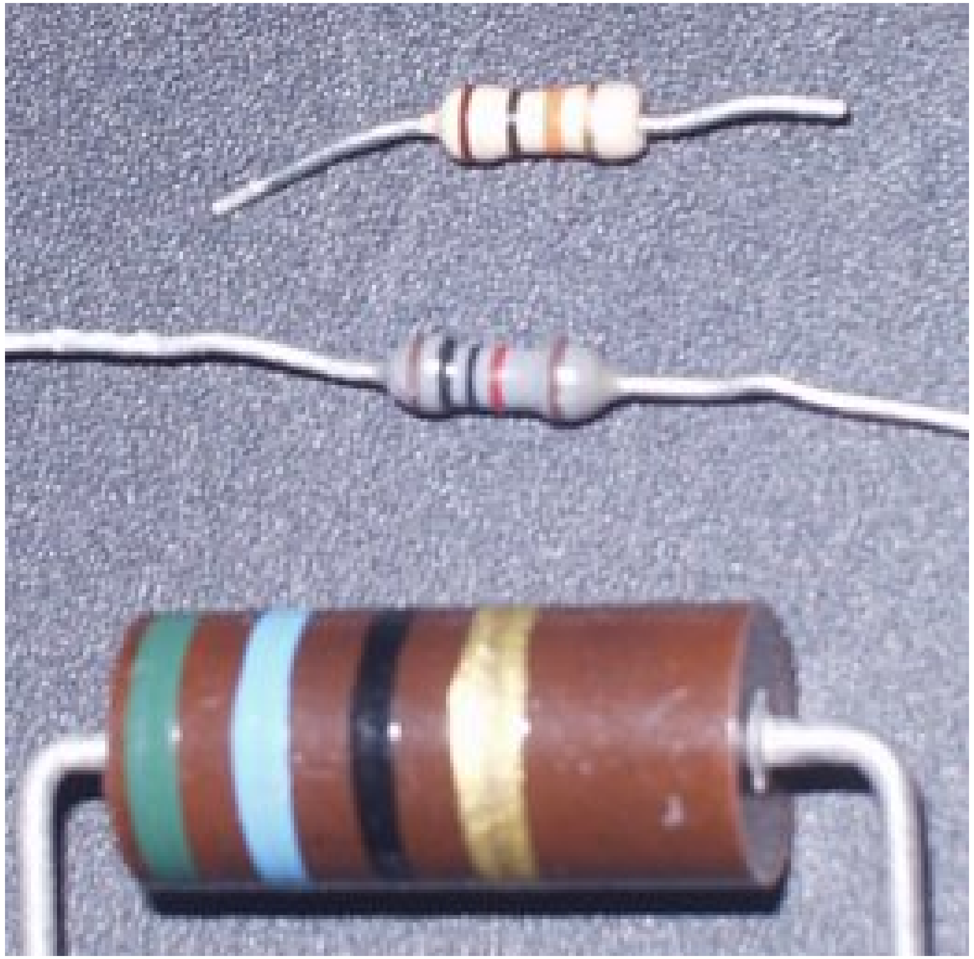
No component is manufactured exactly.

No meter is exact.

No supply voltage is exact.

All the values you measure will deviate from what their values ‘should’ be. The question is, “Is this difference important?”.

The actual answer depends on the situation, but these slides provide a primer on what you may encounter.

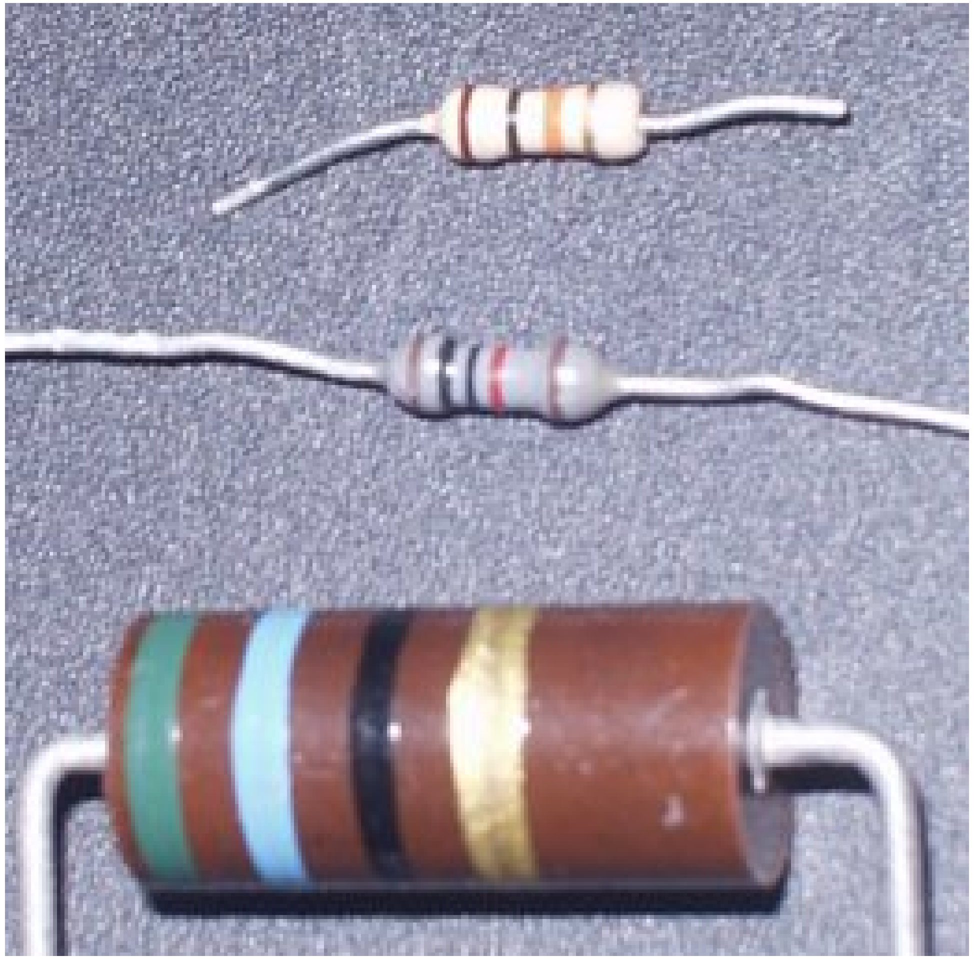


COMPONENT TOLERANCE

No component is manufactured exactly. Therefore, the actual value will be different from the 'nominal' value.

For example, a 10 kΩ ±5% resistor could be anything from 9.5 kΩ to 10.5 kΩ, *before any meter error is taken into account.*

If a meter reads a measurement of 9.6 kΩ, the variation could be solely due to the resistance tolerance.



230V SUPPLY VARIATION

The mains is meant to be 230 V, but due to the ever-changing nature of the grid, the value is never 230 V in practise.

Some premises are wired as 240 V installations.

The standard voltage tolerance is ±6%.

230V SUPPLY VARIATION

The voltage at the connection point of an installation could be anything between 216 V (230-6%) and 254 V (240+6%).

There is a further 5% drop allowance for installation wiring, giving a total range of 205 V (230-11% at full load) to 254 V (240+6%).

INSTRUMENT ERROR – GENERAL

All values we measure have errors caused by the meter.

The meter on the right (similar to the laboratory APPA meters) has the following accuracy specifications:

DC Volts: ±(0.5%+2dgt)

AC Volts: ±(1.5%+5dgt) 50 Hz - 500 Hz for sine waveforms only

Resistance: ±(0.7%+3dgt) 200 Ω – 200 kΩ

INSTRUMENT ERROR – RATIO ERROR

The percentage error is a ratio error.

It means that all readings can vary by the ratio as a percentage. The percentage error is the percentage error of the full scale reading.

For example, the resistance range has a ratio error of ± 0.7%. This means that a even a perfect 10 kΩ resistor can have a reading between 9.93 kΩ to 10.07k.

INSTRUMENT ERROR – DIGIT ERROR

The 'dgt' error means that the rightmost digit (least significant digit or LSD) on the display could have that many digits of variation, *in addition to the ratio error*.

The effect of the digit error gets worse if the number of significant digits is reduced.

Note the effect of the "digit error" on accuracy is 10 times worse for values with digits 0-999, 100 times worse for values 0-99, and 1000 times worse for values 0-9!

INSTRUMENT ERROR – ZERO ERROR

Sometimes, an error on the least significant digit can be removed by 'zeroing' the meter.

This is a common problem on low resistance ranges, where even with the leads shorted, the meter may read a value like '0.2'.

If you are confident the error is only additive, it can be subtracted from any reading.

INSTRUMENT ERROR – EXAMPLE

As an example, the meter could read anything within the ranges shown on the following measurements…

DC 12 Volts: 11.92 V to 12.08 V ($\pm$0.5%+3dgt → $\pm$0.57%)

AC 230 Volts: 222 V to 238 V ($\pm$1.5%+5dgt → $\pm$3.9%)

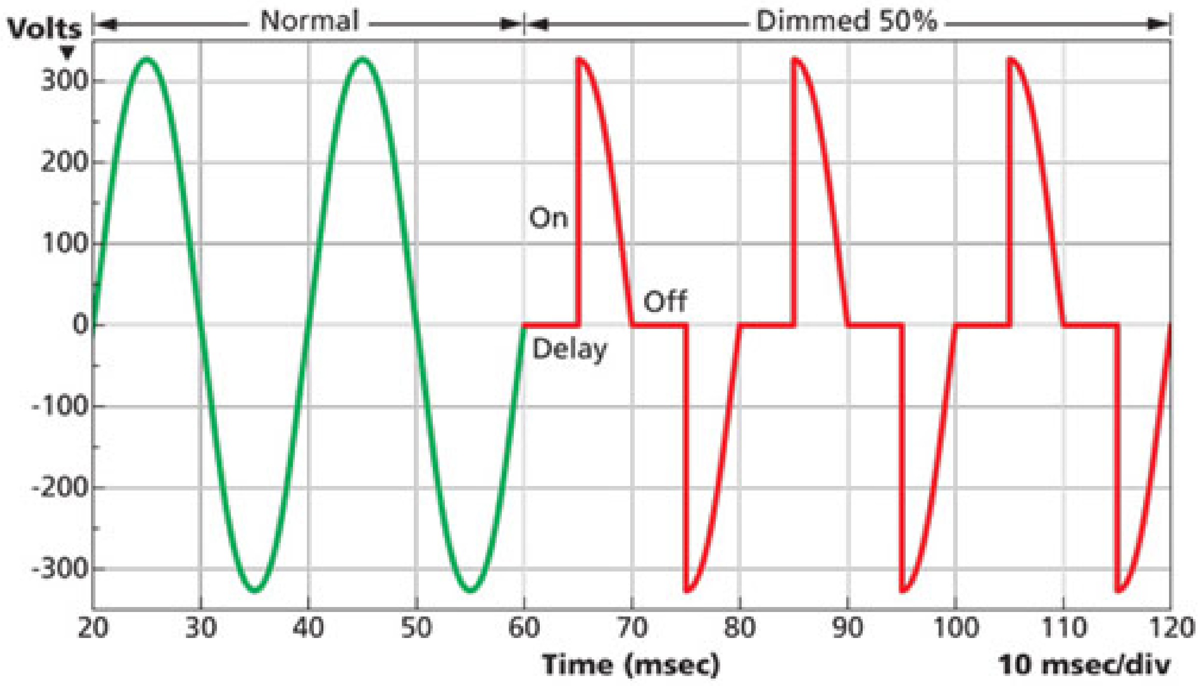
Resistance 10 kΩ: 9.90 to 10.10 kΩ ($\pm$0.7%+3dgt → $\pm$1%)

AC/RMS ERROR

AC meters that are not “True RMS” are only calibrated for measuring sinusoidal waveforms.

The green waveform on the right shows normal 230 V RMS 50 Hz mains sine wave. The red waveform shows the voltage supplied to a light being driven by a dimmer at half power.

A non-true RMS meter will likely give an inaccurate voltage reading if used to measure the red waveform.



MEASUREMENT ERRORS

Meters and measurement setups are prone to misreading.

Did you take into account the lead resistance?

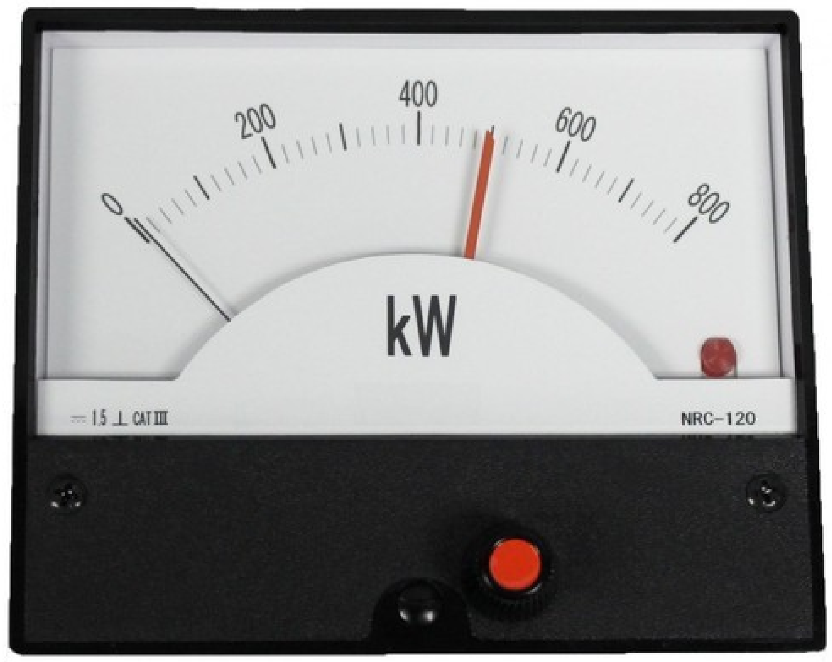
Did you read the scale on the meter properly?

Did you use the correct type of meter (e.g. AC meter on AC circuit)?

Did you line up the pointer on the meter so there's no parallax error?

Were the leads properly seated and continuous?

Are you measuring the correct quantity in the circuit?



230V SUPPLY VARIATION

The voltage at the connection point of an installation could be anything between 216 V (230-6%) and 254 V (240+6%). There is a further 5% drop allowance for installation wiring, giving a total range of 205 V (230-11% at full load) to 254 V (240+6%).

Add in the ±1.5%+5d meter error, and any meter reading from 196 V (205-1.5%-5d) to 262 V (254+1.5%+5d) could be acceptable reading for mains voltage from this meter.

DIGIT ERROR EXAMPLE - MAIN EARTH WIRE RESISTANCE

The maximum resistance of the main earth wire (the wire from the switchboard to the earth stake) is 0.5 Ω.

Let's say you get a measurement of 0.3 Ω, which the meter displays as '0.3'. Based on a 3d digit error, a resistance value of 0.3 could mean any resistance from < 0.1 Ω to 0.6 Ω.

There's a chance the main earth wire does not comply, since the maximum resistance is 0.5 Ω. With this information, you cannot prove with your measurement that the resistance is 0.5 Ω or less.

DIGIT ERROR EXAMPLE - MAIN EARTH WIRE RESISTANCE

Suppose you short the leads on the multimeter, and it reads ‘0.2’.

If you’re confident the error only adds to the reading, you could say a reading of ‘0.3’ could be thought of as ‘0.1’.

With the digit error, the reading could mean anything from < 0.1 Ω (at least too small to measure) to 0.4 Ω.

In this case, you could say the conductor complies.

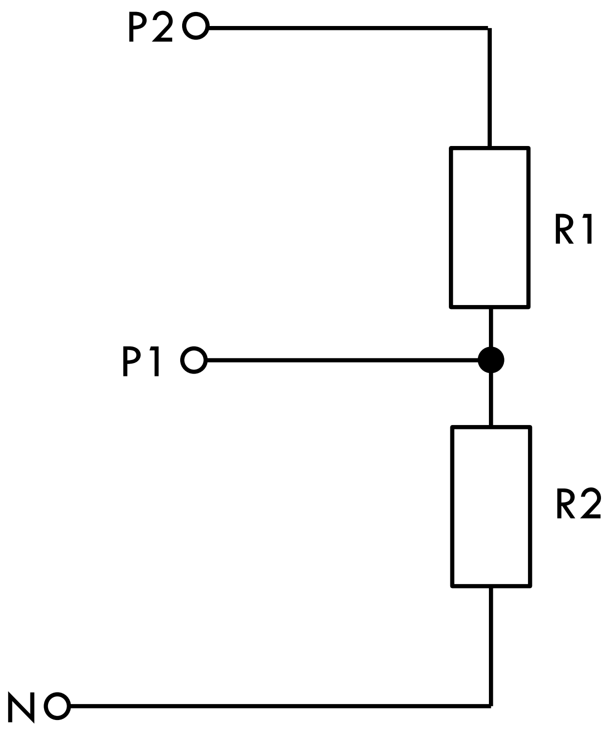
THREE-HEAT CIRCUIT

THREE-HEAT CIRCUIT

There is a circuit that enables three heat settings from two identical resistors only. This is called the ‘three-heat circuit’.

The circuit is shown at right. There is a connection to neutral shown, there is also a connection to 230 V ‘live’ (L) available.

It consists of a two-resistor ‘ladder’ connected to neutral, with two connection points at P1 and P2. The ladder wiring never changes, the connections of P1 and P2 are managed by a special switch.



NOTE: R1 and R2 have the same value.

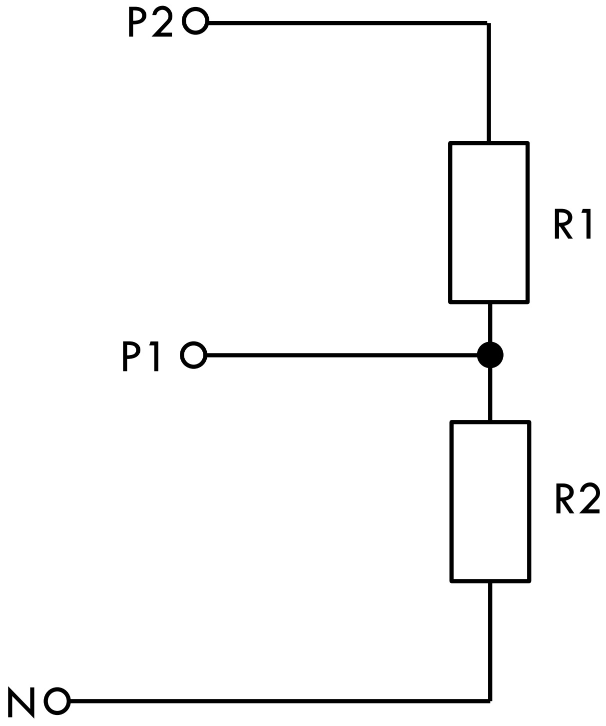
THREE-HEAT CIRCUIT – CONNECTIONS

Position 0 ‘OFF’: P1 No connection (NC), P2 NC. There is no power because there is no path for current to flow through any of the resistors.

Position 1 ‘LO’: P1 NC, P2 L. Current flows through the two resistors in series.

Position 2 ‘MED’: P1 L, P2 NC (or L). Current flows through R2 only. R1 dissipates no power, because it either has no voltage across it (P2 connected to L), or no current through it (P2 NC).

Position 3 ‘HI’: P1 L, P2 N. P1 provides a supply for both resistors. Since P2 is at neutral voltage, the resistors are effectively connected in parallel.



NOTE: R1 and R2 have the same value.

THREE-HEAT CIRCUIT – ELECTRIC BLANKET

A 230V electric blanket has two 1058 Ω resistors and is connected using a three-heat switch. What is the power output at each setting?

First, calculate the resistances at each setting.

Low: 2 in series → 2116 Ω

Medium: 1 only → 1058 Ω

High: 2 in parallel → 529Ω

Calculate the power using V^2/R.

Low: $P = 230^2 / 2116 = 25$ W

Medium: $P = 230^2 / 1058 = 50$ W

High: $P = 230^2 / 529 = 100$ W

MEASURING TEMPERATURE THROUGH RESISTANCE

INTRODUCTION

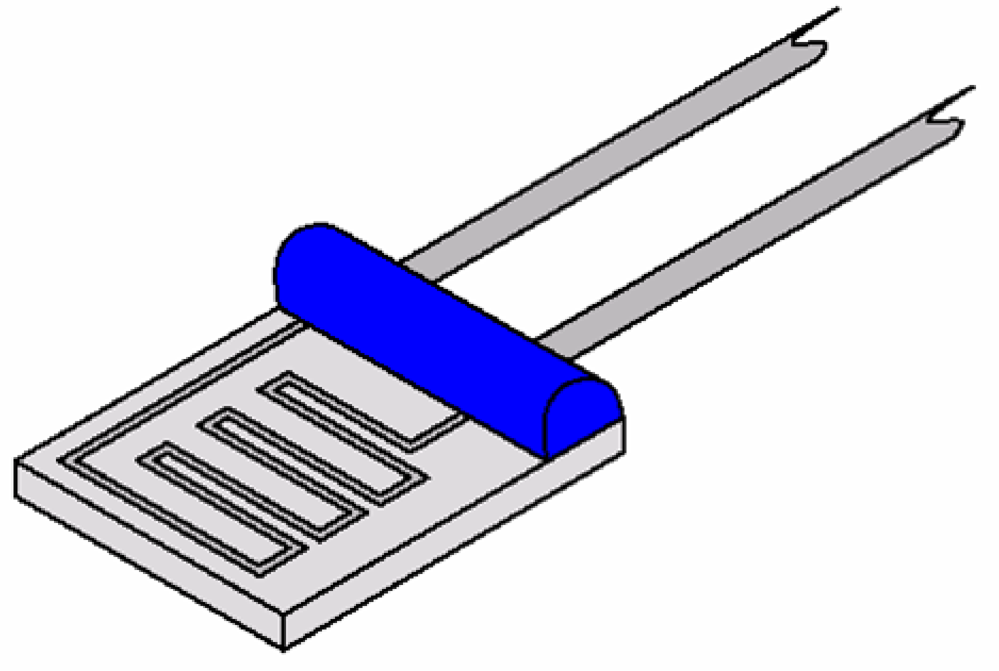
It's not always easy to physically measure temperature inside electrical devices, especially inside cables, motors and transformer windings.

However, we can use the change in resistance of a conductor to calculate the average temperature of that conductor.

RESISTIVE TEMPERATURE DETECTORS

Resistive temperature detectors (RTD) can be used to sense temperature through measuring the resistance of a carefully calibrated section of metallic conductor.

The conductor is usually platinum for chemical stability. They are useful for temperatures of $-200°C$ to $500°C$, and can be accurate to $\pm0.03°C$ over this entire range.



RESISTIVE TEMPERATURE MEASUREMENT

Resistance temperature measurement requires a reference resistance, a reference temperature, and the temperature coefficient of resistance at that reference temperature.

The basic formula is

$\Delta T = ((R_2 / R_1) - 1) / a_1$

where ΔT is the temperature rise, R_2 is the measured resistance, R_1 is the reference resistance, and a_1 is the TCR at the reference temperature.

The formula for ΔT comes from transposing the resistance formula $R_2 = R_1 \times (1 + a_1 \Delta T)$.

The final temperature T_2 is calculated as follows:

$T_2 = T_1 + \Delta T$

where T_1 is the reference temperature, and ΔT is the temperature rise.

RESISTIVE TEMPERATURE MEASUREMENT EXAMPLE

Example:

The resistance of a copper motor winding at 20°C is 7.3 Ω. The motor is run at rated output for an hour or so, until the motor is at operating temperature. The resistance is measured again, and is found to be 9.88 Ω. How hot is the winding?

The temperature coefficient of resistivity of copper is 0.00393 $°C^{-1}$ at 20°C.

RESISTIVE TEMPERATURE MEASUREMENT EXAMPLE SOLUTION

Answer:

The temperature rise is:

$\Delta T = ((R_2 / R_1) - 1) / a_1$

We know that $R_2 = 9.88\ \Omega$, $R_1 = 7.3\ \Omega$, $a_1 = 0.00393°C^{-1}$, and $T_1 = 20°C$.

Computing the temperature rise…

$\Delta T = ((9.88 / 7.3) - 1) / 0.00393$

$\Delta T = 0.3534 / 0.00393$

$\Delta T = 89.93°C$

Our reference temperature is 20°C, so our final temperature T2 is…

$T_2 = T_1 + \Delta T$

$T_2 = 20 + 89.93$

$T_2 = 110°C$

The average winding temperature (excluding "hot spots") is 110°C.