Physics Factsheet
www.curriculum-press.co.uk Number 276

Second Law of Thermodynamics Engines and Reversed Heat Engines

The Laws of Thermodynamics

There are three basic laws of thermodynamics. These can be summarised as:

The Zeroth Law is about **thermodynamic equilibrium and temperature**

When two objects are in thermodynamic equilibrium with a third object, they are all in thermodynamic equilibrium with each other.

The First Law is about work, heat and energy

The change in internal energy of a system equals the difference between the heat energy put into the system and the work done by the system.

The Second Law is about entropy

A system change will always go in the direction which causes entropy to increase.

Thermodynamic Equilibrium

An isolated system will adjust spontaneously to achieve a state of thermodynamic equilibrium. The state of thermodynamic equilibrium will be a state of maximum entropy or disorder. Flow of heat energy will occur from regions of high temperature to regions of low temperature. This may also be expressed as heat energy always flows from areas of high concentration to areas of low concentration.

THE SECOND LAW OF THERMODYNAMICS basically states that entropy increases.

Entropy

Entropy (S) may be considered as the degree of disorder or randomness of a system.

Entropy can be calculated if you know the internal energy (Q) and the temperature (T) of the system. **S = Q/T**

We are usually more interested in entropy changes. The change in entropy ΔS of a system describes the heat energy transferred ΔQ per degree kelvin of the temperature T of the system.

$\Delta S = \Delta Q / T$

Temperature must be measured in degrees kelvin, K.

Statements: The 2nd Law Of Thermodynamics

LORD KELVIN stated: There is no process possible which results *only* in the conversion of heat energy into work.

CLAUSIUS stated: There is *no process* possible which results only in the transfer of heat from a body at a lower temperature to a body at a higher temperature.

GENERAL STATEMENT: Heat cannot be transferred continuously into work without simultaneously transferring some heat from a hotter body to a cooler one.

Although energy can and does transfer from a cooler body to a hotter one in the form of electromagnetic radiation or more energetic (hot) particles, the net transfer of heat energy is always from the hotter body to the cooler one for any spontaneous process.

Second Law and Heat Engines

An engine always operates *between* a *heat source* and a *heat sink* (the heat sink will absorb heat from the engine).

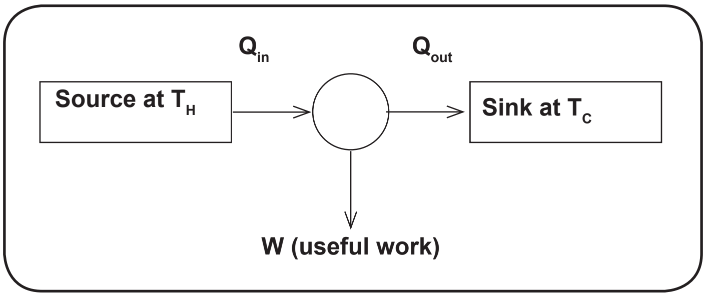
Efficiency of an engine is defined as the ratio of the work (W) done by the engine divided by the heat energy (Q) supplied.

$$\text{Efficiency} = \frac{W}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}}$$ where W is the work done in joules.

Q_{in} is the heat supplied, and Q_{out} is the heat given to the heat sink (in joules).

$$\text{Maximum Theroretical Efficiency} = \frac{T_H - T_C}{T_H}$$

where T_H and T_C are the temperatures of the heat source and heat sink in K.



Q1: A heat engine operates between a heat source which is at 506K and a heat sink which is at 253K. Calculate the *maximum theoretical efficiency* of the heat engine.

Answer to Q1:

Substituting the values into the equation gives:
(506 – 253) ÷ 506 = 0.5 or 50%

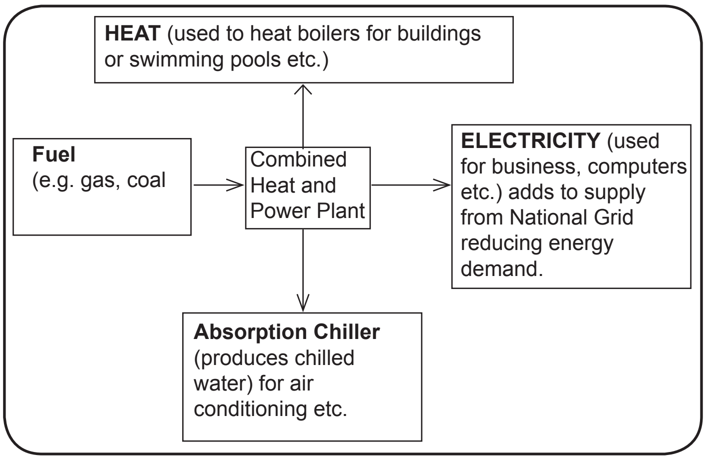
The efficiency of a real, practical, heat engine is lower than the maximum theoretical value due to:

1. **Energy loss by friction**. Friction results in energy being needed and used to overcome the friction between the components of the heat engine.
2. **Incomplete combustion of the fuel used.**
3. **Waste heat is transferred to and dissipated by the surrounding area and so lost.**

Some wastage can be avoided by transferring the waste heat to nearby houses or business premises to heat them. ***COMBINED HEAT AND POWER SCHEMES*** are used to ***maximise the use of any waste heat*** rather than allowing it to escape into the surroundings and be lost.

Combined Heat and Power Schemes (CHPs)

These are designed to maximise the use of W and Q_{out}



Advantages of Combined Heat and Power Schemes

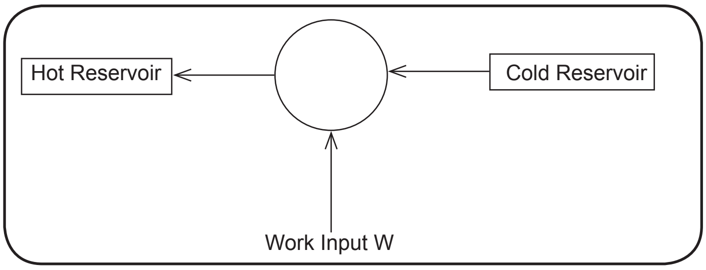
- The average efficiency of a traditional power plant is about 35 to 40% whereas CHP schemes claim efficiencies of over 80%.
- The increased efficiency is gained because no by-products (e.g. heat) are wasted.
- The losses which occur during transmission and distribution are avoided.
- There is a reduction in carbon emissions and other air pollutants and in emission of greenhouse gases because less fuel is burnt to produce each unit of energy.
- The system is independent of the National Grid and so will not be so affected by a National Grid black out.

Possible Disadvantages of Combined Heat and Power Schemes

- A CHP scheme is not an actual energy source (such as coal or oil). Its installation extends the energy use of an existing system and incurs additional maintenance costs.
- The initial installation cost is high. Savings will tend to be long term.
- The additional heat can be used for central heating in the winter, but may not be useful in summer. However, it may be usefully turned to air conditioning (using absorption chillers).

Reversed Heat Engines

There is work input and there is a net amount of work done on the working fluid.



Energy is taken (or *extracted*) from a cold reservoir and given (or *supplied*) to a hot reservoir.

Refrigerators take as much heat energy as possible from the cold reservoir. This means their design has the aim of *taking* the maximum possible amount of energy from the cold reservoir per joule of work done.

Heat pumps provide the maximum possible amount of energy to the hot reservoir. This means they are designed with the aim of *supplying* the maximum amount of energy per joule of work done.

Coefficients of Performance (COP)

Coefficients of performance represent how good the device is at changing (or converting) the energy supplied (as work) into the transfer of heat. For example, a coefficient of performance of 3.5 would mean that the device transfers 3.5 J of heat energy for each joule of work done.

Refrigerator

The coefficient of performance is given by:

(heat transferred from the cold space in joules) ÷ (work done in joules)

$$COP_{Refrigerator} = \frac{Q_{cold}}{W} = \frac{Q_{cold}}{Q_{hot} - Q_{cold}}$$

and for the theoretical maximum efficiency we have:

$$COP_{Refrigerator} = \frac{T_c}{T_h - T_c}$$

where T_C is the temperature of the cold space in *K* and T_h is the temperature of the hot space in *K*.

Heat Pump

The coefficient of performance is given by:

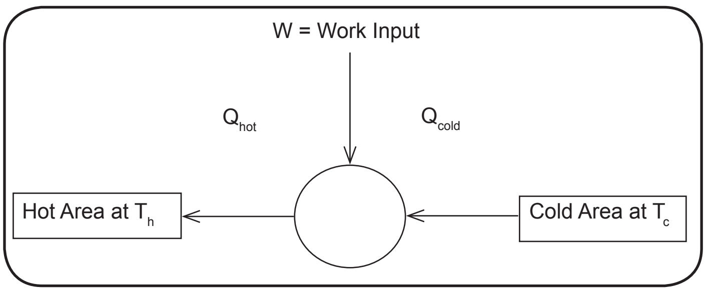
(heat transferred from the hot space in joules) ÷ (work done in joules)

$$COP_{Heat\ pump} = \frac{Q_{hot}}{W} = \frac{Q_{hot}}{Q_{hot} - Q_{cold}}$$

and for the theoretical maximum efficiency we have:

$$COP_{Heat\ pump} = \frac{T_h}{T_h - T_c}$$

where T_h is the temperature of hot space in *K* and T_c is the temperature of the cold space in *K*.



For both the heat pump and the refrigerator the coefficient of performance increases when the temperature difference decreases.

Q2: A freezer is kept in a garage and used to keep food at a temperature of minus 1°C. In summer the outside temperature is 24°C, and in winter the outside temperature falls to 5°C. Compare the coefficients of performance in summer and winter. You may assume that the freezer always works at maximum theoretical efficiency.

Answer to Q2:

Converting the temperatures to K we have T_c = minus 1°C = 272K, summer T_h = 24°C = 297K and winter T_h = 5°C = 278K. Coefficient of performance in summer = 272 ÷ (297 − 272) = 272 ÷ 25 = 10.88. Coefficient of performance in winter = 272 ÷ (278 − 272) = 45.33

Worked Example

A keen gardener decides on a scheme to heat his greenhouses by using a heat pump which will extract energy from an area of surrounding soil. He asks a student to help him with his calculations. The coefficient of performance of the heat pump is 2.95 and the electrical power input is 700W.

1) Calculate the rate at which energy is supplied to the greenhouses. (1 mark)
   [*Coefficient of Performance x rate of work input = rate of energy supplied*]
   2.95 × 700W = 2065W

2) Calculate the rate at which energy is extracted from the ground. (1 mark)
   [*Rate of energy supplied − rate of work input = rate at which energy is extracted from ground*]
   2065W – 700W = 1365W

3) Given the results of these calculations, the gardener concludes that the heat pump would be producing a greater amount of energy than that supplied to it and so the student's calculations must be wrong. Explain to the gardener why the results do not contradict the Law of Conservation of Energy and 2nd Law of Thermodynamics. (4 marks)

   There is energy input from soil which is the cold space and this adds to the energy input as work done on the system (1 mark).

   Work done + energy from the soil = the energy transferred to the greenhouse (or hot space). Thus this is in accordance with the Law of Conservation of Energy. (1 mark).

   The heat pump operates (as a reverse heat engine) between a hot space or source and a cold space or sink. The work done on the system involves the transfer of energy from a heat engine (1 mark).

   Thus the heat energy is 'spread out' which is in accordance with the Second Law of Thermodynamics. (1 mark).

Practice Questions

1) Define the term coefficient of performance for a heat pump. State and explain how this is different from the coefficient of performance for a refrigerator. (2 marks)
2) Why can a heat engine only operate between a heat source and a heat sink? (1 mark)
3) Give two reasons why the efficiency of a practical engine is lower than the calculated maximum. (2 marks)
4) Give two examples of how the use of W and Q_{out} are maximised by combined heat and power schemes. (2 marks)
5) A company claims that they can supply a generator driven by a heat engine operating between 1600K and 350K with an efficiency of 80%. Is this claim justified? (2 marks)
6) A heat engine consumes biogas at a rate of 5.50×10^{-3} $m^3 s^{-1}$.
   (a) Calculate the input power if the calorific value of the biogas is 52.5 MJm^{-3}. (1 mark)
   (b) The output power is 210 kW. Calculate the efficiency of the heat engine. (1 mark)

Answers to Practice Questions

1) The coefficient of performance for a heat pump is the ratio of the *heat transferred for heating* to the energy supplied as electrical input. (1 mark) The refrigerator is used to extract heat energy and so the important quantity is the heat extracted and the ratio becomes the *heat extracted* to the energy supplied. (1 mark)
2) The Second Law of Thermodynamics states that it is *not possible to extract heat energy from a hot source (or reservoir) and convert it all into work*. This results in the creation of a heat sink or reservoir into which the heat is discharged. (1 mark)
3) Any two from: Energy is lost by friction between the components of a heat engine; Heat is wasted and lost by transfer into the surroundings; Incomplete combustion of the fuel which is being used. (2 marks)
4) Any two from: Heat can be used to heat buildings etc.; Electricity can be used to reduce the demand for electricity from the National Grid; Absorption chiller for air conditioning, etc.
5) Maximum theoretical efficiency for this heat engine
   = (1600 − 350) ÷ 1600 = 1250 ÷ 1600 = 0.78 or 78% (1 mark)
   The claim is *not* justified because the maximum theoretical efficiency is lower than the 80% which the company claim.
   (1 mark)
6) (a) Input power = 5.50×10^{-3} m^3s^{-1} × 52.5×10^6 Jm^{-3}
   = 288.75 = 290 kW. (1mark)
   (b) Efficiency of the engine is given by output power ÷ input power = 210 kW ÷ 290 kW = 0.724 = 72%. (1 mark)

Acknowledgements: *This* ***Physics Factsheet*** *was researched and written by* **Christine Collier** *and published in* ***January 2018*** *by* ***Curriculum Press****.*

ISSN 1351-5136