Chapter- 4

# Heat Engine

In thermodynamics, a **heat engine** performs the conversion of heat energy to mechanical work by exploiting the temperature gradient between a hot "source" and a cold "sink". Heat is transferred from the source, through the "working body" of the engine, to the sink, and in this process some of the heat is converted into work by exploiting the properties of a working substance (usually a gas or liquid).

Heat engines are often confused with the cycles they attempt to mimic. Typically when describing the physical device the term 'engine' is used. When describing the model the term 'cycle' is used.
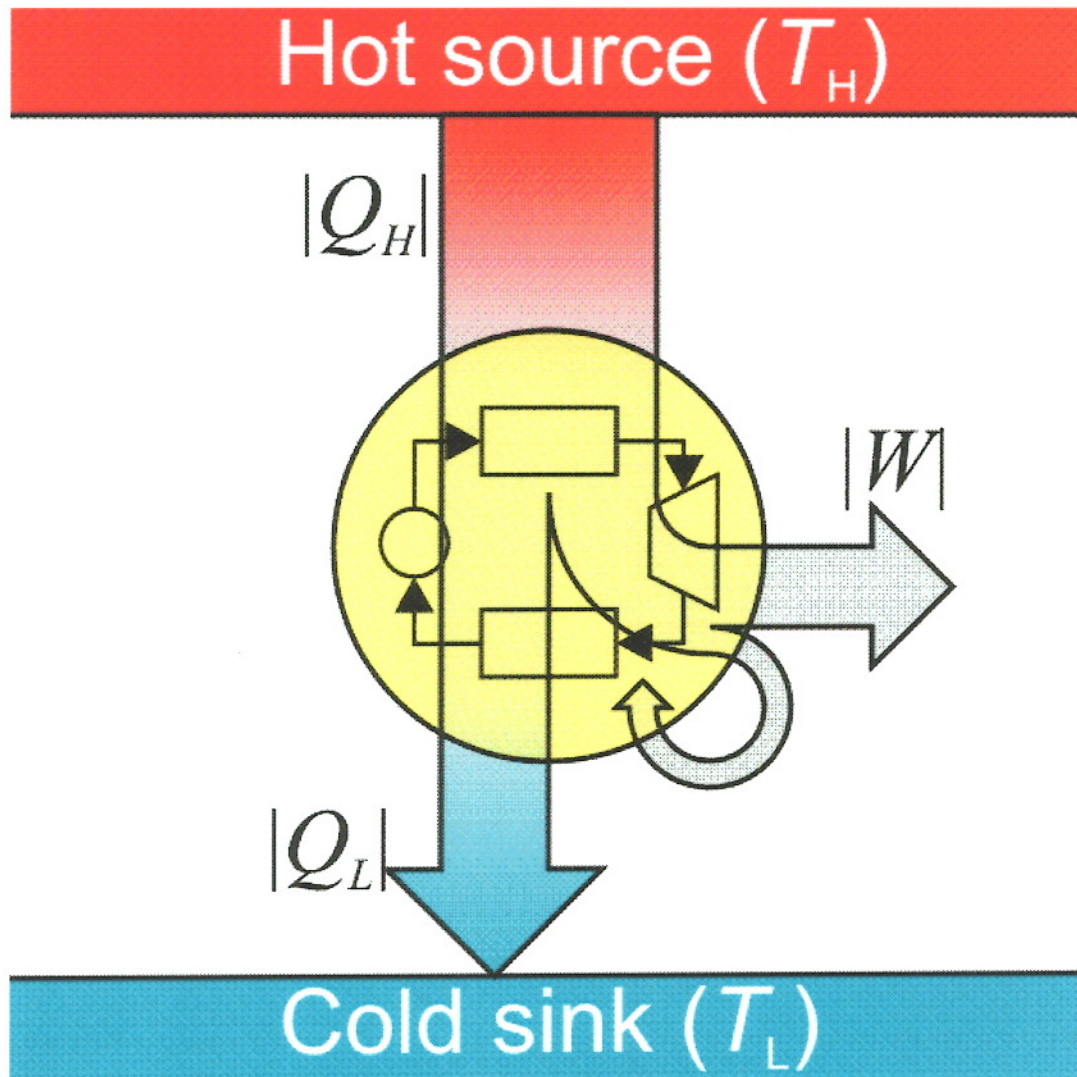
## Overview

Figure 1: **Heat engine diagram**

In thermodynamics, heat engines are often modeled using a standard engineering model such as the Otto cycle. The theoretical model can be refined and augmented with actual data from an operating engine, using tools such as an indicator diagram. Since very few actual implementations of heat engines exactly match their underlying thermodynamic cycles, one could say that a thermodynamic cycle is an ideal case of a mechanical engine. In any case, fully understanding an engine and its efficiency requires gaining a good understanding of the (possibly simplified or idealized) theoretical model, the practical nuances of an actual mechanical engine, and the discrepancies between the two.

In general terms, the larger the difference in temperature between the hot source and the cold sink, the larger is the potential thermal efficiency of the cycle. On Earth, the cold side of any heat engine is limited to being close to the ambient temperature of the

environment, or not much lower than 300 Kelvin, so most efforts to improve the thermodynamic efficiencies of various heat engines focus on increasing the temperature of the source, within material limits. The maximum theoretical efficiency of a heat engine (which no engine ever obtains) is equal to the temperature difference between the hot and cold ends divided by the temperature at the hot end, all expressed in absolute temperature or kelvins.

The efficiency of various heat engines proposed or used today ranges from 3 percent(97 percent waste heat) for the OTEC ocean power proposal through 25 percent for most automotive engines, to 45 percent for a supercritical coal plant, to about 60 percent for a steam-cooled combined cycle gas turbine.

All of these processes gain their efficiency (or lack thereof) due to the temperature drop across them.

### Power

Heat engines can be characterized by their specific power, which is typically given in kilowatts per litre of engine displacement (in the U.S. also horsepower per cubic inch). The result offers an approximation of the peak-power output of an engine. This is not to be confused with fuel efficiency, since high-efficiency often requires a lean fuel-air ratio, and thus lower power density. A modern high-performance car engine makes in excess of 75 kW/L (1.65 hp/in$^3$).

## Everyday examples

Examples of everyday heat engines include the steam engine, the diesel engine, and the gasoline (petrol) engine in an automobile. A common toy that is also a heat engine is a drinking bird. Also the stirling engine is a heat engine. All of these familiar heat engines are powered by the expansion of heated gases. The general surroundings are the heat sink, providing relatively cool gases which, when heated, expand rapidly to drive the mechanical motion of the engine.

## Examples of heat engines

It is important to note that although some cycles have a typical combustion location (internal or external), they often can be implemented as the other combustion cycle. For example, John Ericsson developed an external heated engine running on a cycle very much like the earlier Diesel cycle. In addition, the externally heated engines can often be implemented in open or closed cycles.

What this boils down to is there are thermodynamic cycles and a large number of ways of implementing them with mechanical devices called engines.

### Phase change cycles

In these cycles and engines, the working fluids are gases and liquids. The engine converts the working fluid from a gas to a liquid, from liquid to gas, or both, generating work from the fluid expansion or compression.

- Rankine cycle (classical steam engine)
- Regenerative cycle (steam engine more efficient than Rankine cycle)
- Organic Rankine Cycle (Coolant changing phase in temperature ranges of ice and hot liquid water)
- Vapor to liquid cycle (Drinking bird, Injector, Minto wheel)
- Liquid to solid cycle (Frost heaving — water changing from ice to liquid and back again can lift rock up to 60 cm.)
- Solid to gas cycle (Dry ice cannon — Dry ice sublimes to gas.)

## Gas only cycles

In these cycles and engines the working fluid is always a gas (i.e., there is no phase change):

- Carnot cycle (Carnot heat engine)
- Ericsson Cycle (Caloric Ship John Ericsson)
- Stirling cycle (Stirling engine, thermoacoustic devices)
- Internal combustion engine (ICE):
    - Otto cycle (e.g. Gasoline/Petrol engine, high-speed diesel engine)
    - Diesel cycle (e.g. low-speed diesel engine)
    - Atkinson Cycle (Atkinson Engine)
    - Brayton cycle or Joule cycle originally Ericsson Cycle (gas turbine)
    - Lenoir cycle (e.g., pulse jet engine)
    - Miller cycle

## Liquid only cycles

In these cycles and engines the working fluid are always like liquid:

- Stirling Cycle (Malone engine)
- Heat Regenerative Cyclone

## Electron cycles

- Johnson thermoelectric energy converter
- Thermoelectric (Peltier-Seebeck effect)
- Thermionic emission
- Thermotunnel cooling

## Magnetic cycles

- Thermo-magnetic motor (Tesla)

### Cycles used for refrigeration

A domestic refrigerator is an example of a heat pump: a heat engine in reverse. Work is used to create a heat differential. Many cycles can run in reverse to move heat from the cold side to the hot side, making the cold side cooler and the hot side hotter. Internal combustion engine versions of these cycles are, by their nature, not reversible.

Refrigeration cycles include:

- Vapor-compression refrigeration
- Stirling cryocoolers
- Gas-absorption refrigerator
- Air cycle machine
- Vuilleumier refrigeration
- Magnetic refrigeration

### Evaporative Heat Engines

The Barton evaporation engine is a heat engine based on a cycle producing power and cooled moist air from the evaporation of water into hot dry air.

## Efficiency

The efficiency of a heat engine relates how much useful work is output for a given amount of heat energy input.

From the laws of thermodynamics:

$$dW \ = \ dQ_c \ - \ (-dQ_h)$$

where
$dW = -PdV$ is the work extracted from the engine. (It is negative since work is *done by* the engine.)
$dQ_h = T_h dS_h$ is the heat energy taken from the high temperature system. (It is negative since heat is extracted from the source, hence $(-dQ_h)$ is positive.)
$dQ_c = T_c dS_c$ is the heat energy delivered to the cold temperature system. (It is positive since heat is added to the sink.)

In other words, a heat engine absorbs heat energy from the high temperature heat source, converting part of it to useful work and delivering the rest to the cold temperature heat sink.

In general, the efficiency of a given heat transfer process (whether it be a refrigerator, a heat pump or an engine) is defined informally by the ratio of "what you get out" to "what you put in."

In the case of an engine, one desires to extract work and puts in a heat transfer.

$$\eta = \frac{-dW}{-dQ_h} = \frac{-dQ_h - dQ_c}{-dQ_h} = 1 - \frac{dQ_c}{-dQ_h}$$

The *theoretical* maximum efficiency of any heat engine depends only on the temperatures it operates between. This efficiency is usually derived using an ideal imaginary heat engine such as the Carnot heat engine, although other engines using different cycles can also attain maximum efficiency. Mathematically, this is because in reversible processes, the change in entropy of the cold reservoir is the negative of that of the hot reservoir (i.e., $dS_c = -dS_h$), keeping the overall change of entropy zero. Thus:

$$\eta_{max} = 1 - \frac{T_c dS_c}{-T_h dS_h} = 1 - \frac{T_c}{T_h}$$

where $T_h$ is the absolute temperature of the hot source and $T_c$ that of the cold sink, usually measured in kelvin. Note that $dS_c$ is positive while $dS_h$ is negative; in any reversible work-extracting process, entropy is overall not increased, but rather is moved from a hot (high-entropy) system to a cold (low-entropy one), decreasing the entropy of the heat source and increasing that of the heat sink.

The reasoning behind this being the **maximal** efficiency goes as follows. It is first assumed that if a more efficient heat engine than a Carnot engine is possible, then it could be driven in reverse as a heat pump. Mathematical analysis can be used to show that this assumed combination would result in a net decrease in entropy. Since, by the second law of thermodynamics, this is statistically improbable to the point of exclusion, the Carnot efficiency is a theoretical upper bound on the reliable efficiency of *any* process.

Empirically, no engine has ever been shown to run at a greater efficiency than a Carnot cycle heat engine.

Figure 2 and Figure 3 show variations on Carnot cycle efficiency. Figure 2 indicates how efficiency changes with an increase in the heat addition temperature for a constant compressor inlet temperature. Figure 3 indicates how the efficiency changes with an increase in the heat rejection temperature for a constant turbine inlet temperature.

# Carnot Cycle Efficiency



**Turbine Inlet Temperature: 800 [K]**
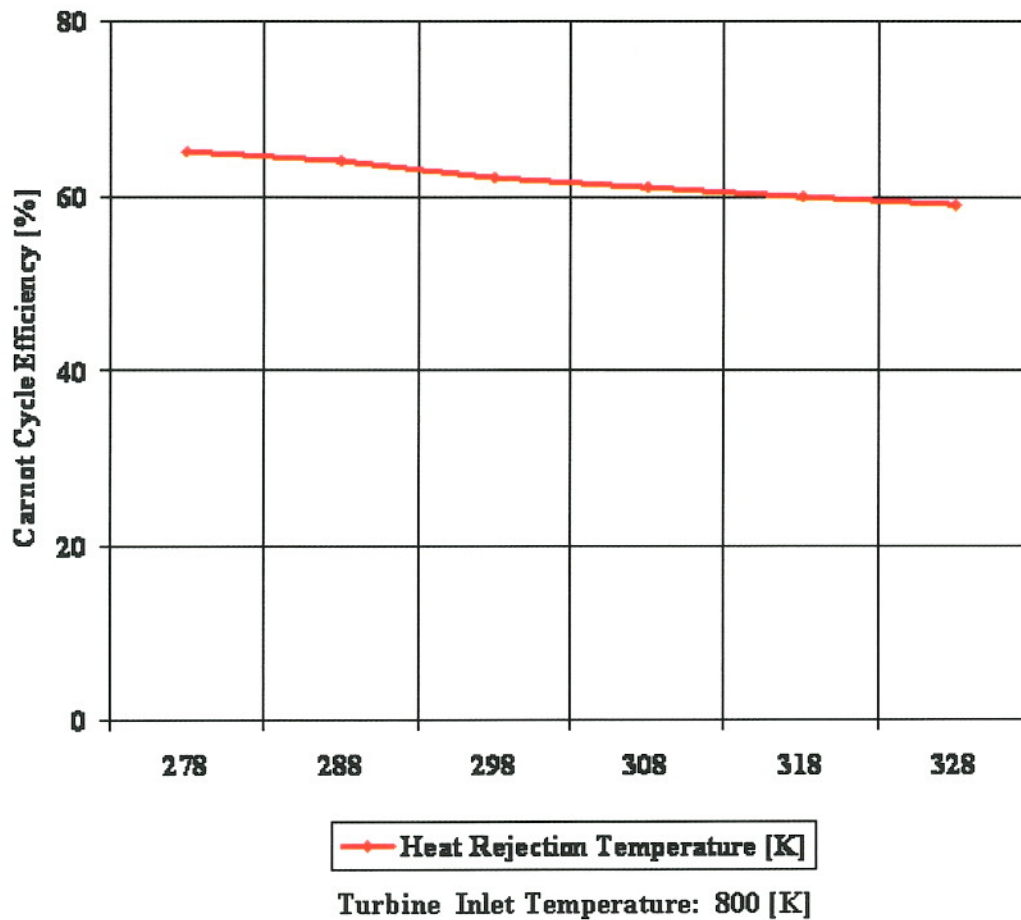
Carnot cycle efficiency with changing heat rejection temperature.

## Endoreversible heat engines

The most Carnot efficiency as a criterion of heat engine performance is the fact that by its nature, any maximally efficient Carnot cycle must operate at an infinitesimal temperature gradient. This is because *any* transfer of heat between two bodies at differing temperatures is irreversible, and therefore the Carnot efficiency expression only applies in the infinitesimal limit. The major problem with that is that the object of most heat engines is to output some sort of power, and infinitesimal power is usually not what is being sought.

A different measure of ideal heat engine efficiency is given by considerations of endoreversible thermodynamics, where the cycle is identical to the Carnot cycle except in that the two processes of heat transfer are *not* reversible (Callen 1985):

$$\eta = 1 - \sqrt{\frac{T_c}{T_h}}$$ (Note: Units K or °R)

This model does a better job of predicting how well real-world heat engines can do:

**Efficiencies of Power Plants**

| Power Plant | $T_c$ (°C) | $T_h$ (°C) | $\eta$ (Carnot) | $\eta$ (Endoreversible) | $\eta$ (Observed) |
|---|---|---|---|---|---|
| West Thurrock (UK) coal-fired power plant | 25 | 565 | 0.64 | 0.40 | 0.36 |
| CANDU (Canada) nuclear power plant | 25 | 300 | 0.48 | 0.28 | 0.30 |
| Larderello (Italy) geothermal power plant | 80 | 250 | 0.33 | 0.178 | 0.16 |

As shown, the endoreversible efficiency much more closely models the observed data.

# History

Heat engines have been known since antiquity but were only made into useful devices at the time of the industrial revolution in the eighteenth century. They continue to be developed today.

# Heat engine enhancements

Engineers have studied the various heat engine cycles extensively in an effort to improve the amount of usable work they could extract from a given power source. The Carnot Cycle limit cannot be reached with any gas-based cycle, but engineers have worked out at least two ways to possibly go around that limit, and one way to get better efficiency without bending any rules.

1. Increase the temperature difference in the heat engine. The simplest way to do this is to increase the hot side temperature, which is the approach used in modern combined-cycle gas turbines. Unfortunately, physical limits (such as the melting point of the materials from which the engine is constructed) and environmental concerns regarding $NO_x$ production restrict the maximum temperature on workable heat engines. Modern gas turbines run at temperatures as high as possible within the range of temperatures necessary to maintain acceptable $NO_x$ output. Another way of increasing efficiency is to lower the output temperature. One new method of doing so is to use mixed chemical working fluids, and then

exploit the changing behavior of the mixtures. One of the most famous is the so-called Kalina cycle, which uses a 70/30 mix of ammonia and water as its working fluid. This mixture allows the cycle to generate useful power at considerably lower temperatures than most other processes.

2. Exploit the physical properties of the working fluid. The most common such exploitation is the use of water above the so-called critical point, or so-called supercritical steam. The behavior of fluids above their critical point changes radically, and with materials such as water and carbon dioxide it is possible to exploit those changes in behavior to extract greater thermodynamic efficiency from the heat engine, even if it is using a fairly conventional Brayton or Rankine cycle. A newer and very promising material for such applications is $CO_2$. $SO_2$ and xenon have also been considered for such applications, although $SO_2$ is a little toxic for most.

3. Exploit the chemical properties of the working fluid. A fairly new and novel exploit is to use exotic working fluids with advantageous chemical properties. One such is nitrogen dioxide ($NO_2$), a toxic component of smog, which has a natural dimer as di-nitrogen tetraoxide ($N_2O_4$). At low temperature, the $N_2O_4$ is compressed and then heated. The increasing temperature causes each $N_2O_4$ to break apart into two $NO_2$ molecules. This lowers the molecular weight of the working fluid, which drastically increases the efficiency of the cycle. Once the $NO_2$ has expanded through the turbine, it is cooled by the heat sink, which causes it to recombine into $N_2O_4$. This is then fed back to the compressor for another cycle. Such species as aluminium bromide ($Al_2Br_6$), $NOCl$, and $Ga_2I_6$ have all been investigated for such uses. To date, their drawbacks have not warranted their use, despite the efficiency gains that can be realized.

# Heat engine processes

| Cycle | Process 1-2 (Compression) | Process 2-3 (Heat Addition) | Process 3-4 (Expansion) | Process 4-1 (Heat Rejection) | Notes |
|---|---|---|---|---|---|
| Power cycles normally with external combustion - or heat pump cycles: | | | | | |
| Bell Coleman | adiabatic | isobaric | adiabatic | isobaric | A reversed Brayton cycle |
| Brayton | adiabatic | isobaric | adiabatic | isobaric | Jet engines aka first Ericsson cycle from 1833 |
| Carnot | isentropic | isothermal | isentropic | isothermal | |
| Diesel | adiabatic | isobaric | adiabatic | isochoric | |

| | | | | | |
|---|---|---|---|---|---|
| **Ericsson** | isothermal | isobaric | isothermal | isobaric | the second Ericsson cycle from 1853 |
| **Scuderi** | adiabatic | variable pressure and volume | adiabatic | isochoric | |
| **Stirling** | isothermal | isochoric | isothermal | isochoric | |
| **Stoddard** | adiabatic | isobaric | adiabatic | isobaric | |

Power cycles normally with internal combustion:

| | | | | | |
|---|---|---|---|---|---|
| **Lenoir** | isobaric | isochoric | adiabatic | isobaric | Pulse jets (Note: 3 of the 4 processes are different) |
| **Otto** | adiabatic | isochoric | adiabatic | isochoric | Gasoline / petrol engines |
| **Brayton** | adiabatic | isobaric | adiabatic | isobaric | Steam engine |

Each process is one of the following:

- isothermal (at constant temperature, maintained with heat added or removed from a heat source or sink)
- isobaric (at constant pressure)
- isometric/isochoric (at constant volume), also referred to as iso-volumetric
- adiabatic (no heat is added or removed from the system during adiabatic process which is equivalent to saying that the entropy remains constant)