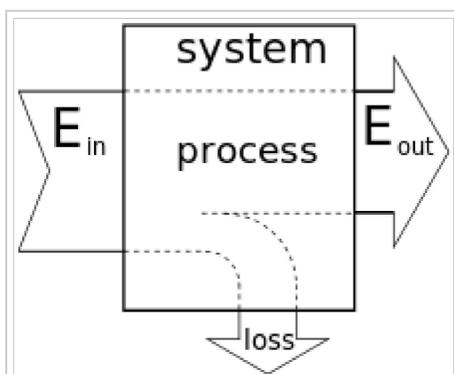# Thermal efficiency

From Wikipedia, the free encyclopedia

In thermodynamics, the **thermal efficiency** (η_{th}) is a dimensionless performance measure of a device that uses thermal energy, such as an internal combustion engine, a steam turbine or a steam engine, a boiler, a furnace, or a refrigerator for example.

Contents

Overview

Output energy is always lower than input energy

In general, energy conversion efficiency is the ratio between the useful output of a device and the input, in energy terms. For thermal efficiency, the input, Q_{in}, to the device is heat, or the heat-content of a fuel that is consumed. The desired output is mechanical work, W_{out}, or heat, Q_{out}, or possibly both. Because the input heat normally has a real financial cost, a memorable, generic definition of thermal efficiency is[1]

$$\eta_{th} \equiv \frac{\text{output}}{\text{input}}.$$

From the first law of thermodynamics, the energy output cannot exceed the input, so

$$0 \leq \eta_{th} \leq 1$$

When expressed as a percentage, the thermal efficiency must be between 0% and 100%. Due to inefficiencies such as friction, heat loss, and other factors, thermal engines' efficiencies are typically much less than 100%. For example, a typical gasoline automobile engine operates at around 25%

efficiency, and a large coal-fueled electrical generating plant peaks at about 46%. The largest diesel engine in the world peaks at 51.7%. In a combined cycle plant, thermal efficiencies are approaching 60%.[2] Such a real-world value may be used as a figure of merit for the device.

For engines where a fuel is burned there are two types of thermal efficiency: indicated thermal efficiency and brake thermal efficiency.[3] This efficiency is only appropriate when comparing similar types or similar devices.

For other systems the specifics of the calculations of efficiency vary but the non dimensional input is still the same. Efficiency = Output energy / input energy

Heat engines

Heat engines transform thermal energy, or heat, Q_{in} into mechanical energy, or work, W_{out}. They cannot do this task perfectly, so some of the input heat energy is not converted into work, but is dissipated as waste heat Q_{out} into the environment

$$Q_{in} = W_{out} + Q_{out}$$

The thermal efficiency of a heat engine is the percentage of heat energy that is transformed into work. Thermal efficiency is defined as

$$\eta_{th} \equiv \frac{W_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

The efficiency of even the best heat engines is low; usually below 50% and often far below. So the energy lost to the environment by heat engines is a major waste of energy resources, although modern cogeneration, combined cycle and energy recycling schemes are beginning to use this heat for other purposes. Since a large fraction of the fuels produced worldwide go to powering heat engines, perhaps up to half of the useful energy produced worldwide is wasted in engine inefficiency. This inefficiency can be attributed to three causes. There is an overall theoretical limit to the efficiency of any heat engine due to temperature, called the Carnot efficiency. Second, specific types of engines have lower limits on their efficiency due to the inherent irreversibility of the engine cycle they use. Thirdly, the nonideal behavior of real engines, such as mechanical friction and losses in the combustion process causes further efficiency losses.

Carnot efficiency

Main article: Carnot's theorem (thermodynamics)

The second law of thermodynamics puts a fundamental limit on the thermal efficiency of all heat engines. Even an ideal, frictionless engine can't convert anywhere near 100% of its input heat into work. The limiting factors are the temperature at which the heat enters the engine, T_H, and the temperature of the environment into which the engine exhausts its waste heat, T_C, measured in an absolute scale, such as the Kelvin or Rankine scale. From Carnot's theorem, for any engine working between these two temperatures:[4]

$$\eta_{th} \le 1 - \frac{T_C}{T_H}$$

This limiting value is called the **Carnot cycle efficiency** because it is the efficiency of an unattainable, ideal, reversible engine cycle called the Carnot cycle. No device converting heat into mechanical energy, regardless of its construction, can exceed this efficiency.

Examples of T_H are the temperature of hot steam entering the turbine of a steam power plant, or the temperature at which the fuel burns in an internal combustion engine. T_C is usually the ambient temperature where the engine is located, or the temperature of a lake or river that waste heat is discharged into. For example, if an automobile engine burns gasoline at a temperature of $T_H = 1089K$ and the ambient temperature is $T_C = 294K$, then its maximum possible efficiency is:

$$\eta_{th} \le 1 - \frac{294K}{1089K} = 73.0\%$$

It can be seen that since T_C is fixed by the environment, the only way for a designer to increase the Carnot efficiency of an engine is to increase T_H, the temperature at which the heat is added to the engine. The efficiency of ordinary heat engines also generally increases with operating temperature, and advanced structural materials that allow engines to operate at higher temperatures is an active area of research.

Due to the other causes detailed below, practical engines have efficiencies far below the Carnot limit. For example, the average automobile engine is less than 35% efficient.

Carnot's theorem only applies to heat engines, where fuel is burned. Devices that convert the fuel's energy directly into work without burning it, such as fuel cells, can exceed the Carnot efficiency.

Engine cycle efficiency

The Carnot cycle is reversible and thus represents the upper limit on efficiency of an engine cycle. Practical engine cycles are irreversible and thus have inherently lower efficiency than the Carnot efficiency when operated between the same temperatures T_H and T_C. One of the factors determining efficiency is how heat is added to the working fluid in the cycle, and how it is removed. The Carnot cycle achieves maximum efficiency because all the heat is added to the working fluid at the maximum temperature T_H, and removed at the minimum temperature T_C. In contrast, in an internal combustion engine, the temperature of the fuel-air mixture in the cylinder is nowhere near its peak temperature as the fuel starts to burn, and only reaches the peak temperature as all the fuel is consumed, so the average temperature at which heat is added is lower, reducing efficiency.

An important parameter in the efficiency of combustion engines is the specific heat ratio of the air-fuel mixture, γ. This varies somewhat with the fuel, but is generally close to the air value of 1.4. This standard value is usually used in the engine cycle equations below, and when this approximation is made the cycle is called an *air-standard cycle*.

- **Otto cycle: automobiles** The Otto cycle is the name for the cycle used in spark-ignition internal combustion engines such as gasoline and hydrogen fueled automobile engines. Its theoretical

efficiency depends on the compression ratio r of the engine and the specific heat ratio γ of the gas in the combustion chamber.[4]

$$\eta_{th} = 1 - \frac{1}{r^{\gamma-1}}$$

Thus, the efficiency increases with the compression ratio. However the compression ratio of Otto cycle engines is limited by the need to prevent the uncontrolled combustion known as knocking. Modern engines have compression ratios in the range 8 to 11, resulting in ideal cycle efficiencies of 56% to 61%.

- **Diesel cycle: trucks and trains** In the Diesel cycle used in diesel truck and train engines, the fuel is ignited by compression in the cylinder. The efficiency of the Diesel cycle is dependent on r and γ like the Otto cycle, and also by the *cutoff ratio*, r_c, which is the ratio of the cylinder volume at the beginning and end of the combustion process:[4]

$$\eta_{th} = 1 - \frac{r^{1-\gamma}(r_c^{\gamma} - 1)}{\gamma(r_c - 1)}$$

The Diesel cycle is less efficient than the Otto cycle when using the same compression ratio. However, practical Diesel engines are 30% - 35% more efficient than gasoline engines.[5] This is because, since the fuel is not introduced to the combustion chamber until it is required for ignition, the compression ratio is not limited by the need to avoid knocking, so higher ratios are used than in spark ignition engines.

- **Rankine cycle: steam power plants** The Rankine cycle is the cycle used in steam turbine power plants. The overwhelming majority of the world's electric power is produced with this cycle. Since the cycle's working fluid, water, changes from liquid to vapor and back during the cycle, their efficiencies depend on the thermodynamic properties of water. The thermal efficiency of modern steam turbine plants with reheat cycles can reach 47%, and in combined cycle plants, in which a steam turbine is powered by exhaust heat from a gas turbine, it can approach 60%.[4]
- **Brayton cycle: gas turbines and jet engines** The Brayton cycle is the cycle used in gas turbines and jet engines. It consists of a compressor that increases pressure of the incoming air, then fuel is continuously added to the flow and burned, and the hot exhaust gasses are expanded in a turbine. The efficiency depends largely on the ratio of the pressure inside the combustion chamber p_2 to the pressure outside p_1[4]

$$\eta_{th} = 1 - \left(\frac{p_2}{p_1}\right)^{\frac{1-\gamma}{\gamma}}$$

Other inefficiencies

The above efficiency formulas are based on simple idealized mathematical models of engines, with no friction and working fluids that obey simple thermodynamic rules called the ideal gas law. Real engines have many departures from ideal behavior that waste energy, reducing actual efficiencies far below the theoretical values given above. Examples are:

- friction of moving parts
- inefficient combustion

- heat loss from the combustion chamber
- departure of the working fluid from the thermodynamic properties of an ideal gas
- aerodynamic drag of air moving through the engine
- energy used by auxiliary equipment like oil and water pumps
- inefficient compressors and turbines
- imperfect valve timing

Another source of inefficiency is that engines must be optimized for other goals besides efficiency, such as low pollution. The requirements for vehicle engines are particularly stringent: they must be designed for low emissions, adequate acceleration, fast starting, light weight, low noise, etc. These require compromises in design (such as altered valve timing to reduce emissions) that reduce efficiency. The average automobile engine is only about 35% efficient, and must also be kept idling at stoplights, wasting an additional 17% of the energy, resulting in an overall efficiency of 18%.[5] Large stationary electric generating plants have fewer of these competing requirements as well as more efficient Rankine cycles, so they are significantly more efficient than vehicle engines, around 50% Therefore, replacing internal combustion vehicles with electric vehicles, which run on a battery that is charged with electricity generated by burning fuel in a power plant, has the theoretical potential to increase the thermal efficiency of energy use in transportation, thus decreasing the demand for fossil fuels.

When comparing different heat engines as sources of power, such as electric power or the power to run vehicles, the engine efficiency alone is only one factor. To give a meaningful comparison, the overall efficiency of the entire energy supply chain from the fuel source to the consumer must be considered. Although the heat wasted by heat engines is usually the largest source of inefficiency, factors such as the energy cost of fuel refining and transportation, and energy loss in electrical transmission lines to transport it, may offset the advantage of a more efficient heat engine.

Energy conversion

For a device that converts energy from another form into thermal energy (such as an electric heater, boiler, or furnace), the thermal efficiency is

$$\eta_{th} \equiv \frac{Q_{out}}{Q_{in}}$$

where the Q quantities are heat-equivalent values.

So, for a boiler that produces 210 kW (or 700,000 BTU/h) output for each 300 kW (or 1,000,000 BTU/h) heat-equivalent input, its thermal efficiency is $210/300 = 0.70$, or 70%. This means that 30% of the energy is lost to the environment.

An electric resistance heater has a thermal efficiency close to 100%.[6] When comparing heating units, such as a highly efficient electric resistance heater to an 80% efficient natural gas-fueled furnace, an economic analysis is needed to determine the most cost-effective choice.

Effects of fuel heating value

Main article: Heating value

The **heating value** of a fuel is the amount of heat released during an exothermic reaction (e.g., combustion) and is a characteristic of each substance. It is measured in units of energy per unit of the substance, usually mass in engineering contexts or per mol in scientific contexts, i.e. kJ/kg or J/mol etc.

The heating value for fuels is expressed as the HHV, LHV, or GHV to distinguish treatment of the heat of phase changes:

- **Higher heating value (HHV)** is determined by bringing all the products of combustion back to the original pre-combustion temperature, and in particular condensing any vapor produced. This is the same as the thermodynamic heat of combustion.
- **Lower heating value (LHV)** (or *net calorific value*) is determined by subtracting the heat of vaporisation of the water vapor from the higher heating value. The energy required to vaporise the water therefore is not realised as heat.
- **Gross heating value** accounts for water in the exhaust leaving as vapor, and includes liquid water in the fuel prior to combustion. This value is important for fuels like wood or coal, which will usually contain some amount of water prior to burning.

Use of HHV is correct for energy calculations, although this has been neglected in some older texts leading to much inaccuracy and confusion. Incorrect use of heating values may significantly affect any quoted efficiency, therefore the reference value should be stated; incorrect values such as 'LHV' render calculations very misleading.

Heat pumps and refrigerators

Heat pumps, refrigerators and air conditioners use work to move heat from a colder to a warmer place, so their function is the opposite of a heat engine. The work energy (W_{in}) that is applied to them is converted into heat, and the sum of this energy and the heat energy that is moved from the cold reservoir (Q_C) is equal to the total heat energy added to the hot reservoir (Q_H)

$$Q_H = Q_C + W_{in}$$

Their efficiency is measured by a coefficient of performance (COP). Heat pumps are measured by the efficiency with which they add heat to the hot reservoir, $COP_{heating}$; refrigerators and air conditioners by the efficiency with which they remove heat from the cold interior, $COP_{cooling}$:

$$COP_{heating} \equiv \frac{Q_H}{W_{in}}$$

$$COP_{cooling} \equiv \frac{Q_C}{W_{in}}$$

The reason for not using the term 'efficiency' is that the coefficient of performance can often be greater than 100%. Since these devices are moving heat, not creating it, the amount of heat they move can be greater than the input work. Therefore, heat pumps can be a more efficient way of heating than simply converting the input work into heat, as in an electric heater or furnace.

Since they are heat engines, these devices are also limited by Carnot's theorem. The limiting value of the Carnot 'efficiency' for these processes, with the equality theoretically achievable only with an ideal 'reversible' cycle, is:

$$\text{COP}_\text{heating} \leq \frac{T_H}{T_H - T_C}$$

$$\text{COP}_\text{cooling} \leq \frac{T_C}{T_H - T_C}$$

The same device used between the same temperatures is more efficient when considered as a heat pump than when considered as a refrigerator:

$$\text{COP}_\text{heating} - \text{COP}_\text{cooling} = 1$$

This is because when heating, the work used to run the device is converted to heat and adds to the desired effect, whereas if the desired effect is cooling the heat resulting from the input work is just an unwanted byproduct.

Energy efficiency

The 'thermal efficiency' is sometimes called the **energy efficiency**. In the United States, in everyday usage the SEER is the more common measure of energy efficiency for cooling devices, as well as for heat pumps when in their heating mode. For energy-conversion heating devices their peak steady-state thermal efficiency is often stated, e.g., 'this furnace is 90% efficient', but a more detailed measure of seasonal energy effectiveness is the Annual Fuel Utilization Efficiency (AFUE).[7]

Energy Efficiency of heat exchangers

A counter flow heat exchanger is generally 100% efficient in transferring heat energy from one circuit to the other, albeit at a slight loss in temperature. However, for a more complete picture of heat exchanger efficiency, exergetic considerations must be taken into account.

See also

- Kalina cycle
- Electrical efficiency
- Mechanical efficiency
- Heat engine
- Federal Roofing Tax Credit for Energy Efficiency (in the US)
- Figure of merit
- Heat of combustion
- Lower heating value
- Relative cost of electricity generated by different sources
- Higher heating value
- Energy conversion efficiency

References

1. ^ *Fundamentals of Engineering Thermodynamics*, by Howell and Buckius, McGraw-Hill, New York, 1987
2. ^ GE Power's H Series Turbine (http://www.ge-energy.com/prod_serv/products/gas_turbines_cc/en/h_system/index.htm)
3. ^ The Internal Combustion Engine in Theory and Practice: Vol. 1 - 2nd Edition, Revised, MIT Press, 1985, Charles Fayette Taylor - Equation 1-4, page 9
4. ^ *a b c d e* Holman, Jack P. (1980). *Thermodynamics*. New York: McGraw-Hill. p. 217. ISBN 0-07-029625-1.
5. ^ *a b* "Where does the energy go?" (http://www.fueleconomy.gov/feg/atv.shtml) . *Advanced technologies and energy efficiency, Fuel Economy Guide*. US Dept. of Energy. 2009. Retrieved 2009-12-02.
6. ^ http://www.energysavers.gov/your_home/space_heating_cooling/index.cfm/mytopic=12520
7. ^ HVAC Systems and Equipment volume of the *ASHRAE Handbook*, ASHRAE, Inc., Atlanta, GA, USA, 2004