Cooling Technology

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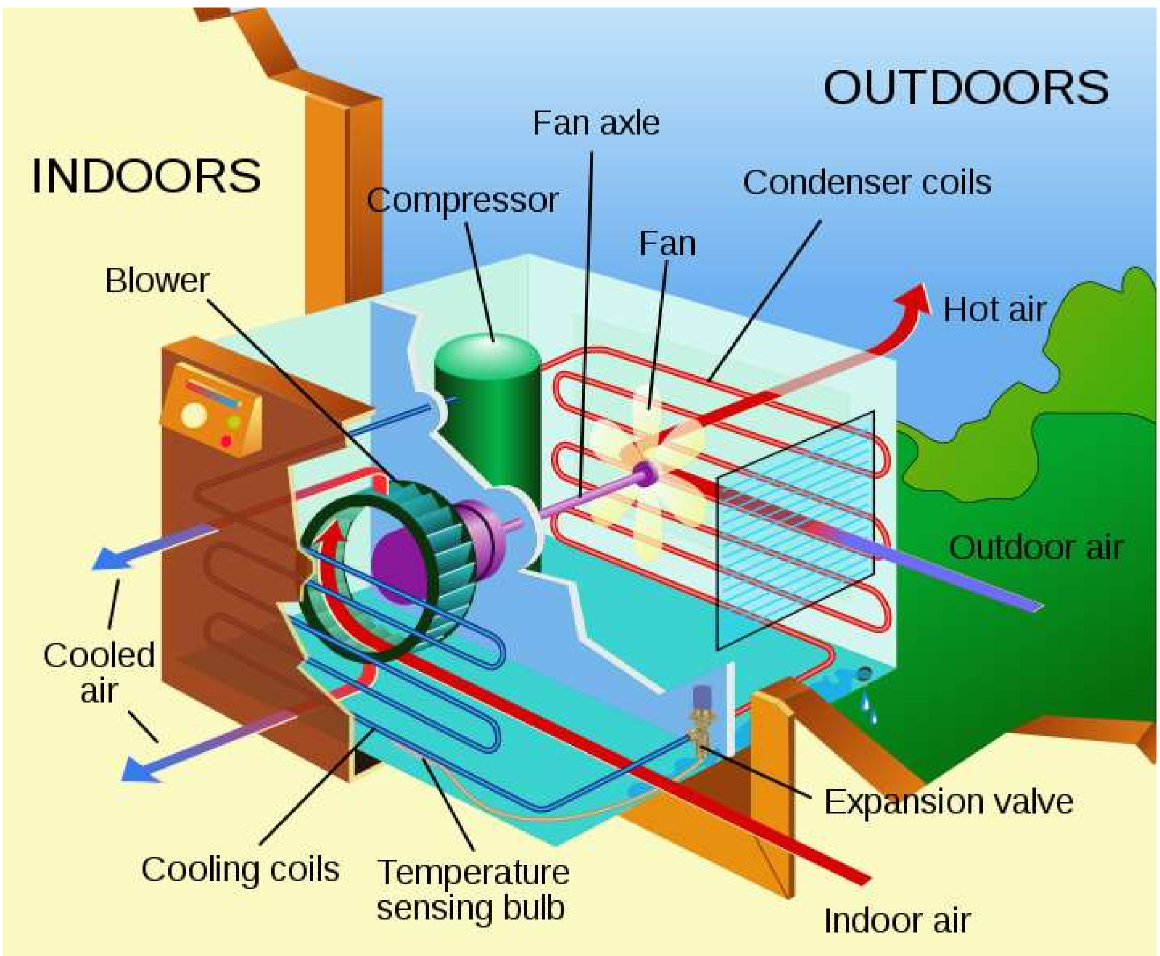
Air Conditioner



A typical home air conditioning unit.

An **air conditioner** (often referred to as **AC**) is a home appliance, system, or mechanism designed to dehumidify and extract heat from an area. The cooling is done using a simple refrigeration cycle. In construction, a complete system of heating, ventilation and air conditioning is referred to as "HVAC". Its purpose, in a building or an automobile, is to provide comfort during either hot or cold weather.

History

In 1758, Benjamin Franklin and John Hadley, professor of chemistry at Cambridge University, conducted an experiment to explore the principle of evaporation as a means to rapidly cool an object. Franklin and Hadley confirmed that evaporation of highly volatile liquids such as alcohol and ether could be used to drive down the temperature of an object past the freezing point of water. They conducted their experiment with the bulb of a mercury thermometer as their object and with a bellows used to "quicken" the evaporation; they lowered the temperature of the thermometer bulb to 7 °F (−14 °C) while the ambient temperature was 65 °F (18 °C). Franklin noted that soon after they passed the freezing point of water (32 °F) a thin film of ice formed on the surface of the thermometer's bulb and that the ice mass was about a quarter inch thick when they stopped the experiment upon reaching 7 °F (−14 °C). Franklin concluded, "From this experiment, one may see the possibility of freezing a man to death on a warm summer's day".

In 1820, British scientist and inventor Michael Faraday discovered that compressing and liquefying ammonia could chill air when the liquefied ammonia was allowed to evaporate. In 1842, Florida physician John Gorrie used compressor technology to create ice, which he used to cool air for his patients in his hospital in Apalachicola, Florida. He hoped eventually to use his ice-making machine to regulate the temperature of buildings. He even envisioned centralized air conditioning that could cool entire cities. Though his prototype leaked and performed irregularly, Gorrie was granted a patent in 1851 for his ice-making machine. His hopes for its success vanished soon afterward when his chief financial backer died; Gorrie did not get the money he needed to develop the machine. According to his biographer Vivian M. Sherlock, he blamed the "Ice King", Frederic Tudor, for his failure, suspecting that Tudor had launched a smear campaign against his invention. Dr. Gorrie died impoverished in 1855 and the idea of air conditioning faded away for 50 years.

Early commercial applications of air conditioning were manufactured to cool air for industrial processing rather than personal comfort. In 1902 the first modern electrical air conditioning was invented by Willis Carrier in Syracuse, New York. Designed to improve manufacturing process control in a printing plant, his invention controlled not only temperature but also humidity. The low heat and humidity were to help maintain consistent paper dimensions and ink alignment. Later Carrier's technology was applied to increase productivity in the workplace, and The Carrier Air Conditioning Company of America was formed to meet rising demand. Over time air conditioning came to be used to improve comfort in homes and automobiles. Residential sales expanded dramatically in the 1950s.

In 1906, Stuart W. Cramer of Charlotte, North Carolina, was exploring ways to add moisture to the air in his textile mill. Cramer coined the term "air conditioning", using it in a patent claim he filed that year as an analogue to "water conditioning", then a well-known process for making textiles easier to process. He combined moisture with ventilation to "condition" and change the air in the factories, controlling the humidity so necessary in textile plants. Willis Carrier adopted the term and incorporated it into the name of his company. This evaporation of water in air, to provide a cooling effect, is now known as evaporative cooling.

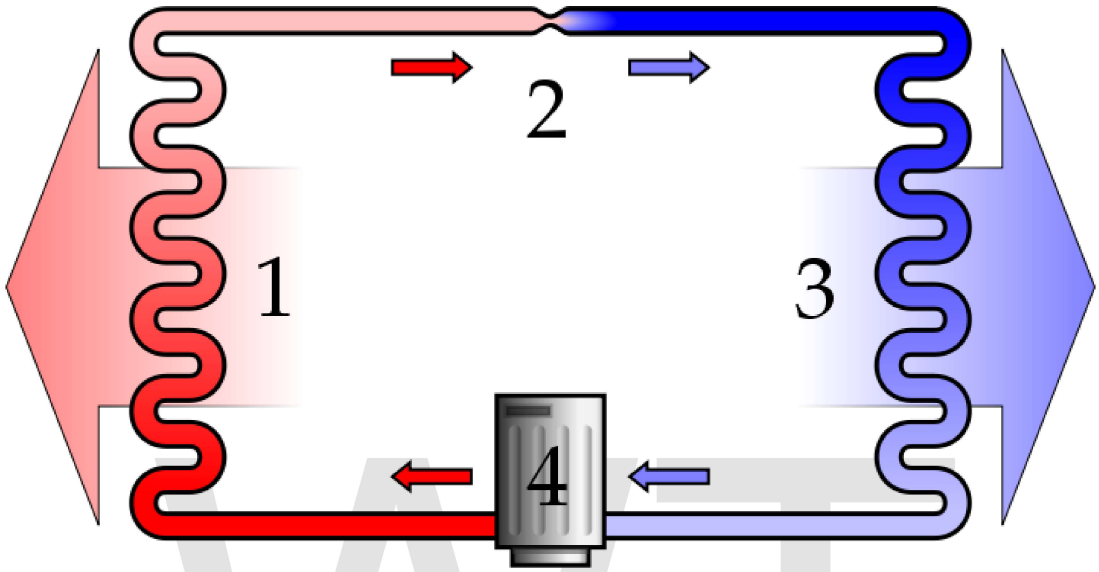
The first air conditioners and refrigerators employed toxic or flammable gases like ammonia, methyl chloride and propane, which could result in fatal accidents when they leaked. Thomas Midgley, Jr. created the first chlorofluorocarbon gas, Freon, in 1928. The refrigerant was much safer for humans but was later claimed to be harmful to the atmosphere's ozone layer. *Freon* is a trademark name of DuPont for any chlorofluorocarbon (CFC), hydrogenated CFC (HCFC), or hydrofluorocarbon (HFC) refrigerant, the name of each including a number indicating molecular composition (R-11, R-12, R-22, R-134A). The blend most used in direct-expansion home and building comfort cooling is an HCFC known as R-22. It is to be phased out for use in new equipment by 2010 and completely discontinued by 2020. R-12 was the most common blend used in automobiles in the United States until 1994 when most changed to R-134A. R-11 and R-12 are no longer manufactured in the United States, the only source for purchase being the cleaned and purified gas recovered from other air conditioner systems. Several non-ozone depleting refrigerants have been developed as alternatives, including R-410A, known by the brand name *Puron*. The most common ozone-depleting refrigerants are R-22, R-11 and R-123.

Innovation in air conditioning technologies continues, with much recent emphasis placed on energy efficiency and improving indoor air quality. As an alternative to conventional refrigerants, natural alternatives like CO_2 (R-744) have been proposed.

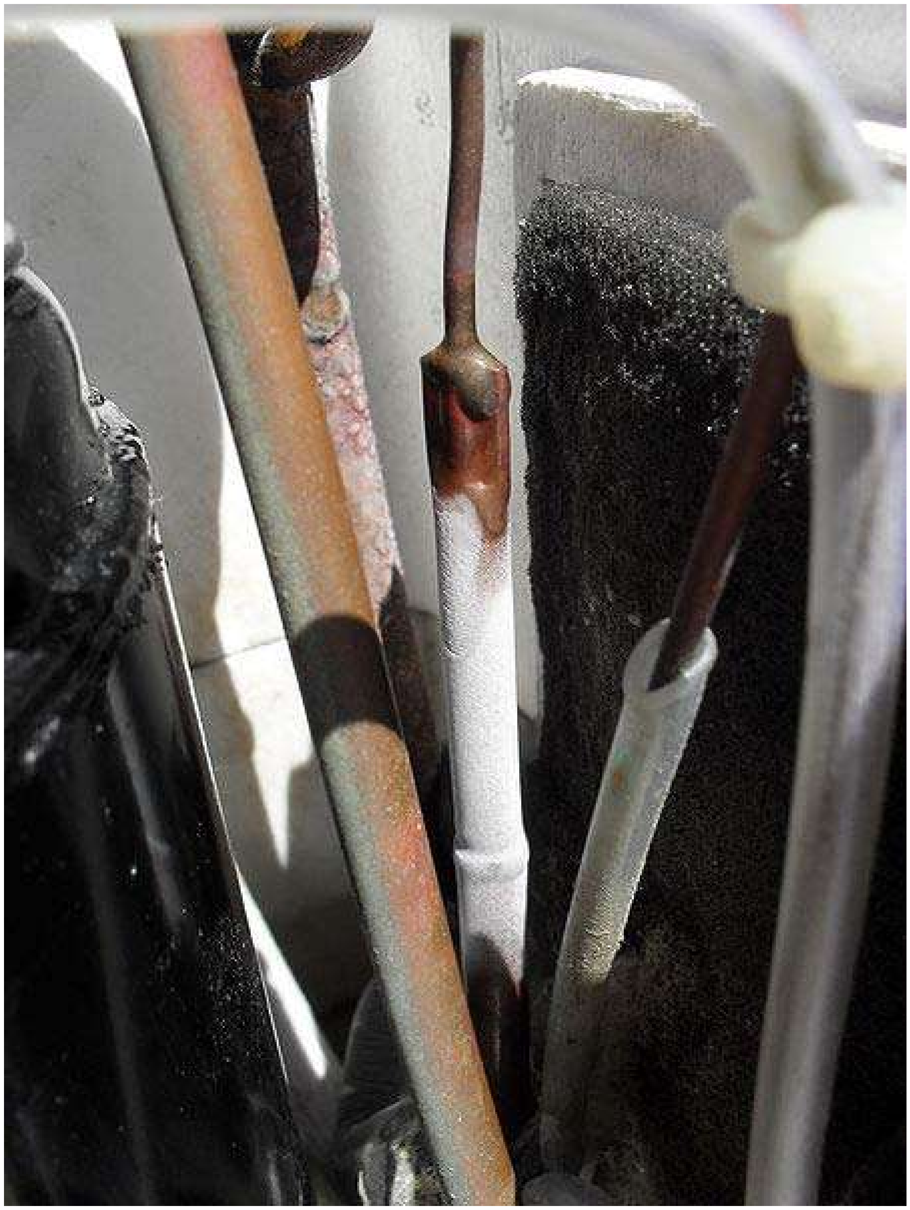
The increase in use of air conditioning over the years has been implicated as a contributor to increasing obesity, because appetite naturally decreases in uncomfortably high temperatures.

Air conditioning system basics and theories

Refrigeration cycle



A simple stylized diagram of the refrigeration cycle: 1) condensing coil, 2) expansion valve, 3) evaporator coil, 4) compressor.



Capillary expansion valve connection to evaporator inlet. Notice frost formation.

In the refrigeration cycle, a heat pump transfers heat from a lower-temperature heat source into a higher-temperature heat sink. Heat would naturally flow in the opposite direction. This is the most common type of air conditioning. A refrigerator works in much the same way, as it pumps the heat out of the interior and into the room in which it stands.

This cycle takes advantage of the way phase changes work, where latent heat is released at a constant temperature during a liquid/gas phase change, and where varying the pressure of a pure substance also varies its condensation/boiling point.

The most common refrigeration cycle uses an electric motor to drive a compressor. In an automobile, the compressor is driven by a belt over a pulley, the belt being driven by the engine's crankshaft (similar to the driving of the pulleys for the alternator, power steering, etc.). Whether in a car or building, both use electric fan motors for air circulation. Since evaporation occurs when heat is absorbed, and condensation occurs when heat is released, air conditioners use a compressor to cause pressure changes between two compartments, and actively condense and pump a refrigerant around. A refrigerant is pumped into the evaporator coil, located in the compartment to be cooled, where the low pressure causes the refrigerant to evaporate into a vapor, taking heat with it. At the opposite side of the cycle is the condenser, which is located outside of the cooled compartment, where the refrigerant vapor is compressed and forced through another heat exchange coil, condensing the refrigerant into a liquid, thus rejecting the heat previously absorbed from the cooled space.

By placing the condenser (where the heat is rejected) inside a compartment, and the evaporator (which absorbs heat) in the ambient environment (such as outside), or merely running a normal air conditioner's refrigerant in the opposite direction, the overall effect is the opposite, and the compartment is heated. This is usually called a heat pump, and is capable of heating a home to comfortable temperatures (25 °C; 70 °F), even when the outside air is below the freezing point of water (0 °C; 32 °F).

Cylinder unloaders are a method of load control used mainly in commercial air conditioning systems. On a semi-hermetic (or open) compressor, the heads can be fitted with unloaders which remove a portion of the load from the compressor so that it can run better when full cooling is not needed. Unloaders can be electrical or mechanical.

Humidity

Air conditioning equipment usually reduces the humidity of the air processed by the system. The relatively cold (below the dew point) evaporator coil condenses water vapor from the processed air, much as a cold drink will condense water on the outside of a glass. The water is drained, removing water vapor from the cooled space and thereby lowering its relative humidity. Since humans perspire to provide natural cooling by the evaporation of perspiration from the skin, drier air (up to a point) improves the comfort provided. The comfort air conditioner is designed to create a 40% to 60% relative humidity in the occupied space. In food retail establishments, large, open chiller cabinets act as highly effective dehumidifiers.

Some air conditioning units dry the air without cooling it. These work like a normal air conditioner, except that a heat exchanger is placed between the intake and exhaust. In combination with convection fans, they achieve a similar level of comfort as an air cooler in humid tropical climates, but only consume about one-third the energy. They are also preferred by those who find the draft created by air coolers uncomfortable.

Refrigerants

A modern R-134a refrigeration compressor

"Freon" is a trade name for a family of haloalkane refrigerants manufactured by DuPont and other companies. These refrigerants were commonly used due to their superior stability and safety properties. However, these chlorine-bearing refrigerants reach the upper atmosphere when they escape. Once the refrigerant reaches the stratosphere, UV radiation from the Sun cleaves the chlorine-carbon bond, yielding a chlorine radical. These chlorine atoms catalyze the breakdown of ozone into diatomic oxygen, depleting the ozone layer that shields the Earth's surface from strong UV radiation. Each chlorine radical remains active as a catalyst unless it binds with another chlorine radical, forming a stable molecule and breaking the chain reaction. The use of CFC as a refrigerant was once common, being used in the refrigerants R-11 and R-12. In most countries the manufacture and use of CFCs has been banned or severely restricted due to concerns about ozone depletion. In light of these environmental concerns, beginning on November 14, 1994, the Environmental Protection Agency has restricted the sale, possession and use of refrigerant to only licensed technicians, per Rules 608 and 609 of the EPA rules and regulations; failure to comply may result in criminal and civil sanctions. Newer and more environmentally-safe refrigerants such as HCFCs (R-22, used in most homes today) and HFCs (R-134a, used in most cars) have replaced most CFC use. HCFCs in turn are being phased out under the Montreal Protocol and replaced by hydrofluorocarbons

(HFCs) such as R-410A, which lack chlorine. Carbon dioxide (R-744) is being rapidly adopted as a refrigerant in Europe and Japan. R-744 is an effective refrigerant with a global warming potential of 1. It must use higher compression to produce an equivalent cooling effect.

Types of air conditioner equipment

The external section of a typical single-room air conditioning unit. For ease of installation, these are frequently placed in a window. This one was installed through a hole cut in the wall.

The internal section of the above unit. The front panel swings down to reveal the controls.

Window and through-wall units

Room air conditioners come in two forms: unitary and packaged terminal PTAC systems. Unitary systems, the common one room air conditioners, sit in a window or wall opening, with interior controls. Interior air is cooled as a fan blows it over the evaporator. On the exterior the air is heated as a second fan blows it over the condenser. In this process, heat is drawn from the room and discharged to the environment. A large house or building may have several such units, permitting each room be cooled separately. PTAC systems are also known as wall split air conditioning systems or ductless systems. These PTAC systems which are frequently used in hotels have two separate units (terminal packages), the evaporative unit on the interior and the condensing unit on the exterior, with tubing passing through the wall and connecting them. This minimizes the interior system footprint and allows each room to be adjusted independently. PTAC systems may be adapted to provide heating in cold weather, either directly by using an electric strip, gas or other heater, or by reversing the refrigerant flow to heat the interior and draw heat from the exterior air, converting the air conditioner into a heat pump. While room air conditioning provides maximum flexibility, when cooling many rooms it is generally more expensive than central air conditioning.

Evaporative coolers

In very dry climates, evaporative coolers, sometimes referred to as swamp coolers or desert coolers, are popular for improving comfort during hot weather. This type of cooler is the dominant cooler used in Iran, which has the largest number of these units of any country in the world, causing some to refer to these units as "Persian coolers." An evaporative cooler is a device that draws outside air through a wet pad, such as a large sponge soaked with water. The sensible heat of the incoming air, as measured by a dry bulb thermometer, is reduced. The total heat (sensible heat plus latent heat) of the entering air is unchanged. Some of the sensible heat of the entering air is converted to latent heat by the evaporation of water in the wet cooler pads. If the entering air is dry enough, the results can be quite comfortable; evaporative coolers tend to feel as if they are not working during times of high humidity, when there is not much dry air with which the coolers can work to make the air as cool as possible for dwelling occupants. Unlike air conditioners, evaporative coolers rely on the outside air to be channeled through cooler pads that cool the air before it reaches the inside of a house through its air duct system; this cooled outside air must be allowed to push the warmer air within the house out through an exhaust opening such as an open door or window.

These coolers cost less and are mechanically simple to understand and maintain.

An early type of cooler, using ice for a further effect, was patented by John Gorrie of Apalachicola, Florida in 1842. He used the device to cool the patients in his malaria hospital.

Portable air conditioners

Portable air conditioners are movable units that can be used to cool a specific region of building in a modular fashion, not requiring permanent installation. Most portable air conditioners are refrigeration based rather than evaporative, and it is this type that is described here. Portable air conditioner units are often rented in emergency situations such as power failures at warehouses or data centers.

All refrigerated type portable air conditioners require exhaust hoses for venting. Through this process of air intake, cooling and venting, air is continually cycled through the unit until the room reaches the desired temperature setting. Also, the refrigerant works to not only cool the air but also dehumidify air in the room, owing to the temperature decrease in the air which results in the saturation of the water content of the air, causing condensation when the air is returned to the room. The air will therefore be left without this ional water content. The water loss rate is sufficiently high to require collection or drainage. The exact conditions for the condensation of the water from the air can be estimated using a Psychrometric chart for air at room pressure.

Single hosed units

A single hosed unit has one hose that runs from the back of the portable air conditioner to the vent kit where hot air can be released. A typical single hosed portable air conditioner can cool a room that is 475 sq ft (44.1 m^2) or smaller and has at most a cooling power of 12,000 BTUs. However, single hosed units cool a room less effectively than dual hosed as the air expelled from the room through the single hose creates negative pressure inside the room. Because of this, air (potentially warm air) from neighboring rooms is pulled into the room with the cooling unit to compensate.

Dual hosed units

Dual hosed units are typically used in larger rooms. One hose is used as the exhaust hose to vent hot air and the other as the intake hose to draw in additional air (usually from the outside). These units generally have a cooler power of 12,000-14,000 BTUs and cool rooms that are around 500 sq ft (46 m^2). The reason an intake hose is needed to draw in extra air is because with higher BTU units, air is cycled in large amounts and hot air is expelled at a faster rate. This would create negative air pressure in the room, so the intake hose eliminates reduction of room air pressure which would draw outside air into the room.

Split units

Portable units are also available in split configuration, often with the compressor and evaporator located in a separate external package and the two units connected via two detachable refrigerant pipes, as is the case with fixed split systems. Split portable units are superior to both single and dual hosed mono-portable units in that interior noise and size of the internal unit can be greatly reduced due to the external location of the compressor, and the water collected can be pumped to the outdoor unit using a pump, avoiding the need to drain water from the indoor unit periodically when running in cooling mode..

A drawback of split portable units compared with mono-portables is that a surface exterior to the building, such as a balcony must be provided for the external compressor unit to be located.

Unlike window ACs the split AC does not have an option of exchange of indoor and outdoor air.

Heat and cool units

Some portable air conditioner units are also able to provide heat by reversing the cooling process so that cool air is collected from a room and warm air is released. These units are not meant to replace actual heaters though and should not be used to cool rooms lower than 50 °F (10 °C).

Central air conditioning

Central air conditioning, commonly referred to as *central air* (U.S.) or *air-con* (UK), is an air conditioning system that uses ducts to distribute cooled and/or dehumidified air to more than one room, or uses pipes to distribute chilled water to heat exchangers in more than one room, and which is not plugged into a standard electrical outlet.

With a typical *split system*, the condenser and compressor are located in an outdoor unit; the evaporator is mounted in the air handler unit. With a *package system*, all components are located in a single outdoor unit that may be located on the ground or roof.

Central air conditioning performs like a regular air conditioner but has several added benefits:

- When the air handling unit turns on, room air is drawn in from various parts of the building through return-air ducts. This air is pulled through a filter where airborne particles such as dust and lint are removed. Sophisticated filters may remove microscopic pollutants as well. The filtered air is routed to air supply ductwork that carries it back to rooms. Whenever the air conditioner is running, this cycle repeats continually.

- Because the condenser unit (with its fan and the compressor) is located outside the home, it offers a lower level of indoor noise than a free-standing air conditioning unit.

Mini (small) duct, high velocity

A central air conditioning system using high velocity air forced through small ducts (also called mini-ducts), typically round, flexible hoses about 2 inches in diameter. Using the principle of aspiration, the higher velocity air mixes more effectively with the room air, eliminating temperature discrepancies and drafts. A high velocity system often consumes more electricity to pump around air, and can be louder than a conventional system if sound attenuators are not used, though they come standard on most, if not all, systems.

The smaller, flexible tubing used for a mini-duct system allows it to be more easily installed in historic buildings, and structures with solid walls, such as log homes. These small ducts are also typically longer contiguous pieces, and therefore less prone to leakage. Another added benefit of this type of ducting is the prevention of foreign particle buildup within the ducts, due to a combination of the higher velocity air, as well as the lack of hard corners.

Passive ground source-based cooling

If underground conditions are suitable, then by far the most energy-efficient way to chill air, is to pump up the coldness of ground water or from underground soil or rock formations, and use that coldness directly (without a heat pump compressor) to chill indoor air. Unless next to open water, they requires high initial investment: drilling deep holes and fitting them with pipes or a filter and pump. But after that, such systems consume five to twenty times less energy then heat pump-based systems. These systems have the disadvantage that they can not chill below or even near the temperature of the deeper underground, so they only work good if winters or nearby mountains cool groundwater below roughly sixteen Celsius (60 Fahrenheit). Also, in the longer run such systems have a tendency to 'deplete' underground coldness, which makes them less efficient. This can be fixed in the winter months, by collecting winter coldness from the air through a roof top heat exchanger and pumping it into the underground cold-source. Unfortunately, such systems are as yet hardly developed. One factor is that some of the world's leading manufacturers of air conditioners also manufacture the boilers and turbines for large electricity plants. Therefore they have little incentive to reduce electricity use of air conditioners. For large buildings, ground source-coldness is successfully used to reduce energy consumption of central air conditioner systems, often in combination with heat pump based heating systems.

Thermostats

Thermostats control the operation of HVAC systems, turning on the heating or cooling systems to bring the building to the set temperature. Typically the heating and cooling systems have separate control systems (even though they may share a thermostat) so that the temperature is only controlled "one-way." That is, in cold weather, a building that is too hot will not be cooled by the thermostat. Thermostats may also be incorporated into facility energy management systems in which the power utility customer may control the overall energy expenditure. In addition, a growing number of power utilities have made available a device which, when professionally installed, will control or limit the power to an HVAC system during peak use times in order to avoid necessitating the use of rolling blackouts. The customer is given a credit of some sort in exchange, so it is often to the advantage of the consumer to buy the most efficient thermostat possible.

Equipment capacity

Air conditioner equipment power in the U.S. is often described in terms of "tons of refrigeration". A "ton of refrigeration" is approximately equal to the cooling power of one short ton (2000 pounds or 907 kilograms) of ice melting in a 24-hour period. The value is defined as 12,000 BTU per hour, or 3517 watts. Residential central air systems are usually from 1 to 5 tons (3 to 20 kilowatts (kW)) in capacity.

The use of electric/compressive air conditioning puts a major demand on the electrical power grid in hot weather, when most units are operating under heavy load. In the aftermath of the 2003 North America blackout locals were asked to keep their air conditioning off. During peak demand, additional power plants must often be brought online, usually expensive peaker plants. A 1995 meta-analysis of various utility studies concluded that the average air conditioner wasted 40% of the input energy. This energy is lost in the form of heat, which must be pumped out.

In an automobile, the A/C system will use around 5 horsepower (4 kW) of the engine's power.

Seasonal energy efficiency ratio (SEER)

For residential homes, some countries set minimum requirements for energy efficiency. In the United States, the efficiency of air conditioners is often (but not always) rated by the *seasonal energy efficiency ratio (SEER)*. The higher the SEER rating, the more energy efficient is the air conditioner. The SEER rating is the BTU of cooling output during its normal annual usage divided by the total electric energy input in watt hours (W·h) during the same period.

SEER = BTU ÷ (W·h)

this can also be rewritten as:

SEER = (BTU / h) ÷ W, where "W" is the average electrical power in Watts, and (BTU/h) is the rated cooling power.

For example, a 5000 BTU/h air-conditioning unit, with a SEER of 10, would consume 5000/10 = 500 Watts of power on average.

The electrical energy consumed per year can be calculated as the average power multiplied by the annual operating time:

500 W × 1000 h = 500,000 W·h = 500 kWh

Assuming 1000 hours of operation during a typical cooling season (i.e., 8 hours per day for 125 days per year).

Another method that yields the same result, is to calculate the total annual cooling output:

5000 BTU/h × 1000 h = 5,000,000 BTU

Then, for a SEER of 10, the annual electrical energy usage would be:

5,000,000 BTU ÷ 10 = 500,000 W·h = 500 kWh

SEER is related to the coefficient of performance (COP) commonly used in thermodynamics and also to the Energy Efficiency Ratio (EER). The EER is the efficiency rating for the equipment at a particular pair of external and internal temperatures, while SEER is calculated over a whole range of external temperatures (i.e., the temperature distribution for the geographical location of the SEER test). SEER is unusual in that it is composed of an Imperial unit divided by an SI unit. The COP is a ratio with the same metric units of energy (joules) in both the numerator and denominator. They cancel out, leaving a dimensionless quantity. Formulas for the approximate conversion between SEER and EER or COP are available from the Pacific Gas and Electric Company:

(1) **SEER = EER ÷ 0.9**
(2) **SEER = COP x 3.792**
(3) **EER = COP x 3.413**

From equation (2) above, a SEER of 13 is equivalent to a COP of 3.43, which means that 3.43 units of heat energy are pumped per unit of work energy.

Today, it is rare to see systems rated below SEER 9 in the United States, since older units are being replaced with higher-efficiency units. The United States now requires that residential systems manufactured in 2006 have a minimum SEER rating of 13 (although window-box systems are exempt from this law, so their SEER is still around 10). Substantial energy savings can be obtained from more efficient systems. For example by upgrading from SEER 9 to SEER 13, the power consumption is reduced by 30% (equal to 1 - 9/13). It is claimed that this can result in an energy savings valued at up to US$300 per year (depending on the usage rate and the cost of electricity). In many cases, the lifetime energy savings are likely to surpass the higher initial cost of a high-efficiency unit.

As an example, the annual cost of electric power consumed by a 72,000 BTU/h air conditioning unit operating for 1000 hours per year with a SEER rating of 10 and a power cost of $0.08 per kilowatt hour (kW·h) may be calculated as follows:

unit size, BTU/h × hours per year, h × power cost, $/kW·h ÷ (SEER, BTU/W·h × 1000 W/kW)
(72,000 BTU/h) × (1000 h) × ($0.08/kW·h) ÷ [(10 BTU/W·h) × (1000 W/kW)] = $576.00 annual cost

A common misconception is that the SEER rating system also applies to heating systems. However, SEER ratings only apply to air conditioning.

Air conditioners (for cooling) and heat pumps (for heating) both work similarly in that heat is transferred or "pumped" from a cooler heat source to a warmer "heat sink". Air conditioners and heat pumps usually operate most effectively at temperatures around 10 to 13 degrees Celsius (°C) (50 to 55 degrees Fahrenheit (°F)). A balance point is reached when the heat source temperature falls below about 4 °C (40 °F), and the system is not able to pull any more heat from the heat source (this point varies from heat pump to heat pump). Similarly, when the heat sink temperature rises to about 49 °C (120 °F), the system will operate less effectively, and will not be able to "push" out any more heat. Geothermal heat pumps do not have this problem of reaching a balance point because they use the ground as a heat source/heat sink and the ground's thermal inertia prevents it from becoming too cold or too warm when moving heat from or to it. The ground's temperature does not vary nearly as much over a year as that of the air above it.

Insulation

In order to maintain building temperature, the air conditioning system must remove heat from the building during the cooling season, and add heat during the heating season. Insulation slows the speed at which heat is gained or lost, and therefore reduces the required power of the air conditioning system. Thick building walls, reflective roofing, curtains and trees next to buildings help reduce heat gain, most notably solar heat gain, and also help cut down on system and energy requirements.

Home air conditioning systems around the world

Domestic air conditioning is most prevalent and ubiquitous in developed Asian and Middle Eastern nations and territories. This especially applies to capitals and urbanized areas where most of the population lives in small high-rise flats. In these areas, with high summer temperatures and a somewhat high standard of living, air conditioning is considered a necessity and not a luxury. Japanese-made domestic air conditioners are usually window or split types, the latter being more modern and expensive. In Israel, virtually all residential systems are split types.

In the United States of America, home air conditioning is most prevalent in the South/Southwest and on the East Coast. Central air systems are most common in the United States of America, and are virtually standard many times in all new dwellings in most states.

In Canada, home air conditioning is less common than in East Asia and the United States, but it still quite prevalent. This is especially true of the Great Lakes regions of southern Ontario and Quebec, where there are especially high humidity levels. While window and split units are common in these regions, central air systems are the most widespread in Western Canada. Most Western Canadian homes are built with already-compatible central forced air natural gas heating systems, making installing a central air system very simple. In Central Canada separate room-based hydro powered heating is more common, leading to the higher cost of retrofitting a central air system. The majority of modern urban high-rise condominiums built in Canadian cities have air conditioning systems. It is also offered as a relatively low-cost option on most new built homes. While energy is comparatively very cheap in Canada, the large size of the average Canadian home and cold winters make heating and cooling one of the largest household expenses. Canadian summers are uncomfortably hot, but rarely reach the dangerous temperatures experienced in the United States or Asia. As such, many Canadians, especially in older homes, simply choose to forgo air conditioning in lieu of simple fans and evaporative coolers. Aside from the cost, air conditioning is often considered environmentally unfriendly, even though the majority of household energy in Canada comes from hydro and nuclear. There have been a number of advances in more environmentally friendly technologies, including geothermal cooling, and the Enwave deep lake system in Toronto that cools a number of office towers using cold water from Lake Ontario.

In Europe, home air conditioning is generally less common, in part due to higher energy costs and moderate summer temperatures. Southern European countries such as Greece, on the other hand, have seen a wide proliferation of home air-conditioning units in recent years. The lack of air conditioning in residences, residential care homes and medical facilities was identified as a contributing factor to the estimated 35,000 deaths – mostly in Germany, France and Italy – left in the wake of the 2003 heat wave.

Chapter 2

Air Cooling and Coolant

Air cooling

A Cooler Master V8 has a lot of heatpipes.

Air cooling is a method of dissipating heat. It works by making the object to be cooled have a larger surface area or have an increased flow of air over its surface, or both. An example of the former is to add fins to the surface of the object, either by making them integral or by attaching them tightly to the object's surface (to ensure efficient heat transfer). In the case of the latter it is done by using a fan blowing air into or onto the object one wants to cool. In many cases the addition of fins adds to the total surface area making a heatsink that makes for greater efficiency in cooling.

In all cases, the air has to be cooler than the object or surface from which it is expected to remove heat. This is due to the second law of thermodynamics, which states that heat will only move spontaneously from a hot reservoir (the heat sink) to a cold reservoir (the air).

Examples

Air-cooled *boxer* engine on a 1954 BMW motorcycle

Vehicles

Air is mainly used for cooling internal combustion engines (ICE), particularly those powering aircraft, because it is a readily available fluid and is often at a suitable temperature to be used efficiently. While many such ICE are called "*liquid cooled*" the cooling liquid is usually cooled by air passing through a radiator or heat exchanger. Examples of direct air cooling in automobiles are rarer. The most common example is the flat or *Boxer* engine, once used extensively by Porsche and still in use on BMW motorcycles. Notable past models include the Volkswagen Beetle and related models, the Citroën 2CV, the Chevrolet Corvair, and the Porsche 911 until 1998.

Turbines

Gas turbine engines (e.g. turbojets, turbofans, etc) incorporate turbines, which are exposed to the hot gases exiting the combustion chamber. Where necessary, relatively cold air is bled from the compression system and used to cool the turbine blades and vanes, to prevent them from melting.

Electronics

Its use is widespread in computers and CPU cooling, where the computer processors produce large quantities of heat that, if not dissipated, could damage the CPU and other electronic components. In this case air has the advantage of being a good insulator too. However, in the future, new processors might generate too much heat to be dissipated through direct air cooling and it would follow that such direct cooling for computers and their components will become obsolete. Water cooling is somewhat popular in very high-power situations, such as large servers or heavily overclocked amateur systems.

Industries

A very large number of industrial processes use air as a cooling medium, either directly or indirectly. Air conditioning is a very common process in which the air in a room, or a whole building, is cooled in order to maintain a comfortable environment for its occupants. Often the air has been cooled by chilled water or brine and the heat transferred to that medium is transported outside the building where, often, fan-driven water-to-air heat exchanging is again effected to reject the heat into the atmosphere. A common sight around, for example, power stations are the large waisted concrete towers that emit steam more or less constantly. These are, in part, using air cooling on a grand scale.

Coolant

A **coolant** is a fluid which flows through a device to prevent its overheating, transferring the heat produced by the device to other devices that use or dissipate it. An ideal coolant has high thermal capacity, low viscosity, is low-cost, non-toxic, and chemically inert, neither causing nor promoting corrosion of the cooling system. Some applications also require the coolant to be an electrical insulator.

While the term **coolant** is commonly used in automotive, residential and commercial temperature-control applications, in industrial processing, **heat transfer fluid** is one technical term more often used, in high temperature as well as low temperature manufacturing applications.

The coolant can either keep its phase and stay liquid or gaseous, or can undergo a phase change, with the latent heat adding to the cooling efficiency. The latter, when used to achieve low temperatures, is more commonly known as refrigerant.

Gases

Air is a common form of a coolant. Air cooling uses either convective airflow (passive cooling), or a forced circulation using fans.

Hydrogen is used as a high-performance gaseous coolant. Its thermal conductivity is higher than of all gases, it has high specific heat capacity, and low density and therefore low viscosity, which is an advantage for rotary machines susceptible to windage losses. Hydrogen-cooled turbogenerators are currently the most common electrical generators in large power plants.

Inert gases are frequently used as coolants in gas-cooled nuclear reactors. Helium is the most favored coolant due to its low tendency to absorb neutrons and become radioactive. Nitrogen and carbon dioxide are frequently used as well.

Sulfur hexafluoride is used for cooling and insulating of some high-voltage power systems (circuit breakers, switches, some transformers, etc.).

Steam can be used where high specific heat capacity is required in gaseous form and the corrosive properties of hot water are accounted for.

Liquids

The most common coolant is water. Its high heat capacity and low cost makes it a suitable heat-transfer medium. It is usually used with additives, like corrosion inhibitors and antifreeze. Antifreeze, a solution of a suitable organic chemical (most often ethylene glycol, diethylene glycol, or propylene glycol) in water, is used when the water-based coolant has to withstand temperatures below 0 °C, or when its boiling point has to be raised. Betaine is a similar coolant, with the exception that it is made from pure plant juice, and is therefore not toxic or difficult to dispose of ecologically.

Very pure deionized water, due to its relatively low electrical conductivity, is used to cool some electrical equipment, often high-power transmitters and high-power vacuum tubes.

Heavy water is used in some nuclear reactors; it also serves as a neutron moderator.

Polyalkylene Glycol or PAG's are used as high temperature, thermally stable heat transfer fluids exhibiting strong resistance to oxidation. Modern PAG's can also be non-toxic and non-hazardous.

Cutting fluid is a coolant that also serves as a lubricant for metal-shaping machine tools.

Oils are used for applications where water is unsuitable. With higher boiling points than water, oils can be raised to considerably higher temperatures (above 100 degrees Celsius) without introducing high pressures within the container or loop system in question.

- Mineral oils serve as both coolants and lubricants in many mechanical gears. Castor oil is also used. Due to their high boiling points, mineral oils are used in portable electric radiator-style space heaters in residential applications, and in closed-loop systems for industrial process heating and cooling.
- Silicone oils are favored for their wide range of operating temperatures. However their high cost limits their applications.
- Fluorocarbon oils are used for the same reasons.
- Transformer oil is used for cooling and additional electric insulation of high-power electric transformers.

Fuels are frequently used as coolants for engines. A cold fuel flows over some parts of the engine, absorbing its waste heat and being preheated before combustion. Kerosene and other jet fuels frequently serve in this role in aviation engines.

Freons were frequently used for immersive cooling of e.g. electronics.

Refrigerants are coolants used for reaching low temperatures by undergoing phase change between liquid and gas. Halomethanes were frequently used, most often R-12 and R-22, but due to environmental concerns are being phased out, often with liquified propane or other haloalkanes like R-134a. Anhydrous ammonia is frequently used in large commercial systems, and sulfur dioxide was used in early mechanical refrigerators. Carbon dioxide (R-744) is used as a working fluid in climate control systems for cars, residential air conditioning, commercial refrigeration, and vending machines.

Heat pipes are a special application of refrigerants.

Molten metals and salts

Liquid fusible alloys can be used as coolants in applications where high temperature stability is required, e.g. some fast breeder nuclear reactors. Sodium (in sodium cooled fast reactors) or sodium-potassium alloy NaK are frequently used; in special cases lithium can be employed. Another liquid metal used as a coolant is lead, in e.g. lead cooled fast reactors, or a lead-bismuth alloy. Some early fast neutron reactors used mercury.

For very high temperature applications, e.g. molten salt reactors or very high temperature reactors, molten salts can be used as coolants. One of the possible combinations is the mix of sodium fluoride and sodium tetrafluoroborate ($NaF-NaBF_4$). Other choices are FLiBe and FLiNaK.

Liquid gases

Liquified gases are used as coolants for cryogenic applications, including cryo-electron microscopy, overclocking of computer processors, applications using superconductors, or extremely sensitive sensors and very low-noise amplifiers.

Liquid nitrogen, which boils at about -196 °C (77K), is the most common and least expensive coolant in use. Liquid air is used to a lesser extent, due to its liquid oxygen content which makes it prone to cause fire or explosions when in contact with combustible materials.

Lower temperatures can be reached using liquified neon which boils at about -246 °C. The lowest temperatures, used for the most powerful superconducting magnets, are reached using liquid helium.

Liquid hydrogen at -250 to -265 °C can also be used as a coolant. In the Reaction Engines Scimitar and the Reaction Engines SABRE hypersonic aircraft engines liquid hydrogen is used as a coolant in the precooler to cool down the air in the intake. At Mach 5, the intake can reach as high as 1000 °C so a precooler is needed to avoid melting of the engine parts. Liquid hydrogen is also used both as a fuel and as a coolant to cool nozzles and combustion chambers of rocket engines.

Nanofluids

An emerging and new class of coolants are nanofluids which consist of a carrier liquid, such as water, dispersed with tiny nano-scale particles known as nanoparticles. Purpose-designed nanoparticles of e.g. CuO, alumina, titanium dioxide, carbon nanotubes, silica, or metals (e.g. copper, or silver nanorods) dispersed into the carrier liquid the enhances the heat transfer capabilities of the resulting coolant compared to the carrier liquid alone. The enhancement can be theoretically as high as 350%. The experiments however did not prove so high thermal conductivity improvements, but found significant increase of the critical heat flux of the coolants.

Some significant improvements are achievable; e.g. silver nanorods of 55±12 nm diameter and 12.8 μm average length at 0.5 vol.% increased the thermal conductivity of water by 68%, and 0.5 vol.% of silver nanorods increased thermal conductivity of ethylene glycol based coolant by 98%. Alumina nanoparticles at 0.1% can increase the critical heat flux of water by as much as 70%; the particles form rough porous surface on the cooled object, which encourages formation of new bubbles, and their hydrophilic nature then helps pushing them away, hindering the formation of the steam layer.

Solids

In some applications, solid materials are used as coolants. The materials require high energy to vaporize; this energy is then carried away by the vaporized gases. This approach is common in spaceflight, for ablative atmospheric reentry shields and for cooling of rocket engine nozzles. The same approach is also used for fire protection of structures, where ablative coating is applied.

Chapter 3

Cooling Tower

Natural draft wet cooling hyperbolic towers at Didcot Power Station, UK

An abandoned cooling tower at the derelict Thorpe Marsh Power Station in Yorkshire, England.

A mechanical induced-draft cooling tower

Cooling towers are heat removal devices used to transfer process waste heat to the atmosphere. Cooling towers may either use the evaporation of water to remove process heat and cool the working fluid to near the wet-bulb air temperature or in the case of "Close Circuit Dry Cooling Towers" rely solely on air to cool the working fluid to near the dry-bulb air temperature. Common applications include cooling the circulating water used in oil refineries, chemical plants, power stations and building cooling. The towers vary in size from small roof-top units to very large hyperboloid structures (as in Image 1) that can be up to 200 metres tall and 100 metres in diameter, or rectangular structures (as in Image 2) that can be over 40 metres tall and 80 metres long. Smaller towers are normally factory-built, while larger ones are constructed on site. They are often associated with nuclear power plants in popular culture.

A hyperboloid cooling tower was patented by Frederik van Iterson and Gerard Kuypers in 1918.

Classification by use

HVAC

An HVAC cooling tower is a subcategory rejecting heat from a chiller. Water-cooled chillers are normally more energy efficient than air-cooled chillers due to heat rejection to tower water at or near wet-bulb temperatures. Air-cooled chillers must reject heat at the dry-bulb temperature, and thus have a lower average reverse-Carnot cycle effectiveness. Large office buildings, hospitals, and schools typically use one or more cooling towers as part of their air conditioning systems. Generally, industrial cooling towers are much larger than HVAC towers.

HVAC use of a cooling tower pairs the cooling tower with a water-cooled chiller or water-cooled condenser. A *ton* of air-conditioning is the removal of 12,000 Btu/hour (3517 W). The *equivalent ton* on the cooling tower side actually rejects about 15,000 Btu/hour (4396 W) due to the heat-equivalent of the energy needed to drive the chiller's compressor. This *equivalent ton* is defined as the heat rejection in cooling 3 U.S. gallons/minute (1,500 pound/hour) of water 10 °F (5.56 °C), which amounts to 15,000 Btu/hour, or a chiller coefficient of performance (COP) of 4.0. This COP is equivalent to an energy efficiency ratio (EER) of 13.65.

Cooling towers are also used in HVAC systems that have multiple water source heat pumps that share a common piping "water loop". In this type of system, the water circulating inside the "water loop" removes heat from the condenser of the heat pumps whenever the heat pumps are working in the cooling mode, then the cooling tower is used to remove heat from the water loop and reject it to the atmosphere. When the heat pumps are working in heating mode, the condensers draw heat out of the loop water and reject it into the space to be heated.

Industrial cooling towers

Industrial cooling towers can be used to remove heat from various sources such as machinery or heated process material. The primary use of large, industrial cooling towers is to remove the heat absorbed in the circulating cooling water systems used in power plants, petroleum refineries, petrochemical plants, natural gas processing plants, food processing plants, semi-conductor plants, and for other industrial facilities such as in condensers of distillation columns, for cooling liquid in crystallization, etc. The circulation rate of cooling water in a typical 700 MW coal-fired power plant with a cooling tower amounts to about 71,600 cubic metres an hour (315,000 U.S. gallons per minute) and the circulating water requires a supply water make-up rate of perhaps 5 percent (i.e., 3,600 cubic metres an hour).

If that same plant had no cooling tower and used **once-through cooling** water, it would require about 100,000 cubic metres an hour and that amount of water would have to be continuously returned to the ocean, lake or river from which it was obtained and continuously re-supplied to the plant. Furthermore, discharging large amounts of hot water may raise the temperature of the receiving river or lake to an unacceptable level for the local ecosystem. Elevated water temperatures can kill fish and other aquatic organisms. A cooling tower serves to dissipate the heat into the atmosphere instead and wind and air diffusion spreads the heat over a much larger area than hot water can distribute heat in a body of water. Some coal-fired and nuclear power plants located in coastal areas do make use of once-through ocean water. But even there, the offshore discharge water outlet requires very careful design to avoid environmental problems.

Petroleum refineries also have very large cooling tower systems. A typical large refinery processing 40,000 metric tonnes of crude oil per day (300,000 barrels (48,000 m^3) per day) circulates about 80,000 cubic metres of water per hour through its cooling tower system.

The world's tallest cooling tower is the 200 metre tall cooling tower of Niederaussem Power Station.

Heat transfer methods

Mechanical draft crossflow cooling tower used in an HVAC application

With respect to the heat transfer mechanism employed, the main types are:

- *Wet cooling towers* or simply *open circuit cooling towers* operate on the principle of evaporation. The working fluid and the evaporated fluid (usually H_2O) are one and the same.
- *Dry Cooling Towers* operate by heat transfer through a surface that separates the working fluid from ambient air, such as in a tube to air heat exchanger, utilizing convective heat transfer. They do not use evaporation.
- *Fluid coolers* or *Closed Circuit Cooling Towers* are hybrids that pass the working fluid through a tube bundle, upon which clean water is sprayed and a fan-induced draft applied. The resulting heat transfer performance is much closer to that of a wet cooling tower, with the advantage provided by a dry cooler of protecting the working fluid from environmental exposure and contamination.

In a wet cooling tower (or Open Circuit Cooling Tower), the warm water can be cooled to a temperature lower than the ambient air dry-bulb temperature, if the air is relatively dry. (see: dew point and psychrometrics). As ambient air is drawn past a flow of water, an small portion of the water evaporate, the energy required by that portion of the water to evaporate is taken from the remaining mass of water reducing his temperature (aproximately by 970 BTU for each pound of evaporated water). Evaporation results in saturated air conditions, lowering the temperature of the water process by the tower to a value close to wet bulb air temperature, which is lower than the ambient dry bulb air temperature, the difference determined by the humidity of the ambient air.

To achieve better performance (more cooling), a medium called *fill* is used to increase the surface area and the time of contact between the air and water flows. *Splash fill* consists of material placed to interrupt the water flow causing splashing. *Film fill* is composed of thin sheets of material (usually PVC) upon which the water flows. Both methods create increased surface area and time of contact between the fluid (water) and the gas (air).

Air flow generation methods

A forced draft cooling tower

With respect to drawing air through the tower, there are three types of cooling towers:

- *Natural draft*, which utilizes buoyancy via a tall chimney. Warm, moist air *naturally* rises due to the density differential to the dry, cooler outside air. Warm moist air is less dense than drier air at the same pressure. This moist air buoyancy produces a current of air through the tower.
- *Mechanical draft*, which uses power driven fan motors to force or draw air through the tower.
    - *Induced draft*: A mechanical draft tower with a fan at the discharge which pulls air through tower. The fan *induces* hot moist air out the discharge. This produces low entering and high exiting air velocities, reducing the possibility of *recirculation* in which discharged air flows back into the air intake. This fan/fin arrangement is also known as *draw-through*.
    - *Forced draft*: A mechanical draft tower with a blower type fan at the intake. The fan *forces* air into the tower, creating high entering and low exiting air velocities. The low exiting velocity is much more susceptible to

recirculation. With the fan on the air intake, the fan is more susceptible to complications due to freezing conditions. Another disadvantage is that a forced draft design typically requires more motor horsepower than an equivalent induced draft design. The forced draft benefit is its ability to work with high static pressure. They can be installed in more confined spaces and even in some indoor situations. This fan/fill geometry is also known as *blow-through*.

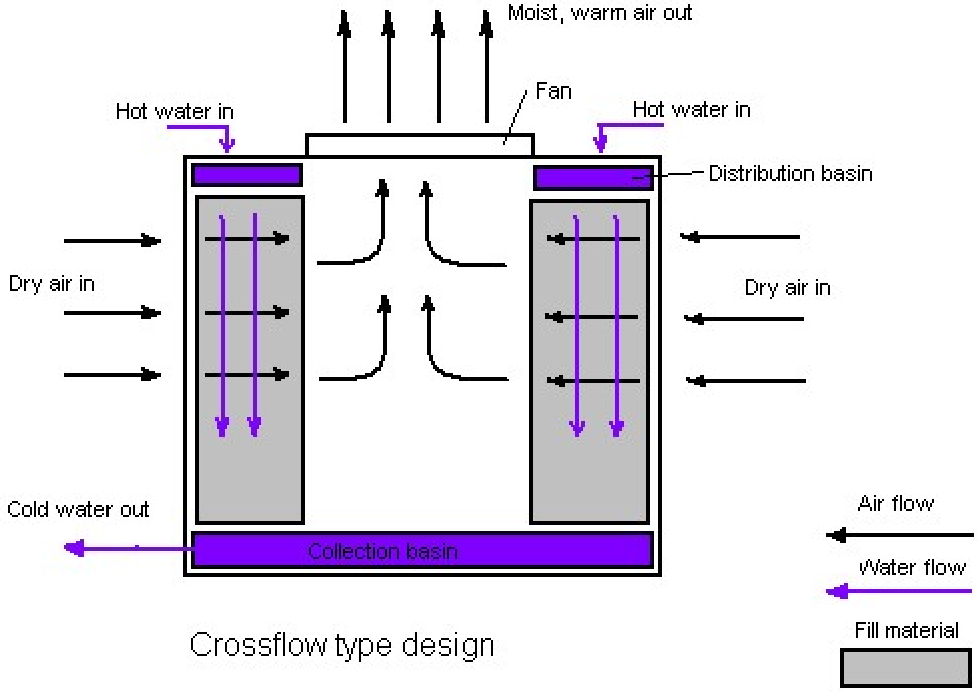
- Fan assisted natural draft. A hybrid type that appears like a natural draft though airflow is assisted by a fan.

Hyperboloid (a.k.a. hyperbolic) cooling towers (Image 1) have become the design standard for all natural-draft cooling towers because of their structural strength and minimum usage of material. The hyperboloid shape also aids in accelerating the upward convective air flow, improving cooling efficiency. They are popularly associated with nuclear power plants. However, this association is misleading, as the same kind of cooling towers are often used at large coal-fired power plants as well. Similarly, not all nuclear power plants have cooling towers, instead cooling their heat exchangers with lake, river or ocean water.

Categorization by air-to-water flow

Crossflow

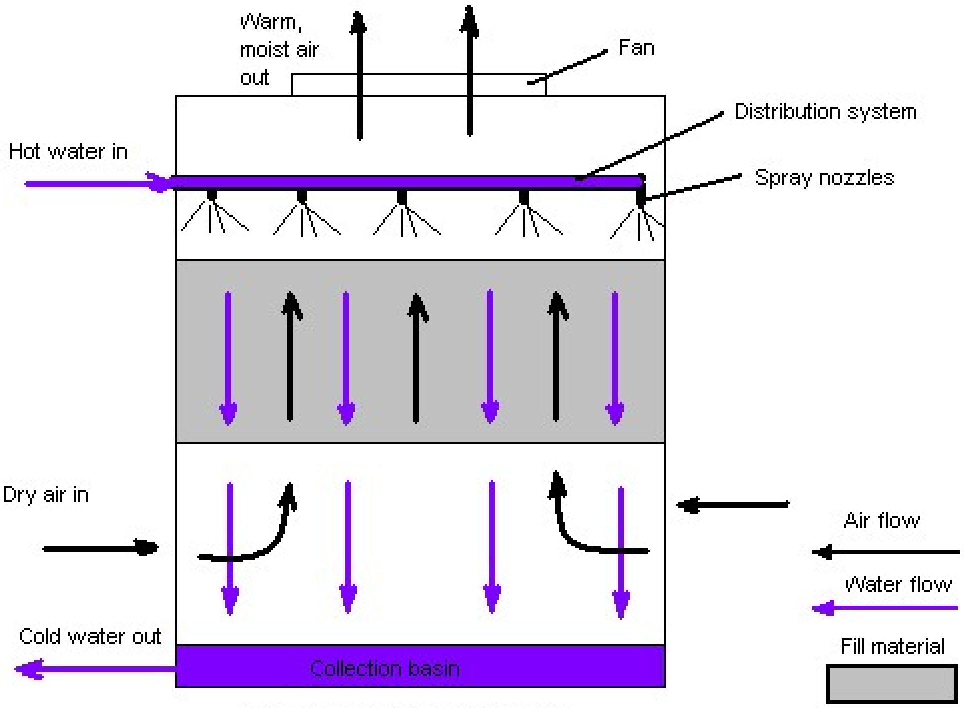
Crossflow is a design in which the air flow is directed perpendicular to the water flow. Air flow enters one or more vertical faces of the cooling tower to meet the fill material. Water flows (perpendicular to the air) through the fill by gravity. The air continues through the fill and thus past the water flow into an open plenum area. A *distribution* or *hot water basin* consisting of a deep pan with holes or *nozzles* in the bottom is utilized in a crossflow tower. Gravity distributes the water through the nozzles uniformly across the fill material.



Crossflow type design

Counterflow

In a counterflow design the air flow is directly opposite to the water flow. Air flow first enters an open area beneath the fill media and is then drawn up vertically. The water is sprayed through pressurized nozzles and flows downward through the fill, opposite to the air flow.



Counterflow type design

Common to both designs:

- The interaction of the air and water flow allow a partial equalization and evaporation of water.
- The air, now saturated with water vapor, is discharged from the cooling tower.
- A *collection* or *cold water basin* is used to contain the water after its interaction with the air flow.

Both crossflow and counterflow designs can be used in natural draft and mechanical draft cooling towers.

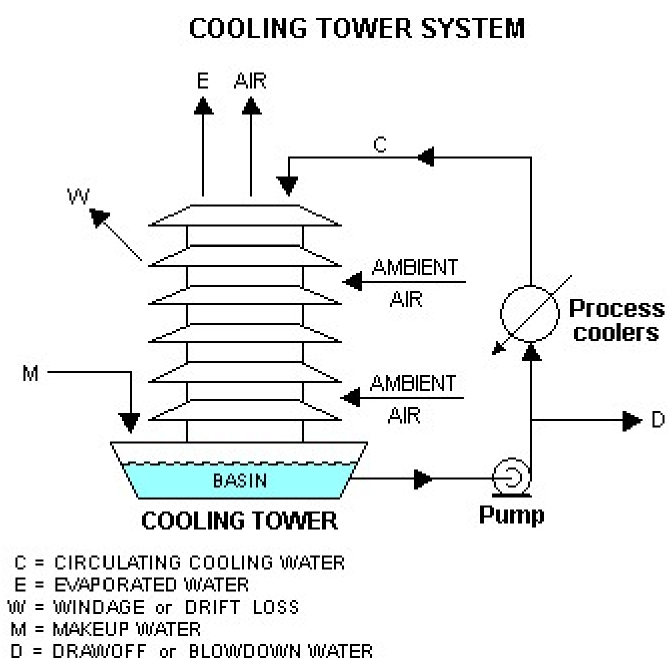
Cooling tower as a flue gas stack

At some modern power stations, equipped with flue gas purification like the Power Station Staudinger Grosskrotzenburg and the Power Station Rostock, the cooling tower is also used as a flue gas stack (industrial chimney). At plants without flue gas purification, problems with corrosion may occur.

Base of a cooling tower with falling water

Wet cooling tower material balance

Quantitatively, the material balance around a wet, evaporative cooling tower system is governed by the operational variables of makeup flow rate, evaporation and windage losses, draw-off rate, and the concentration cycles:



M = Make-up water in m^3/h
C = Circulating water in m^3/h
D = Draw-off water in m^3/h
E = Evaporated water in m^3/h
W = Windage loss of water in m^3/h
X = Concentration in ppmw (of any completely soluble salts … usually chlorides)
$\mathbf{X_M}$ = Concentration of chlorides in make-up water (M), in ppmw
$\mathbf{X_C}$ = Concentration of chlorides in circulating water (C), in ppmw
Cycles = Cycles of concentration = X_C / X_M (dimensionless)
ppmw = parts per million by weight

In the above sketch, water pumped from the tower basin is the cooling water routed through the process coolers and condensers in an industrial facility. The cool water absorbs heat from the hot process streams which need to be cooled or condensed, and the absorbed heat warms the circulating water (C). The warm water returns to the top of the cooling tower and trickles downward over the fill material inside the tower. As it trickles down, it contacts ambient air rising up through the tower either by natural draft or by forced draft using large fans in the tower. That contact causes a small amount of the water to be lost as windage (W) and some of the water (E) to evaporate. The heat required to evaporate the water is derived from the water itself, which cools the water back to the original basin water temperature and the water is then ready to recirculate. The evaporated water leaves its dissolved salts behind in the bulk of the water which has not been evaporated, thus raising the salt concentration in the circulating cooling water. To prevent the salt concentration of the water from becoming too high, a portion of the water is drawn off (D) for disposal. Fresh water makeup (M) is supplied to the tower basin to compensate for the loss of evaporated water, the windage loss water and the draw-off water.

A water balance around the entire system is:

$$M = E + D + W$$

Since the evaporated water (E) has no salts, a chloride balance around the system is:

$$M (X_M) = D (X_C) + W (X_C) = X_C (D + W)$$

and, therefore:

$$\mathbf{X_C / X_M = \text{Cycles of concentration} = M \div (D + W) = M \div (M - E) = 1 + [E \div (D + W)]}$$

From a simplified heat balance around the cooling tower:

$$\mathbf{E = C \cdot \Delta T \cdot c_p \div H_V}$$

where:

$\mathbf{H_V}$ = latent heat of vaporization of water = ca. 2260 kJ / kg

$\mathbf{\Delta T}$ = water temperature difference from tower top to tower bottom, in °C

$\mathbf{c_p}$ = specific heat of water = ca. 4.184 kJ / (kg.°C)

Windage (or drift) losses (W) from large-scale industrial cooling towers, in the absence of manufacturer's data, may be assumed to be:

W = 0.3 to 1.0 percent of C for a natural draft cooling tower without windage drift eliminators
W = 0.1 to 0.3 percent of C for an induced draft cooling tower without windage drift eliminators
W = about 0.005 percent of C (or less) if the cooling tower has windage drift eliminators

Cycles of concentration represents the accumulation of dissolved minerals in the recirculating cooling water. Draw-off (or blowdown) is used principally to control the buildup of these minerals.

The chemistry of the makeup water including the amount of dissolved minerals can vary widely. Makeup waters low in dissolved minerals such as those from surface water supplies (lakes, rivers etc.) tend to be aggressive to metals (corrosive). Makeup waters from ground water supplies (wells) are usually higher in minerals and tend to be scaling (deposit minerals). Increasing the amount of minerals present in the water by cycling can make water less aggressive to piping however excessive levels of minerals can cause scaling problems.

As the cycles of concentration increase the water may not be able to hold the minerals in solution. When the solubility of these minerals have been exceeded they can precipitate out as mineral solids and cause fouling and heat exchange problems in the cooling tower or the heat exchangers. The temperatures of the recirculating water, piping and heat exchange surfaces determine if and where minerals will precipitate from the recirculating water. Often a professional water treatment consultant will evaluate the makeup water and the operating conditions of the cooling tower and recommend an appropriate range for the cycles of concentration. The use of water treatment chemicals, pretreatment such as water softening, pH adjustment, and other techniques can affect the acceptable range of cycles of concentration.

Concentration cycles in the majority of cooling towers usually range from 3 to 7. In the United States the majority of water supplies are well waters and have significant levels of dissolved solids. On the other hand one of the largest water supplies, New York City, has a surface supply quite low in minerals and cooling towers in that city are often allowed to concentrate to 7 or more cycles of concentration.

Besides treating the circulating cooling water in large industrial cooling tower systems to minimize scaling and fouling, the water should be filtered and also be dosed with biocides and algaecides to prevent growths that could interfere with the continuous flow of the water. For closed loop evaporative towers, corrosion inhibitors may be used, but caution should be taken to meet local environmental regulations as some inhibitors use chromates.

Ambient conditions dictate the efficiency of any given tower due to the amount of water vapor the air is able to absorb and hold, as can be determined on a psychrometric chart.

Cooling towers and Legionnaires' disease

Cooling tower and water discharge of a nuclear power plant

Another very important reason for using biocides in cooling towers is to prevent the growth of ***Legionella***, including species that cause legionellosis or ***Legionnaires' disease***, most notably *L. pneumophila*. The various *Legionella* species are the cause of *Legionnaires' disease* in humans and transmission is via exposure to aerosols—the inhalation of mist droplets containing the bacteria. Common sources of *Legionella* include cooling towers used in open recirculating evaporative cooling water systems, domestic hot water systems, fountains, and similar disseminators that tap into a public water supply. Natural sources include freshwater ponds and creeks.

French researchers found that *Legionella* spread through the air up to 6 kilometres from a large contaminated cooling tower at a petrochemical plant in Pas-de-Calais, France. That outbreak killed 21 of the 86 people that had a laboratory-confirmed infection.

Drift (or windage) is the term for water droplets of the process flow allowed to escape in the cooling tower discharge. Drift eliminators are used in order to hold drift rates typically to 0.001%-0.005% of the circulating flow rate. A typical drift eliminator provides multiple directional changes of airflow while preventing the escape of water droplets. A well-designed and well-fitted drift eliminator can greatly reduce water loss and potential for Legionella or other chemical exposure.

Many governmental agencies, cooling tower manufacturers and industrial trade organizations have developed design and maintenance guidelines for preventing or controlling (by using Neosens FS sensor for example, the growth of *Legionella* in cooling towers. Below is a list of sources for such guidelines:

- Centers for Disease Control and PreventionPDF (1.35 MB) - Procedure for Cleaning Cooling Towers and Related Equipment (pages 239 and 240 of 249)
- Cooling Technology InstitutePDF (240 KB) - Best Practices for Control of Legionella, July, 2006
- Association of Water TechnologiesPDF (964 KB) - Legionella 2003
- California Energy CommissionPDF (194 KB) - Cooling Water Management Program Guidelines For Wet and Hybrid Cooling Towers at Power Plants
- SPX Cooling TechnologiesPDF (119 KB) - Cooling Towers Maintenance Procedures
- SPX Cooling TechnologiesPDF (789 KB) - ASHRAE Guideline 12-2000 - Minimizing the Risk of Legionellosis
- SPX Cooling TechnologiesPDF (83.1 KB) - Cooling Tower Inspection Tips {especially page 3 of 7}
- PERFECT Cooling Towers|109 KB}} - Legionella Control
- Tower Tech Modular Cooling TowersPDF (109 KB) - Legionella Control
- GE Infrastructure Water & Process Technologies Betz DearbornPDF (195 KB) - Chemical Water Treatment Recommendations For Reduction of Risks Associated with Legionella in Open Recirculating Cooling Water Systems

Cooling tower fog

Under certain ambient conditions, plumes of water vapor (fog) can be seen rising out of the discharge from a cooling tower (see Image 1), and can be mistaken as smoke from a fire. If the outdoor air is at or near saturation, and the tower adds more water to the air, saturated air with liquid water droplets can be discharged—what is seen as fog. This phenomenon typically occurs on cool, humid days, but is rare in many climates.

Cooling tower operation in freezing weather

Cooling towers with malfunctions can freeze during very cold weather. Typically, freezing starts at the corners of a cooling tower with a reduced or absent heat load. Increased freezing conditions can create growing volumes of ice, resulting in increased structural loads. During the winter, some sites continuously operate cooling towers with 40 °F (4 °C) water leaving the tower. Basin heaters, tower draindown, and other freeze protection methods are often employed in cold climates.

- Do not operate the tower unattended.
- Do not operate the tower without a heat load. This can include basin heaters and heat trace. Basin heaters maintain the temperature of the water in the tower pan at an acceptable level. Heat trace is a resistive element that runs along water pipes located in cold climates to prevent freezing.
- Maintain design water flow rate over the fill.
- Manipulate airflow to maintain water temperature above freezing point.

Some commonly used terms in the cooling tower industry

- **Drift -** Water droplets that are carried out of the cooling tower with the exhaust air. Drift droplets have the same concentration of impurities as the water entering the tower. The drift rate is typically reduced by employing baffle-like devices, called drift eliminators, through which the air must travel after leaving the fill and spray zones of the tower. Drift can also be reduced by using warmer entering cooling tower temperatures.
- **Blow-out -** Water droplets blown out of the cooling tower by wind, generally at the air inlet openings. Water may also be lost, in the absence of wind, through splashing or misting. Devices such as wind screens, louvers, splash deflectors and water diverters are used to limit these losses.
- **Plume -** The stream of saturated exhaust air leaving the cooling tower. The plume is visible when water vapor it contains condenses in contact with cooler ambient air, like the saturated air in one's breath fogs on a cold day. Under certain conditions, a cooling tower plume may present fogging or icing hazards to its surroundings. Note that the water evaporated in the cooling process is "pure" water, in contrast to the very small percentage of drift droplets or water blown out of the air inlets.
- **Blow-down -** The portion of the circulating water flow that is removed in order to maintain the amount of dissolved solids and other impurities at an acceptable level. It may be noted that higher TDS (total dissolved solids) concentration in solution results in greater potential cooling tower efficiency. However the higher

the TDS concentration, the greater the risk of scale, biological growth and corrosion.

- **Leaching -** The loss of wood preservative chemicals by the washing action of the water flowing through a wood structure cooling tower.

- **Noise -** Sound energy emitted by a cooling tower and heard (recorded) at a given distance and direction. The sound is generated by the impact of falling water, by the movement of air by fans, the fan blades moving in the structure, and the motors, gearboxes or drive belts.

- **Approach -** The approach is the difference in temperature between the cooled-water temperature and the entering-air wet bulb temperature (twb). Since the cooling towers are based on the principles of evaporative cooling, the maximum cooling tower efficiency depends on the wet bulb temperature of the air. The wet-bulb temperature is a type of temperature measurement that reflects the physical properties of a system with a mixture of a gas and a vapor, usually air and water vapor

- **Range -** The range is the temperature difference between the water inlet and water exit.

- **Fill -** Inside the tower, fills are added to increase contact surface as well as contact time between air and water. Thus they provide better heat transfer. The efficiency of the tower also depends on them. There are two types of fills that may be used:
    - **Film type fill** (causes water to spread into a thin film)
    - **Splash type fill** (breaks up water and interrupts its vertical progress)

- **Full-Flow Filtration-** Full-flow filtration continuously strains the entire system flow. For example, in a 100-ton system, the flow rate would be roughly 300 gal/min. A filter would be selected to accommodate the entire 300 gal/min flow rate. In this case, the filter typically is installed after the cooling tower on the discharge side of the pump. While this is the preferred method of filtration, for higher flow systems, it may be cost prohibitive.

- **Side-Stream Filtration-** Side-stream filtration, although popular, does not provide complete protection, but it can be effective. With side-stream filtration, a portion of the water is filtered continuously. This method works on the principle that continuous particle removal will keep the system clean. Manufacturers typically package side-stream filters on a skid, complete with a pump and controls. For high flow systems, this method is cost-effective.

Properly sizing a side-stream filtration system is critical to obtain satisfactory filter performance. There is some debate over how to properly size the side-stream system. Many engineers size the system to continuously filter the cooling tower basin water at a rate equivalent to 10% of the total circulation flow rate. For example, if the total flow of a system is 1,200 gal/min (a 400-ton system), a 120 gal/min side-stream system is specified.

Fire hazards

Cooling towers which are constructed in whole or in part of combustible materials can support propagating internal fires. The resulting damage can be sufficiently severe to require the replacement of the entire cell or tower structure. For this reason, some codes and standards recommend combustible cooling towers be provided with an automatic fire sprinkler system. Fires can propagate internally within the tower structure during maintenance when the cell is not in operation (such as for maintenance or construction), and even when the tower is in operation, especially those of the induced-draft type because of the existence of relatively dry areas within the towers.

Stability

Ferrybridge power station

Two hyperboloid cooling towers on Kharkov Power Station #5

Being very large structures, they are susceptible to wind damage, and several spectacular failures have occurred in the past. At Ferrybridge power station on 1 November 1965, the station was the site of a major structural failure, when three of the cooling towers collapsed due to vibrations in 85 mph (137 km/h) winds. Although the structures had been built to withstand higher wind speeds, the shape of the cooling towers meant that westerly winds were funnelled into the towers themselves, creating a vortex. Three out of the original eight cooling towers were destroyed and the remaining five were severely damaged. The towers were rebuilt and all eight cooling towers were strengthened to tolerate adverse weather conditions. Building codes were changed to include improved structural support, and wind tunnel tests introduced to check tower structures and configuration.

Chapter 4

Doppler Cooling

Doppler cooling is a mechanism that can be used to trap and cool atoms. The term is sometimes used synonymously with laser cooling, though laser cooling includes other techniques.

History

Doppler cooling was simultaneously proposed by two groups in 1975, the first being David J. Wineland and Hans Georg Dehmelt and the second being Theodor W. Hänsch and Arthur Leonard Schawlow. It was first demonstrated by Wineland, Drullinger, and Walls in 1978 and shortly afterwards by Neuhauser, Hohenstatt, Toschek and Dehmelt. One conceptually simple form of Doppler cooling is referred to as optical molasses, since the dissipative optical force resembles the viscous drag on a body moving through molasses. Steven Chu, Claude Cohen-Tannoudji and William D. Phillips were awarded the 1997 Nobel Prize in Physics for their work in laser cooling and atom trapping.

Brief Explanation

Doppler cooling involves light whose frequency is tuned slightly below an electronic transition in an atom. Because the light is detuned to the "red" (i.e. at lower frequency) of the transition, the atoms will absorb more photons if they move towards the light source, due to the Doppler effect. Thus if one applies light from two opposite directions, the atoms will always absorb more photons from the laser beam pointing opposite to their direction of motion. In each absorption event, the atom loses a momentum equal to the momentum of the photon. If the atom, which is now in the excited state, emits a photon spontaneously, it will be kicked by the same amount of momentum but in a random direction. The result of the absorption and emission process is a reduced speed of the atom, provided its initial speed is larger than the recoil velocity from scattering a single photon. If the absorption and emission are repeated many times, the mean velocity, and therefore the kinetic energy of the atom will be reduced. Since the temperature of an ensemble of atoms is a measure of the random internal kinetic energy, this is equivalent to cooling the atoms.

The Doppler cooling limit is the minimum temperature achievable with Doppler cooling.

Detailed Explanation

The vast majority of photons that come anywhere near a particular atom are almost completely unaffected by that atom. The atom is almost completely transparent to most frequencies (colors) of photons.

A few photons happen to "resonate" with the atom, in a few very narrow bands of frequencies (a single color rather than a mixture like white light). When one of those photons comes close to the atom, the atom typically absorbs that photon (absorption spectrum) for a brief period of time, then emits an identical photon (emission spectrum) in some random, unpredictable direction.

The popular idea that lasers increase the thermal energy of matter is not the case when examining individual atoms. If a given atom is practically motionless (a "cold" atom), and the frequency of a laser focused upon it can be controlled, most frequencies do not affect the atom — it is invisible at those frequencies. There are only a few points of electromagnetic frequency that have any effect on that atom. At those frequencies, the atom can absorb a photon from the laser, while transitioning to an excited electronic state, and pick up the momentum of that photon. Since the atom now has the photon's momentum, the atom must begin to drift in the direction the photon was traveling. A short time later, the atom will spontaneously emit a photon in a random direction, as it relaxes to a lower electronic state. If that photon is emitted in the direction of the original photon, the atom will give up its momentum to the photon and will become motionless again. If the photon is emitted in the opposite direction, the atom will have to provide momentum in that opposite direction, which means the atom will pick up even more momentum in the direction of the original photon (to conserve momentum), with double its original velocity. But usually the photon speeds away in some *other* direction, giving the atom at least some sideways thrust.

Another way of changing frequencies is to change the positioning of the laser. For example, using a monochromatic (single-color) laser that has a frequency that is a little below one of the "resonant" frequencies of this atom (at which frequency the laser will not directly affect the atom's state). If the laser were to be positioned so that it was moving *towards* the observed atoms, then the doppler effect would raise its frequency. At one specific velocity, the frequency would be precisely correct for said atoms to begin absorbing photons.

Something very similar happens in a laser cooling apparatus, except such devices start with a warm cloud of atoms moving in numerous directions at variable velocity. Starting with a laser frequency well below the resonant frequency, photons from any one laser pass right through the majority of atoms. However, atoms moving rapidly *towards* a particular laser catch the photons for that laser, slowing those atoms down until they become transparent again. (Atoms rapidly moving *away* from that laser are transparent to that laser's photons — but they are rapidly moving *towards* the laser directly opposite it). This utilization of a specific velocity to induce absorption is also seen in Mossbauer spectroscopy.

On a graph of atom velocities (atoms moving rapidly to the right correspond with stationary dots far to the right, atoms moving rapidly to the left correspond with stationary dots far to the left), there is a narrow band on the left edge corresponding to the speed those atoms start absorbing photons from the left laser. Atoms in that band are the only ones that interact with the left laser. When a photon from the left laser slams into one of those atoms, it suddenly slows down an amount corresponding to the momentum of that photon (the dot would be redrawn some fixed "quantum" distance further to the right). If the atom releases the photon directly to the right, then the dot is redrawn that same distance to the left, putting it back in the narrow band of interaction. But usually the atom releases the photon in some other random direction, and the dot is redrawn that quantum distance in the opposite direction.

Such an apparatus would be constructed with many lasers, corresponding to many boundary lines that completely surround that cloud of dots.

As the laser frequency is increased, the boundary contracts, pushing all the dots on that graph towards zero velocity, the given definition of "cold".

Limitations

Minimum temperature

The atom performs a random walk in momentum space with steps equal to the photon momentum due to spontaneous emission and photon absorption. This constitutes a heating effect, which counteracts the cooling process and imposes a limit on the amount by which the atom can be cooled. Moreover, the optical transition used for cooling in reality must have a finite frequency width, which limits the velocity discrimination (i.e. the likelihood that an atom will scatter light from the "correct" beam, as described above), and therefore the temperature. This temperature is called the Doppler temperature. Lower temperatures, down to the recoil temperature, may be obtained by sub-Doppler cooling such as Raman Cooling. Beyond that, evaporative cooling is used to further cool the ultracold atoms.

Maximum concentration

The concentration must be minimal to prevent the absorption of the photons into the gas in the form of heat. This absorption happens when two atoms collide with each other while one of them has an excited electron. There is then a possibility of the excited electron dropping back to the ground state with its extra energy liberated in additional kinetic energy to the colliding atoms — which heats the atoms. This works against the cooling process and therefore limits the maximum concentration of gas that can be cooled using this method.

Atomic Structure

Only certain atoms and ions have optical transitions amenable to laser cooling, since it is extremely difficult to generate the amounts of laser power needed at wavelengths much shorter than 300 nm. Furthermore, the more hyperfine structure an atom has, the more ways there are for it to emit a photon from the upper state and *not* return to its original state, putting it in a dark state and removing it from the cooling process. It is possible to use other lasers to optically pump those atoms back into the excited state and try again, but the more complex the hyperfine structure is, the more (narrow-band, frequency locked) lasers are required. Since frequency-locked lasers are both complex and expensive, atoms which need more than one extra *repump* laser are rarely cooled; the common rubidium Magneto-optical trap, for example, requires one repump laser. This is also the reason why, to date, molecules have not been laser cooled: in addition to hyperfine structure, molecules also have rovibronic couplings and so can also decay into excited rotational or vibrational states.

Configurations

Counter-propagating sets of laser beams in all three Cartesian dimensions may be used to cool the three motional degrees of freedom of the atom. Common laser-cooling configurations include optical molasses, the magneto-optical trap, and the Zeeman slower.

Atomic ions, trapped in an ion trap, can be cooled with a single laser beam as long as that beam has a component along all three motional degrees of freedom. This is in contrast to the six beams required to trap neutral atoms. The original laser cooling experiments were performed on ions in ion traps. (In theory, neutral atoms could be cooled with a single beam if they could be trapped in a deep trap, but in practice neutral traps are much shallower than ion traps and a single recoil event can be enough to kick a neutral atom out of the trap.)

Applications

The one use for Doppler cooling is the optical molasses technique. This process itself forms a part of the magneto-optical trap but it can be used independently.

Doppler cooling is also used in spectroscopy and metrology, where cooling allows narrower spectroscopic features. For example, all of the best atomic clock technologies involve Doppler cooling at some point.

Chapter 5

Heat Pump

Outdoor components of a residential air-source heat pump

A **heat pump** is a machine or device that moves heat from one location (the 'source') at a lower temperature to another location (the 'sink' or 'heat sink') at a higher temperature using mechanical work or a high-temperature heat source. A heat pump can be used to provide heating or cooling. Even though the heat pump can heat, it still uses the same basic refrigeration cycle to do this. In other words a heat pump can change which coil is the condenser and which the evaporator. This is normally achieved by a reversing valve.

In cooler climates it is common to have heat pumps that are designed only to provide heating.

Common examples are food refrigerators and freezers, air conditioners, and reversible-cycle heat pumps for providing building space heating. In heating, ventilation, and air conditioning (HVAC) applications, a heat pump normally refers to a vapor-compression refrigeration device that includes a reversing valve and optimized heat exchangers so that the direction of heat flow may be reversed. Most commonly, heat pumps draw heat from the air or from the ground.

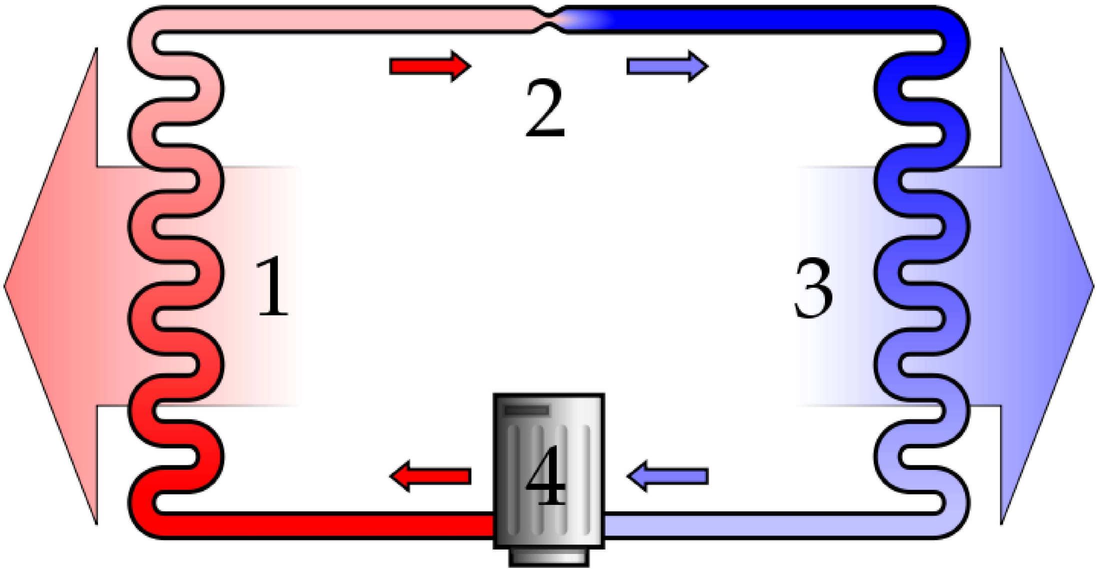
Overview

Heat pumps have the ability to move heat energy from one environment to another, and in either direction. This allows the heat pump to both bring heat into an occupied space, and take it out. In the cooling mode a heat pump works the same as an ordinary air conditioner (A/C). A heat pump uses an intermediate fluid called a refrigerant which absorbs heat as it vaporizes and releases the heat when it condenses. It uses an evaporator to absorb heat from inside an occupied space and rejects this heat to the outside through the condenser. The refrigerant flows outside of the space to be conditioned, where the condenser and compressor are located, while the evaporator is inside. The key component that makes a heat pump different from an A/C is the reversing valve. The reversing valve allows for the flow direction of the refrigerant to be changed. This allows the heat to be pumped in either direction.

- In **heating mode** the outdoor coil becomes the evaporator, while the indoor becomes the condenser which absorbs the heat from the refrigerant and dissipates to the air flowing through it. The air outside even at 0 °C has heat energy in it. With the refrigerant flowing in the opposite direction the evaporator (outdoor coil) is absorbing the heat from the air and moving it inside. Once it picks up heat it is compressed and then sent to the condenser (indoor coil). The indoor coil then rejects the heat into the air handler, which moves the heated air through out the house.
- In **cooling mode** the outdoor coil is now the condenser. This makes the indoor coil now the evaporator. The indoor coil is now the evaporator in the sense that it is going to be used to absorb the heat from inside the enclosed space. The evaporator absorbs the heat from the inside, and takes it to the condenser where it is rejected into the outside air.

Operating principles

Since the heat pump or refrigerator uses a certain amount of work to move the refrigerant, the amount of energy deposited on the hot side is greater than taken from the cold side. One common type of heat pump works by exploiting the physical properties of an evaporating and condensing fluid known as a refrigerant.



A simple stylized diagram of a heat pump's vapor-compression refrigeration cycle: 1) condenser, 2) expansion valve, 3) evaporator, 4) compressor.

The working fluid, in its gaseous state, is pressurized and circulated through the system by a compressor. On the discharge side of the compressor, the now hot and highly pressurized vapor is cooled in a heat exchanger, called a condenser, until it condenses into a high pressure, moderate temperature liquid. The condensed refrigerant then passes through a pressure-lowering device also called a metering device like an expansion valve, capillary tube, or possibly a work-extracting device such as a turbine. The low pressure, liquid refrigerant leaving the expansion device enters another heat exchanger, the evaporator, in which the fluid absorbs heat and boils. The refrigerant then returns to the compressor and the cycle is repeated.

In such a system it is essential that the refrigerant reach a sufficiently high temperature when compressed, since the second law of thermodynamics prevents heat from flowing from a cold fluid to a hot heat sink. Practically, this means the refrigerant must reach a temperature greater than the ambient around the high-temperature heat exchanger. Similarly, the fluid must reach a sufficiently low temperature when allowed to expand, or heat cannot flow from the cold region into the fluid, i.e. the fluid must be colder than the ambient around the cold-temperature heat exchanger. In particular, the pressure difference must be great enough for the fluid to condense at the hot side and still evaporate in the lower pressure region at the cold side. The greater the temperature difference, the greater the required pressure difference, and consequently the more energy needed to compress the fluid. Thus as with all heat pumps, the Coefficient of Performance (amount of heat moved per unit of input work required) decreases with increasing temperature difference.

Insulation is used to reduce the work and energy required to achieve and maintain a lower temperature in the cooled space.

Due to the variations required in temperatures and pressures, many different refrigerants are available. Refrigerators, air conditioners, and some heating systems are common applications that use this technology.

Heat sources

Many heat pumps also use an auxiliary heat source for heating mode. This means that, even though the heat pump is the primary source of heat, another form is available as a back-up. Electricity, oil, or gas are the most common sources. This is put in place so that if the heat pump fails or can't provide enough heat, the auxiliary heat will kick on to make up the difference.

Geothermal heat pumps use the ground as a heat source and sink and water as the heat transport medium. They work in the same manner as an air to air heat pump, but instead of indoor and outdoor coils they use water pumped through earth materials as a heat transfer medium. These are very eco-friendly and are a cheaper alternative in the long run due to lower operating cost. Operating costs can be further reduced by storing summer heat in the ground for use during winter, and (for larger buildings requiring lots of air conditioning) by storing winter cold underground for use during summer.

Applications

In HVAC applications, a heat pump is typically a vapor-compression refrigeration device that includes a reversing valve and optimized heat exchangers so that the direction of heat flow may be reversed. The reversing valve switches the direction of refrigerant through the cycle and therefore the heat pump may deliver either heating or cooling to a building. In the cooler climates the default setting of the reversing valve is heating. The default setting in warmer climates is cooling. Because the two heat exchangers, the condenser and evaporator, must swap functions, they are optimized to perform adequately in both modes. As such, the efficiency of a reversible heat pump is typically slightly less than two separately optimized machines.

In plumbing applications, a heat pump is sometimes used to heat or preheat water for swimming pools or domestic water heaters.

In somewhat rare applications, both the heat extraction and addition capabilities of a single heat pump can be useful, and typically results in very effective use of the input energy. For example, when an air cooling need can be matched to a water heating load, a single heat pump can serve two useful purposes. That is, a heat pump domestic water heater located in the living area of a home could cool the home, reducing or eliminating the need for additional air conditioning. This installation would be best-suited to a climate that is warm or hot most of the year. Unfortunately, these situations are rare because the demand profiles for heating and cooling are often significantly different.

Future developments

In the near future, heat pumps for larger buildings will increasingly run on oil or natural gas, being integrated into generator units which also provide electricity for the same building. These systems are more efficient than current electrical ground source heat pumps already are. In a next development they will be scaled down to single home size engines, producing both electricity and geothermal heat. In such systems, excess heat production during summer will be stored in the ground source for winter heating. Such a system will be much more energy efficient than any currently existing system, both in producing heat and electricity. If such individual systems are interlinked in small neighbor groups of, say, five or ten houses, they will also become as reliable as the national power grid, and this linking allows further gains in energy efficiency. Once these developments are rolled out nationally, they will enormously reduce the need for central electricity production, and they have the potential to reduce total carbon emissions for building services by up to 50 percent.

Refrigerants

Until the 1990s, the refrigerants were often chlorofluorocarbons such as R-12 (dichlorodifluoromethane), one in a class of several refrigerants using the brand name Freon, a trademark of DuPont. Its manufacture was discontinued in 1995 because of the damage that CFCs were alleged to cause to the ozone layer if released into the atmosphere. One widely adopted replacement refrigerant is the hydrofluorocarbon (HFC) known as R-134a (1,1,1,2-tetrafluoroethane). R-134a is not as efficient as the R-12 it replaced (in automotive applications) and therefore, more energy is required to operate systems utilizing R-134a than those using R-12. Other substances such as liquid R-717 ammonia are widely used in large-scale systems, or occasionally the less corrosive but more flammable propane or butane, can also be used.

Since 2001, carbon dioxide, R-744, has increasingly been used, utilizing the transcritical cycle. In residential and commercial applications, the hydrochlorofluorocarbon (HCFC) R-22 is still widely used, however, HFC R-410A does not deplete the ozone layer and is being used more frequently. Hydrogen, helium, nitrogen, or plain air is used in the Stirling cycle, providing the maximum number of options in environmentally friendly gases.

More recent refrigerators are now exploiting the R600A which is isobutane, and does not deplete the ozone and is friendly to the environment.

Dimethyl ether (DME) is also gaining popularity as a refrigerant.

Efficiency

When comparing the performance of heat pumps, it is best to avoid the word "efficiency" which has a very specific thermodynamic definition. The term coefficient of performance (COP) is used to describe the ratio of useful heat movement to work input. Most vapor-compression heat pumps utilize electrically powered motors for their work input. However, in most vehicle applications, shaft work, via their internal combustion engines, provide the needed work.

When used for heating a building on a mild day of say 10 °C, a typical air-source heat pump has a COP of 3 to 4, whereas a typical electric resistance heater has a COP of 1.0. That is, one joule of electrical energy will cause a resistance heater to produce one joule of useful heat, while under ideal conditions, one joule of electrical energy can cause a heat pump to move much more than one joule of heat from a cooler place to a warmer place.

Note that the heat pump is more efficient on average in hotter climates than cooler ones, so when the weather is much warmer (in a desert city or southern city) the unit will perform better than average COP. Conversely in cold weather the COP approaches 1. Thus when there is a wide temperature differential on a hot day the COP is higher than average (better).

When there is a high temperature differential on a cold day, e.g., when an air-source heat pump is used to heat a house on a very cold winter day of say 0 °C, it takes more work to move the same amount of heat indoors than on a mild day. Ultimately, due to Carnot efficiency limits, the heat pump's performance will approach 1.0 as the outdoor-to-indoor temperature difference increases for colder climates (temperature gets colder). This typically occurs around −18 °C (0 °F) outdoor temperature for air source heat pumps. Also, as the heat pump takes heat out of the air, some moisture in the outdoor air may condense and possibly freeze on the outdoor heat exchanger. The system must periodically melt this ice. In other words, when it is extremely cold outside, it is simpler, and wears the machine less, to heat using an electric-resistance heater than to strain an air-source heat pump.

Geothermal heat pumps, on the other hand, are dependent upon the temperature underground, which is "mild" (typically 10 °C at a depth of more than 1.5m for the UK) all year round. Their COP is therefore normally in the range of 4.0 to 5.0.

The design of the evaporator and condenser heat exchangers is also very important to the overall efficiency of the heat pump. The heat exchange surface areas and the corresponding temperature differential (between the refrigerant and the air stream) directly affect the operating pressures and hence the work the compressor has to do in order to provide the same heating or cooling effect. Generally the larger the heat exchanger the lower the temperature differential and the more efficient the system. Since heat exchangers are expensive, and the heat pump industry generally competes on price rather than efficiency, the drive towards more efficient heat pumps and air conditioners is often led by legislative measures on minimum efficiency standards.

In cooling mode a heat pump's operating performance is described as its energy efficiency ratio (EER) or seasonal energy efficiency ratio (SEER), and both measures have units of BTU/(h·W) (1 BTU/(h·W) = 0.293 W/W). A larger EER number indicates better performance. The manufacturer's literature should provide both a COP to describe performance in heating mode and an EER or SEER to describe performance in cooling mode. Actual performance varies, however, and depends on many factors such as installation, temperature differences, site elevation, and maintenance.

Heat pumps are more *effective* for heating than for cooling if the temperature difference is held equal. This is because the compressor's input energy is largely converted to useful heat when in heating mode, and is discharged along with the moved heat via the condenser. But for cooling, the condenser is normally outdoors, and the compressor's dissipated work is rejected rather than put to a useful purpose.

For the same reason, opening a food refrigerator or freezer heats up the room rather than cooling it because its refrigeration cycle rejects heat to the indoor air. This heat includes the compressor's dissipated work as well as the heat removed from the inside of the appliance.

The COP for a heat pump in a heating or cooling application, with steady-state operation, is:

$$COP_{\text{heating}} = \frac{\Delta Q_{\text{hot}}}{\Delta A} \leq \frac{T_{\text{hot}}}{T_{\text{hot}} - T_{\text{cool}}}$$
$$COP_{\text{cooling}} = \frac{\Delta Q_{\text{cool}}}{\Delta A} \leq \frac{T_{\text{cool}}}{T_{\text{hot}} - T_{\text{cool}}}$$

where

- ΔQ_{cool} is the amount of heat extracted from a cold reservoir at temperature T_{cool},
- ΔQ_{hot} is the amount of heat delivered to a hot reservoir at temperature T_{hot},
- ΔA is the compressor's dissipated work.
- All temperatures are absolute temperatures usually measured in kelvins (K).

COP and lift

The COP increases as the temperature difference, or "lift", decreases between heat source and destination. The COP can be maximised at design time by choosing a heating system requiring only a low final water temperature (e.g. underfloor heating), and by choosing a heat source with a high average temperature (e.g. the ground). Domestic hot water (DHW) and radiators require high water temperatures, affecting the choice of heat pump technology.

Pump type and source	Typical use case	COP variation with Output Temperature 35 °C (e.g. heated screed floor)	45 °C (e.g. heated screed floor)	55 °C (e.g. heated timber floor)	65 °C (e.g. radiator or DHW)	75 °C (e.g. radiator & DHW)	85 °C (e.g. radiator & DHW)
High efficiency air source heat pump (ASHP). Air at −20 °C		2.2	2.0	-	-	-	-
Two-stage ASHP air at −20 °C	Low source temp.	*2.4*	2.2	1.9	-	-	-
High efficiency ASHP air at 0 °C	Low output temp.	*3.8*	2.8	2.2	2.0	-	-
Prototype transcritical CO_2 (R744) heat pump with tripartite gas cooler, source at 0 °C	High output temp.	3.3	-	-	*4.2*	-	3.0
Ground source heat pump (GSHP). Water at 0 °C		5.0	3.7	2.9	2.4	-	-
GSHP ground at 10 °C	Low output temp.	*7.2*	5.0	3.7	2.9	2.4	-
Theoretical Carnot cycle limit, source −20 °C		5.6	4.9	4.4	4.0	3.7	3.4
Theoretical Carnot cycle limit, source 0 °C		8.8	7.1	6.0	5.2	4.6	4.2

Theoretical Lorentz cycle limit (CO_2 pump), return fluid 25 °C, source 0 °C	10.1	8.8	7.9	7.1	6.5	6.1
Theoretical Carnot cycle limit, source 10 °C	12.3	9.1	7.3	6.1	5.4	4.8

Types

The two main types of heat pumps are compression heat pumps and absorption heat pumps. Compression heat pumps always operate on mechanical energy (through electricity), while absorption heat pumps may also run on heat as an energy source (through electricity or burnable fuels). An absorption heat pump may be fueled by natural gas or LP gas, for example. While the Gas Utilization Efficiency in such a device, which is the ratio of the energy supplied to the energy consumed, may average only 1.5, that is better than a natural gas or LP gas furnace, which can only approach 1. Although an absorption heat pump may not be as efficient as an electric compression heat pump, an absorption heat pump fueled by natural gas may be advantageous in locations where electricity is relatively expensive and natural gas is relatively inexpensive. A natural gas-fired absorption heat pump might also avoid the cost of an electrical service upgrade which is sometimes necessary for an electric heat pump installation. In the case of air-to-air heat pumps, an absorption heat pump might also have an advantage in colder regions, due to a lower minimum operating temperature.ROBUR heat pumps comparison

A number of sources have been used for the heat source for heating private and communal buildings.

- air source heat pump (extracts heat from outside air)
    - air–air heat pump (transfers heat to inside air)
    - air–water heat pump (transfers heat to a tank of water)
- exhaust air heat pump (extracts heat from the exhaust air of a building, requires mechanical ventilation)
    - exhaust air - water heat pump (transfers heat to a tank of water)
- geothermal heat pump (extracts heat from the ground or similar sources)
    - geothermal–air heat pump (transfers heat to inside air)
        - ground–air heat pump (ground as a source of heat)
        - rock–air heat pump (rock as a source of heat)
        - water–air heat pump (body of water as a source of heat)
    - geothermal–water heat pump (transfers heat to a tank of water)
        - ground–water heat pump (ground as a source of heat)
        - rock–water heat pump (rock as a source of heat)
        - water–water heat pump (body of water as a source of heat)

Heat sources

Most commonly, heat pumps draw heat from the air (outside or inside air) or from the ground (groundwater or soil). The heat drawn from the ground is in most cases stored solar heat, and it should not be confused with geothermal heat, though the latter will contribute in some small measure to all heat in the ground. Other heat sources include water; nearby streams and other natural water bodies have been used, and sometimes domestic waste water which is often warmer than the ambient temperature.

Air-source heat pumps

Air source heat pumps are relatively easy (and inexpensive) to install and have therefore historically been the most widely used heat pump type. However, they suffer limitations due to their use of the outside air as a heat source or sink. The higher temperature differential during periods of extreme cold or heat leads to declining efficiency, as explained above. In mild weather, COP may be around 4.0, while at temperatures below around −8 °C (17 °F) an air-source heat pump can achieve a COP of 2.5 or better, which is considerably more than the energy efficiency that may be achieved by a 1980's heating systems, and very similar to state of the art oil or gas heaters. The average COP over seasonal variation is typically 2.5-2.8, with exceptional models able to exceed 6.0 in very mild climate, but not in freezing climates. (2.8 kW).

Air source heat pumps for cold climates

At least two manufacturers are selling heat pumps that maintain better heating output at lower outside temperatures than conventional air source heat pumps. These low temperature optimized models make air source heat pumps more practical for cold climates because they don't freeze to a stop that quickly. Some models however, defrost their outdoor unit electrically at regular intervals, which increases electricity consumption dramatically during coldest the weeks. In areas where only one fossil fuel is currently available (e.g. heating oil; no natural gas pipes available) these heat pumps could be used as an alternative, supplemental heat source to reduce a building's direct dependence on fossil fuel. Depending on fuel and electricity prices, using the heat pump for heating may be less expensive than fossil fuel. A backup, fossil-fuel heat source may still be required for the coldest days.

The heating output of low temperature optimized heat pumps (and hence their energy efficiency) still declines dramatically as the temperature drops, but the threshold at which the decline starts is lower than conventional pumps, as shown in the following table (temperatures are approximate and may vary by manufacturer and model):

Air Source Heat Pump Type	Full heat output at or above this temperature	Heat output down to 60% of maximum at
Conventional	47 °F (8.3 °C)	17 °F (-8.3 °C)
Low Temp Optimized	14 °F (-10 °C)	-13 °F (-25 °C)

Ground source heat pumps

Ground source heat pumps, which are also referred to as Geothermal heat pumps, typically have higher efficiencies than air-source heat pumps. This is because they draw heat from the ground or groundwater which is at a relatively constant temperature all year round below a depth of about thirty feet (9 m). This means that the temperature differential is lower, leading to higher efficiency. Ground-source heat pumps typically have COPs of 3.5-4.0 at the beginning of the heating season, with lower COPs as heat is drawn from the ground. The trade off for this improved performance is that a ground-source heat pump is more expensive to install due to the need for the digging of wells or trenches in which to place the pipes that carry the heat exchange fluid. When compared versus each other, groundwater heat pumps are generally more efficient than heat pumps using heat from the soil. Their efficiency can be further improved, by pumping summer heat into the ground. One way is to use ground water to cool the floors on hot days. Another way is to make large solar collectors, for instance by putting plastic pipes just under the roof tiles or in the tarmac of the parking lot. The most cost effective way is to put a large air to water heat exchanger on the rooftop.

Heat distribution

Heat pumps are only highly efficient when they distribute produced heat at a low temperature, ideally around or below 32 °C (90 °F). Normal steel plate radiators are no good: they would need to have four to six times their current size. Underfloor heating is the ideal solution. When wooden floors or carpets would spoil their efficiency, wall heaters (plastic pipes covered with a thick layer of chalk) and piped ceilings can be used. Both systems have the disadvantage that they are slow starters, and that they would require extensive renovation in existing buildings. The alternative is a warm air system in which water runs through a ventilator driven water to air heater. Such a thing can either complement floor heating during warm up, or it can be a quick and economical way to implement a heat pump system into existing buildings. Oversizing them reduces their noise. To efficiently distribute warm water or air from a heat pump, water pipes or air shafts should have significantly larger diameters then in conventional systems, and underfloor heaters should have much more pipes per square meter.

Solid state heat pumps

In 1881, the German physicist Emil Warburg put a block of iron into a strong magnetic field and found that it increased very slightly in temperature. Some commercial ventures to implement this technology are underway, claiming to cut energy consumption by 40% compared to current domestic refrigerators. The process works as follows: Powdered gadolinium is moved into a magnetic field, heating the material by 2 to 5 °C (4 to 9 °F). The heat is removed by a circulating fluid. The material is then moved out of the magnetic field, reducing its temperature below its starting temperature.

Solid state heat pumps using the Thermoelectric Effect have improved over time to the point where they are useful for certain refrigeration tasks. Commercially available technologies have efficiencies that are currently well below that of mechanical heat pumps, however this area of technology is currently the subject of active research in materials science.

Chapter 6

Refrigeration

Ice is used to refrigerate and preserve food such as this Northern kingfish

Refrigeration is a process in which work is done to remove heat from one location to another. Refrigeration has many applications including but not limited to; household refrigerators, industrial freezers, cryogenics, air conditioning, and heat pumps. In order to satisfy the Second Law of Thermodynamics, some form of work must be performed to accomplish this. The work is traditionally done by mechanical work but can also be done by magnetism, laser or other means.

Methods of refrigeration

Methods of refrigeration can be classified as *non-cyclic*, *cyclic* and *thermoelectric*.

Non-cyclic refrigeration

In non-cyclic refrigeration, cooling is accomplished by melting ice or by subliming dry ice (frozen carbon dioxide). These methods are used for small-scale refrigeration such as in laboratories and workshops, or in portable coolers.

Ice owes its effectiveness as a cooling agent to its constant melting point of 0 °C (32 °F). In order to melt, ice must absorb 333.55 kJ/kg (approx. 144 Btu/lb) of heat. Foodstuffs maintained at this temperature or slightly above have an increased storage life.

Solid carbon dioxide has no liquid phase at normal atmospheric pressure, so sublimes directly from the solid to vapor phase at a temperature of -78.5 °C (-109.3 °F), and is therefore effective for maintaining products at low temperatures during the period of sublimation. Systems such as this where the refrigerant evaporates and is vented into the atmosphere are known as "total loss refrigeration".

Cyclic refrigeration

This consists of a refrigeration cycle, where heat is removed from a low-temperature space or source and rejected to a high-temperature sink with the help of external work, and its inverse, the thermodynamic power cycle. In the power cycle, heat is supplied from a high-temperature source to the engine, part of the heat being used to produce work and the rest being rejected to a low-temperature sink. This satisfies the second law of thermodynamics.

A *refrigeration cycle* describes the changes that take place in the refrigerant as it alternately absorbs and rejects heat as it circulates through a refrigerator. It is also applied to HVACR work, when describing the "process" of refrigerant flow through an HVACR unit, whether it is a packaged or split system.

Heat naturally flows from hot to cold. Work is applied to cool a living space or storage volume by pumping heat from a lower temperature heat source into a higher temperature heat sink. Insulation is used to reduce the work and energy required to achieve and maintain a lower temperature in the cooled space. The operating principle of the refrigeration cycle was described mathematically by Sadi Carnot in 1824 as a heat engine.

The most common types of refrigeration systems use the reverse-Rankine vapor-compression refrigeration cycle although absorption heat pumps are used in a minority of applications.

Cyclic refrigeration can be classified as:

1. Vapor cycle, and
2. Gas cycle

Vapor cycle refrigeration can further be classified as:

1. Vapor-compression refrigeration
2. Vapor-absorption refrigeration

Vapor-compression cycle

The vapor-compression cycle is used in most household refrigerators as well as in many large commercial and industrial refrigeration systems. Figure 1 provides a schematic diagram of the components of a typical vapor-compression refrigeration system.

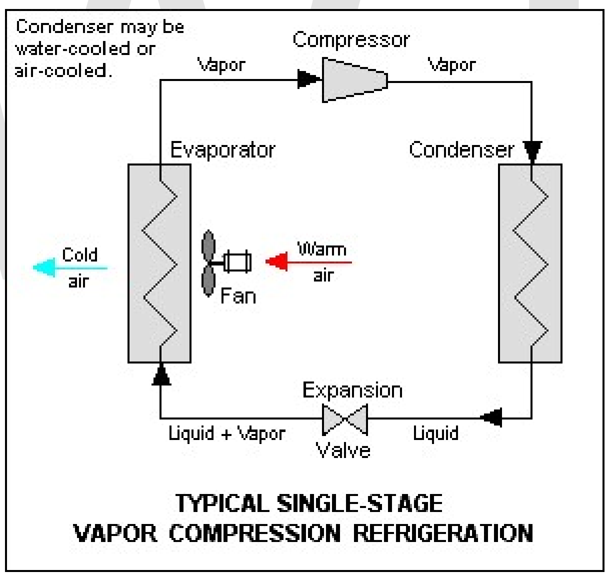


Figure 1: Vapor compression refrigeration

The thermodynamics of the cycle can be analyzed on a diagram as shown in Figure 2. In this cycle, a circulating refrigerant such as Freon enters the compressor as a vapor. From point 1 to point 2, the vapor is compressed at constant entropy and exits the compressor as a vapor at a higher temperature, but still below the vapor pressure at that temperature. From point 2 to point 3 and on to point 4, the vapor travels through the condenser which cools the vapor until it starts condensing, and then condenses the vapor into a liquid by removing additional heat at constant pressure and temperature. Between points 4 and 5, the liquid refrigerant goes through the expansion valve (also called a throttle valve) where its pressure abruptly decreases, causing flash evaporation and auto-refrigeration of, typically, less than half of the liquid.

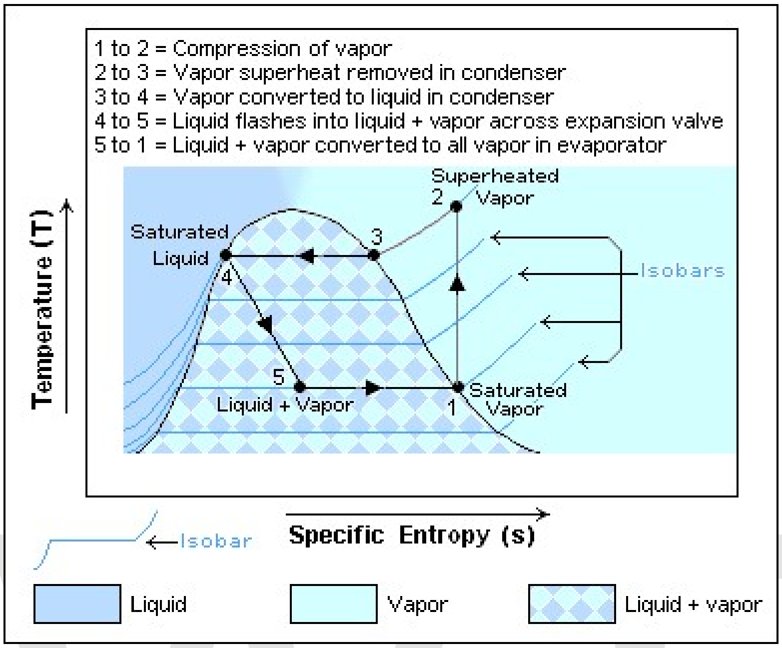


Figure 2: Temperature–Entropy diagram

That results in a mixture of liquid and vapor at a lower temperature and pressure as shown at point 5. The cold liquid-vapor mixture then travels through the evaporator coil or tubes and is completely vaporized by cooling the warm air (from the space being refrigerated) being blown by a fan across the evaporator coil or tubes. The resulting refrigerant vapor returns to the compressor inlet at point 1 to complete the thermodynamic cycle.

The above discussion is based on the ideal vapor-compression refrigeration cycle, and does not take into account real-world effects like frictional pressure drop in the system, slight thermodynamic irreversibility during the compression of the refrigerant vapor, or non-ideal gas behavior (if any).

More information about the design and performance of vapor-compression refrigeration systems is available in the classic *Perry's Chemical Engineers' Handbook*.

Vapor absorption cycle

In the early years of the twentieth century, the vapor absorption cycle using water-ammonia systems was popular and widely used. After the development of the vapor compression cycle, the vapor absorption cycle lost much of its importance because of its low coefficient of performance (about one fifth of that of the vapor compression cycle). Today, the vapor absorption cycle is used mainly where fuel for heating is available but electricity is not, such as in recreational vehicles that carry LP gas. It is also used in industrial environments where plentiful waste heat overcomes its inefficiency.

The absorption cycle is similar to the compression cycle, except for the method of raising the pressure of the refrigerant vapor. In the absorption system, the compressor is replaced by an absorber which dissolves the refrigerant in a suitable liquid, a liquid pump which raises the pressure and a generator which, on heat addition, drives off the refrigerant vapor from the high-pressure liquid. Some work is required by the liquid pump but, for a given quantity of refrigerant, it is much smaller than needed by the compressor in the vapor compression cycle. In an absorption refrigerator, a suitable combination of refrigerant and absorbent is used. The most common combinations are ammonia (refrigerant) and water (absorbent), and water (refrigerant) and lithium bromide[absorbent].

Gas cycle

When the working fluid is a gas that is compressed and expanded but doesn't change phase, the refrigeration cycle is called a *gas cycle*. Air is most often this working fluid. As there is no condensation and evaporation intended in a gas cycle, components corresponding to the condenser and evaporator in a vapor compression cycle are the hot and cold gas-to-gas heat exchangers in gas cycles.

The gas cycle is less efficient than the vapor compression cycle because the gas cycle works on the reverse Brayton cycle instead of the reverse Rankine cycle. As such the working fluid does not receive and reject heat at constant temperature. In the gas cycle, the refrigeration effect is equal to the product of the specific heat of the gas and the rise in temperature of the gas in the low temperature side. Therefore, for the same cooling load, a gas refrigeration cycle will require a large mass flow rate and would be bulky.

Because of their lower efficiency and larger bulk, *air cycle* coolers are not often used nowadays in terrestrial cooling devices. The air cycle machine is very common, however, on gas turbine-powered jet aircraft because compressed air is readily available from the engines' compressor sections. These jet aircraft's cooling and ventilation units also serve the purpose of pressurizing the aircraft.

Thermoelectric refrigeration

Thermoelectric cooling uses the Peltier effect to create a heat flux between the junction of two different types of materials. This effect is commonly used in camping and portable coolers and for cooling electronic components and small instruments.

Magnetic refrigeration

Magnetic refrigeration, or adiabatic demagnetization, is a cooling technology based on the magnetocaloric effect, an intrinsic property of magnetic solids. The refrigerant is often a paramagnetic salt, such as cerium magnesium nitrate. The active magnetic dipoles in this case are those of the electron shells of the paramagnetic atoms.

A strong magnetic field is applied to the refrigerant, forcing its various magnetic dipoles to align and putting these degrees of freedom of the refrigerant into a state of lowered entropy. A heat sink then absorbs the heat released by the refrigerant due to its loss of entropy. Thermal contact with the heat sink is then broken so that the system is insulated, and the magnetic field is switched off. This increases the heat capacity of the refrigerant, thus decreasing its temperature below the temperature of the heat sink.

Because few materials exhibit the required properties at room temperature, applications have so far been limited to cryogenics and research.

Other methods

Other methods of refrigeration include the air cycle machine used in aircraft; the vortex tube used for spot cooling, when compressed air is available; and thermoacoustic refrigeration using sound waves in a pressurized gas to drive heat transfer and heat exchange; steam jet cooling popular in the early 1930s for air conditioning large buildings; thermoelastic cooling using a smart metal alloy stretching and relaxing. Many Stirling cycle heat engines can be run backwards to act as a refrigerator, and therefore these engines have a niche use in cryogenics.

Unit of refrigeration

The units of refrigeration are always a unit of power. Domestic and commercial refrigerators may be rated in kJ/s, or Btu/h of cooling. For commercial and industrial refrigeration systems most of the world uses the kilowatt (kW) as the basic unit refrigeration. Typically, commercial and industrial refrigeration systems North America are rated in Tons of Refrigeration (TR). Historically, one Ton of Refrigeration was defined as the energy removal rate that will freeze one short ton of water at 0 °C (32 °F) in one day. This was very important because many early refrigeration systems were in ice houses. The simple unit allowed owners of these refrigeration systems measure a days output of ice against energy consumption and compare their plant to one down the street. While ice houses make up a much smaller part of the refrigeration industry than they once did the unit of Tons of Refrigeration has remained in North America. The unit's value as historically defined is approximately 11,958 BTU/hr (3.505 kW) has been redefined to be exactly 12,000 BTU/hr (3.517 kW).

While not truly a unit, a refrigeration system's Coefficient of Performance (CoP) is very important in determining a system's overall efficiency. It is defined as refrigeration capacity in kW divided by the energy input in kW. While CoP is a very simple measure, like the kW, it is typically not used for industrial refrigeration in North America. Owners and manufacturers of these systems typically use Performance Factor. A system's Performance Factor is defined as a system's energy input in horsepower divided by its refrigeration capacity in Tons of Refrigeration. Both Coefficient of Performance and

Performance Factor can be applied to either the entire system or to system components. For example an individual compressor can be rated by looking at the energy required to run the compressor versus the expected refrigeration capacity based on inlet volume flow rate. It is important to note that both Coefficient of Performance and Performance Factor for a refrigeration system are only defined at a specific operating conditions. Moving away from those operating conditions can dramatically change a system's performance.

Chapter 7

Pulse Tube Refrigerator

The **pulse tube refrigerator** or **pulse tube cryocooler** is a developing technology that emerged largely in the early 1980's with a series of other innovations in the broader field of thermoacoustics. In contrast with other cryocoolers (eg Stirling cryocooler and Gifford-McMahon cooler), this cryocooler can be made without moving parts in the low temperature part of the device, making the cooler suitable for a wide variety of applications.

Uses

Pulse tube cryocoolers have been used in industrial applications such as semiconductor fabrication and in military applications such as for the cooling of infrared sensors. Pulse tubes are also being developed for cooling of astronomical detectors where liquid cryogens are typically used, such as the Atacama Cosmology Telescope or the QUBIC experiment (an interferometer for cosmology studies). Pulse tubes will be particularly useful in space-based telescopes where it is not possible to replenish the cryogens as they are depleted. It has also been suggested that pulse tubes could be used to liquefy oxygen on Mars.

The ice cream manufacturer Ben and Jerry's invested in a related thermoacoustic cooling technology, funding a pilot thermoacoustic ice-cream refrigerator project in New York City. The technology's environmentally clean alternative to chemicals used in conventional freezers is attractive to Ben and Jerry's.

Description

Here the so-called Stirling-type single-orifice pulse-tube refrigerator will be treated operating with an ideal gas (helium) as the working fluid. Figure 1 represents the Stirling-type single-orifice Pulse-Tube Refrigerator (PTR). From left to right the components are:

- a compressor, with a piston moving back and forth at room temperature T_H;

- a heat exchanger X_1 where heat is released to the surroundings;
- a regenerator consisting of a porous medium with a large specific heat;
- a heat exchanger X_2 where the useful cooling power $\dot{Q}_L$ is delivered at the low temperature T_L;
- a tube, often called "the pulse tube";
- a heat exchanger X_3 at room temperature where heat is released to the surroundings;
- a flow resistance (often called orifice);
- a buffer volume (a large closed volume at practically constant pressure).

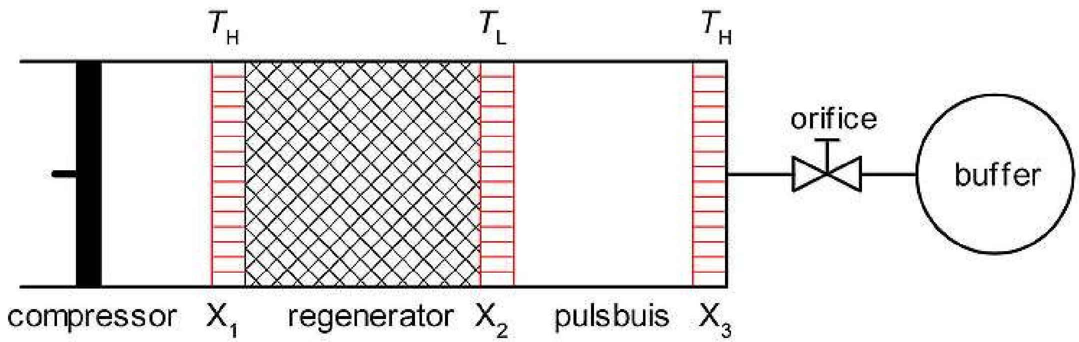


Figure 1: Schematic drawing of a Stirling-type single-orifice PTR. From left to right: a compressor, a heat exchanger (X_1), a regenerator, a heat exchanger (X_2), a tube (often called "the pulse tube"), a heat exchanger (X_3), a flow resistance (O), and a buffer volume. The cooling is generated at the low temperature T_L. Room temperature is T_H. The dotted line represents the thermal isolation (vacuum chamber) of the cold parts.

The part in between X_1 and X_3 is thermally insulated from the surroundings, usually by vacuum. The cooler is filled with helium at a pressure in the range from 10 to 30 bar. The pressure varies gradually and the velocities of the gas are low. So the name "pulse" tube cooler is very misleading since there are no pulses whatsoever in the system.

How it operates

The piston moves periodically from left to right and back. As a result the gas also moves from left to right and back while the pressure within the system increases and decreases. If the gas from the compressor space moves to the right it enters the regenerator with temperature T_H and leaves the regenerator at the cold end with temperature T_L, hence heat is transferred into the regenerator material. On its return the heat stored within the regenerator is transferred back into the gas.

The performance of the cooler is determined mainly by the quality of the regenerator. It has to satisfy conflicting requirements: it must have a low flow resistance (so it must be short with wide channels), but the heat exchange should also be good (so it must be long with narrow channels). The material must have a large heat capacity. At temperatures above 50 K practically all materials are suitable. Bronze or stainless steel is often used.

For temperatures between 10 and 50 K lead is most suitable. Below 10 K one uses magnetic materials which are specially developed for this application.

The thermal environment of a gas element near X_2, that moves back and forth in the system, changes when it passes the heat exchanger. In the regenerator and in the heat exchanger (X1) the heat contact between the gas and its surrounding material is good. Here the temperature of the gas is practically the same as of the surrounding medium. However, in the pulse tube the gas element is thermally isolated, so, in the pulse tube, the temperature of the gas element varies with the pressure.

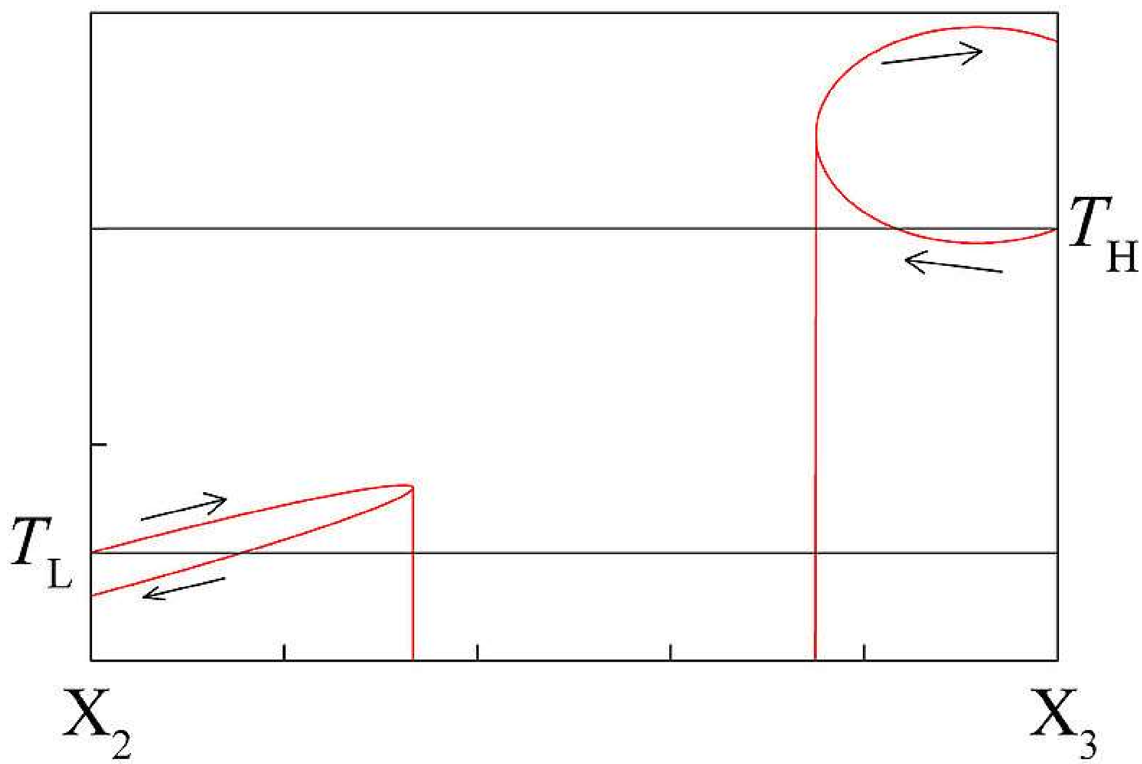


Figure 2: Left: (near X_2): a gas element enters the pulse tube with temperature T_L and leaves it with a lower temperature. Right: (near X_3): a gas element enters the tube with temperature T_H and leaves it with a higher temperature.

Look at figure 2 and concentrate on gas elements close to X_3 (at the hot end) which move in and out of the pulse tube. A gas element that flows into the tube does so when the pressure in the tube is low (it is sucked into the tube via X_3 coming from the orifice and the buffer). At the moment it enters the tube it has the temperature T_H . Later in the cycle it is pushed out the tube again when the pressure inside the tube is high. As a consequence its temperature will be higher than T_H . In the heat exchanger X_3 it releases heat and cools to the ambient temperature T_H .

At the cold end of the pulse tube there is the opposite effect: here gas elements enter the tube via X_2 when the pressure is high with temperature T_L and return when the pressure is low with a temperature below T_L. They take up heat from X_2 : this gives the desired cooling power.

Performance

The so-called Coefficient Of Performance ξ (COP) of coolers is defined as the ratio between the cooling power $\dot{Q}_L$ and the compressor power P. In formula $P : \xi = \dot{Q}_L / P$. For a perfectly reversible cooler, ξ is given by the famous relation

$$\xi_C = \frac{T_L}{T_H - T_L} \quad (1)$$

which is also called the Carnot COP. However, a pulse-tube refrigerator is not perfectly reversible due to the presence of the orifice, which has flow resistance. Therefore equation (1) does not hold. Instead, the COP of an ideal PTR is given by

$$\xi_{PTR} = \frac{T_L}{T_H}. \quad (2)$$

Comparing relations 1 and 2 shows that the COP of PTR's is lower than that of ideal coolers.

Comparison with other coolers

In most coolers gas is compressed and expanded periodically. Well-known coolers such as the Stirling coolers and the popular Gifford-McMahon coolers have a displacer that ensures that the cooling (due to expansion) takes place in a different region of the machine than the heating (due to compression). Due to its clever design the PTR does not have such a displacer. This means that the construction of a PTR is simpler, cheaper, and more reliable. Furthermore there are no mechanical vibrations and no electro-magnetic interferences.

History

The PTR was invented by Mikulin in 1984. He reached a temperature of 105 K. Soon after that, PTR's became better due to the invention of new variations. This is shown in figure 3, where the lowest temperature for PTR's is plotted as a function of time.

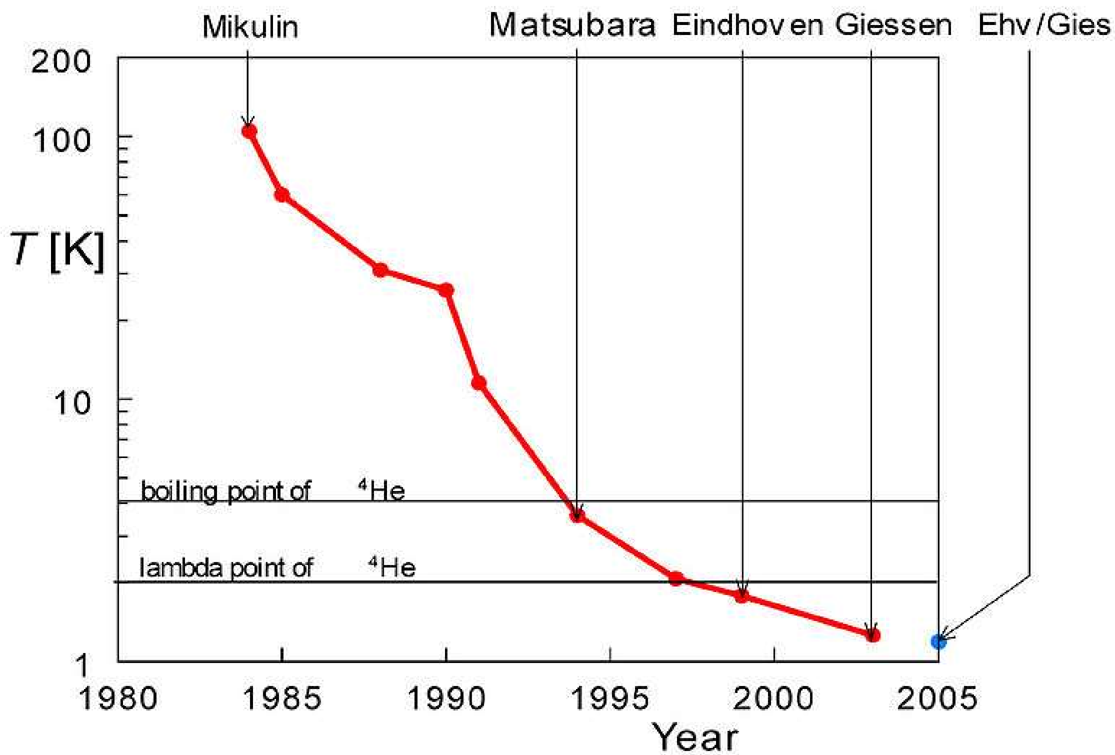


Figure 3: The temperature of PTR's over the years. The temperature of 1.2 K is reached in a collaboration between the groups of Giessen and Eindhoven. They used a superfluid vortex cooler as an additional cooling stage to the PTR.

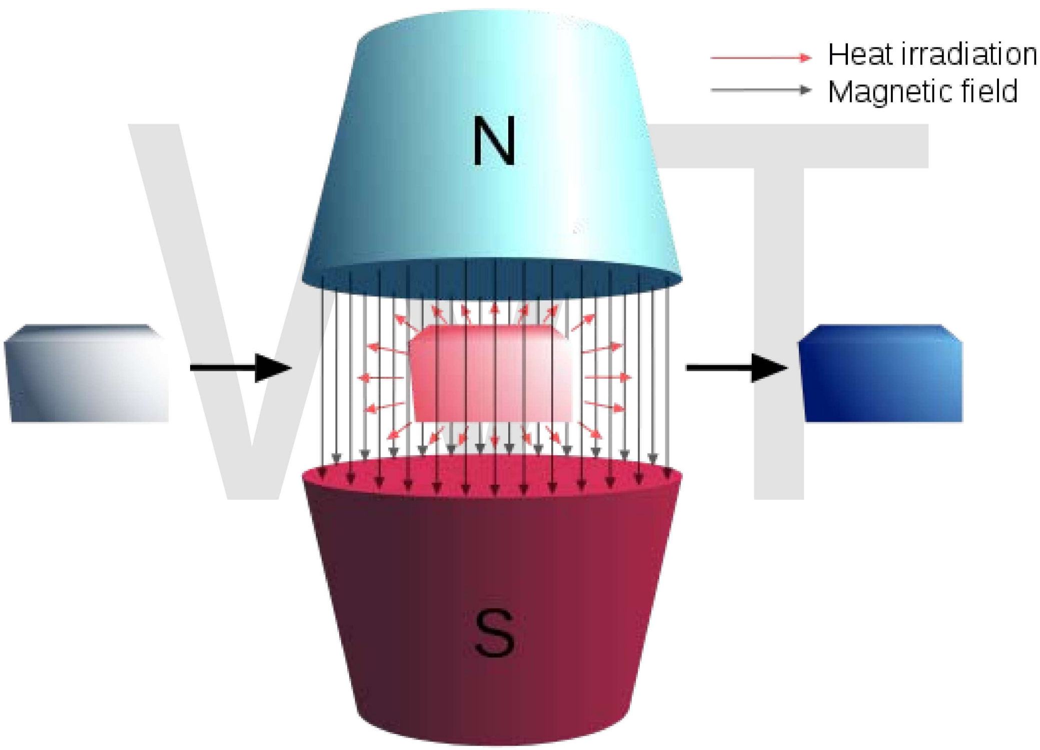
At the moment, the lowest temperature is below the boiling point of helium (4.2 K). Originally this was considered to be impossible. For some time it looked as if it would be impossible to cool below the lambda point of ^{4}He (2.17 K), but the Low-Temperature group of the Eindhoven University of Technology managed to cool to a temperature of 1.73 K by replacing the usual ^{4}He as refrigerant by its rare isotope ^{3}He. Later this record was broken by the Giessen Group that managed to get even below 1.3 K. In a collaboration between the groups from Giessen and Eindhoven a temperature of 1.2 K was reached by combining a PTR with a superfluid vortex cooler.

Prospects

The COP of PTR's at room temperature is low, so it is not likely that they will play a role in domestic cooling. However, below about 80 K the COP is comparable with other coolers (compare Eqs.(1) and (2)) and in the low-temperature region the advantages get the upper hand. For the 70K- and the 4K temperature regions PTR's are commercially available. They are applied in infrared detection systems, for reduction of thermal noise in devices based on (high-T_c) superconductivity such as SQUID's, and filters for telecommunication. PTR's are also suitable for cooling MRI-systems and energy-related systems using superconducting magnets. In so-called dry magnets, coolers are used so that no cryoliquid is needed at all or for the recondensation of the evaporated helium. Also the combination of cryocoolers with ^3He-^4He dilution refrigerators (dry dilution refrigerators) for the temperature region down to 2 mK is attractive since in this way the whole temperature range from room temperature to 2 mK will be easier to access.

Chapter 8

Magnetic Refrigeration



Gadolinium alloy heats up inside the magnetic field and loses thermal energy to the environment, so it exits the field cooler than when it entered.

Magnetic refrigeration is a cooling technology based on the **magnetocaloric effect**. This technique can be used to attain extremely low temperatures (well below 1 K), as well as the ranges used in common refrigerators, depending on the design of the system.

The effect was first observed by the German physicist Emil Warburg (1880) and the fundamental principle was suggested by Debye (1926) and Giauque (1927). The first working magnetic refrigerators were constructed by several groups beginning in 1933.

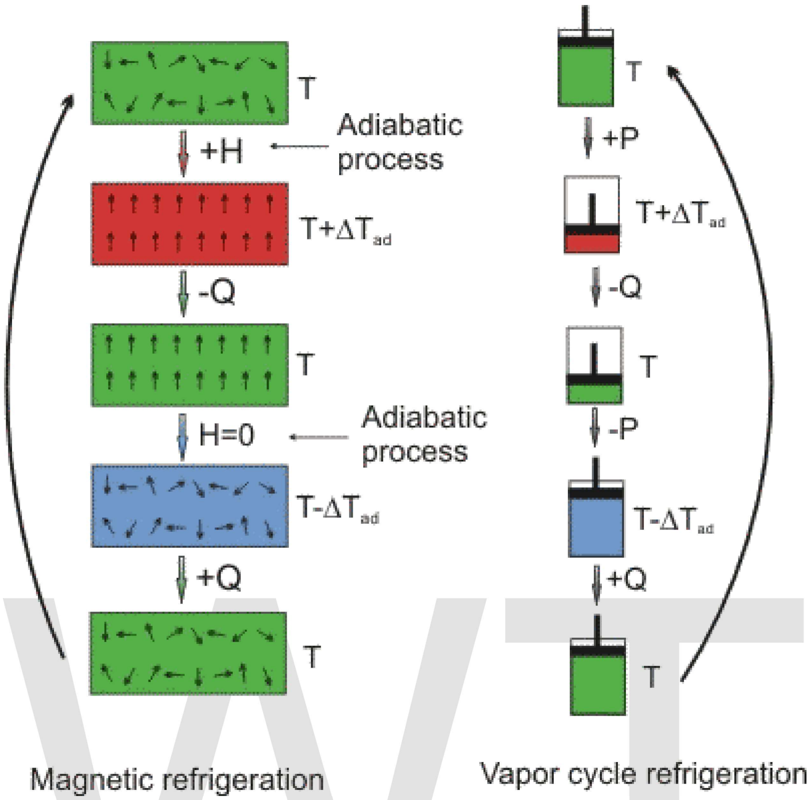
Magnetic refrigeration was the first method developed for cooling below about 0.3 K (a temperature attainable by ^{3}He refrigeration, that is pumping on the ^{3}He vapors).

The magnetocaloric effect

The magnetocaloric effect (MCE, from *magnet* and *calorie*) is a magneto-thermodynamic phenomenon in which a reversible change in temperature of a suitable material is caused by exposing the material to a changing magnetic field. This is also known by low temperature physicists as **adiabatic demagnetization**, due to the application of the process specifically to create a temperature drop. In that part of the overall refrigeration process, a decrease in the strength of an externally applied magnetic field allows the magnetic domains of a chosen (magnetocaloric) material to become disoriented from the magnetic field by the agitating action of the thermal energy (phonons) present in the material. If the material is isolated so that no energy is allowed to (re)migrate into the material during this time, *i.e.*, an adiabatic process, the temperature drops as the domains absorb the thermal energy to perform their reorientation. The randomization of the domains occurs in a similar fashion to the randomization at the curie temperature, except that magnetic dipoles overcome a decreasing external magnetic field while energy remains constant, instead of magnetic domains being disrupted from internal ferromagnetism as energy is added.

One of the most notable examples of the magnetocaloric effect is in the chemical element gadolinium and some of its alloys. Gadolinium's temperature is observed to increase when it enters certain magnetic fields. When it leaves the magnetic field, the temperature drops. The effect is considerably stronger for the gadolinium alloy $Gd_5(Si_2Ge_2)$. Praseodymium alloyed with nickel ($PrNi_5$) has such a strong magnetocaloric effect that it has allowed scientists to approach within one thousandth of a degree of absolute zero.

Thermodynamic cycle



Analogy between magnetic refrigeration and vapor cycle or conventional refrigeration. *H* = externally applied magnetic field; *Q* = heat quantity; *P* = pressure; ΔT_{ad} = adiabatic temperature variation

The cycle is performed as a refrigeration cycle, analogous to the Carnot cycle, and can be described at a starting point whereby the chosen working substance is introduced into a magnetic field, *i.e.*, the magnetic flux density is increased. The working material is the refrigerant, and starts in thermal equilibrium with the refrigerated environment.

- **Adiabatic magnetization:** A magnetocaloric substance is placed in an insulated environment. The increasing external magnetic field (+*H*) causes the magnetic dipoles of the atoms to align, thereby decreasing the material's magnetic entropy and heat capacity. Since overall energy is not lost (yet) and therefore total entropy is not reduced (according to thermodynamic laws), the net result is that the item heats up ($T + \Delta T_{ad}$).

- **Isomagnetic enthalpic transfer:** This added heat can then be removed (-*Q*) by a fluid or gas — gaseous or liquid helium, for example. The magnetic field is held constant to prevent the dipoles from reabsorbing the heat. Once sufficiently cooled, the magnetocaloric substance and the coolant are separated (*H*=0).

- **Adiabatic demagnetization:** The substance is returned to another adiabatic (insulated) condition so the total entropy remains constant. However, this time the magnetic field is decreased, the thermal energy causes the magnetic moments to overcome the field, and thus the sample cools, *i.e.*, an adiabatic temperature change. Energy (and entropy) transfers from thermal entropy to magnetic entropy (disorder of the magnetic dipoles).

- **Isomagnetic entropic transfer:** The magnetic field is held constant to prevent the material from heating back up. The material is placed in thermal contact with the environment being refrigerated. Because the working material is cooler than the refrigerated environment (by design), heat energy migrates into the working material (+*Q*).

Once the refrigerant and refrigerated environment are in thermal equilibrium, the cycle begins again.

Applied technique

The basic operating principle of an adiabatic demagnetization refrigerator (ADR) is the use of a strong magnetic field to control the entropy of a sample of material, often called the "refrigerant". Magnetic field constrains the orientation of magnetic dipoles in the refrigerant. The stronger the magnetic field, the more aligned the dipoles are, and this corresponds to lower entropy and heat capacity because the material has (effectively) lost some of its internal degrees of freedom. If the refrigerant is kept at a constant temperature through thermal contact with a heat sink (usually liquid helium) while the magnetic field is switched on, the refrigerant must lose some energy because it is equilibrated with the heat sink. When the magnetic field is subsequently switched off, the heat capacity of the refrigerant rises again because the degrees of freedom associated with orientation of the dipoles are once again liberated, pulling their share of equipartitioned energy from the motion of the molecules, thereby lowering the overall temperature of a system with decreased energy. Since the system is now insulated when the magnetic field is switched off, the process is adiabatic, *i.e.*, the system can no longer exchange energy with its surroundings (the heat sink), and its temperature decreases below its initial value, that of the heat sink.

The operation of a standard ADR proceeds roughly as follows. First, a strong magnetic field is applied to the refrigerant, forcing its various magnetic dipoles to align and putting these degrees of freedom of the refrigerant into a state of lowered entropy. The heat sink then absorbs the heat released by the refrigerant due to its loss of entropy. Thermal contact with the heat sink is then broken so that the system is insulated, and the magnetic field is switched off, increasing the heat capacity of the refrigerant, thus decreasing its temperature below the temperature of the helium heat sink. In practice, the magnetic field is decreased slowly in order to provide continuous cooling and keep the sample at an approximately constant low temperature. Once the field falls to zero or to some low limiting value determined by the properties of the refrigerant, the cooling power of the ADR vanishes, and heat leaks will cause the refrigerant to warm up.

Working materials

The magnetocaloric effect is an intrinsic property of a magnetic solid. This thermal response of a solid to the application or removal of magnetic fields is maximized when the solid is near its magnetic ordering temperature.

The magnitudes of the magnetic entropy and the adiabatic temperature changes are strongly dependent upon the magnetic order process: the magnitude is generally small in antiferromagnets, ferrimagnets and spin glass systems; it can be substantial for normal ferromagnets which undergo a second order magnetic transition; and it is generally the largest for a ferromagnet which undergoes a first order magnetic transition.

Also, crystalline electric fields and pressure can have a substantial influence on magnetic entropy and adiabatic temperature changes.

Currently, alloys of gadolinium producing 3 to 4 K per tesla (K/T) of change in a magnetic field can be used for magnetic refrigeration.

Recent research on materials that exhibit a giant entropy change showed that $Gd_5(Si_xGe_{1-x})_4$, $La(Fe_xSi_{1-x})_{13}H_x$ and $MnFeP_{1-x}As_x$ alloys, for example, are some of the most promising substitutes for gadolinium and its alloys — GdDy, GdTy, etc. These materials are called giant magnetocaloric effect materials (GMCE).

Gadolinium and its alloys are the best material available today for magnetic refrigeration near room temperature since they undergo second-order phase transitions which have no magnetic or thermal hysteresis involved.

Paramagnetic salts

The originally suggested refrigerant was a paramagnetic salt, such as cerium magnesium nitrate. The active magnetic dipoles in this case are those of the electron shells of the paramagnetic atoms.

In a paramagnetic salt ADR, the heat sink is usually provided by a pumped ^4He (about 1.2 K) or ^3He (about 0.3 K) cryostat. An easily attainable 1 T magnetic field is generally required for the initial magnetization. The minimum temperature attainable is determined by the self-magnetization tendencies of the chosen refrigerant salt, but temperatures from 1 to 100 mK are accessible. Dilution refrigerators had for many years supplanted paramagnetic salt ADRs, but interest in space-based and simple to use lab-ADRs has remained, due to the complexity and unreliability of the dilution refrigerator

Eventually paramagnetic salts become either diamagnetic or ferromagnetic, limiting the lowest temperature which can be reached using this method.

Nuclear demagnetization

One variant of adiabatic demagnetization that continues to find substantial research application is nuclear demagnetization refrigeration (NDR). NDR follows the same principle described above, but in this case the cooling power arises from the magnetic dipoles of the nuclei of the refrigerant atoms, rather than their electron configurations. Since these dipoles are of much smaller magnitude, they are less prone to self-alignment and have lower intrinsic minimum fields. This allows NDR to cool the nuclear spin system to very low temperatures, often 1 μK or below. Unfortunately, the small magnitudes of nuclear magnetic dipoles also makes them less inclined to align to external fields. Magnetic fields of 3 teslas or greater are often needed for the initial magnetization step of NDR.

In NDR systems, the initial heat sink must sit at very low temperatures (10–100 mK). This precooling is often provided by the mixing chamber of a dilution refrigerator or a paramagnetic salt.

Commercial development

This refrigeration, once proven viable, could be used in any possible application where cooling, heating or power generation is used today. Since it is only at an early stage of development, there are several technical and efficiency issues that should be analyzed. The magnetocaloric refrigeration system is composed of pumps, electric motors, secondary fluids, heat exchangers of different types, magnets and magnetic materials. These processes are greatly affected by irreversibilities and should be adequately considered.

Appliances using this method could have a smaller environmental impact if the method is perfected and replaces hydrofluorocarbon (HFCs) refrigerators (some refrigerators still use HFCs which have considerable effect on the ozone layer. At present, however, the superconducting magnets that are used in the process have to themselves be cooled down to the temperature of liquid nitrogen, or with even colder, and relatively expensive, liquid helium. Considering these fluids have boiling points of 77.36 K and 4.22 K respectively, the technology is clearly not cost- and energy-efficient for home appliances, but for experimental, laboratory, and industrial use only.

Recent research on materials that exhibit a large entropy change showed that alloys are some of the most promising substitutes of gadolinium and its alloys — GdDy, GdTb, etc. Gadolinium and its alloys are the best material available today for magnetic refrigeration near room temperature. There are still some thermal and magnetic hysteresis problems to be solved for them to become truly useful [V. Provenzano, A.J. Shapiro, and R.D. Shull, Nature 429, 853 (2004)] and scientists are working hard to achieve this goal. Thermal hysteresis problems is solved therefore in adding ferrite (5:4).

Research and a demonstration proof of concept in 2001 succeeded in applying commercial-grade materials and permanent magnets at room temperatures to construct a magnetocaloric refrigerator which promises wide use.

This technique has been used for many years in cryogenic systems for producing further cooling in systems already cooled to temperatures of 4 K and lower. In England, a company called Cambridge Magnetic Refrigeration produces cryogenic systems based on the magnetocaloric effect.

On August 20, 2007, the Risø National Laboratory at the Technical University of Denmark, claimed to have reached a milestone in their magnetic cooling research when they reported a temperature span of 8.7 C. They hope to introduce the first commercial applications of the technology by 2010.

Current and future uses

There are still some thermal and magnetic hysteresis problems to be solved for these first-order phase transition materials that exhibit the GMCE to become really useful; this is a subject of current research. A useful review on magnetocaloric materials published in 2005 is entitled "Recent developments in magnetocaloric materials" by Dr. Karl A. Gschneidner, et al. This effect is currently being explored to produce better refrigeration techniques, especially for use in spacecraft. This technique is already used to achieve cryogenic temperatures in the laboratory setting (below 10K). As an object displaying MCE is moved into a magnetic field, the magnetic spins align, lowering the entropy. Moving that object out of the field allows the object to increase its entropy by absorbing heat from the environment and disordering the spins. In this way, heat can be taken from one area to another. Should materials be found to display this effect near room temperature, refrigeration without the need for compression may be possible, increasing energy efficiency.

The use of this technology for domestic refrigerators though is very remote due to the high efficiency of current Vapor-compression refrigeration in the range of 60% of Carnots efficiency. Gas molecules are responsible for heat transfer, they absorb heat in the inner side of the refrigerator by expanding and release this heat in the outside by condensing. The work provided to do this work is a cheap and highly efficient compressor, driven by an electric motor that is more than 80% efficient.

This technology could eventually compete with other cryogenic heat pumps for gas liquefaction purposes.

Controversy

Gschneidner stated in 1999 that: "large-scale applications using magnetic refrigeration, such as commercial air conditioning and supermarket refrigeration systems, could be available within 5–10 years. Within 10–15 years, the technology could be available in home refrigerators and air conditioners."

History

The effect was discovered in pure iron in 1880 by German physicist Emil Warburg. Originally, the cooling effect varied between 0.5 to 2 K/T.

Major advances first appeared in the late 1920s when cooling via adiabatic demagnetization was independently proposed by two scientists, Peter Debye in 1926 and William Giauque in 1927.

This cooling technology was first demonstrated experimentally by chemist Nobel Laureate William F. Giauque and his colleague Dr. D.P. MacDougall in 1933 for cryogenic purposes when they reached 0.25 K. Between 1933 and 1997, a number of advances in utilization of the MCE for cooling occurred.

In 1997, the first near room temperature proof of concept magnetic refrigerator was demonstrated by Prof. Karl A. Gschneidner, Jr. by the Iowa State University at Ames Laboratory. This event attracted interest from scientists and companies worldwide who started developing new kinds of room temperature materials and magnetic refrigerator designs. A major breakthrough came 2002 when a group at the University of Amsterdam demonstrated the giant magnetocaloric effect in MnFe(P,As) alloys that are based on earth abundant materials.

Refrigerators based on the magnetocaloric effect have been demonstrated in laboratories, using magnetic fields starting at 0.6 T up to 10 T. Magnetic fields above 2 T are difficult to produce with permanent magnets and are produced by a superconducting magnet (1 T is about 20,000 times the Earth's magnetic field).

Room temperature devices

Some recent research has focused on the use of the process to perform refrigeration near "room temperature". Constructed examples of room temperature magnetic refrigerators are listed in the table below:

Room temperature magnetic refrigerators

Institute/Company	Location	Announcement date	Type	Max. cooling power (W)	Max ΔT (K)	Magnetic field (T)	Solid refrigerant	Quantity (kg)
Ames Laboratory/Astronautics	Ames, Iowa/Madison, Wisconsin, USA	February 20, 1997	Reciprocating	600	10	5 (S)	Gd spheres	
Mater. Science Institute Barcelona	Barcelona, Spain	May 2000	Rotary	?	5	0.95 (P)	Gd foil	
Chubu Electric/Toshiba	Yokohama, Japan	Summer 2000	Reciprocating	100	21	4 (S)	Gd spheres	

University of Victoria	Victoria, British Columbia Canada	July 2001	Reciprocating	2	14	2 (S)	Gd & $Gd_{1-x}Tb_x$ L.B.	
Astronautics	Madison, Wisconsin, USA	September 18, 2001	Rotary	95	25	1.5 (P)	Gd spheres	
Sichuan Inst. Tech./Nanjing University	Nanjing, China	23 April 2002	Reciprocating	?	23	1.4 (P)	Gd spheres and $Gd_5Si_{1.985}Ge_{1.985}Ga_{0.03}$ powder	
Chubu Electric/Toshiba	Yokohama, Japan	October 5, 2002	Reciprocating	40	27	0.6 (P)	$Gd_{1-x}Dy_x$ L.B.	
Chubu Electric/Toshiba	Yokohama, Japan	March 4, 2003	Rotary	60	10	0.76 (P)	Gd $_{1-x}Dy_x$ L.B.	1
Lab. d'Electrotechnique Grenoble	Grenoble, France	April 2003	Reciprocating	8.8	4	0.8 (P)	Gd foil	
George Washington University	USA	July 2004	Reciprocating	?	5	2 (P)	Gd foil	
Astronautics	Madison, Wisconsin, USA	2004	Rotary	95	25	1.5 (P)	Gd and GdEr spheres / $La(Fe_{0.88}Si_{0.12})_{13}H_{1.0}$	
University of Victoria	Victoria, British Columbia Canada	2006	Reciprocating	15	50	2 (S)	Gd, $Gd_{0.74}Tb_{0.26}$ and $Gd_{0.85}Er_{0.15}$ pucks	0.12

[1]maximum cooling power at zero temperature difference (ΔT=0); [2]maximum temperature span at zero cooling capacity (W=0); L.B. = layered bed; P = permanent magnet; S = superconducting magnet

In one example, Prof. Karl A. Gschneidner, Jr. unveiled a proof of concept magnetic refrigerator near room temperature on February 20, 1997. He also announced the discovery of the giant MCE (GMCE) in $Gd_5Si_2Ge_2$ on June 9, 1997 . Since then, hundreds of peer-reviewed articles have been written describing materials exhibiting magnetocaloric effects.

Chapter 9

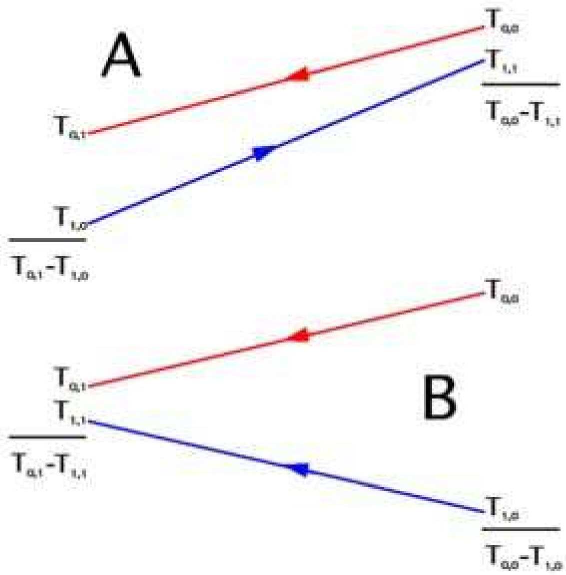
Heat Exchanger

An interchangeable plate heat exchanger

Tubular heat exchanger.

A **heat exchanger** is a piece of equipment built for efficient heat transfer from one medium to another. The media may be separated by a solid wall, so that they never mix, or they may be in direct contact. They are widely used in space heating, refrigeration, air conditioning, power plants, chemical plants, petrochemical plants, petroleum refineries, natural gas processing, and sewage treatment. One common example of a heat exchanger is the radiator in a car, in which the heat source, being a hot engine-cooling fluid, water, transfers heat to air flowing through the radiator (i.e. the heat transfer medium).

Flow arrangement



Countercurrent (A) and parallel (B) flows

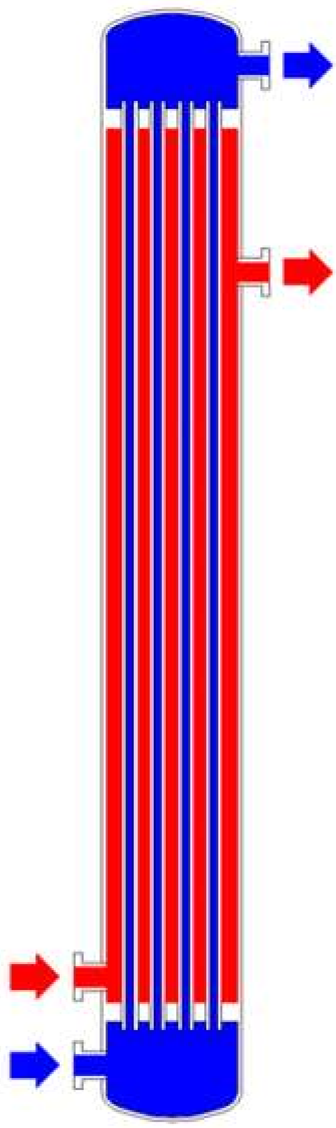


Fig. 1: Shell and tube heat exchanger, single pass (1-1 parallel flow)

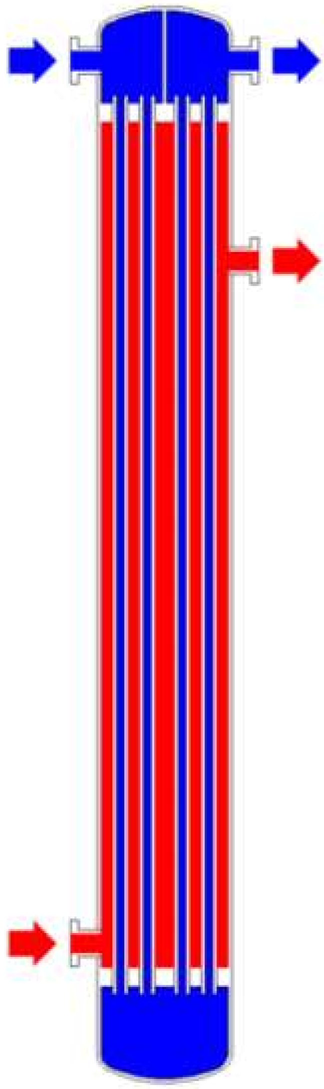


Fig. 2: Shell and tube heat exchanger, 2-pass tube side (1-2 crossflow)

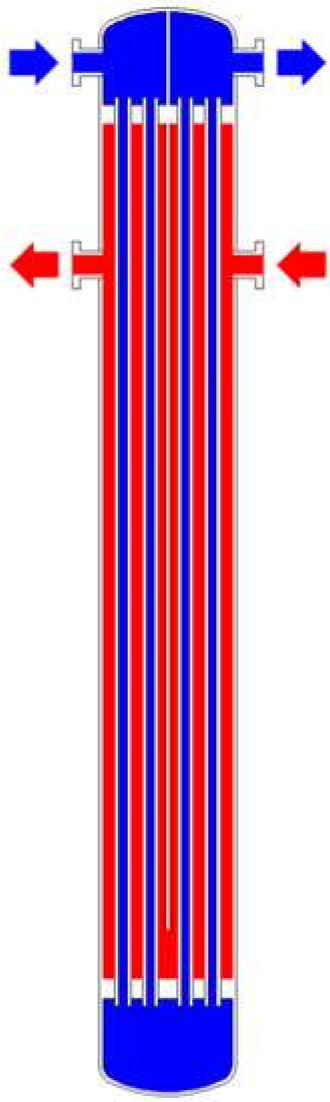


Fig. 3: Shell and tube heat exchanger, 2-pass shell side, 2-pass tube side (2-2 countercurrent)

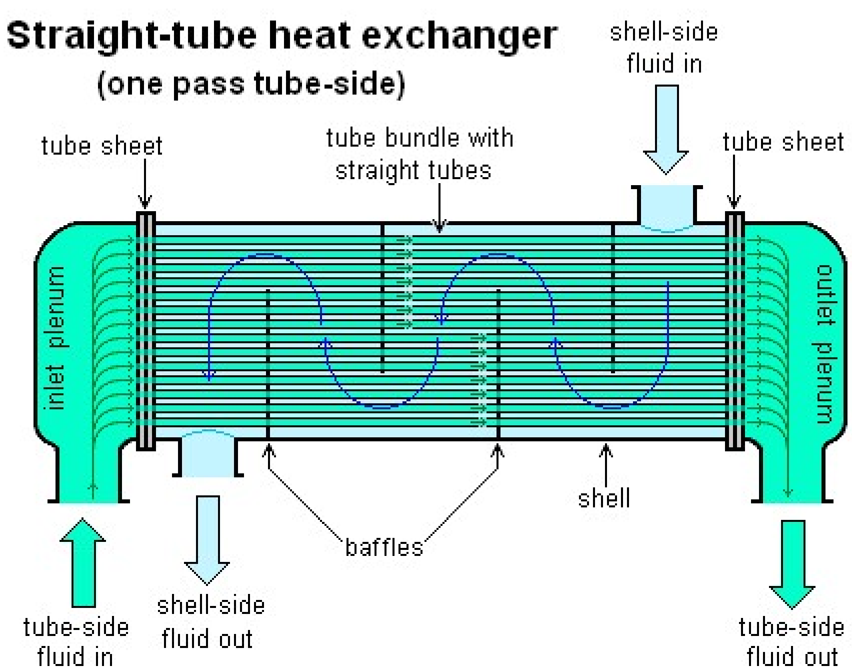
There are two primary classifications of heat exchangers according to their flow arrangement. In *parallel-flow* heat exchangers, the two fluids enter the exchanger at the same end, and travel in parallel to one another to the other side. In *counter-flow* heat exchangers the fluids enter the exchanger from opposite ends. The counter current design is most efficient, in that it can transfer the most heat from the heat (transfer) medium.

For efficiency, heat exchangers are designed to maximize the surface area of the wall between the two fluids, while minimizing resistance to fluid flow through the exchanger. The exchanger's performance can also be affected by the addition of fins or corrugations in one or both directions, which increase surface area and may channel fluid flow or induce turbulence.

The driving temperature across the heat transfer surface varies with position, but an appropriate mean temperature can be defined. In most simple systems this is the "log mean temperature difference" (LMTD). Sometimes direct knowledge of the LMTD is not available and the NTU method is used.

Types of heat exchangers

Shell and tube heat exchanger



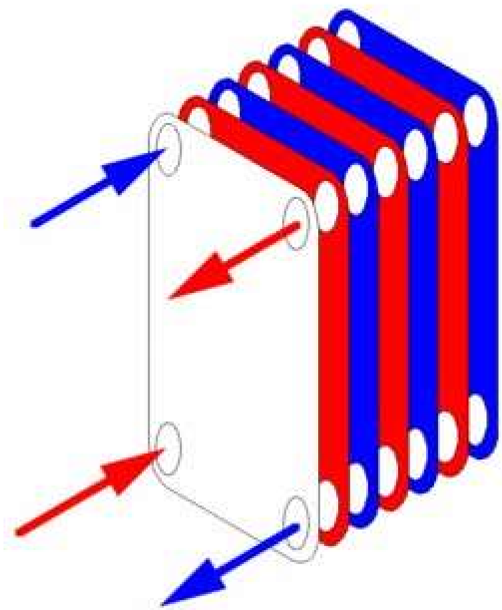
A Shell and Tube heat exchanger

Shell and tube heat exchangers consist of a series of tubes. One set of these tubes contains the fluid that must be either heated or cooled. The second fluid runs over the tubes that are being heated or cooled so that it can either provide the heat or absorb the heat required. A set of tubes is called the tube bundle and can be made up of several types of tubes: plain, longitudinally finned, etc. Shell and tube heat exchangers are typically used for high-pressure applications (with pressures greater than 30 bar and temperatures greater than 260°C). This is because the shell and tube heat exchangers are robust due to their shape.
There are several thermal design features that are to be taken into account when designing the tubes in the shell and tube heat exchangers. These include:

- Tube diameter: Using a small tube diameter makes the heat exchanger both economical and compact. However, it is more likely for the heat exchanger to foul up faster and the small size makes mechanical cleaning of the fouling difficult. To prevail over the fouling and cleaning problems, larger tube diameters can be used. Thus to determine the tube diameter, the available space, cost and the fouling nature of the fluids must be considered.

- Tube thickness: The thickness of the wall of the tubes is usually determined to ensure:
  - There is enough room for corrosion
  - That flow-induced vibration has resistance
  - Axial strength
  - Availability of spare parts
  - Hoop strength (to withstand internal tube pressure)
  - Buckling strength (to withstand overpressure in the shell)
- Tube length: heat exchangers are usually cheaper when they have a smaller shell diameter and a long tube length. Thus, typically there is an aim to make the heat exchanger as long as physically possible whilst not exceeding production capabilities. However, there are many limitations for this, including the space available at the site where it is going to be used and the need to ensure that there are tubes available in lengths that are twice the required length (so that the tubes can be withdrawn and replaced). Also, it has to be remembered that long, thin tubes are difficult to take out and replace.
- Tube pitch: when designing the tubes, it is practical to ensure that the tube pitch (i.e., the centre-centre distance of adjoining tubes) is not less than 1.25 times the tubes' outside diameter. A larger tube pitch leads to a larger overall shell diameter which leads to a more expensive heat exchanger.
- Tube corrugation: this type of tubes, mainly used for the inner tubes, increases the turbulence of the fluids and the effect is very important in the heat transfer giving a better performance.
- Tube Layout: refers to how tubes are positioned within the shell. There are four main types of tube layout, which are, triangular (30°), rotated triangular (60°), square (90°) and rotated square (45°). The triangular patterns are employed to give greater heat transfer as they force the fluid to flow in a more turbulent fashion around the piping. Square patterns are employed where high fouling is experienced and cleaning is more regular.
- Baffle Design: baffles are used in shell and tube heat exchangers to direct fluid across the tube bundle. They run perpendicularly to the shell and hold the bundle, preventing the tubes from sagging over a long length. They can also prevent the tubes from vibrating. The most common type of baffle is the segmental baffle. The semicircular segmental baffles are oriented at 180 degrees to the adjacent baffles forcing the fluid to flow upward and downwards between the tube bundle. Baffle spacing is of large thermodynamic concern when designing shell and tube heat exchangers. Baffles must be spaced with consideration for the conversion of pressure drop and heat transfer. For thermo economic optimization it is suggested that the baffles be spaced no closer than 20% of the shell’s inner diameter. Having baffles spaced too closely causes a greater pressure drop because of flow redirection. Consequently having the baffles spaced too far apart means that there may be cooler spots in the corners between baffles. It is also important to ensure

the baffles are spaced close enough that the tubes do not sag. The other main type of baffle is the disc and donut baffle which consists of two concentric baffles, the outer wider baffle looks like a donut, whilst the inner baffle is shaped as a disk. This type of baffle forces the fluid to pass around each side of the disk then through the donut baffle generating a different type of fluid flow.



Conceptual diagram of a plate and frame heat exchanger.

A single plate heat exchanger

An interchangeable plate heat exchanger applied to the system of a swimming pool

Plate heat exchanger

Another type of heat exchanger is the plate heat exchanger. One is composed of multiple, thin, slightly-separated plates that have very large surface areas and fluid flow passages for heat transfer. This stacked-plate arrangement can be more effective, in a given space, than the shell and tube heat exchanger. Advances in gasket and brazing technology have made the plate-type heat exchanger increasingly practical. In HVAC applications, large heat exchangers of this type are called *plate-and-frame*; when used in open loops, these heat exchangers are normally of the gasket type to allow periodic disassembly, cleaning, and inspection. There are many types of permanently-bonded plate heat exchangers, such as dip-brazed and vacuum-brazed plate varieties, and they are often specified for closed-loop applications such as refrigeration. Plate heat exchangers also differ in the types of plates that are used, and in the configurations of those plates. Some plates may be stamped with "chevron" or other patterns, where others may have machined fins and/or grooves.

Adiabatic wheel heat exchanger

A third type of heat exchanger uses an intermediate fluid or solid store to hold heat, which is then moved to the other side of the heat exchanger to be released. Two examples of this are adiabatic wheels, which consist of a large wheel with fine threads rotating through the hot and cold fluids, and fluid heat exchangers.

Plate fin heat exchanger

This type of heat exchanger uses "sandwiched" passages containing fins to increase the effectivity of the unit. The designs include crossflow and counterflow coupled with various fin configurations such as straight fins, offset fins and wavy fins.

Plate and fin heat exchangers are usually made of aluminium alloys which provide higher heat transfer efficiency. The material enables the system to operate at a lower temperature and reduce the weight of the equipment. Plate and fin heat exchangers are mostly used for low temperature services such as natural gas, helium and oxygen liquefaction plants, air separation plants and transport industries such as motor and aircraft engines.

Advantages of plate and fin heat exchangers:

- High heat transfer efficiency especially in gas treatment
- Larger heat transfer area
- Approximately 5 times lighter in weight than that of shell and tube heat exchanger
- Able to withstand high pressure

Disadvantages of plate and fin heat exchangers:

- Might cause clogging as the pathways are very narrow
- Difficult to clean the pathways
- Aluminum alloys are susceptible to Mercury Liquid Embrittlement Failure

Pillow plate heat exchanger

A pillow plate exchanger is commonly used in the dairy industry for cooling milk in large direct-expansion stainless steel bulk tanks. The pillow plate allows for cooling across nearly the entire surface area of the tank, without gaps that would occur between pipes welded to the exterior of the tank.

The pillow plate is constructed using a thin sheet of metal spot-welded to the surface of another thicker sheet of metal. The thin plate is welded in a regular pattern of dots or with a serpentine pattern of weld lines. After welding the enclosed space is pressurized with sufficient force to cause the thin metal to bulge out around the welds, providing a space for heat exchanger liquids to flow, and creating a characteristic appearance of a swelled pillow formed out of metal.

Fluid heat exchangers

This is a heat exchanger with a gas passing upwards through a shower of fluid (often water), and the fluid is then taken elsewhere before being cooled. This is commonly used for cooling gases whilst also removing certain impurities, thus solving two problems at once. It is widely used in espresso machines as an energy-saving method of cooling super-heated water to be used in the extraction of espresso.

Waste heat recovery units

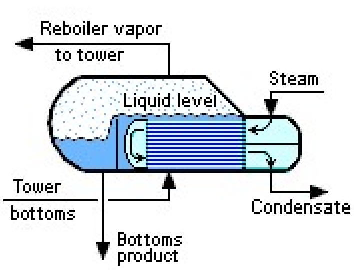
A Waste Heat Recovery Unit (WHRU) is a heat exchanger that recovers heat from a hot gas stream while transferring it to a working medium, typically water or oils. The hot gas stream can be the exhaust gas from a gas turbine or a diesel engine or a waste gas from industry or refinery.

Dynamic scraped surface heat exchanger

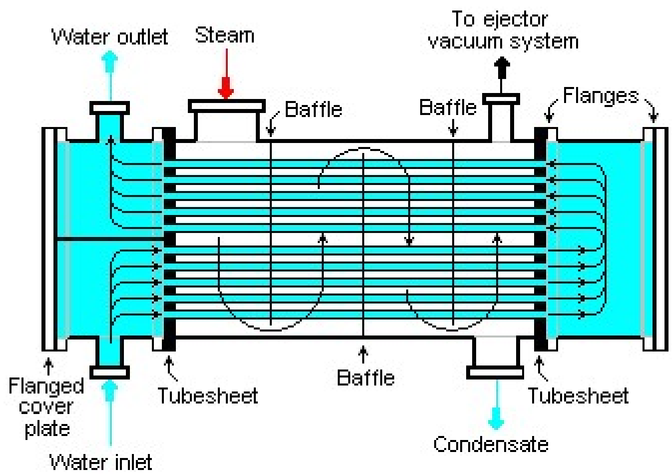
Another type of heat exchanger is called "(dynamic) scraped surface heat exchanger". This is mainly used for heating or cooling with high-viscosity products, crystallization processes, evaporation and high-fouling applications. Long running times are achieved due to the continuous scraping of the surface, thus avoiding fouling and achieving a sustainable heat transfer rate during the process.

The formula used for this will be Q=A*U*LMTD, whereby Q= heat transfer rate.

Phase-change heat exchangers



Typical kettle reboiler used for industrial distillation towers



Typical water-cooled surface condenser

In addition to heating up or cooling down fluids in just a single phase, heat exchangers can be used either to heat a liquid to evaporate (or boil) it or used as condensers to cool a vapor and condense it to a liquid. In chemical plants and refineries, reboilers used to heat incoming feed for distillation towers are often heat exchangers.

Distillation set-ups typically use condensers to condense distillate vapors back into liquid.

Power plants which have steam-driven turbines commonly use heat exchangers to boil water into steam. Heat exchangers or similar units for producing steam from water are often called boilers or steam generators.

In the nuclear power plants called pressurized water reactors, special large heat exchangers which pass heat from the primary (reactor plant) system to the secondary (steam plant) system, producing steam from water in the process, are called steam generators. All fossil-fueled and nuclear power plants using steam-driven turbines have surface condensers to convert the exhaust steam from the turbines into condensate (water) for re-use.

To conserve energy and cooling capacity in chemical and other plants, regenerative heat exchangers can be used to transfer heat from one stream that needs to be cooled to another stream that needs to be heated, such as distillate cooling and reboiler feed pre-heating.

This term can also refer to heat exchangers that contain a material within their structure that has a change of phase. This is usually a solid to liquid phase due to the small volume difference between these states. This change of phase effectively acts as a buffer because it occurs at a constant temperature but still allows for the heat exchanger to accept additional heat. One example where this has been investigated is for use in high power aircraft electronics.

Direct contact heat exchangers

Direct contact heat exchangers involve heat transfer between hot and cold streams of two phases in the absence of a separating wall. Thus such heat exchangers can be classified as:

- Gas – liquid
- Immiscible liquid – liquid
- Solid-liquid or solid – gas

Most direct contact heat exchangers fall under the Gas- Liquid category, where heat is transferred between a gas and liquid in the form of drops, films or sprays.

Such types of heat exchangers are used predominantly in air conditioning, humidification, water cooling and condensing plants.

Phases	Continuous phase	Driving force	Change of phase	Examples
Gas – Liquid	Gas	Gravity	No	Spray columns, packed columns
			Yes	Cooling towers, falling droplet evaporators
		Forced	No	Spray coolers/quenchers
		Liquid flow	Yes	Spray condensers/evaporation, jet condensers
	Liquid	Gravity	No	Bubble columns, perforated tray columns
			Yes	Bubble column condensers
		Forced	No	Gas spargers
		Gas flow	Yes	Direct contact evaporators, submerged combustion

HVAC air coils

One of the widest uses of heat exchangers is for air conditioning of buildings and vehicles. This class of heat exchangers is commonly called *air coils*, or just *coils* due to their often-serpentine internal tubing. Liquid-to-air, or air-to-liquid HVAC coils are typically of modified crossflow arrangement. In vehicles, heat coils are often called heater cores.

On the liquid side of these heat exchangers, the common fluids are water, a water-glycol solution, steam, or a refrigerant. For *heating coils*, hot water and steam are the most common, and this heated fluid is supplied by boilers, for example. For *cooling coils*, chilled water and refrigerant are most common. Chilled water is supplied from a chiller that is potentially located very far away, but refrigerant must come from a nearby condensing unit. When a refrigerant is used, the cooling coil is the evaporator in the vapor-compression refrigeration cycle. HVAC coils that use this direct-expansion of refrigerants are commonly called *DX coils*.

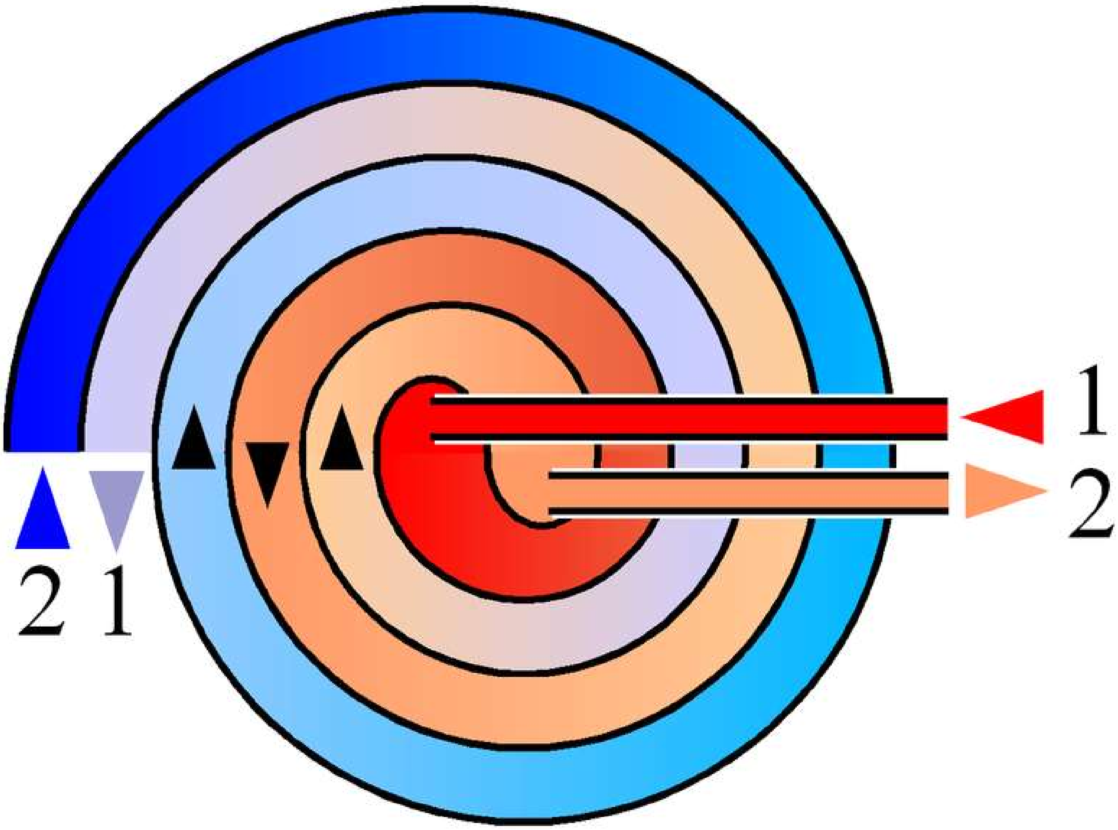
On the air side of HVAC coils a significant difference exists between those used for heating, and those for cooling. Due to psychrometrics, air that is cooled often has moisture condensing out of it, except with extremely dry air flows. Heating some air increases that airflow's capacity to hold water. So heating coils need not consider moisture condensation on their air-side, but cooling coils *must* be adequately designed and selected to handle their particular *latent* (moisture) as well as the *sensible* (cooling) loads. The water that is removed is called *condensate*.

For many climates, water or steam HVAC coils can be exposed to freezing conditions. Because water expands upon freezing, these somewhat expensive and difficult to replace thin-walled heat exchangers can easily be damaged or destroyed by just one freeze. As such, freeze protection of coils is a major concern of HVAC designers, installers, and operators.

The introduction of indentations placed within the heat exchange fins controlled condensation, allowing water molecules to remain in the cooled air. This invention allowed for refrigeration without icing of the cooling mechanism.

The heat exchangers in direct-combustion furnaces, typical in many residences, are not 'coils'. They are, instead, gas-to-air heat exchangers that are typically made of stamped steel sheet metal. The combustion products pass on one side of these heat exchangers, and air to be conditioned on the other. A *cracked heat exchanger* is therefore a dangerous situation requiring immediate attention because combustion products are then likely to enter the building.

Spiral heat exchangers



Schematic drawing of a spiral heat exchanger.

A spiral heat exchanger (SHE), may refer to a helical (coiled) tube configuration, more generally, the term refers to a pair of flat surfaces that are coiled to form the two channels in a counter-flow arrangement. Each of the two channels has one long curved path. A pair of fluid ports are connected tangentially to the outer arms of the spiral, and axial ports are common, but optional.

The main advantage of the SHE is its highly efficient use of space. This attribute is often leveraged and partially reallocated to gain other improvements in performance, according to well known tradeoffs in heat exchanger design. (A notable tradeoff is capital cost vs operating cost.) A compact SHE may be used to have a smaller footprint and thus lower all-around capital costs, or an over-sized SHE may be used to have less pressure drop, less pumping energy, higher thermal efficiency, and lower energy costs.

Construction

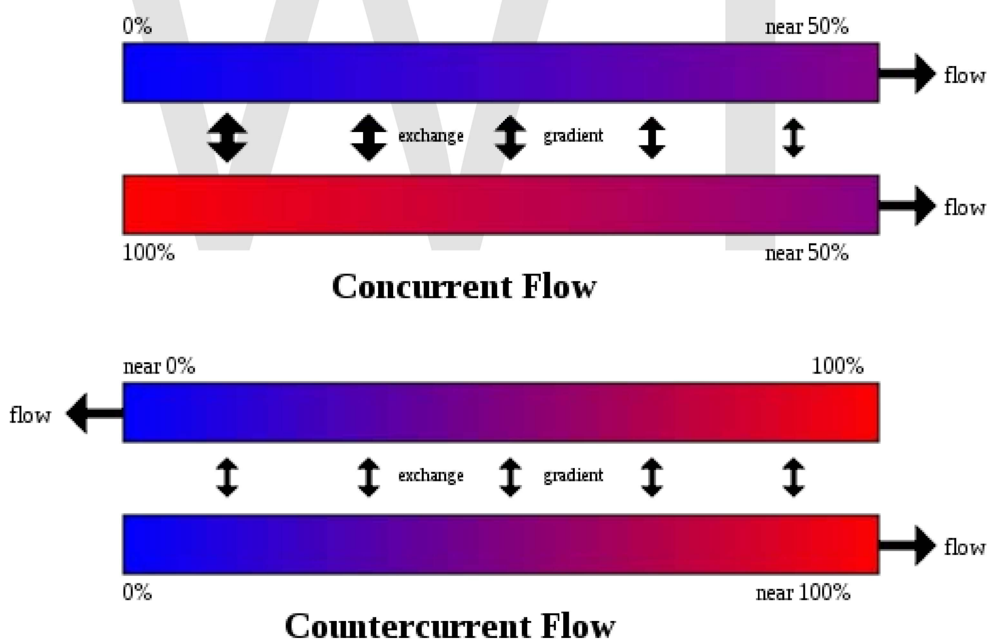
The distance between the sheets in the spiral channels are maintained by using spacer studs that were welded prior to rolling. Once the main spiral pack has been rolled, alternate top and bottom edges are welded and each end closed by a gasketed flat or conical cover bolted to the body. This ensures no mixing of the two fluids will occur. If a leakage happens, it will be from the periphery cover to the atmosphere, or to a passage containing the same fluid.

Self cleaning

SHEs are often used in the heating of fluids which contain solids and thus have a tendency to foul the inside of the heat exchanger. The low pressure drop gives the SHE its ability to handle fouling easier. The SHE uses a “self cleaning” mechanism, whereby fouled surfaces cause a localized increase in fluid velocity, thus increasing the drag (or fluid friction) on the fouled surface, thus helping to dislodge the blockage and keep the heat exchanger clean. "The internal walls that make up the heat transfer surface are often rather thick, which makes the SHE very robust, and able to last a long time in demanding environments." They are also easily cleaned, opening out like an oven where any build up of foulant can be removed by pressure washing.

Self-Cleaning Water filters are used to keep the system clean and running without the need to shut down or replace cartridges and bags.

Flow Arrangements



Concurrent and countercurrent flow.

There are three main types of flows in a spiral heat exchanger:

1. **Countercurrent Flow**: Fluids flow in opposite directions. These are used for liquid-liquid, condensing and gas cooling applications. Units are usually mounted

vertically when condensing vapour and mounted horizontally when handling high concentrations of solids.

2. **Spiral Flow/Cross Flow:** One fluid is in spiral flow and the other in a cross flow. Spiral flow passages are welded at each side for this type of spiral heat exchanger. This type of flow is suitable for handling low density gases which passes through the cross flow, avoiding pressure loss. It can be used for liquid-liquid applications if one liquid has a considerably greater flow rate than the other.
3. **Distributed Vapour/Spiral flow:** This design is a condenser, and is usually mounted vertically. It is designed to cater for the sub-cooling of both condensate and non-condensables. The coolant moves in a spiral and leaves via the top. Hot gases that enter leave as condensate via the bottom outlet.

Applications

The SHE is good for applications such as pasteurization, digester heating, heat recovery, pre-heating (see: recuperator), and effluent cooling. For sludge treatment, SHEs are generally smaller than other types of heat exchangers.

Selection

Due to the many variables involved, selecting optimal heat exchangers is challenging. Hand calculations are possible, but many iterations are typically needed. As such, heat exchangers are most often selected via computer programs, either by system designers, who are typically engineers, or by equipment vendors.

In order to select an appropriate heat exchanger, the system designers (or equipment vendors) would firstly consider the design limitations for each heat exchanger type. Although cost is often the first criterion evaluated, there are several other important selection criteria which include:

- High/ Low pressure limits
- Thermal Performance
- Temperature ranges
- Product Mix (liquid/liquid, particulates or high-solids liquid)
- Pressure Drops across the exchanger
- Fluid flow capacity
- Cleanability, maintenance and repair
- Materials required for construction
- Ability and ease of future expansion

Choosing the right heat exchanger (HX) requires some knowledge of the different heat exchanger types, as well as the environment in which the unit must operate. Typically in the manufacturing industry, several differing types of heat exchangers are used for just the one process or system to derive the final product. For example, a kettle HX for pre-heating, a double pipe HX for the 'carrier' fluid and a plate and frame HX for final cooling. With sufficient knowledge of heat exchanger types and operating requirements, an appropriate selection can be made to optimise the process.

Monitoring and maintenance

Online monitoring of commercial heat exchangers is done by tracking the overall heat transfer coefficient. The overall heat transfer coefficient tends to decline over time due to fouling.

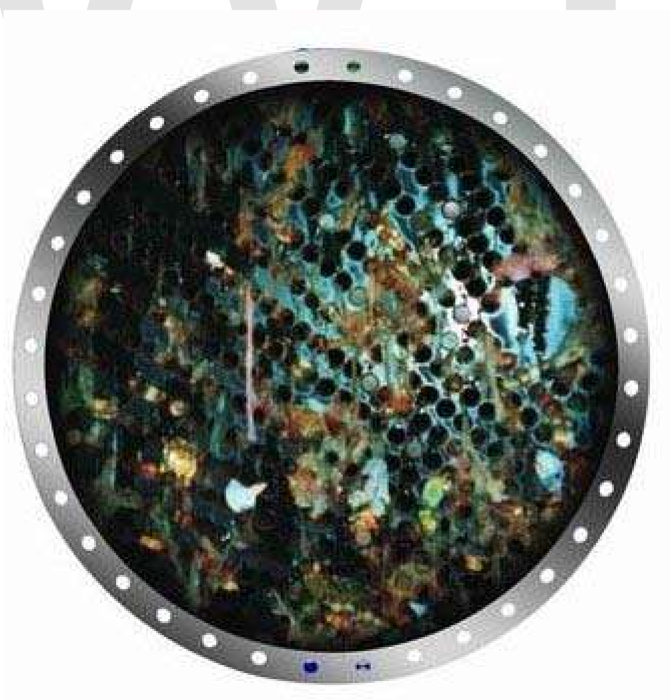
$U=Q/A\Delta T_{lm}$

By periodically calculating the overall heat transfer coefficient from exchanger flow rates and temperatures, the owner of the heat exchanger can estimate when cleaning the heat exchanger will be economically attractive.

Integrity inspection of plate and tubular heat exchanger can be tested in situ by the conductivity or helium gas methods. These methods confirm the integrity of the plates or tubes to prevent any cross contamination and the condition of the gaskets.

Mechanical integrity monitoring of heat exchanger tubes may be conducted through Nondestructive methods such as eddy current testing.

Fouling



A heat exchanger in a steam power station contaminated with macrofouling.

Fouling occurs when impurities deposit on the heat exchange surface. Deposition of these impurities can be caused by:

- Low wall shear stress
- Low fluid velocities
- High fluid velocities
- Reaction product solid precipitation
- Precipitation of dissolved impurities due to elevated wall temperatures

The rate of heat exchanger fouling is determined by the rate of particle deposition less re-entrainment/suppression. This model was originally proposed in 1959 by Kern and Seaton.

Crude Oil Exchanger Fouling. In commercial crude oil refining, crude oil is heated from 70F to 650F prior to entering the distillation column. A series of shell and tube heat exchangers is typically used to exchange heat between the crude oil and other oil streams, in order to get the crude to 500F prior to heating in a furnace. Fouling occurs on the crude side of these exchangers due to asphaltene insolubility. The nature of asphaltene solubility in crude oil was successfully modeled by Wiehe and Kennedy. The precipitation of insoluble asphaltenes in crude preheat trains has been successfully modeled as a first order reaction by Ebert and Panchal who expanded on the work of Kern and Seaton.

Cooling Water Fouling. Cooling water systems are susceptible to fouling. Cooling water typically has a high total dissolved solids content and suspended colloidal solids. Localized precipitation of dissolved solids occurs at the heat exchange surface due to wall temperatures higher than bulk fluid temperature. Low fluid velocities allow suspended solids to settle on the heat exchange surface. Cooling water is typically on the tube side of a shell and tube exchanger because it's easy to clean. To prevent fouling, designers typically ensure that cooling water velocity is greater than 3 ft/s and bulk fluid temperature is maintained less than 140F. Other approaches to control fouling control combine the “blind” application of biocides and anti-scale chemicals with periodic lab testing.

Maintenance

Plate heat exchangers need to be disassembled and cleaned periodically. Tubular heat exchangers can be cleaned by such methods as acid cleaning, sandblasting, high-pressure water jet, bullet cleaning, or drill rods.

In large-scale cooling water systems for heat exchangers, water treatment such as purification, addition of chemicals, and testing, is used to minimize fouling of the heat exchange equipment. Other water treatment is also used in steam systems for power plants, etc. to minimize fouling and corrosion of the heat exchange and other equipment.

A variety of companies have started using water borne oscillations technology to prevent biofouling. Without the use of chemicals, this type of technology has helped in providing a low-pressure drop in heat exchangers.

In nature

Humans

The human nasal passages serve as a heat exchanger, which warms air being inhaled and cools air being exhaled. You can demonstrate its effectiveness by putting your hand in front of your face and exhaling, first through your nose and then through your mouth. Air exhaled through your nose will be substantially cooler.

In species that have external testes (such as humans), the artery to the testis is surrounded by a mesh of veins called the pampiniform plexus. This cools the blood heading to the testis, while reheating the returning blood.

Birds, fish, marine mammals

"Countercurrent" heat exchangers occur naturally in the circulation system of fish, whales and other marine mammals. Arteries to the skin carrying warm blood are intertwined with veins from the skin carrying cold blood, causing the warm arterial blood to exchange heat with the cold venous blood. This reduces the overall heat loss in cold waters. Heat exchangers are also present in the tongue of baleen whales as large volumes of water flow through their mouths. Wading birds use a similar system to limit heat losses from their body through their legs into the water.

In industry

Heat exchangers are widely used in industry both for cooling and heating large scale industrial processes. The type and size of heat exchanger used can be tailored to suit a process depending on the type of fluid, its phase, temperature, density, viscosity, pressures, chemical composition and various other thermodynamic properties.

In many industrial processes there is waste of energy or a heat stream that is being exhausted, heat exchangers can be used to recover this heat and put it to use by heating a different stream in the process. This practice saves a lot of money in industry as the heat supplied to other streams from the heat exchangers would otherwise come from an external source which is more expensive and more harmful to the environment.

Heat exchangers are used in many industries, some of which include:

- Waste water treatment
- Refrigeration systems
- Wine-brewery industry
- Petroleum industry.

In the waste water treatment industry, heat exchangers play a vital role in maintaining optimal temperatures within anaerobic digesters so as to promote the growth of microbes which remove pollutants from the waste water. The common types of heat exchangers used in this application are the double pipe heat exchanger as well as the plate and frame heat exchanger.

In aircraft

In commercial aircraft heat exchangers are used to take heat from the engine's oil system to heat cold fuel. This improves fuel efficiency, as well as reduces the possibility of water entrapped in the fuel freezing in components.

In early 2008, a Boeing 777 flying as British Airways Flight 38 crashed just short of the runway. In an early-2009 Boeing-update sent to aircraft operators, the problem was identified as specific to the Rolls-Royce engine oil-fuel flow heat exchangers. Other heat exchangers, or Boeing 777 aircraft powered by GE or Pratt and Whitney engines, are not affected by the problem.

A model of a simple heat exchanger

A simple heat exchanger might be thought of as two straight pipes with fluid flow, which are thermally connected. Let the pipes be of equal length L, carrying fluids with heat capacity C_i (energy per unit mass per unit change in temperature) and let the mass flow rate of the fluids through the pipes be j_i (mass per unit time), where the subscript i applies to pipe 1 or pipe 2.

The temperature profiles for the pipes are $T_1(x)$ and $T_2(x)$ where x is the distance along the pipe. Assume a steady state, so that the temperature profiles are not functions of time. Assume also that the only transfer of heat from a small volume of fluid in one pipe is to the fluid element in the other pipe at the same position. There will be no transfer of heat along a pipe due to temperature differences in that pipe. By Newton's law of cooling the rate of change in energy of a small volume of fluid is proportional to the difference in temperatures between it and the corresponding element in the other pipe:

$$\frac{du_1}{dt} = \gamma(T_2 - T_1)$$
$$\frac{du_2}{dt} = \gamma(T_1 - T_2)$$

where $u_i(x)$ is the thermal energy per unit length and γ is the thermal connection constant per unit length between the two pipes. This change in internal energy results in a change in the temperature of the fluid element. The time rate of change for the fluid element being carried along by the flow is:

$$\frac{du_1}{dt} = J_1 \frac{dT_1}{dx}$$
$$\frac{du_2}{dt} = J_2 \frac{dT_2}{dx}$$

where $J_i = C_i j_i$ is the "thermal mass flow rate". The differential equations governing the heat exchanger may now be written as:

$$J_1 \frac{\partial T_1}{\partial x} = \gamma(T_2 - T_1)$$
$$J_2 \frac{\partial T_2}{\partial x} = \gamma(T_1 - T_2).$$

Note that, since the system is in a steady state, there are no partial derivatives of temperature with respect to time, and since there is no heat transfer along the pipe, there are no second derivatives in x as is found in the heat equation. These two coupled first-order differential equations may be solved to yield:

$$T_1 = A - \frac{Bk_1}{k} e^{-kx}$$
$$T_2 = A + \frac{Bk_2}{k} e^{-kx}$$

where $k_1 = \gamma / J_1$, $k_2 = \gamma / J_2$, $k = k_1 + k_2$ and A and B are two as yet undetermined constants of integration. Let T_{10} and T_{20} be the temperatures at x=0 and let T_{1L} and T_{2L} be the temperatures at the end of the pipe at x=L. Define the average temperatures in each pipe as:

$$\overline{T}_1 = \frac{1}{L} \int_0^L T_1(x) dx$$
$$\overline{T}_2 = \frac{1}{L} \int_0^L T_2(x) dx.$$

Using the solutions above, these temperatures are:

$$T_{10} = A - \frac{Bk_1}{k} \qquad T_{20} = A + \frac{Bk_2}{k}$$
$$T_{1L} = A - \frac{Bk_1}{k} e^{-kL} \qquad T_{2L} = A + \frac{Bk_2}{k} e^{-kL}$$
$$\overline{T}_1 = A - \frac{Bk_1}{k^2 L}(1 - e^{-kL}) \qquad \overline{T}_2 = A + \frac{Bk_2}{k^2 L}(1 - e^{-kL}).$$

Choosing any two of the above temperatures will allow the constants of integration to be eliminated, and that will allow the other four temperatures to be found. The total energy transferred is found by integrating the expressions for the time rate of change of internal energy per unit length:

$$\frac{dU_1}{dt} = \int_0^L \frac{du_1}{dt}\,dx = J_1(T_{1L} - T_{10}) = \gamma L(\overline{T}_2 - \overline{T}_1)$$
$$\frac{dU_2}{dt} = \int_0^L \frac{du_2}{dt}\,dx = J_2(T_{2L} - T_{20}) = \gamma L(\overline{T}_1 - \overline{T}_2).$$

By the conservation of energy, the sum of the two energies is zero. The quantity $\overline{T}_2 - \overline{T}_1$ is known as the "log mean temperature difference" and is a measure of the effectiveness of the heat exchanger in transferring heat energy.

Chapter 10

Radiator (Engine Cooling)

A typical automobile coolant radiator

Radiators are used for cooling internal combustion engines, mainly in automobiles but also in piston-engined aircraft, railway locomotives, motorcycles, stationary generating plant or any similar use of such an engine.

They operate by passing a liquid *coolant* through the engine block, where it is heated, then through the radiator itself where it loses this heat to the atmosphere. This coolant is usually water-based, but may also be oil. It is usual for the coolant flow to be pumped, also for a fan to blow air through the radiator.

Automobiles

In automobiles with a liquid-cooled internal combustion engine a radiator is connected to channels running through the engine and cylinder head, through which a liquid (coolant) is pumped. This liquid may be water (in climates where water is unlikely to freeze), but is more commonly a mixture of water and antifreeze in proportions appropriate to the climate. Antifreeze itself is usually ethylene glycol or propylene glycol (with a small amount of corrosion inhibitor).

The radiator transfers the heat from the fluid inside to the air outside, thereby cooling the engine. Radiators are also often used to cool automatic transmissions, air conditioners, and sometimes to cool engine oil. Radiators are typically mounted in a position where they receive airflow from the forward movement of the vehicle, such as behind a front grill. Where engines are mid- or rear-mounted, it is common to mount the radiator behind a front grill to achieve sufficient airflow, even though this requires long coolant pipes. Alternatively, the radiator may draw air from the flow over the top of the vehicle or from a side-mounted grill. For long vehicles, such as buses, side airflow is most common for engine and transmission cooling and top airflow most common for air conditioner cooling.

Radiator construction

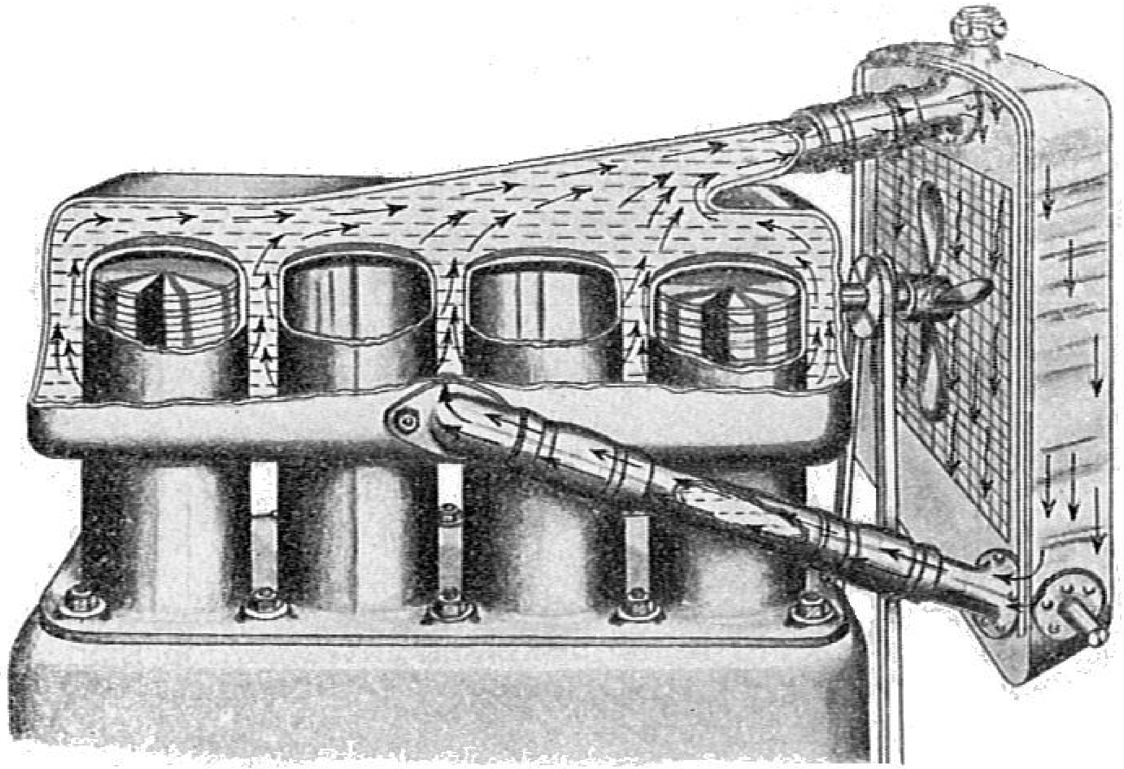
Automobile radiators are constructed of a pair of header tanks, linked by a core with many narrow passageways, thus a high surface area relative to its volume. This core is usually made of stacked layers of metal sheet, pressed to form channels and soldered or brazed together. For many years radiators were made from brass or copper cores soldered to brass headers. Modern radiators save money and weight by using plastic headers and may use aluminium cores. This construction is less easily repaired than traditional materials.

Honeycomb radiator tubes

An earlier construction method was the honeycomb radiator. Round tubes were swaged into hexagons at their ends, then stacked together and soldered. As they only touched at their ends, this formed what became in effect a solid water tank with many air tubes through it.

Vintage cars may also have used radiator cores made from coiled tube, a less-efficient but simpler construction.

Coolant pumps



Thermosysphon cooling system of 1937, without circulating pump

Radiators first used downward vertical flow, driven solely by a thermosyphon effect. Coolant is heated in the engine, becoming less dense and so rising, cooled, denser coolant in the radiator falling in turn. This effect is sufficient for low-power stationary engines, but inadequate for all but the earliest automobiles. A common fallacy is to assume that a greater vertical separation between engine and radiator can increase the thermosyphon effect. Once the hot and cold headers are separated sufficiently to reach their equilibrium temperatures though, any further separation merely increases pipework length and flow restriction.

All automobiles for many years have used centrifugal pumps to circulate their coolant, driven by geared drives or more commonly by a belt drive. This "fan belt" has a well-established reputation for being slightly unreliable, a failure being rapidly obvious as the engine overheats. Despite the name though, it's the *coolant pump's* failure that causes the overheating, not the fan.

Heater

A system of valves or baffles, or both, is usually incorporated to simultaneously operate a small radiator inside the car. This small radiator, and the associated blower fan, is called the heater core, and serves to warm the cabin interior. Like the radiator, the heater core acts by removing heat from the engine. For this reason, automotive technicians often advise operators to turn ***on*** the heater and set it to high if the engine is overheating.

Temperature control

Waterflow control

Car engine thermostat

The engine temperature is primarily controlled by a wax-pellet type of thermostat, a valve which opens once the engine has reached its optimum operating temperature.

When the engine is cold the thermostat is closed, with a small bypass flow so that the thermostat experiences changes to the coolant temperature as the engine warms up. Coolant is directed by the thermostat to the inlet of the circulating pump and is returned directly to the engine, bypassing the radiator. Directing water to circulate only through the engine allows the temperature to reach optimum operating temperature as quickly as possible whilst avoiding localised "hot spots". Once the coolant reaches the thermostat's activation temperature it opens, allowing water to flow through the radiator to prevent the temperature rising higher.

Once at optimum temperature, the thermostat controls the flow of coolant to the radiator so that the engine continues to operate at optimum temperature. Under peak load conditions, such as labouring slowly up a steep hill whilst heavily laden on a hot day, the thermostat will be approaching fully open because the engine will be producing near to maximum power while the velocity of air flow across the radiator is low. (The velocity of air flow across the radiator has a major effect on its ability to dissipate heat.) Conversely, when cruising fast downhill on a motorway on a cold night on a light throttle, the thermostat will be nearly closed because the engine is producing little power, and the radiator is able to dissipate much more heat than then engine is producing. Allowing too much flow of coolant to the radiator would result in the engine being over cooled and operating at lower than optimum temperature. A side effect of this would be that the passenger compartment heater would not be able to put out enough heat to keep the passengers warm.

The thermostat is therefore constantly moving throughout its range, responding to changes in vehicle operating load, speed and external temperature, to keep the engine at its optimum operating temperature.

Airflow control

Other factors influence the temperature of the engine including radiator size and the type of radiator fan. The size of the radiator (and thus its cooling capacity) is chosen such that it can keep the engine at the design temperature under the most extreme conditions a vehicle is likely to encounter (such as climbing a mountain whilst fully loaded on a hot day).

Airflow speed through a radiator is a major influence on the heat it loses. Vehicle speed affects this, in rough proportion to the engine effort, thus giving crude self-regulatory feedback. Where an additional cooling fan is driven by the engine, this also tracks engine speed similarly.

Engine-driven fans are often regulated by a viscous-drive clutch from the drivebelt, which slips and reduces the fan speed at low temperatures. This improves fuel efficiency by not wasting power on driving the fan unnecessarily. On modern vehicles, further regulation of cooling rate is provided by either variable speed or cycling radiator fans. Electric fans are controlled by a thermostatic switch or the engine control unit. Electric fans also have the advantage of giving good airflow and cooling at low engine revs or when stationary, such as in slow-moving traffic.

Before the development of viscous-drive and electric fans, engines were fitted with simple fixed fans that drew air through the radiator at all times. Vehicles whose design required the installation of a large radiator to cope with heavy work at high temperatures, such as commercial vehicles and tractors would often run cool in cold weather under light loads, even with the presence of a thermostat, as the large radiator and fixed fan caused a rapid and significant drop in coolant temperature as soon as the thermostat opened. This problem could be solved by fitting a **radiator blind** to the radiator which could be adjusted to partially or fully block the airflow. At its simplest the blind was a roll of material (such as canvas or rubber that was unfurled along the length of the radiator to cover the desired portion. Some vehicles had a series of shutters that could be adjusted from the driver's seat to provide a very fine degree of control.

These AEC Regent III RT buses are fitted with radiator blinds, seen here covering the lower half of the radiators.

Coolant pressure

Because the thermal efficiency of internal combustion engines increases with internal temperature the coolant is kept at higher-than-atmospheric pressure to increase its boiling point. A calibrated pressure-relief valve is usually incorporated in the radiator's fill cap. This pressure varies between models, but typically ranges from 9 psi (0.6 bar) to 15 psi (1.0 bar).

As the coolant expands with increasing temperature its pressure in the closed system must increase. Ultimately the pressure relief valve opens and excess fluid is dumped into an overflow container. Fluid overflow ceases when the thermostat modulates the rate of cooling to keep the temperature of the coolant at optimum. When the coolant cools and contracts (as conditions change or when the engine is switched off) the fluid is returned to the radiator through additional valving in the cap.

Coolant

Before World War II, radiator coolant was usually plain water. Antifreeze was used solely to control freezing, and this was often only done in cold weather.

Development in high-performance aircraft engines required improved coolants with higher boiling points, leading to the adoption of glycol or water-glycol mixtures. These led to the adoption of glycols for their antifreeze properties.

Since the development of aluminium or mixed-metal engines, corrosion inhibition has become even more important than antifreeze, and in all regions and seasons.

Boiling or overheating

On this type system, if the coolant in the overflow container gets too low, fluid transfer to overflow will cause an increased loss by vaporizing the engine coolant.

Severe engine damage can be caused by overheating, by overloading or system defect, when the coolant is evaporated to a level below the water pump. This can happen without warning because, at that point, the sending units are not exposed to the coolant to indicate the excessive temperature.

To protect the unwary the cap often contains a mechanism that attempts to relieve the internal pressure before the cap can be fully opened. Some scalding of one's hands can easily occur in this event. Opening a hot radiator drops the system pressure immediately and may cause a sudden ebullition of super-heated coolant which can cause severe burns.

History

The invention of the automobile water radiator is attributed to Karl Benz. Wilhelm Maybach designed the first honeycomb radiator for the Mercedes 35hp.

Supplementary radiators

It is sometimes necessary for a car to be equipped with a second, or auxiliary, radiator to increase the cooling capacity, when the size of the original radiator cannot be increased. The second radiator is plumbed in series with the main radiator in the circuit. This was the case when the Audi 100 was first turbocharged creating the 200. These are not to be confused with intercoolers.

Some engines have an oil cooler, a separate small radiator to cool the engine oil. Cars with an automatic transmission often have extra connections to the radiator, allowing the transmission fluid to transfer its heat to the coolant in the radiator. These may be either oil-air radiators, as for a smaller version of the main radiator. More simply they may be oil-water coolers, where an oil pipe is inserted inside the water radiator. As water is denser than air, this offers comparable cooling (within limits) from a less complex and thus cheaper oil cooler.

Turbo charged or supercharged engines may have an intercooler, which is an air-to-air or air-to-water radiator used to cool the incoming air charge—not to cool the engine.

Aircraft

Aircraft with liquid-cooled piston engines (usually inline engines rather than radial) also require radiators. As airspeed is higher than for cars, these are efficiently cooled in flight and so do not require large areas or cooling fans. Many high-performance aircraft however suffer extreme overheating problems when idling on the ground - a mere 7 minutes for a Spitfire.

Surface radiators

Reducing drag is a major goal in aircraft design, including the design of cooling systems. An early technique was to take advantage of an aircraft's abundant airflow to replace the honeycomb core (many surfaces, with a high ratio of surface to volume) by a surface mounted radiator. This uses a single surface blended into the fuselage or wing skin, with the coolant flowing through pipes at the back of this surface.

As they are so dependent on airspeed, surface radiators are even more prone to overheating when ground-running. Racing aircraft such as the Supermarine S.6B, a racing seaplane with radiators built into the upper surfaces of its floats, have been described as "being flown on the temperature gauge" as the main limit on their performance.

Surface radiators have also been used by a few high-speed racing cars, such as Malcolm Campbell's Blue Bird of 1928.

Radiator thrust

An aircraft radiator comprises a duct wherein heat is added. As a result, this is effectively a jet engine. High-performance piston aircraft with well-designed low-drag radiators (notably the P-51 Mustang) derived thrust from this effect. The thrust was significant enough to offset the drag of the duct the radiator was enclosed in and allowed the aircraft to achieve zero cooling drag. At one point, there were even plans to equip the Spitfire with a ramjet, by injecting fuel into this duct after the radiator and igniting it. Although ramjets normally require a supersonic airspeed, this light-up speed can be reduced where heat is being added, such as in a radiator duct.

Steam cooling

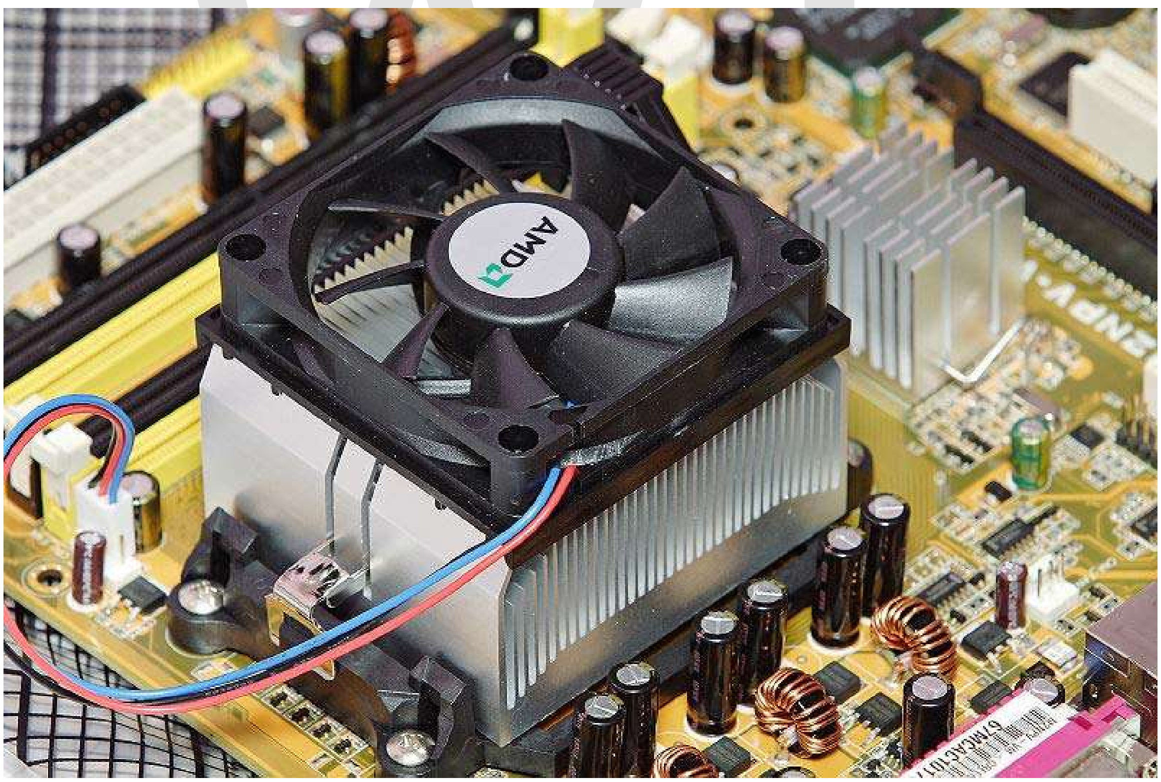
Pressurized cooling systems operate by adding heat to the coolant fluid, causing it to rise in temperature in inverse proportion to its specific heat capacity. With the need to keep the final temperature below boiling point, this limits the amount of heat that a given mass-flow of coolant can dissipate.

Attempts were made with aero-engines of the 1930s, notably the Rolls-Royce Goshawk, to exceed this limit by *allowing* the coolant to boil. This absorbs an amount of heat equivalent to the specific heat of vaporization, which for water is more than five times the energy required to heat the same quantity of water from 0°C to 100°C. Obviously this allows the necessary cooling effect with far less mass of coolant.

The practical difficulty was the need to provide condensers rather than radiators. Cooling was now needed not just for hot, dense liquid coolant, but for low-density vapor. This required a condenser far larger, and with higher drag, than a radiator. For aircraft, especially high-speed aircraft, it was soon realized this configuration was unworkable and so evaporative cooling was abandoned.

Chapter 11

Computer Cooling



An OEM AMD heatsink mounted onto a motherboard.

Computer cooling is required to remove the waste heat produced by computer components, to keep components within their safe operating temperature limits. Various cooling methods help to improve processor performance or reduce the noise of cooling fans.

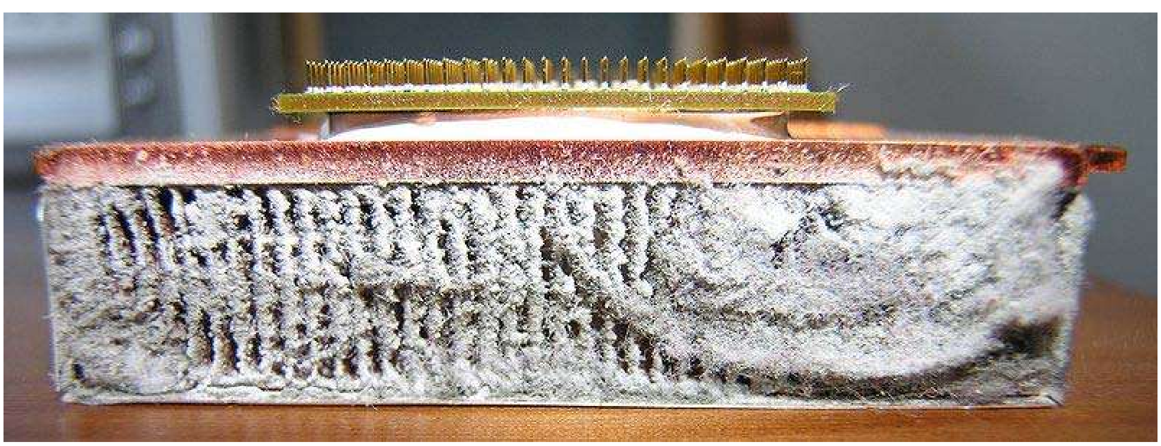
Components which produce heat and are susceptible to performance loss and damage include integrated circuits such as CPUs, chipset and graphics cards, along with hard drives (though excessive cooling of hard drives has been found to have negative effects). Overheated parts fail early and may give sporadic problems resulting in system freezes or crashes.

Both integral and peripheral means are used to keep the temperature of each component at a safe level. With regard to integral means, CPU and GPUs are designed with energy efficiency, including heat dissipation, in mind; though improved efficiency may only allow increased performance instead of reduced heat. Peripheral means include heat sinks to increase the surface area which dissipates heat, fans to speed up the exchange of air heated by the computer parts for cooler ambient air, and in some cases softcooling, the throttling of computer parts in order to decrease heat generation.

As a safety measure, many computers are designed to turn themselves off if the internal temperature exceeds a certain point. Alternatively, some have an option in their BIOS that allows the user to determine if the system emits an alarm beep or shuts itself down when the core temperature reaches the level set by the user. However, setting this incorrectly can result in hardware damage or erratic system behaviour.

Causes of heat build up

The amount of heat generated by an integrated circuit (e.g., a CPU or GPU), the prime cause of heat build up in modern computers, is a function of the efficiency of its design, the technology used in its construction and the frequency and voltage at which it operates.



The dust buildup on this laptop CPU heat sink after three years of use has made the laptop unusable due to frequent thermal shutdowns.

In operation, the temperature of a computer's components will rise until the heat lost to the surroundings is equal to the heat produced by the component, and thus the temperature of the component reaches equilibrium. For reliable operation, the equilibrium temperature must be sufficiently low for the structure of the computer's circuits to survive.

Cooling can be hindered by:

- **Dust** acting as a thermal insulator and impeding airflow, thereby reducing heat sink and fan performance.
- **Poor airflow** including turbulence due to friction against impeding components such as ribbon cables, or improper orientation of fans, can reduce the amount of air flowing through a case and even create localized whirlpools of hot air in the case.
- **Poor heat transfer** due to a lack of, or poor application of thermal compounds and sufficient surface area of heat sinks to radiate off the heat.

Damage prevention

Thermal sensors in some CPUs and GPUs can shut down the computer when high temperatures are detected. However, reliance on such measures may not prevent repeated incidents from permanently damaging the integrated circuit.

An integrated circuit may also shut down parts of the circuit when it is idling, or to scale back the clock speed under low workloads or high temperatures, with the goal of reducing both power use and heat generation.

Air cooling

Fans are most commonly used for air cooling. A *computer fan* may be attached to the computer case, or attached to a CPU, GPU, chipset, PSU, hard drive or PCI slot. Common fan sizes include 40, 60, 80, 92, 120, and 140 mm. Recently, 200mm fans have begun to creep into the performance market, as well as even larger sizes such as 230 and 240mm.

In desktops

Typical airflow through a desktop ATX case.

Desktop computers typically use one or more fans for cooling. Almost all desktop power supplies have at least one fan to exhaust air from the case. Most manufacturers recommend bringing cool, fresh air in at the bottom front of the case, and exhausting warm air from the top rear.

If there is more air being forced into the system than is being pumped out (due to an imbalance in the number or strength of fans), this is referred to as a "positive" airflow, as the pressure inside the unit would be higher than outside. A balanced or neutral airflow is the most efficient, although a slightly positive airflow results in less dust build up if dust filters are used. Negative pressure inside the case can create problems such as clogged optical drives due to sucking in air (and dust).

In high density computing

Data centers typically contain many racks of flat 1U servers. Air is drawn in at the front of the rack and exhausted at the rear. Because data centers typically contain such large numbers of computers and other power-consuming devices, they risk overheating of the various components if no additional measures are taken. Thus, extensive HVAC systems are used. Often a raised floor is used so the area under the floor may be used as a large plenum for cooled air and power cabling.

Another way of accommodating large numbers of systems in a small space are blade chassis. In contrast to the horizontal orientation of flat servers, blade chassis are often oriented vertically. This vertical orientation facilitates convection. When the air is heated by the hot components, it tends to flow to the top on its own, creating a natural air flow along the boards. This stack effect can help to achieve the desired air flow and cooling. Some manufacturers expressly take advantage of this effect.

In laptop computing

Most laptops use air cooling in order to keep the CPU and other components within their operating temperature range. Because the fan's air is forced through a small port, the fan and heatsinks can be clogged by dust or be obstructed by objects placed near the port. This can cause overheating, and can be a cause of component failure in laptops. The severity of this problem varies with laptop design, its use and power dissipation. With recent reductions in CPU power dissipation, this problem can be anticipated to reduce in severity.

Liquid submersion cooling

An uncommon practice is to submerge the computer's components in a thermally conductive liquid. Personal computers that are cooled in this manner do not generally require any fans or pumps, and may be cooled exclusively by passive heat exchange between the computer's parts, the cooling fluid and the ambient air. Extreme component density supercomputers such as the Cray-2 and Cray T90 used additional liquid to chilled liquid heat exchangers in order to facilitate heat removal.

The liquid used must have sufficiently low electrical conductivity in order for it not to interfere with the normal operation of the computer's components. If the liquid is somewhat electrically conductive, it may be necessary to insulate certain parts of components susceptible to electromagnetic interference, such as the CPU. For these reasons, it is preferred that the liquid be dielectric.

Liquids commonly used in this manner include various liquids invented and manufactured for this purpose by 3M, such as Fluorinert. Various oils, including but not limited to cooking, motor and silicone oils have all been successfully used for cooling personal computers.

Evaporation can pose a problem, and the liquid may require either to be regularly refilled or sealed inside the computer's enclosure. Liquid may also slowly seep into and damage components, particularly capacitors, causing an initially functional computer to fail after hours or days immersed.

Waste heat reduction

Where full-power, full-featured modern computers are not required, some companies opt to use less powerful computers or computers with fewer features. For example: in an office setting, the IT department may choose a thin client or a diskless workstation thus cutting out the heat-laden components such as hard drives and optical disks. These devices are also often powered with direct current from an external power supply brick which still wastes heat, but not inside the computer itself.

The components used can greatly affect the power consumption and hence waste heat. A VIA EPIA motherboard with CPU typically generates approximately 25 watts of heat whereas a Pentium 4 motherboard typically generates around 140 watts. While the former has considerably less computing power, both types are adequate and responsive for tasks such as word processing and spreadsheets. Choosing a LCD monitor rather than a CRT can also reduce power consumption and excess room heat, as well as the added benefit of increasing available physical desk space.

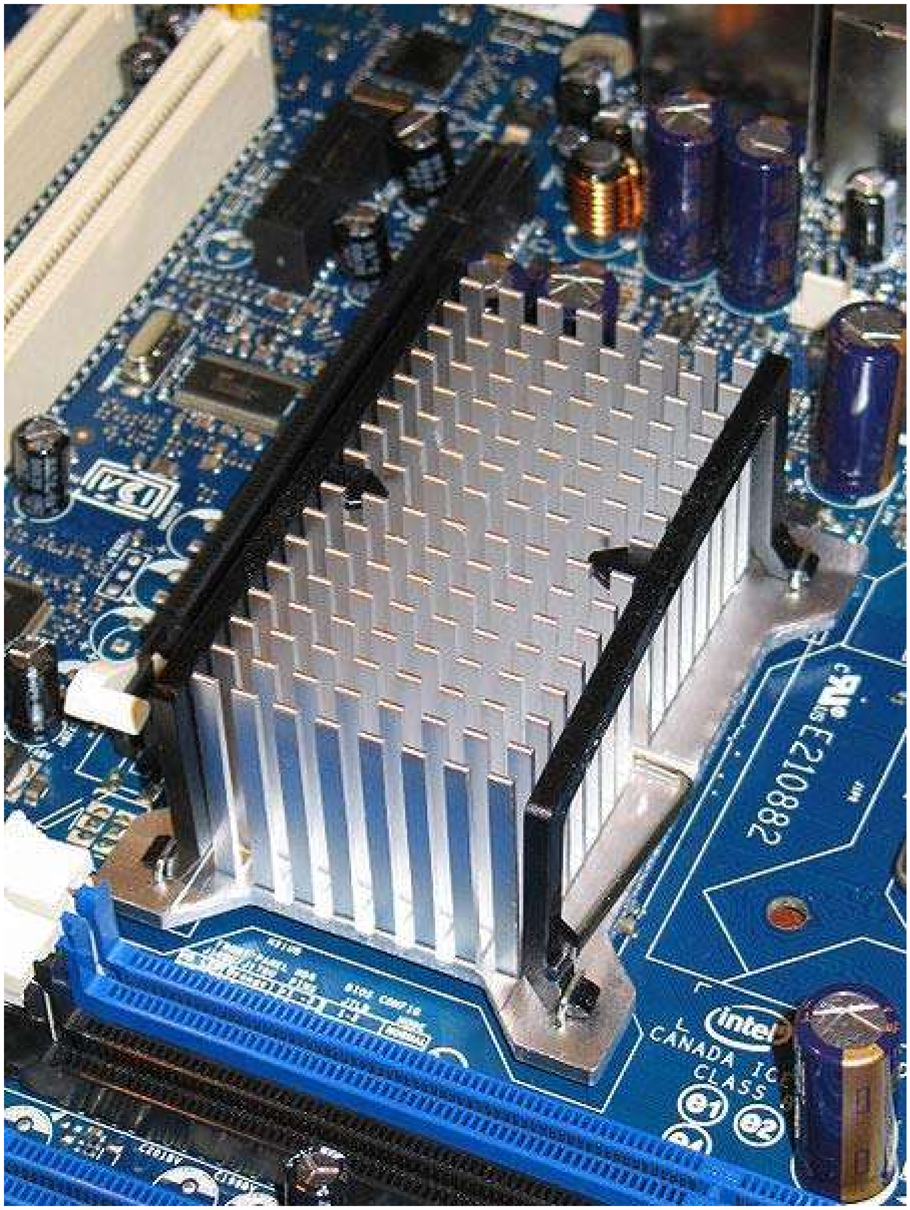
Conductive and radiative cooling

Some laptop components, such as hard drives and optical drives, are commonly cooled by having them make contact with the computer's frame, increasing the surface area which can radiate and otherwise exchange heat.

Spot cooling

In addition to system cooling, various individual components usually have their own cooling systems in place. Components which are individually cooled include, but are not limited to, the CPU, GPU and the Northbridge chip. Some cooling solutions employ one or more methods of cooling, and may also utilize logic and/or temperature sensors in order to vary the power used in active cooling components.

Passive heat-sink cooling



Passive heatsink on an Intel GMA graphics chip.

Passive heat-sink cooling involves attaching a block of machined or extruded metal to the part that needs cooling. A thermal adhesive may be used. More commonly for a personal-computer CPU, a clamp holds the heat sink directly over the chip, with a thermal grease or thermal pad spread between. This block usually has fins and ridges to increase its surface area. The heat conductivity of metal is much better than that of air, and it radiates heat better than does the component that it is protecting (usually an integrated circuit or CPU). Until recently, fan-cooled aluminium heat sinks were the norm for desktop computers. Today, many heat sinks feature copper base-plates or are entirely made of copper.

Dust buildup between the metal fins of a heat sink gradually reduces efficiency, but can be countered with a gas duster by blowing away the dust along with any other unwanted excess material.

Passive heat sinks are commonly found on older CPUs, parts that do not get very hot (such as the chipset), and low-power computers.

Usually a heat-sink is attached to the integrated heat spreader (IHS), essentially a large, flat plate attached to the CPU, with conduction paste layered between. This dissipates or spreads the heat locally. Unlike a heat sink, a spreader is meant to redistribute heat, not to remove it. In addition, the IHS protects the fragile CPU.

Passive cooling involves no fan noise.

Active heat-sink cooling

Active heat sink with a fan and heat pipes.

Active heat-sink cooling uses the same principle as passive, with the addition of a fan that blows over or through the heat sink. The air movement increases the rate at which the heat sink can exchange heat with the ambient air. Active heat sinks are the primary method of cooling modern processors and graphics cards.

The buildup of dust is greatly increased with active heat-sink cooling, because the fan continually takes in the dust present in the surrounding air.

Peltier cooling or thermoelectric cooling

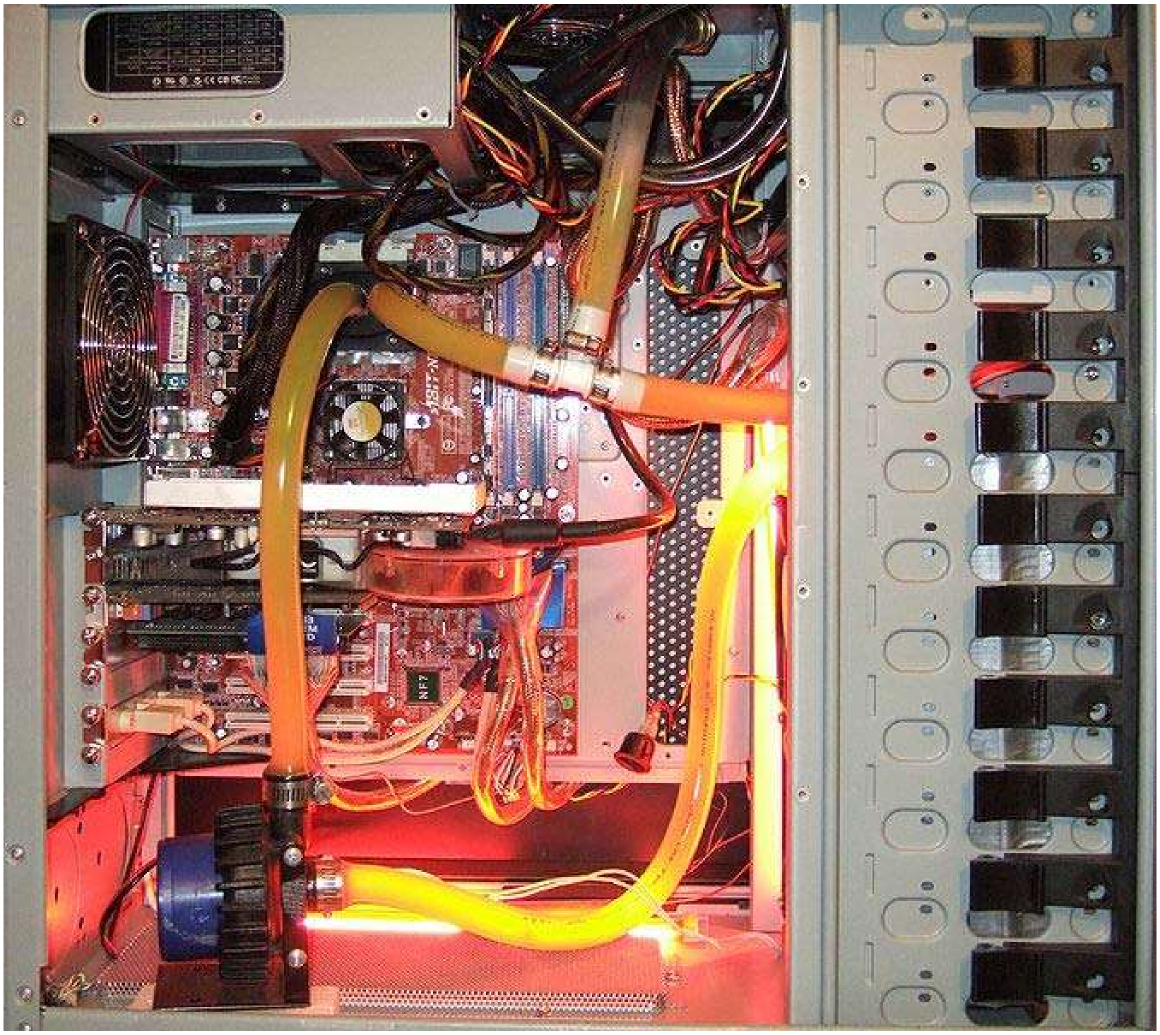
In 1821 T. J. Seebeck discovered that different metals, connected at two different junctions, will develop a micro-voltage if the two junctions are held at different temperatures. This effect is known as the "Seebeck effect"; it is the basic theory behind the TEC (thermoelectric cooling).

In 1834 Jean Peltier discovered the inverse of the Seebeck effect, now known as the "Peltier effect". He found that applying a voltage to a thermocouple creates a temperature differential between two sides. This results in an effective, albeit extremely inefficient heat pump.

Modern TECs use several stacked units each composed of dozens or hundreds of thermocouples laid out next to each other, which allows for a substantial amount of heat transfer. A combination of bismuth and tellurium is most commonly used for thermocouples.

As active heat pumps, TECs can cool the surface of components below ambient temperatures. This is impossible with common radiator cooled water cooling systems and heatpipe HSFs.

Water cooling



DIY Water cooling setup showing 12v pump, CPU Waterblock and the typical application of a T-Line

While originally limited to mainframe computers, water cooling has become a practice largely associated with overclocking in the form of either manufactured kits, or in the form of do-it-yourself setups assembled from individually gathered parts. The past few years has seen water cooling increasing its popularity with pre-assembled, moderate to high performance, desktop computers. Water has the ability to dissipate more heat from the parts being cooled than the various types of metals used in heatsinks, making it suitable for overclocking and high performance computer applications.

Advantages to water cooling include the fact that a system is not limited to cooling one component, but can be set up to cool the central processing unit, graphics processing unit, and/or other components at the same time with the same system. As opposed to air cooling, water cooling is also influenced less by the ambient temperature. Water cooling's comparatively low noise-level compares favorably to that of active cooling, which can become quite noisy. One disadvantage to water cooling is the potential for a coolant leak. Leaked coolant can damage any electronic components it comes in contact with. Another drawback to water cooling is the complexity of the system; an active heat sink is much simpler to build, install, and maintain than a water cooling solution.

Computing folklore holds that users of the Sinclair ZX81, one of the first home computers, had to balance a carton of milk on top of the case to cool it down – perhaps an early form of water cooling.

Heat pipe

A graphics card with a heatpipe cooler design.

A heat pipe is a hollow tube containing a heat transfer liquid. As the liquid evaporates, it carries heat to the cool end, where it condenses and then returns to the hot end (under capillary action, or, in earlier implementations, under gravitation). Heat pipes thus have a much higher effective thermal conductivity than solid materials. For use in computers, the heat sink on the CPU is attached to a larger radiator heat sink. Both heat sinks are hollow as is the attachment between them, creating one large heat pipe that transfers heat from the CPU to the radiator, which is then cooled using some conventional method. This method is expensive and usually used when space is tight (as in small form-factor PCs and laptops), or absolute quiet is needed (such as in computers used in audio production studios during live recording). Because of the efficiency of this method of cooling, many desktop CPUs and GPUs, as well as high end chipsets, use heat pipes in addition to active fan-based cooling to remain within safe operating temperatures.

A new design wrinkle is known as HDT for Heatpipe Direct Touch. In this usage, the heat pipe is in direct contact with the CPU chip skin. Heatpipe Direct Touch was first introduced in the Zaward ZikaRay ZIKA-01 heatsink on February 2007, using a patent obtained from Golden Sun News Techniques Corporation in Taiwan.

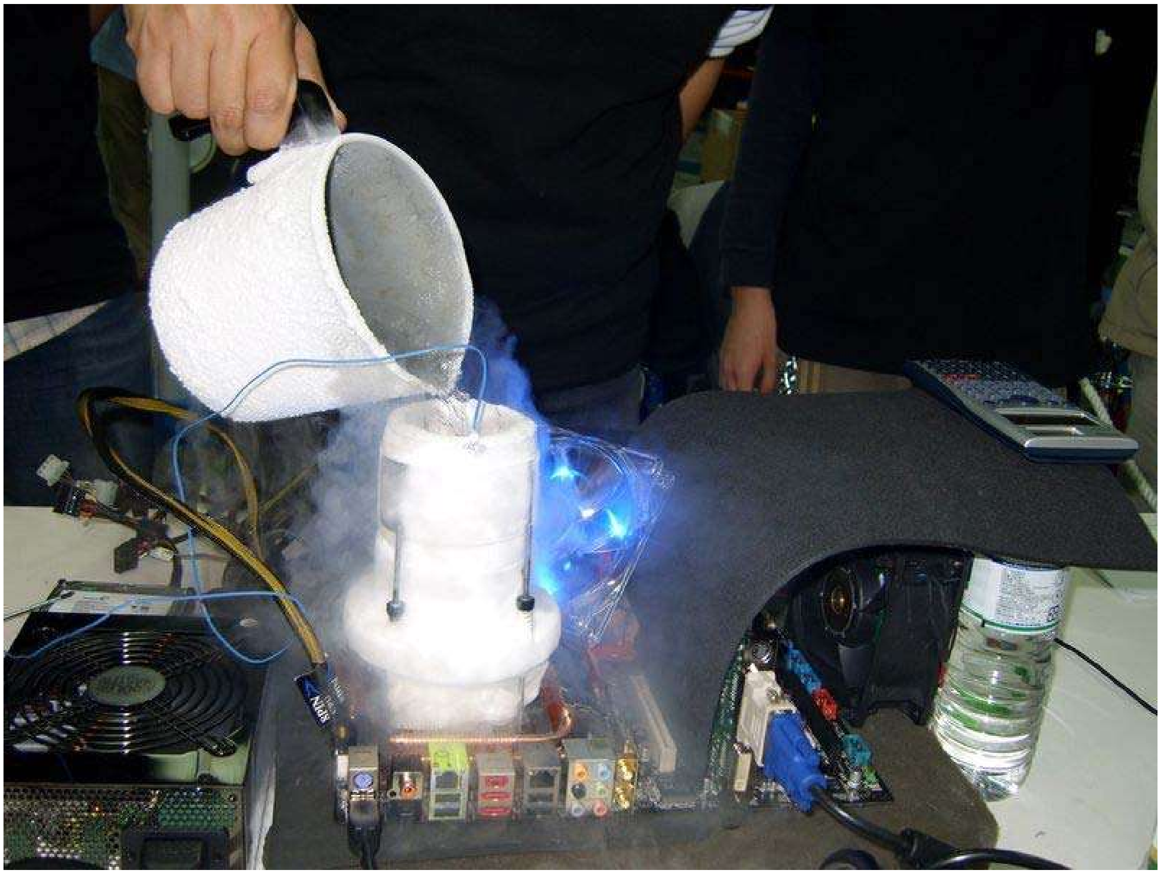
Phase-change cooling

Phase-change cooling is an extremely effective way to cool the processor. A vapor compression phase-change cooler is a unit which usually sits underneath the PC, with a tube leading to the processor. Inside the unit is a compressor of the same type as in a window air conditioner. The compressor compresses a gas (or mixture of gases) which condenses it into a liquid. Then, the liquid is pumped up to the processor, where it passes through an expansion device, this can be from a simple capillary tube to a more elaborate thermal expansion valve. The liquid evaporates (changing phase), absorbing the heat from the processor as it draws extra energy from its environment to accommodate this change. The evaporation can produce temperatures reaching around −15 to -150 degrees Celsius. The gas flows down to the compressor and the cycle begins over again. This way, the processor can be cooled to temperatures ranging from −15 to −150 degrees Celsius, depending on the load, wattage of the processor, the refrigeration system and the gas mixture used. This type of system suffers from a number of issues but mainly one must be concerned with dew point and the proper insulation of all sub-ambient surfaces that must be done (the pipes will sweat, dripping water on sensitive electronics).

Alternately a new breed of cooling system is being developed inserting a pump into the thermo siphon loop. This adds another degree of flexibility for the design engineer as the heat can now be effectively transported away from the heat source and either reclaimed or dissipated to ambient. Junction temperature can be tuned by adjusting the system pressure; higher pressure equals higher fluid saturation temperatures. This allows for smaller condensers, smaller fans and/or the effective dissipation of heat in a high ambient environment. These systems are in essence the next generation liquid cooling paradigm as they are approximately 10 times more efficient than single phase water. Since the system uses a dielectric as the heat transport media, leaks do not cause a catastrophic failure of the electric system.

This type of cooling is seen as a more extreme way to cool components, since the units are relatively expensive compared to the average desktop. They also generate a significant amount of noise, since they are essentially refrigerators, however the compressor choice and air cooling system is the main determinant of this, allowing for flexibility for noise reduction based on the parts chosen.

Liquid nitrogen



Liquid nitrogen may be used to cool an overclocked PC.

As liquid nitrogen boils at -196 °C, far below the freezing point of water, it is valuable as an extreme coolant for short overclocking sessions.

In a typical installation of liquid nitrogen cooling, a copper or aluminum pipe is mounted on top of the processor or graphics card. After being heavily insulated against condensation, the liquid nitrogen is poured into the pipe, resulting in temperatures well below -100°C.

Evaporation devices ranging from cut out heat sinks with pipes attached to custom milled copper containers are used to hold the nitrogen as well as to prevent large temperature changes. However, after the nitrogen evaporates, it has to be refilled. In the realm of personal computers, this method of cooling is seldom used in contexts other than overclocking trial-runs and record-setting attempts, as the CPU will usually expire within a relatively short period of time due to temperature stress caused by changes in internal temperature.

Although liquid nitrogen is non-flammable, it can condense oxygen directly from air. Mixtures of liquid oxygen and flammable materials can be dangerously explosive.

Liquid helium

Liquid helium, colder than liquid nitrogen, has also been used for cooling. Liquid helium evaporates at -269 °C, and temperatures ranging from -230 to -240 °C have been measured from the heatsink.

Soft cooling

Softcooling is the practice of utilizing software to take advantage of CPU power saving technologies to minimize energy use. This is done using halt instructions to turn off or put in standby state CPU subparts that aren't being used or by underclocking the CPU.

Undervolting

Undervolting is a practice of running the CPU or any other component with voltages below the device specifications. An undervolted component draws less power and thus produces less heat. The ability to do this varies by manufacturer, product line, and even different production runs of the same exact product (as well as that of other components in the system), but modern processors are typically shipped with voltages higher than strictly necessary. This provides a buffer zone so that the processor will have a higher chance of performing correctly under sub-optimal conditions, such as a lower quality mainboard (motherboard). However, too low a voltage will not allow the processor to function correctly, producing errors, system freezes or crashes, or the inability to turn the system on. Undervolting too far does not typically lead to hardware damage, though in worst-case scenarios, program or system files can be corrupted.

This technique was generally employed by those seeking low-noise systems, as less cooling is needed because of the reduction of heat production. Since the popularity of hand-held or remote computers (Unmanned vehicles, mobile & cordless phones/camera/viewers, etc), undervolting is used to prolong battery endurance.

Integrated chip cooling techniques

Conventional cooling techniques all attach their “cooling” component to the outside of the computer chip, or via IHS and/or heat sinks. This “attaching” technique will always exhibit some thermal resistance, reducing its effectiveness. The heat can be more efficiently and quickly removed by directly cooling the local hot spots. At these locations, power dissipation of over 300W/cm^2 (typical CPU are less than 100W/cm^2, although future systems are expected to exceed 1000W/cm^2) can occur. This form of local cooling is essential to developing high power density chips. This ideology has led to the investigation of integrating cooling elements into the computer chip. Currently there are two techniques: micro-channel heat sinks, and jet impingement cooling.

In micro-channel heat sinks, channels are fabricated into the silicon chip (CPU), and coolant is pumped through them. The channels are designed with very large surface area which results in large heat transfers. Heat dissipation of 3000W/cm^2 has been reported with this technique . In comparison to the Sun power density of around 7400W/cm^2. The heat dissipation can be further increased if two-phase flow cooling is applied. Unfortunately the system requires large pressure drops, due to the small channels, and the heat flux is lower with dielectric coolants used in electronic cooling. Another local chip cooling technique is jet impingement cooling. In this technique, a coolant is flown through a small orifice to form a jet. The jet is directed toward the surface of the CPU chip, and can effectively remove large heat fluxes. Heat dissipation of over 1000W/cm^{2}has been reported . The system can be operated at lower pressure in comparison to the micro-channel method. The heat transfer can be further increased using two-phase flow cooling and by intergrading return flow channels (hybrid between micro-channel heat sinks and jet impingement cooling).

Cooling and overclocking

Extra cooling is usually required by those who run parts of their computer (such as the CPU and GPU) at higher voltages and frequencies than manufacturer specifications call for, called overclocking. Increasing performance by this modification of settings results in a greater amount of heat generated and thus increasing the risk of damage to components and/or premature failure.

The installation of higher performance, non-stock cooling may also be considered modding. Many overclockers simply buy more efficient, and often, more expensive fan and heat sink combinations, while others resort to more exotic ways of computer cooling, such as liquid cooling, Peltier effect heatpumps, heat pipe or phase change cooling.

There are also some related practices that have a positive impact in reducing system temperatures:

Heat sink lapping

Heat sink lapping is the smoothing and polishing of the contact (bottom) part of a heat sink to increase its heat transfer efficiency. The desired result is a contact area which has a more even surface, as a less even contact surface creates a larger amount of insulating air between the heat sink and the computer part it is attached to. Polishing the surface using a combination of fine sandpaper and abrasive polishing liquids can produce a mirror-like shine, an indicator of a very smooth metal surface. Even a curved surface can become extremely reflective, yet not particularly flat, as is the case with curved mirrors; thus heat sink quality is based on *overall flatness*, more than optical properties. Lapping a high quality heat sink can damage it, because, although the heat sink may become shiny, it is likely that more material will be removed from the edges, making the heat sink less effective overall.

If attempted, a piece of float glass should be used, as it self-levels as it cools and offers the most economical solution to producing a perfectly flat surface.

Use of exotic thermal conductive compounds

Some overclockers use special thermal compounds whose manufacturers claim to have a much higher efficiency than stock thermal pads. Heat sinks clean of any grease or other thermal transfer compounds have a very thin layer of these products applied, and then are placed normally over the CPU. Many of these compounds have a high proportion of silver as their main ingredient due to its high thermal conductivity. The resulting difference in the temperature of the CPU is measurable (several celsius degrees), so the heat transfer does appear to be superior to stock compounds. Some people experience negligible gains and have called to question the advantages of these exotic compounds, calling the style of application more important than the compound itself. Also note that there may be a 'setting' or 'curing' period and negligible gains may improve over time as the compound reaches its optimum thermal conductivity.

Use of rounded cables

Most older PCs use flat ribbon cables to connect storage drives (IDE or SCSI). These large flat cables greatly impede airflow by causing drag and turbulence. Overclockers and modders often replace these with rounded cables, with the conductive wires bunched together tightly to reduce surface area. Theoretically, the parallel strands of conductors in a ribbon cable serve to reduce crosstalk (signal carrying conductors inducing signals in nearby conductors), but there is no empirical evidence of rounding cables reducing performance. This may be because the length of the cable is short enough so that the effect of crosstalk is negligible. Problems usually arise when the cable is not electromagnetically protected and the length is considerable, a more frequent occurrence with older network cables.

These computer cables can then be cable tied to the chassis or other cables to further increase airflow.

This is less of a problem with new computers that use Serial ATA which has a much narrower cable.

Airflow optimization

The colder the cooling medium (the air), the more effective the cooling. Cooling air temperature can be improved with these guidelines:

- Supply cool air to the hot components as directly as possible. Examples are air snorkels and tunnels that feed outside air directly and exclusively to the CPU or GPU cooler. For example, the BTX case design prescribes a CPU air tunnel.
- Expel warm air as directly as possible. Examples are: Conventional PC (ATX) power supplies blow the warm air out the back of the case. Many dual-slot graphics card designs blow the warm air through the cover of the adjacent slot. There are also some aftermarket coolers that do this. Some CPU cooling designs blow the warm air directly towards the back of the case, where it can be ejected by a case fan.
- Air that has already been used to spot-cool a component should not be reused to spot-cool a different component (this follows from the previous items). The ATX case design can be said to violate this rule, since the power supply gets its "cool" air from the inside of the case, where it has been warmed up already. The BTX case design also violates this rule, since it uses the CPU cooler's exhaust to cool the chipset and often the graphics card.
- Prefer cool intake air, avoid inhaling exhaust air (outside air above or near the exhausts). For example, a CPU cooling air duct at the back of a tower case would inhale warm air from a graphics card exhaust. Moving all exhausts to one side of the case, conventionally the back, helps to keep the intake air cool.
- Hiding cables behind motherboard tray or simply apply ziptie and tucking cables away to provide unhindered airflow.

Fewer fans strategically placed will improve the airflow internally within the PC and thus lower the overall internal case temperature in relation to ambient conditions. The use of larger fans also improves efficiency and lowers the amount of waste heat along with the amount of noise generated by the fans while in operation.

There is little agreement on the effectiveness of different fan placement configurations, and little in the way of systematic testing has been done. For a rectangular PC (ATX) case, a fan in the front with a fan in the rear and one in the top has been found to be a suitable configuration. However, AMD's (somewhat outdated) system cooling guidelines notes that "A front cooling fan does not seem to be essential. In fact, in some extreme situations, testing showed these fans to be recirculating hot air rather than introducing cool air." It may be that fans in the side panels could have a similar detrimental effect -- possibly through disrupting the normal air flow through the case. However, this is unconfirmed and probably varies with the configuration.