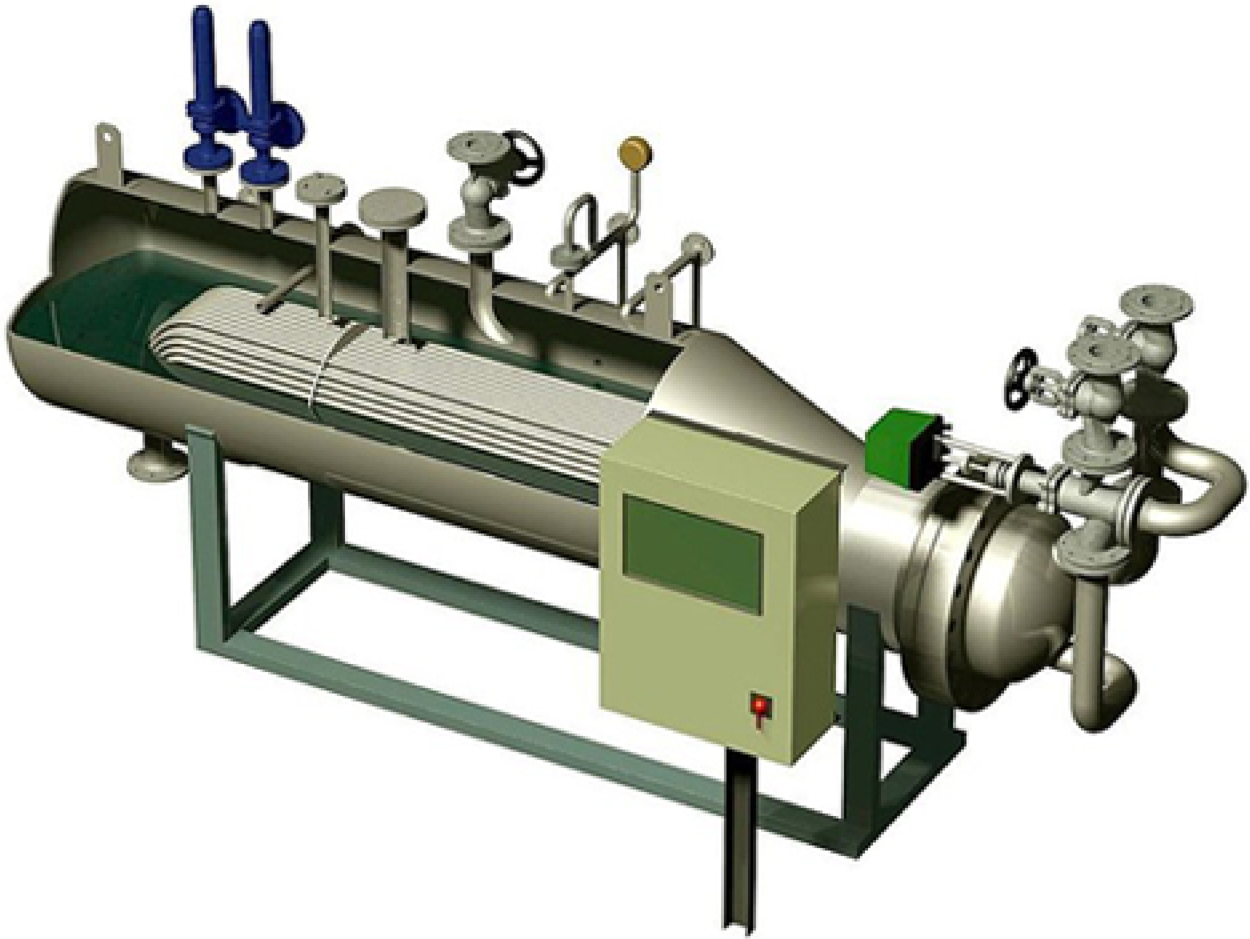
Handbook of

# Heating and Temperature Control Technologies



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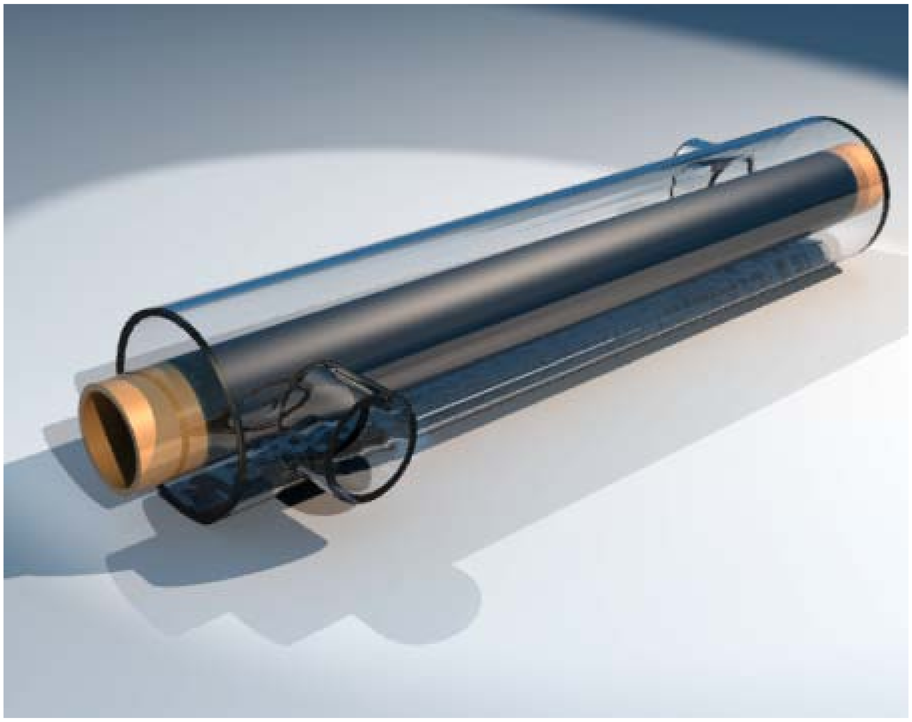
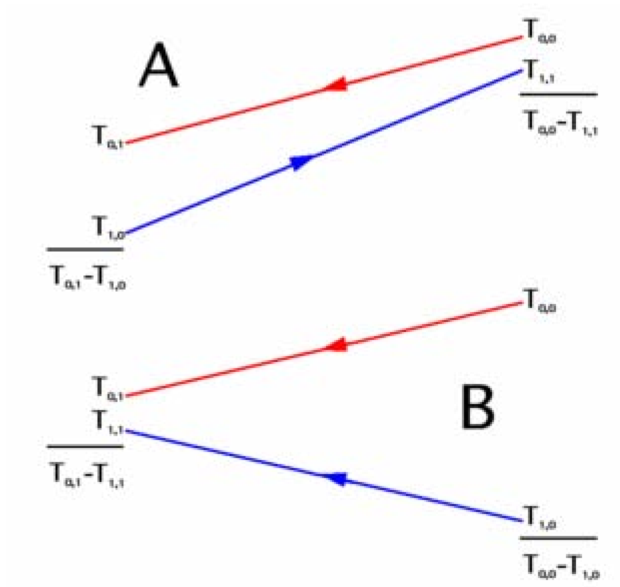


Tubular heat exchanger

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

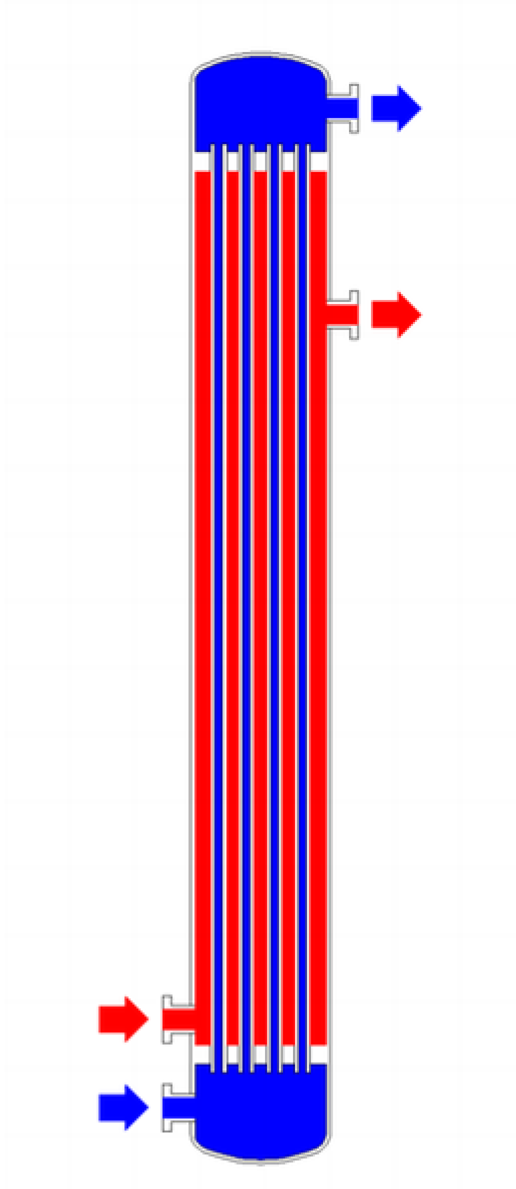


Fig. 1: Shell and tube heat exchanger, single pass (1-1 parallel flow)

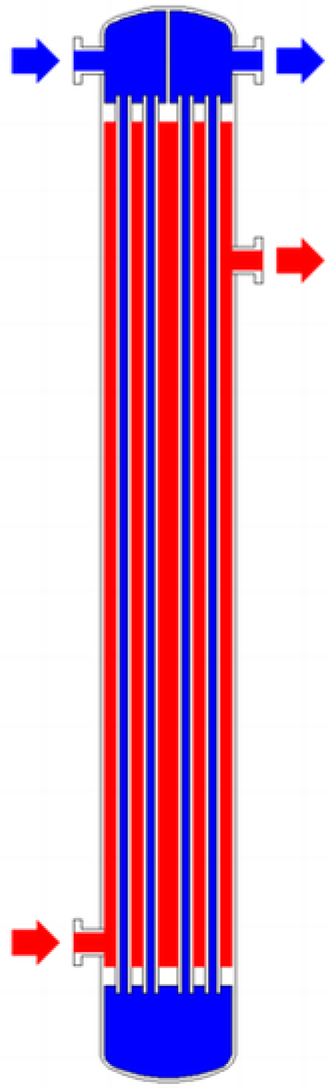


Fig. 2: Shell and tube heat exchanger, 2-pass tube side (1-2 crossflow)

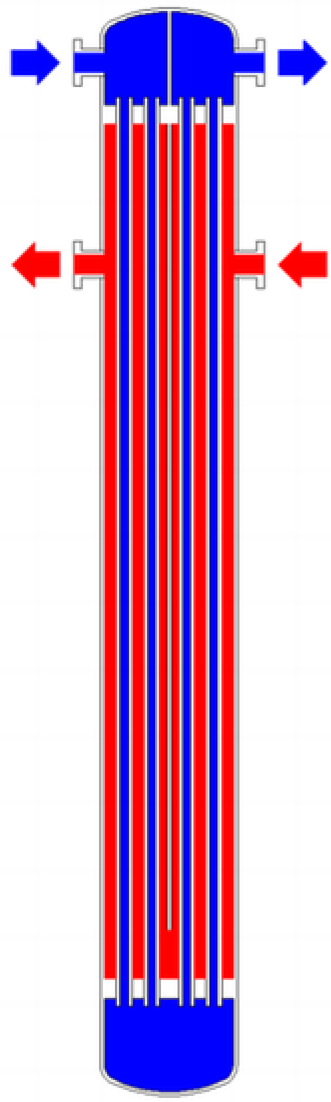


Fig. 3: Shell and tube heat exchanger, 2-pass shell side, 2-pass tube side (2-2 countercurrent)

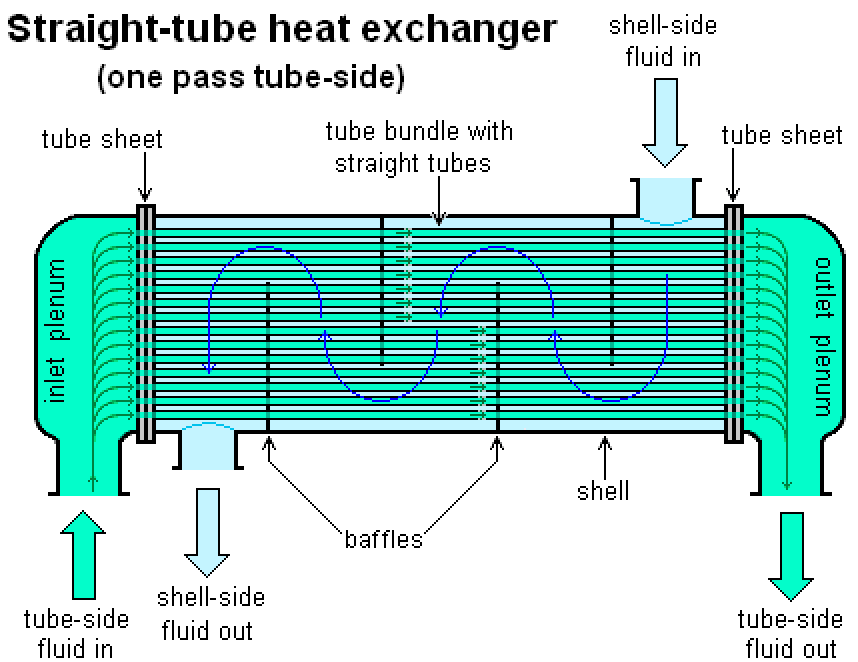
There are two primary classifications of heat exchangers according to their flow arrangement. In *parallel-flow* heat exchangers, the two fluids enter the exchanger at the same end, and travel in parallel to one another to the other side. In *counter-flow* heat exchangers the fluids enter the exchanger 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

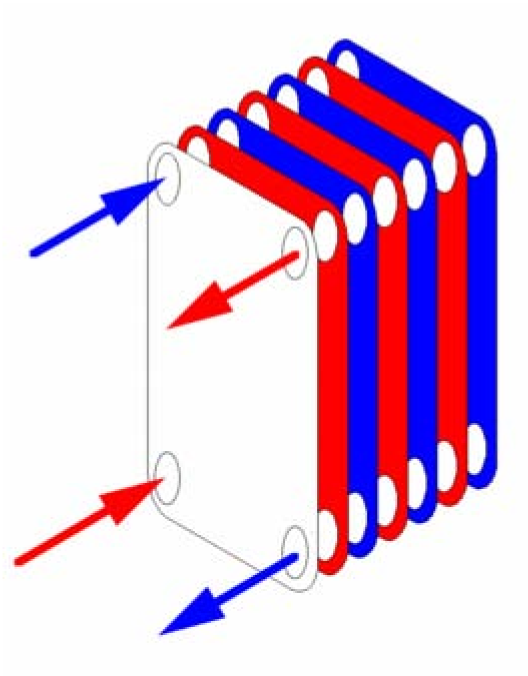



A Shell and Tube heat exchanger

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

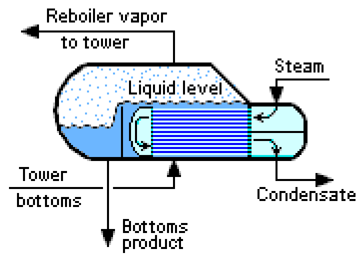
A Waste Heat Recovery Unit (WHRU) is a heat exchanger that recovers heat from a hot gas stream while transferring it to a working medium, typically water or oils. The hot gas stream can be the exhaust gas from a gas turbine or a diesel engine or a waste gas from industry or refinery.

### Dynamic scraped surface heat exchanger

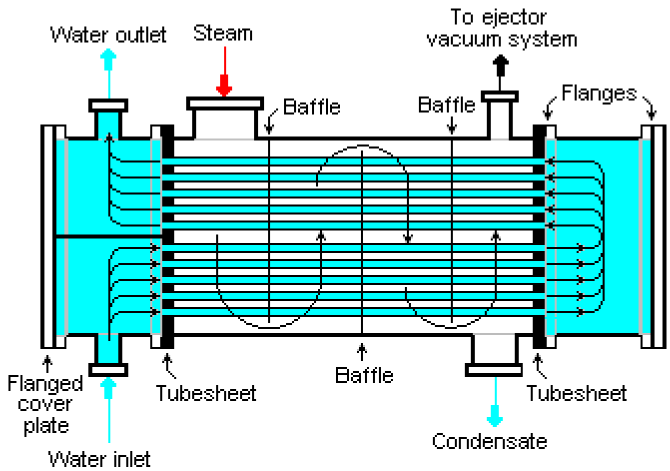
Another type of heat exchanger is called "(dynamic) scraped surface heat exchanger". This is mainly used for heating or cooling with high-viscosity products, crystallization processes, evaporation and high-fouling applications. Long running times are achieved due to the continuous scraping of the surface, 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= amount of heat transferred; U= heat transfer coefficient; A=Heat Transfer Area; LMTD = Log mean temperature differential.

### 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*.

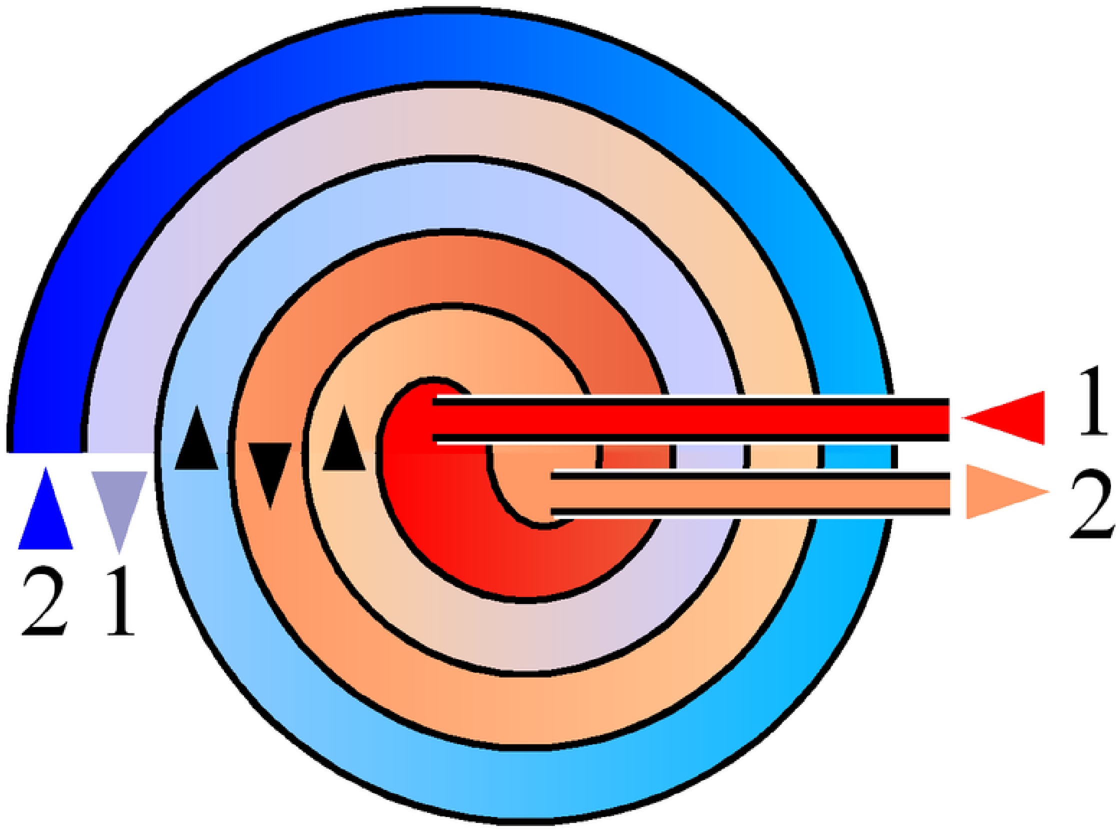
On the air side of HVAC coils a significant difference exists between those used for heating, and those for cooling. Due to psychrometrics, air that is cooled often has moisture condensing out of it, except with extremely dry air flows. Heating some air increases that airflow's capacity to hold water. 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

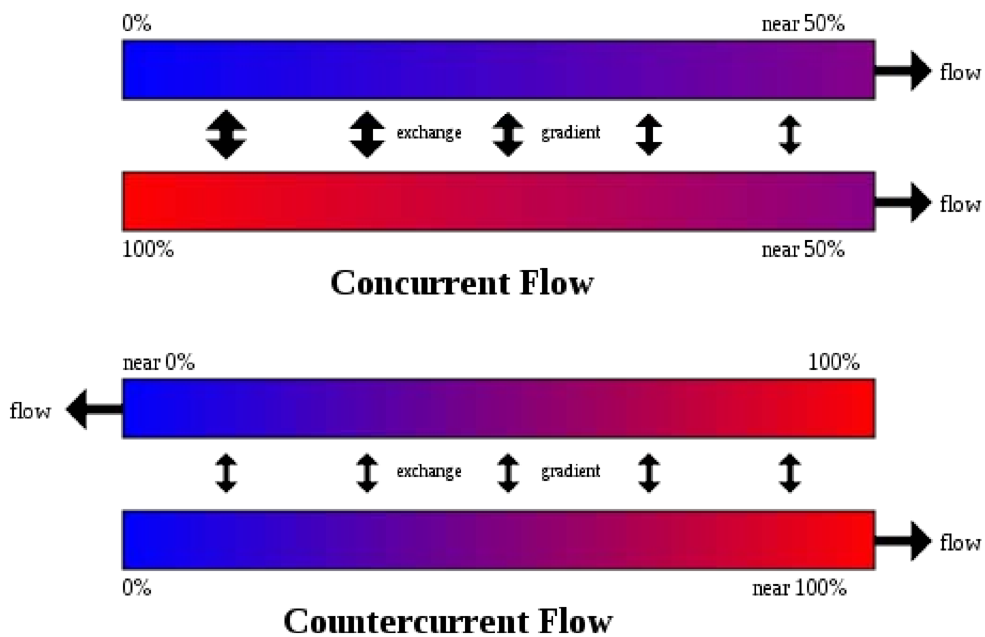
The distance between the sheets in the spiral channels are maintained by using spacer studs that were welded prior to rolling. Once the main spiral pack has been rolled, alternate top and bottom edges are welded and each end closed by a gasketed flat or conical cover bolted to the body. This ensures 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 $\gamma$ 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:

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

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 2

# 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.

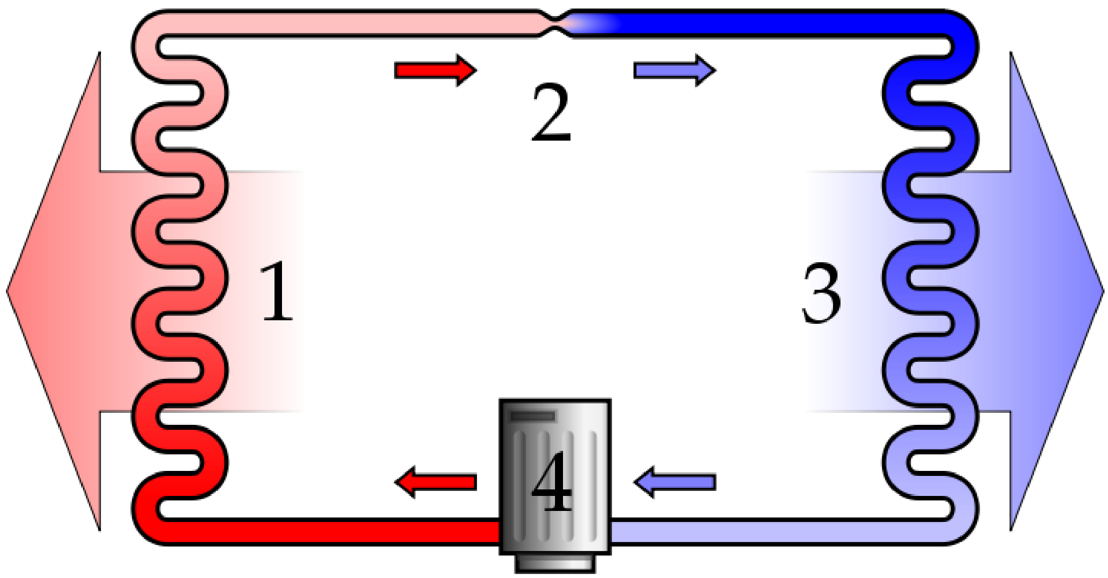
## *Overview*

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.

Solar Assisted Heat Pumps use thermal waste energy from water source heating and cooling systems as "fuel" for a Thermal HVAC system. This is a new technology which uses the energy from the water in holding tanks and a refrigerant to water heat exchange system. The tanks serve as thermal flywheels and thermal buffers, as needed. In this configuration, the water in the middle tank serves as the “fuel” for the system. This fuel is pumped into the cold heat exchanger where the heat in the water is extracted and transferred to warm up the cold refrigerant. The cold water is then pumped into the cold tank. On the opposite side, the hot water is heated by way of the hot heat exchanger and the heated water is put back into the hot tank to either be rejected or used further in other heat exchange processes. In most cases water returns from the zone where work is being done to the neutral tank.

## 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.

### *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 between the hot & cold reservoir's the COP is lower (worse).

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

- $\Delta Q_{cool}$ is the amount of heat extracted from a cold reservoir at temperature $T_{cool}$,
- $\Delta Q_{hot}$ is the amount of heat delivered to a hot reservoir at temperature $T_{hot}$,
- $\Delta A$ 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.

**COP variation with Output Temperature**

| **Pump type and source** | **Typical use case** | **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 the coldest 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.

Near-solid-state heat pumps using Thermoacoustics are commonly used in cryogenic laboratories.

## *History*

Milestones:

- 1748: William Cullen demonstrates artificial refrigeration.
- 1834: Jacob Perkins builds a practical refrigerator with diethyl ether.
- 1852: Lord Kelvin describes the theory underlying heat pump.
- 1855–1857: Peter Ritter von Rittinger develops and builds the first heat pump.

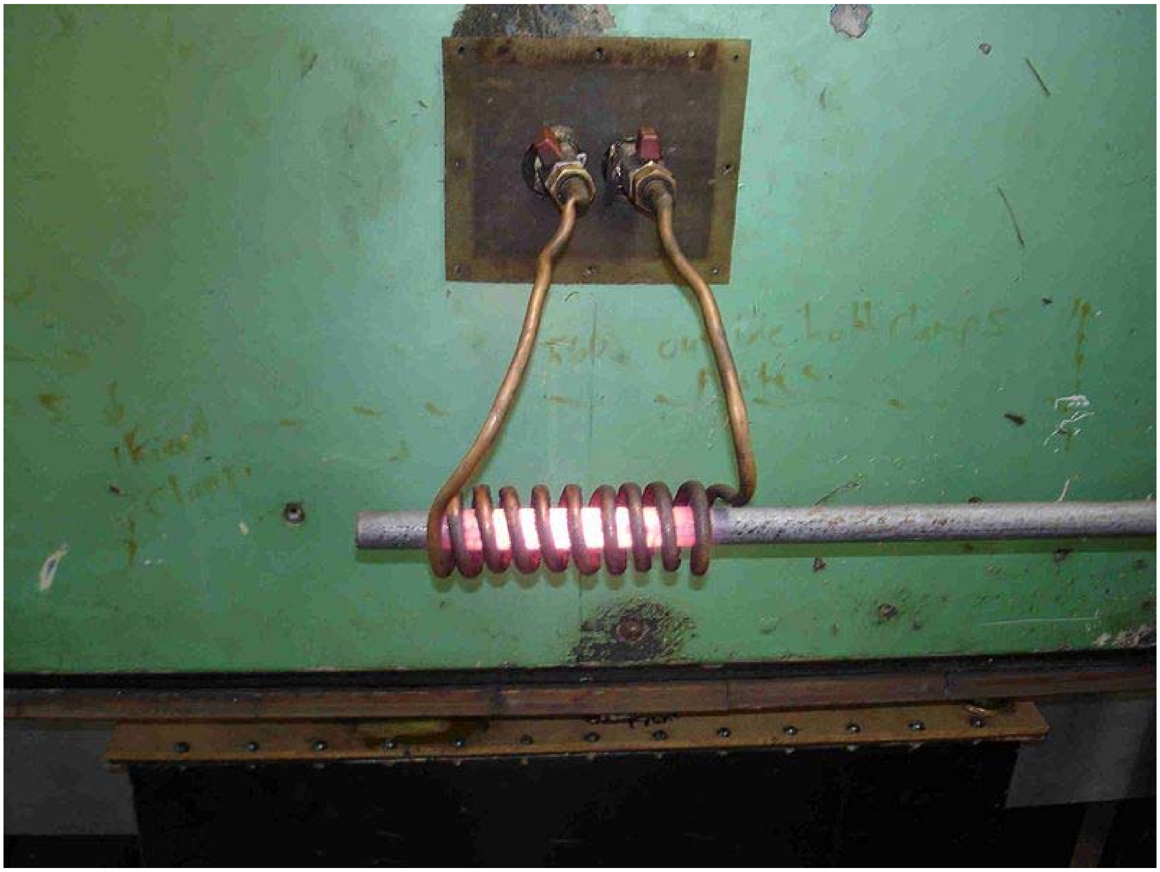
# Chapter 3

# Induction Heating

Component of Stirling radioisotope generator is heated by induction during testing

**Induction heating** is the process of heating an electrically conducting object (usually a metal) by electromagnetic induction, where eddy currents (also called Foucault currents) are generated within the metal and resistance leads to Joule heating of the metal. An induction heater (for any process) consists of an electromagnet, through which a high-frequency alternating current (AC) is passed. Heat may also be generated by magnetic hysteresis losses in materials that have significant relative permeability. The frequency of AC used depends on the object size, material type, coupling (between the work coil and the object to be heated) and the penetration depth.

### *Applications*



Induction heating of 25 mm metal bar using 15 kW at 450 kHz.

Induction heating allow the targeted heating of an applicable item for applications including surface hardening, melting, brazing and soldering and heating to fit. Iron and its alloys respond best to induction heating, due to their ferromagnetic nature. Eddy currents can, however, be generated in any conductor, and magnetic hysteresis can occur in any magnetic material. Induction heating has been used to heat liquid conductors (such as molten metals) and also gaseous conductors. Induction heating is often used to heat graphite crucibles (containing other materials) and is used extensively in the semiconductor industry for the heating of silicon and other semiconductors. Supply frequency (mains, 50/60 Hz) induction heating is used for many lower cost industrial applications as inverters are not required.

## Induction furnace

An induction furnace uses induction to heat metal to its melting point. Once molten, the high-frequency magnetic field can also be used to stir the hot metal, which is useful in ensuring that alloying additions are fully mixed into the melt. Most induction furnaces consist of a tube of water-cooled copper rings surrounding a container of refractory material. Induction furnaces are used in most modern foundries as a cleaner method of melting metals than a reverberatory furnace or a cupola. Sizes range from a kilogram of capacity to a hundred tonnes capacity. Induction furnaces often emit a high-pitched whine or hum when they are running, depending on their operating frequency. Metals melted include iron and steel, copper, aluminium, and precious metals. Because it is a clean and non-contact process it can be used in a vacuum or inert atmosphere. Vacuum furnaces make use of induction heating for the production of specialty steels and other alloys that would oxidize if heated in the presence of air.

## Induction welding

A similar, smaller-scale process is used for induction welding. Plastics may also be welded by induction, if they are either doped with ferromagnetic ceramics (where magnetic hysteresis of the particles provides the heat required) or by metallic particles.

Seams of tubes can be welded this way. Currents induced in a tube run along the open seam and heat the edges resulting in a temperature high enough for welding. At this point the seam edges are forced together and the seam is welded. The RF current can also be conveyed to the tube by brushes, but the result is still the same — the current flows along the open seam, heating it.

## Induction cooking

In induction cooking, an induction coil in the cook-top heats the iron base of cookware. Copper bottomed pans, aluminium pans and other non-ferrous pans are generally unsuitable.

The heat induced in the base is transferred to the food via conduction. Benefits of induction cookers include efficiency, safety (the induction cook-top is not heated itself) and speed. Drawbacks include the fact that non-metallic cookware such as glass and ceramic cannot be used on an induction cook-top. Both installed and portable induction cookers are available.

## Induction brazing

Induction brazing is often used in higher production runs. It produces uniform results and is very repeatable.

## Induction sealing

Induction heating is often used in *cap sealing*.

## Heating to fit

Induction heating is often used to heat an item causing it to expand prior to fitting or assembly. Bearings are routinely heated in this way using mains frequency (50/60 Hz) and a laminated steel transformer type core passing through the centre of the bearing.

## Heat treatment

Induction heating is often used in the heat treatment of metal items. The most common applications are induction hardening of steel parts, induction soldering/brazing as a means of joining metal components and induction Annealing_(metallurgy) to selectively soften a selected area of a steel part.

Induction heating can produce high power densities which allow short interaction times to reach the required temperature. This gives tight control of the heating pattern with the pattern following the applied magnetic field quite closely and allows reduced thermal distortion and damage.

This ability can be used in hardening to produce parts with varying properties. The most common hardening process is to produce a localised surface hardening of an area that needs wear-resistance, while retaining the toughness of the original structure as needed elsewhere. The depth of induction hardened patterns can be controlled through choice of induction-frequency, power-density and interaction time.

There are limits to the flexibility of the process - mainly arising from the need to produce dedicated inductors for many applications. This is quite expensive and requires the marshalling of high current-densities in small copper inductors, which can require specialized engineering and 'copper-fitting'.

## *Details*

The basic setup is an AC power supply that provides electricity with low voltage but very high current and high frequency. The workpiece to heat is placed inside an air coil driven by the power supply, usually in combination with a resonant tank capacitor to increase the reactive power. The alternating magnetic field induces eddy currents in the workpiece.

Applications of frequency ranges

| Frequency (kHz) | Workpiece type |
|---|---|
| 5–30 | Thick materials |
| 100–400 | Small workpieces or shallow penetration |
| 480 | Microscopic pieces |

Magnetic materials improve the induction heat process because of hysteresis. In essence materials with high permeability (100–500) are easier to heat with induction heating.

Hysteresis heating occurs below the Curie temperature where materials lose their magnetic properties.

So high permeability and temperatures below Curie temperature in the workpiece is useful. Also temperature difference, mass, and specific heat influence the workpiece heating.

The energy transfer of induction heating is coupled to the distance between the coil and the workpiece. Energy losses occur through heat conduction from workpiece to fixture, natural convection, and thermal radiation.

The induction coil is usually made of 3.175–4.7625 mm diameter copper tubing and fluid cooled. Diameter, shape, and number of turns influence the efficiency and field pattern.

### *Core type furnace*

The furnace consists of circular hearth which contains the charge to be melted in the form of angular ring. The metal ring is large in diameter and is magnetically interlinked with an electrical winding energized by an AC source.

## Chapter 4

# Electric Heating

30 kw resistance heating coils

**Electric heating** is any process in which electrical energy is converted to heat. Common applications include space heating, cooking, water heating and industrial processes. An **electric heater** is an electrical appliance that converts electrical energy into heat. The heating element inside every electric heater is simply an electrical resistor, and works on the principle of Joule heating: an electric current through a resistor converts electrical energy into heat energy.

Alternatively, a heat pump uses an electric motor to drive a refrigeration cycle, drawing heat from a source such as the ground or outside air and directing it into the space to be warmed. Some systems can be reversed so that the interior space is cooled and the heat is discharged outside or into the ground. Heat pumps can deliver two or three units of heating energy for every unit of electricity purchased.

## *Space heating*

Although they all use the same physical principle to generate heat, electric heaters differ in the way they deliver that heat to the environment. Several types are described in the sections below.

### Radiative heaters

Radiative heaters contain a heating element that reaches a high temperature. The element is usually packaged inside a glass envelope resembling a light bulb and with a reflector to direct the energy output away from the body of the heater. The element emits infrared radiation that travels through air or space until it hits an absorbing surface, where it is partially converted to heat and partially reflected. This heat directly warms people and objects in the room, rather than warming the air. This style of heater is particularly useful in areas which unheated air flows through. They are also ideal for basements and garages where spot heating is desired. More generally, they are an excellent choice for task-specific heating.

Radiative heaters operate silently and present the greatest potential danger to ignite nearby furnishings due to the focused intensity of their output and lack of overheat protection. In the United Kingdom, these appliances are sometimes called electric fires, because they were originally used to replace open fires.

### Convection heaters

In a convection heater, the heating element heats the air next to it by convection. Hot air is less dense than cool air, so it rises due to buoyancy, allowing more cool air to flow in to take its place. This sets up a constant current of hot air that leaves the appliance through vent holes and heats up the surrounding space. They are ideally suited for heating a closed space. They operate silently and have a lower risk of ignition hazard in the event that they make unintended contact with furnishings compared to radiant electric heaters. This is a good choice for long periods of time or if left unattended. They are very safe heaters and there is a very low chance of getting burned.

## Fan heaters

A fan heater, also called a forced convection heater, is a variety of convection heater that includes an electric fan to speed up the airflow. This reduces the thermal resistance between the heating element and the surroundings faster than passive convection, allowing heat to be transferred more quickly.

They operate with considerable noise caused by the fan. They have a moderate risk of ignition hazard in the event that they make unintended contact with furnishings. This type of heater is a good choice for quick heating of enclosed spaces.

## Storage heating

A storage heating system takes advantage of cheaper electricity prices, sold during low demand periods such as overnight. In the United Kingdom, this is branded as Economy 7. The storage heater stores heat in clay bricks, then releases it during the day when required.

## Domestic electrical underfloor heating

These systems are called *radiant heating* systems, regardless of whether they include a heat exchanger (also called a *radiator*) or are electrically powered.

When a home radiant heat system is turned on, current flows through a conductive heating material. For high-voltage radiant heat systems, line voltage (110 V or 230 V) current flows through the heating cable. For low-voltage systems, the line voltage is converted to extra low voltage (8 to 30 V) in the control unit (which contains a step-down transformer) and this low voltage is then applied to the heating element.

The heated material then heats the flooring until it reaches the right temperature set by the floor thermostat. The flooring then heats the adjacent air, which circulates, heating other objects in the room (tables, chairs, people) by convection. As it rises, the heated air will heat the room and all its contents up to the ceiling. This form of heating gives the most consistent room temperature from floor to ceiling compared to any other heating system.

## Heat pumps

A heat pump uses an electrically-driven compressor to operate a refrigeration cycle that extracts heat energy from the outdoor air or from the ground or ground water, and upgrades its temperature to a level high enough to use for space heating. The working fluid boils at a low temperature, absorbing heat in an outdoor heat exchanger, then the resulting vapor is compressed and condenses to liquid form in a condensor inside the building. Heat from the condensor is absorbed by the air in the building (and sometimes also used for domestic hot water). In the summer months the cycle can be reversed to provide air conditioning. Heat pumps may obtain low-grade heat from the outdoor air in mild climates; in areas with average winter temperatures well below freezing, ground source heat pumps extract residual heat stored in the ground at a more constant temperature.

## *Water heating*

### Immersion heater

Water heating by electricity is usually done by an immersion heater mounted in the top of the hot water cylinder. The heater contains an insulated electric resistance heater and a temperature sensor. Domestic immersion heaters (usually rated at 3 kilowatts in the UK) run on the normal domestic electricity supply. Electric shower and tankless heater also use a immersion heater shielded or naked which is turned on by the water passing and turned off when the tap is closed. A group of heater working each one or together provide different heating levels. Electric showers and tankless heaters usually have since 3kilowatts to 7.5kilowatts according the voltage supply. Industrial immersion heaters (such as those used in electric steam boilers) may be rated at 100 kilowatts, or more, and run on a three-phase supply. 11

### Electrode heater

With an electrode heater, there is no wire-wound resistance and the liquid itself acts as the resistance. This has potential hazards so the regulations governing electrode heaters are strict.

## *Environmental and efficiency aspects*

The efficiency of any system depends on the definition of the boundaries of the system. For an electrical energy customer the efficiency of electric space heating can be 100% because all purchased energy is converted to building heat. However, if the power plant supplying electricity is included, the overall efficiency drops. For example, a fossil-fuelled power plant may only deliver 4 units of electrical energy for every 10 units of fuel energy released. Even with a 100% efficient electric heater, the amount of fuel needed for a given amount of heat is more than if the fuel was burned in a furnace or boiler at the building being heated. If the same fuel could be used for space heating by a consumer, it would be more efficient overall to burn the fuel at the end user's building. Not all fuels are suitable for building heating; for example, emissions controls required for coal combustion are too expensive for household-scale furnaces.

In Sweden the use of direct electric heating has been restricted since the 1980s for this reason, and there are plans to phase it out entirely - Oil phase-out in Sweden - while Denmark has banned the installation of electric space heating in new buildings for similar reasons. In the case of new buildings, low-energy building techniques can be used which can virtually eliminate the need for heating, such as those built to the Passive House standard.

In Quebec however, electric heating is still the most popular form of home heating. According to a 2003 Statistics Canada survey, 68% of households in the province uses electricity for space heating. This can be explained by the fact that more than 90% of all power consumed in Quebec is generated by hydroelectric dams, which have lower greenhouse gases emissions than thermal power stations and the low and stable rates charged by Hydro-Québec, the provincially-owned utility.

In order to provide heat more efficiently, an electrically driven heat pump can raise the indoor temperature by extracting heat from the ground, the outside air, or waste streams such as exhaust air. This can cut the electricity consumption to as little as 20% of that used by resistive heating and thus reduce the environmental impact.

Electrical space heating can still be economic where electricity supplies are low-cost. Where the primary source of electrical energy is hydroelectric, nuclear, wind, or other carbon-free source, it may not be practical to exploit that resource directly in heating applications but grid electricity can be conveniently used. Electric space heating is useful in places where air-handling is difficult, such as in laboratories.

## *Economic aspects*

The operation of electric resistance heaters to heat an area for a long period of time is generally considered to be costly. However, intermittent or partial day use can be more cost efficient than whole building heating due to superior zonal control.

Example: A lunch room in an office setting has limited hours of operation. During low use periods a "monitor" level of heat (50 °F/10 °C) is provided by the central heating system. Peak use times between the hours of 11:00–14:00 are heated to "comfort levels" (70 °F/21 °C). Significant savings can be realized in overall energy consumption since infrared radiation losses through thermal radiation are not as large with a smaller temperature gradient both between this space and unheated outside air as well as between the refrigerator and the (now cooler) lunch room.

Economically, electric heat is very efficient, and can be compared to other sources of home heating by calculating the cost per kilowatt hour multiplied by the efficiency of the heater, and then multiplied by the number of kilowatts the heater uses.

## *Industrial electric heating*

Electric heating is widely used in industry.

Advantages of electric heating methods over other forms include precision control of temperature and distribution of heat energy, combustion not used to develop heat, and the ability to attain temperatures not readily achievable with chemical combustion. Electric heat can be accurately applied at the precise point needed in a process, at high concentration of power per unit area or volume. Electric heating apparatus can be built in any required size and can be located anywhere within a plant. Electric heating processes are generally clean, quiet, and do not emit much byproduct heat to the surroundings. Electrical heating equipment has a high speed of response, lending it to rapid-cycling mass-production equipment.

The limitations and disadvantages of electric heating in industry include the higher cost of electrical energy compared to direct use of fuel, and the capital cost of both the electric heating apparatus itself and the infrastructure required to deliver large quantities of electrical energy to the point of use. This may be somewhat offset by efficiency gains in using less energy overall to achieve the same result.

Design of an industrial heating system starts with assessment of the temperature required, the amount of heat required, and the feasible modes of transferring heat energy. In addition to conduction, convection and radiation, electrical heating methods can use electric and magnetic fields to heat material.

Methods of electric heating include resistance heating, electric arc heating, induction heating, and dielectric heating. In some processes (for example, arc welding), electric current is directly applied to the workpiece. In other processes, heat is produced within the workpiece by induction or dielectric losses. As well, heat can be produced then transferred to the work by conduction, convection or radiation.

Industrial heating processes can be broadly categorized as low-temperature (to about 400 C (730 F)), medium temperature (between 400 C and 1150 C (730-2100 F)), and high temperature (beyond 1150 C (2100 F)). Low temperature processes include, baking and drying, curing finishes, soldering, molding and shaping plastics. Medium temperature processes include melting plastics and some non-metals for casting or reshaping, as well as annealing, stress-relieving and heat-treating metals. High-temperature processes include steelmaking, brazing, welding, casting metals, cutting, smelting and the preparation of some chemicals.

## Chapter 5

# Electric Blanket and Heating Pad

## Electric Blanket

An electric blanket

An **electric blanket** is a blanket with an integrated electrical heating device usually placed above the top bed sheet. Another variation of the electric blanket is the electric mattress pad, which is placed below the bottom bed sheet. Electric blankets usually have a control unit which adjusts the amount of heat the blanket produces. Blankets for larger sized beds often have separate controls for each side of the bed. The electric blanket may be used to pre-heat the bed before use or to keep the occupant warm while in bed.

Modern electric blankets have carbon fibre wires. These blankets usually work on 24 volts instead of the 110/240 volts. Therefore, they are advertised as being a safer, more efficient and more comfortable alternative.

### *History*

The first electric blanket was invented in 1912 by American physician Sidney I. Russell. This earliest form of an electric blanket was an ‘underblanket’ under the bed that covered and heated from below. In 1937, Electric 'overblankets' which lie on top of the sleeping person were introduced in the United States.

### *Method*

Like a heating pad, electric blankets use an insulated wire or heating element inserted into a fabric that heats when it is plugged in. The temperature control unit, located between the blanket and the electrical outlet, manages the level of electricity entering into the heat elements in the blanket. Newer electric blankets work on a low voltage of 24 volts and have a shutoff mechanism to prevent the blanket from overheating or catching fire. Older units (10 years or more) may not have a shut-off mechanism and users run the risk of over heating. Older blankets are considered fire hazards. Modern Electric Blankets Some more modern electric blankets use carbon fiber wires to heat the user. These wires are far less bulky and conspicuous than older heating wires. Carbon fiber wires are also used as the heating element in many high-end heated car seats. Blankets can be purchased with rheostats that regulate the heat by managing body heat and blanket temperatures, ensuring a comfortable experience.

### *Health Benefits*

A quarter of people purchasing electric blankets and heated mattress pads do so for health benefits beyond general comfort.

Direct heat therapy is one of the main reasons for using an electric blanket. Applying heat to muscles increases bloodflow; this enhances muscle nutrition and relaxation, which helps with healing and pain and eases sleep. Persons who suffer from back pain, tension, or injuries may find relief through the application of heat to affected areas. Heat provided by electric blankets and mattress pads relieves muscle pain and soreness caused by arthritis and fibromyalgia, according to The Arthritis Helpbook, recommended by the Arthritis Foundation and the Arthritis Society, and Arthritis 101, the official publication of the Arthritis Foundation. Those with Raynaud's phenomenon or post-polio syndrome may use heated bedding to avoid damage and relieve discomfort caused by poor circulation or cold intolerance.

Electric blankets and mattress pads also can help health conditions indirectly, such as sinus conditions and allergies. They allow one to sleep in lower room temperatures and avoid breathing hotter dry air. Conversely, the heat provided by these devices reduces moisture in the bedding, retarding the growth of dust mite populations, a common allergen; using an electric blanket for a month or turning a device on 'high' for a few hours a month can reduce mites by 50%. An electric blanket or pad also allows users to maintain a more comfortable temperature and gain the general benefits associated with deep and uninterrupted sleep.

### *Safety concerns*

Due to the combination of heat, electricity, the abundance of flammable bedding material, and a sleeping occupant, the use of electric blankets is of concern to fire safety officials internationally. Of primary concern are blankets that are older than 10 years and/or have been subject to damage, by creasing, flexing, fraying, or ordinary wear and tear. In the UK, it is estimated that 5,000 fires per year are caused by faulty electric blankets, of which 99% are believed to have been caused by blankets 10 years or older.

Electric blankets also present a burn risk to those who cannot feel pain or are unable to react to it. Individuals included in this group are small children, diabetics, and the elderly.

# Heating Pad

A **heating pad** is a pad used for warming of parts of the body in order to manage pain. Localized application of heat causes the blood vessels in that area to dilate, enhancing perfusion to the targeted tissue. Types of heating pads include electrical, chemical and hot water bottles.

### *Types*

#### Electrical

Electric pads usually operate from household current and must have protection against overheating.

A **moist heating pad** is used dry on the user's skin. These pads register temperatures from 170 to 180 degrees Fahrenheit (76 to 82 °C) and are intended for deep tissue treatment and can be dangerous if left on unattended. Moist heating pads are used mainly by physical therapists but can be found for home use. A moist cloth can be added with a stupe cover to add more moisture to the treatment.

## Chemical


A sodium acetate heat pad

Disposable chemical pads employ a one-time exothermic chemical reaction such as catalyzed rusting of iron, or dissolving calcium chloride. The reagents are kept in separate compartments within the pad. When the user squeezes the pad, they break and the reagents mix together, producing heat.

The most common reusable heat pads contain a supersaturated solution of sodium acetate ($NaCH_3COO$) in water. Crystallization is triggered by flexing a small flat disc of notched ferrous metal embedded in the liquid. Pressing the disc releases very tiny adhered crystals of sodium acetate into the solution which then act as nucleation sites for the crystallization of the sodium acetate into the hydrated salt (sodium acetate trihydrate). Because the liquid is supersaturated, this makes the solution crystallize suddenly, thereby releasing the energy of the crystal lattice. The use of the metal disc was invented in 1978.

The pad can be reused by placing it in boiling water for 10–15 minutes, which redissolves the sodium acetate trihydrate in the contained water and recreates a supersaturated solution. Once the pad has returned to room temperature it can be triggered again. Triggering the pad before it has reached room temperature results in the pad reaching a lower peak temperature, as compared to waiting until it had completely cooled.

## *High specific-heat capacity materials*

Heating packs can also be made by filling a container with a material that has a high specific heat capacity, which then gradually releases the heat over time. A hot water bottle is the most familiar example of this type of heating pad.

A **microwavable heating pad** is a heating pad that is warmed by placing it in a microwave oven before use. Microwavable heating pads are typically made out of a thick insulative fabric such as flannel and filled with grains such as wheat, buckwheat or flax seed. Due to their relative simplicity to make, they are frequently sewn by hand, often with a custom shape to fit the intended area of use. In rare instances, these types of pads have been known to ignite during or after the microwave process and cause fires.

Often, aromatic compounds will also be added to the filler mixture to create a pleasant or soothing smell when heated. The source of these can vary significantly, ranging from adding essential oils to ground up spices such as cloves and nutmeg, or even dried rose petals.

### Phase change materials

Phase change materials can be used for heating pads intended to operate at a fixed temperature. The heat of fusion is used to release the thermal energy.

## *Function*

Many episodes of pain come from muscle exertion or strain, which creates tension in the muscles and soft tissues. This tension can constrict circulation, sending pain signals to the brain. Heat application eases pain by:

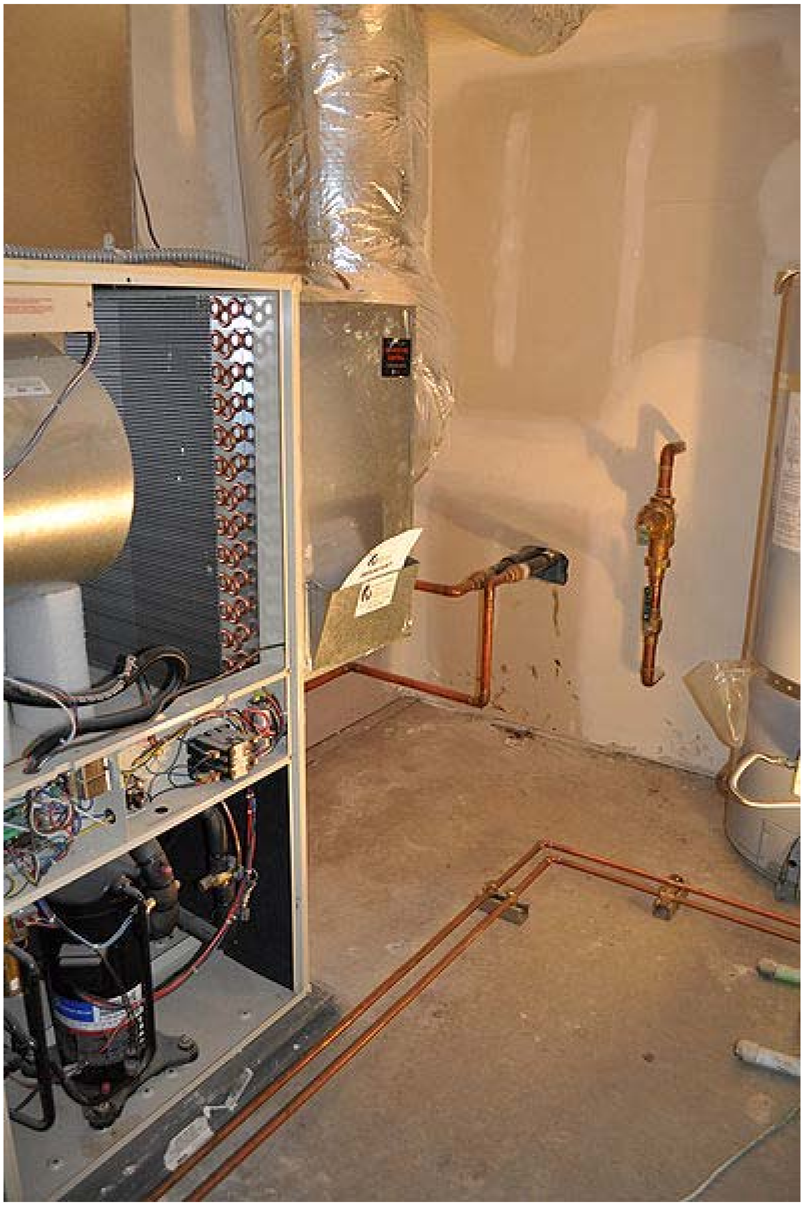
- dilating the blood vessels surrounding the painful area. Increased blood flow provides additional oxygen and nutrients to help heal the damaged muscle tissue.
- stimulating sensation in the skin and therefore decreasing the pain signals being transmitted to the brain
- increasing the flexibility (and decreasing painful stiffness) of soft tissues surrounding the injured area, including muscles and connective tissue.

As many heating pads are portable, heat may be applied as needed at home, at work, or while traveling. Some physicians recommend alternating heat and ice for pain relief. *As with any pain treatment, a physician should be consulted prior to beginning treatment.*

Chapter 6

# Geothermal Heat Pump

Ground source heating and cooling



Ground source heating and cooling

A **geothermal heat pump**, **ground source heat pump** (GSHP), or **ground heat pump** is a central heating and/or cooling system that pumps heat to or from the ground. It uses the earth as a heat source (in the winter) or a heat sink (in the summer). This design takes advantage of the moderate temperatures in the ground to boost efficiency and reduce the operational costs of heating and cooling systems, and may be combined with solar heating to form a geosolar system with even greater efficiency. Geothermal heat pumps are also known by a variety of other names, including **geoexchange, earth-coupled, earth energy** or **water-source heat pumps**. The engineering and scientific communities prefer the terms "geoexchange" or "ground source heat pumps" to avoid confusion with traditional geothermal power, which uses a high temperature heat source to generate electricity. Ground source heat pumps harvest a combination of geothermal energy (from the Earth's core) and solar energy (heat absorbed at the Earth's surface) when heating, but work against these heat sources when used for air conditioning.

Depending on latitude, the upper 3 metres (9.8 ft) of Earth's surface maintains a nearly constant temperature between 10 and 16 °C (50 and 60 °F). Like a refrigerator or air conditioner, these systems use a heat pump to force the transfer of heat from there. Heat pumps can transfer heat from a cool space to a warm space, against the natural direction of flow, or they can enhance the natural flow of heat from a warm area to a cool one. The core of the heat pump is a loop of refrigerant pumped through a vapor-compression refrigeration cycle that moves heat. Heat pumps are always more efficient at heating than pure electric heaters, even when extracting heat from cold winter air. But unlike an air-source heat pump, which transfers heat to or from the outside air, a ground source heat pump exchanges heat with the ground. This is much more energy-efficient because underground temperatures are more stable than air temperatures through the year. Seasonal variations drop off with depth and disappear below seven meters due to thermal inertia. Like a cave, the shallow ground temperature is warmer than the air above during the winter and cooler than the air in the summer. A ground source heat pump extracts ground heat in the winter (for heating) and transfers heat back into the ground in the summer (for cooling). Some systems are designed to operate in one mode only, heating or cooling, depending on climate.

The geothermal pump systems reach fairly high Coefficient of performance (CoP), 3-6, on the coldest of winter nights, compared to 1.75-2.5 for air-source heat pumps on cool days. Ground source heat pumps (GSHPs) are among the most energy efficient technologies for providing HVAC and water heating. Actual CoP of a geothermal system which includes the power required to circulate the fluid through the underground tubes can be lower than 2.5. The setup costs are higher than for conventional systems, but the difference is usually returned in energy savings in 3 to 10 years. System life is estimated at 25 years for inside components and 50+ years for the ground loop. As of 2004, there are over a million units installed worldwide providing 12 GW of thermal capacity, with an annual growth rate of 10%.

### *Differing terms and definitions*

There is a great deal of controversy and confusion with regard to exactly what geothermal heat pumps do. There are several concepts commonly attached to the idea of geothermal:

- Using geologically hot rocks, which have little relationship to the surface climate and derive their heat from deep in the earth, to run a heat engine which produces electricity. Such a system can be operated only until the rock around the bore cools, then it gradually loses its generating ability. All of these systems are in tectonically or volcanically active areas. Most people are pretty clear that this should be called "geothermal power".

- Using geologically hot rocks to heat some type of liquid or gas which is pumped up to be used to heat a building is often called "geothermal heating".

- Using a heat exchanger with a finite amount of external material to incorporate additional thermal mass to a building. This makes the building change temperature slowly, and allows the inhabitants to go through a time period with less overall temperature variation. The most common ones appear to be "geothermal heat pump" by laymen and "ground-source heat pump" by experts, but even these are broad, barely understood terms about which there is no consensus.

Builders may try to smooth out the indoor climate over surface temperature variations resulting from the day-night cycle, variations due to short-term weather patterns, or variations due to entire seasons. The amount of thermal mass incorporated is on a spectrum, so one cannot say their system addresses any of these cycles specifically – a system sized for day-night cycling will still help somewhat in a week-long blizzard. Such a system requires power to pump the coolant, but can be operated indefinitely.

To further complicate things, even though most home-sized systems termed "geothermal" operate primarily on the former principle, the thermal mass in such systems is rarely perfectly finite and closed. Groundwater flows through the area, and heat leaks out and warms/cools the surrounding area. True geothermal heat may play a small or large role in such systems.

When trying to explain this subject, experts may go through a series of explanations and divisions.

First, people separate out terms for geothermal electricity generation:

- geothermal power

Then, they split out geothermal heating, which is commonly used in tectonically or volcanically active regions:

- geothermal heating

Then, they explain the traditional concept of a heat pump which uses only inside and outside air:

- heat pump

After that, they try to identify simple systems in which the coolant is air which is pumped directly out of and back into the building, going through a simple hole in the ground:

- earth tube or earth air heat exchanger
- ground-coupled heat exchanger

After that, they remove systems which depend on large quantities of water or wet ground, primarily for cooling:

- lake water cooling
- deep water source cooling

At this point they may explain the concept of a seasonal thermal store or a thermal mass climate control strategy:

- trombe wall
- seasonal thermal store
- thermal mass

Then, they may try to figure out the size of the system. Is it targeted at a home? A building? Is it a full-scale district heating system?

Then they go into the specifics of the system. First, is the coolant water, and if so is it "open loop" – exposed to groundwater – or "closed loop" – not exposed.

Are other energy sources helping? Is solar absorbed from the house or from a dedicated thermal collector?

- annualized geothermal solar or annualized geo solar
- geosolar or solar combisystem

After this they concentrate on the specific form factor of the system. Is it a grid of pipes buried 3 feet (0.91 m) underneath the owner's garden? Does it consist of a hundred-foot borehole? A thousand-foot borehole? Dozens of 8-foot (2.4 m) boreholes?

- downhole heat exchanger or borehole heat exchanger

Finally they may try to decide what the locals call the system, as identical systems are often called different things in different countries, and in some countries generic terms may be trademarked in others:

- Geoexchange is a trademarked product in the US, but is a standards coalition in Canada.
- Earth tubes, Air-earth heat exchangers and "heat exchanger" in general, appear to be primarily used in the UK.

## *History*

The heat pump was described by Lord Kelvin in 1853 and developed by Peter Ritter von Rittinger in 1855. After experimenting with a freezer, Robert C. Webber built the first direct exchange ground-source heat pump in the late 1940s. The first successful commercial project was installed in the Commonwealth Building (Portland, Oregon) in 1946, and has been designated a National Historic Mechanical Engineering Landmark by ASME. The technology became popular in Sweden in the 1970s, and has been growing slowly in worldwide acceptance since then. Open loop systems dominated the market until the development of polybutylene pipe in 1979 made closed loop systems economically viable. As of 2004, there are over a million units installed worldwide providing 12 GW of thermal capacity. Each year, about 80,000 units are installed in the USA (geothermal energy is used in all 50 U.S. states today, with great potential for near-term market growth and savings) and 27,000 in Sweden.

### ***Ground heat exchanger***

Loop field for a 12-ton system (unusually large for most residential applications)

Heat pumps provide wintertime heating by extracting heat from a source and transferring it to the building. In theory, heat can be extracted from any source, no matter how cold, but a warmer source allows higher efficiency. A ground source heat pump uses the shallow ground as a source of heat, thus taking advantage of its seasonally moderate temperatures.

In the summer, the process can be reversed so the heat pump extracts heat from the building and transfers it to the ground. Transferring heat to a cooler space takes less energy, so the cooling efficiency of the heat pump gain benefits from the lower ground temperatures.

Shallow horizontal heat exchangers experience seasonal temperature cycles due to solar gains and transmission losses to ambient air at ground level. These temperature cycles lag behind the seasons because of thermal inertia, so the heat exchanger can harvest heat deposited by the sun several months earlier. Deep vertical systems rely heavily on migration of heat from surrounding geology, unless they are recharged annually by exhaust heat from air conditioning.

Ground source heat pumps must have a heat exchanger in contact with the ground or groundwater to extract or dissipate heat. This component accounts for a third to a half of the total system cost. Several major design options are available for these, which are classified by fluid and layout. Direct exchange systems circulate refrigerant underground, closed loop systems use a mixture of anti-freeze and water, and open loop systems use natural groundwater.

## Direct exchange

The Direct exchange geothermal heat pump is the oldest type of geothermal heat pump technology. It is also the simplest and easiest to understand. The ground-coupling is achieved through a single loop circulating refrigerant in direct thermal contact with the ground (as opposed to a combination of a refrigerant loop and a water loop). The refrigerant leaves the heat pump appliance cabinet, circulates through a loop of copper tube buried underground, and exchanges heat with the ground before returning to the pump. The name "direct exchange" refers to heat transfer between the refrigerant and the ground without the use of an intermediate fluid. There is no direct interaction between the fluid and the earth; only heat transfer through the pipe wall. Direct exchange heat pumps are not to be confused with "water-source heat pumps" or "water loop heat pumps" since there is no water in the ground loop. ASHRAE defines the term *ground-coupled heat pump* to encompass closed loop and direct exchange systems, while excluding open loops.

Direct exchange systems are significantly more efficient and have potentially lower installation costs than closed loop water systems. Copper's high thermal conductivity contributes to the higher efficiency of the system, but heat flow is predominantly limited by the thermal conductivity of the ground, not the pipe. The main reasons for the higher efficiency are the elimination of the water pump (which uses electricity), the elimination of the water heat exchanger (which is a source of heat losses), and most importantly, the latent heat phase change of the refrigerant in the ground itself.

While they require much more refrigerant and their tubing is more expensive per foot, a direct exchange loop is shorter than a closed water loop for a given capacity. A direct exchange system requires only 15 to 30% of the length of tubing and half the diameter of drilled holes, and the drilling or excavation costs are therefore lower. Refrigerant loops are less tolerant of leaks than water loops because gas can leak out through smaller imperfections. This dictates the use of brazed copper tubing, even though the pressures are similar to water loops. The copper loop must be protected from corrosion in acidic soil through the use of a sacrificial anode or cathodic protection.

## Closed loop

Most installed systems have two loops on the ground side: the primary refrigerant loop is contained in the appliance cabinet where it exchanges heat with a secondary water loop that is buried underground. The secondary loop is typically made of High-density polyethylene pipe and contains a mixture of water and anti-freeze (propylene glycol, denatured alcohol or methanol). After leaving the internal heat exchanger, the water flows through the secondary loop outside the building to exchange heat with the ground before returning. The secondary loop is placed below the frost line where the temperature is more stable, or preferably submerged in a body of water if available. Systems in wet ground or in water are generally more efficient than drier ground loops since it is less work to move heat in and out of water than solids in sand or soil. If the ground is naturally dry, soaker hoses may be buried with the ground loop to keep it wet.

An installed liquid pump pack

Closed loop systems need a heat exchanger between the refrigerant loop and the water loop, and pumps in both loops. Some manufacturers have a separate ground loop fluid pump pack, while some integrate the pumping and valving within the heat pump. Expansion tanks and pressure relief valves may be installed on the heated fluid side. Closed loop systems have lower efficiency than direct exchange systems, so they require longer and larger pipe to be placed in the ground, increasing excavation costs.

Closed loop tubing can be installed horizontally as a loop field in trenches or vertically as a series of long U-shapes in wells. The size of the loop field depends on the soil type and moisture content, the average ground temperature and the heat loss and or gain characteristics of the building being conditioned. A rough approximation of the initial soil temperature is the average daily temperature for the region.

### Vertical

A vertical closed loop field is composed of pipes that run vertically in the ground. A hole is bored in the ground, typically 75 to 500 feet (23–150 m) deep. Pipe pairs in the hole are joined with a U-shaped cross connector at the bottom of the hole. The borehole is commonly filled with a bentonite grout surrounding the pipe to provide a thermal connection to the surrounding soil or rock to improve the heat transfer. Thermally enhanced grouts are available to improve this heat transfer. Grout also protects the ground water from contamination, and prevents artesian wells from flooding the property. Vertical loop fields are typically used when there is a limited area of land available. Bore holes are spaced at least 5–6 m apart and the depth depends on ground and building characteristics. For illustration, a detached house needing 10 kW (3 ton) of heating capacity might need three boreholes 80 to 110 m (260 to 360 ft) deep. (A ton of heat is 12,000 British thermal units per hour (BTU/h) or 3.5 kilowatts.) During the cooling season, the local temperature rise in the bore field is influenced most by the moisture travel in the soil. Reliable heat transfer models have been developed through sample bore holes as well as other tests.

**Horizontal**

A 3-ton slinky loop prior to being covered with soil. The three slinky loops are running out horizontally with three straight lines returning the end of the slinky coil to the heat pump

A horizontal closed loop field is composed of pipes that run horizontally in the ground. A long horizontal trench, deeper than the frost line, is dug and U-shaped or slinky coils are placed horizontally inside the same trench. Excavation for horizontal loop fields is about half the cost of vertical drilling, so this is the most common layout used wherever there is adequate land available. For illustration, a detached house needing 10 kW (3 ton) of heating capacity might need 3 loops 120 to 180 m (390 to 590 ft) long of NPS 3/4 (DN 20) or NPS 1.25 (DN 32) polyethylene tubing at a depth of 1 to 2 m (3.3 to 6.6 ft).

As an alternative to trenching, the horizontal loop field may be laid by mini horizontal directional drilling. (mini-HDD) This technique can lay piping under yards, driveways or other structures without disturbing them, with a cost between those of trenching and vertical drilling.

A slinky (also called coiled) closed loop field is a type of horizontal closed loop where the pipes overlay each other (not a recommended method). The easiest way of picturing a slinky field is to imagine holding a slinky on the top and bottom with your hands and then move your hands in opposite directions. A slinky loop field is used if there is not adequate room for a true horizontal system, but it still allows for an easy installation. Rather than using straight pipe, slinky coils, use overlapped loops of piping laid out horizontally along the bottom of a wide trench. Depending on soil, climate and your heat pump's run fraction, slinky coil trenches can be anywhere from one third to two thirds shorter than traditional horizontal loop trenches. Slinky coil ground loops are essentially a more economic and space efficient version of a horizontal ground loop.

**Pond**

12-ton pond loop system being sunk to the bottom of a pond

A closed pond loop is not common because it depends on proximity to a body of water, where an open loop system is usually preferable. A pond loop may be advantageous where poor water quality precludes an open loop, or where the system heat load is small. A pond loop consists of coils of pipe similar to a slinky loop attached to a frame and located at the bottom of an appropriately sized pond or water source.

## Open loop

In an open loop system (also called a groundwater heat pump), the secondary loop pumps natural water from a well or body of water into a heat exchanger inside the heat pump. ASHRAE calls open loop systems *groundwater heat pumps* or *surface water heat pumps*, depending on the source. Heat is either extracted or added by the primary refrigerant loop, and the water is returned to a separate injection well, irrigation trench, tile field or body of water. The supply and return lines must be placed far enough apart to ensure thermal recharge of the source. Since the water chemistry is not controlled, the appliance may need to be protected from corrosion by using different metals in the heat exchanger and pump. Limescale may foul the system over time and require periodic acid cleaning. Also, as fouling decreases the flow of natural water, it becomes difficult for the heat pump to exchange building heat with the groundwater. If the water contains high levels of salt, minerals, iron bacteria or hydrogen sulfide, a closed loop system is usually preferable.

Deep lake water cooling uses a similar process with an open loop for air conditioning and cooling. Open loop systems using ground water are usually more efficient than closed systems because they are better coupled with ground temperatures. Closed loop systems, in comparison, have to transfer heat across extra layers of pipe wall and dirt.

A growing number of jurisdictions have outlawed open-loop systems that drain to the surface because these may drain aquifers or contaminate wells. This forces the use of more environmentally sound injection wells.

**Standing column well**

A standing column well system is a specialized type of open loop system. Water is drawn from the bottom of a deep rock well, passed through a heat pump, and returned to the top of the well, where traveling downwards it exchanges heat with the surrounding bedrock. The choice of a standing column well system is often dictated where there is near-surface bedrock and limited surface area is available. A standing column is typically not suitable in locations where the geology is mostly clay, silt, or sand. If bedrock is deeper than 200 feet (61 m) from the surface, the cost of casing to seal off the overburden may become prohibitive.

A multiple standing column well system can support a large structure in an urban or rural application. The standing column well method is also popular in residential and small commercial applications. There are many successful applications of varying sizes and well quantities in the many boroughs of New York City, and is also the most common application in the New England states. This type of ground source system has some heat storage benefits, where heat is rejected from the building and the temperature of the well is raised, within reason, during the Summer cooling months which can then be harvested for heating in the Winter months, thereby increasing the efficiency of the heat pump system. As with closed loop systems, sizing of the standing column system is critical in reference to the heat loss and gain of the existing building. As the heat exchange is actually with the bedrock, using water as the transfer medium, a large amount of production capacity (water flow from the well) is not required for a standing column system to work. However, if there is adequate water production, then the thermal capacity of the well system can be enhanced by discharging a small percentage of system flow during the peak Summer and Winter months.

Since this is essentially a water pumping system, standing column well design requires critical considerations to obtain peak operating efficiency. Should a standing column well design be misapplied, leaving out critical shut-off valves for example, the result could be an extreme loss in efficiency and thereby cause operational cost to be higher than anticipated.

### *Building distribution*

Liquid-to-air heat pump

The heat pump is the central unit that becomes the heating and cooling plant for the building. Some models may cover space heating, space cooling, (space heating via conditioned air, hydronic systems and / or radiant heating systems), domestic or pool water preheat (via the desuperheater function, demand hot water, and driveway ice melting all within one appliance with a variety of options with respect to controls, staging and zone control. The heat may be carried to its end use by circulating water or forced air. Almost all types of heat pumps are produced for commercial and residential applications.

*Liquid-to-air* heat pumps (also called *water-to-air*) output forced air, and are most commonly used to replace legacy forced air furnaces and central air conditioning systems. There are variations that allow for split systems, high-velocity systems, and ductless systems. Heat pumps cannot achieve as high of a fluid temperature as a conventional furnace, so they require a higher volume flow rate of air to compensate. When retrofitting a residence, the existing duct work may have to be enlarged to reduce the noise from the higher air flow.

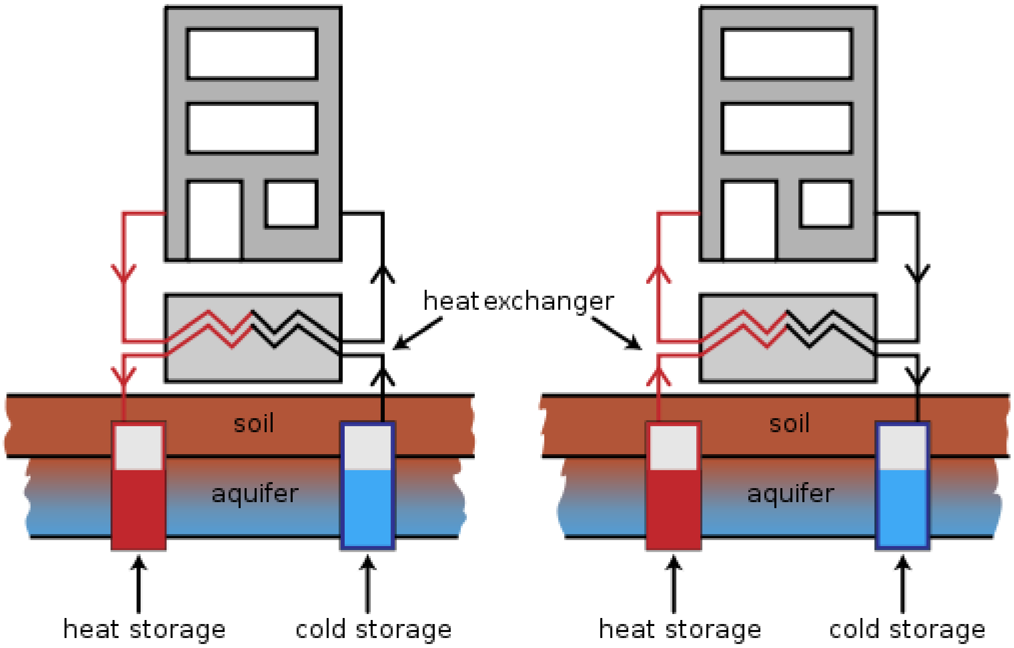
Liquid-to-water heat pump

*Liquid-to-water* heat pumps (also called *water-to-water*) are hydronic systems that use water to carry heating or cooling through the building. Systems such as radiant underfloor heating, baseboard radiators, conventional cast iron radiators would use a liquid-to-water heat pump. These heat pumps are preferred for pool heating or domestic hot water pre-heat. Heat pumps can only heat water to about 50 °C (122 °F) efficiently, whereas a boiler normally reaches 65–95 °C (149–203 °F). Legacy radiators designed for these higher temperatures may have to be doubled in numbers when retrofitting a home. A hot water tank will still be needed to raise water temperatures above the heat pump's maximum, but pre-heating will save 25-50% of hot water costs.

Ground source heat pumps are especially well matched to underfloor heating and baseboard radiator systems which only require warm temperatures (40 °C) to work well. Thus they are ideal for open plan offices. Using large surfaces such as floors, as opposed to radiators, distributes the heat more uniformly and allows for a lower water temperature. Wood or carpet floor coverings dampen this effect because the thermal transfer efficiency of these materials is lower than that of masonry floors (tile, concrete). Underfloor piping, ceiling or wall radiators can also be used for cooling in dry climates, although the temperature of the circulating water must be above the dew point to ensure that atmospheric humidity does not condense on the radiator.

Combination heat pumps are available that can produce forced air and circulating water simultaneously and individually. These systems are largely being used for houses that have a combination of air and liquid conditioning needs, for example central air conditioning and pool heating.

### *Seasonal thermal storage*




A heat pump in combination with heat and cold storage

The efficiency of ground source heat pumps can be improved by using seasonal thermal storage. If heat loss from the ground source is sufficiently low, the heat pumped out of the building in the summer can be retrieved in the winter. Heat storage efficiency increases with scale, so this advantage is most significant in commercial or district heating systems. Geosolar combisystems further augment this efficiency by collecting extra solar energy during the summer (more than is needed for air conditioning) and concentrating it in the store.

Such a system has been used to heat and cool a greenhouse using an aquifer for thermal storage. In summer, the greenhouse is cooled with cold ground water. This heats the water in the aquifer which can become a warm source for heating in winter. The combination of cold and heat storage with heat pumps can be combined with water/humidity regulation. These principles are used to provide renewable heat and renewable cooling to all kinds of buildings.

Also the efficiency of existing small heat pump installations can sometimes be improved a lot by adding large, cheap, water filled solar collectors. These may be integrated into a to be overhauled parking lot, or in walls or roof constructions simply by putting lots of one inch PE pipes into the outer layer. A very simple option is to add a large mechanically ventilated out door water-air heat exchanger (like the one that is in front of your car engine, but larger). In the summer they allow to pump lots of heat, almost free of running cost, into the ground. This only works well when ground water mobility is not too high, and it works better when more houses install this system next to each other. (In the winter such outdoor components have to be drained of water.)

### *Thermal efficiency*

The net thermal efficiency of a heat pump should take into account the efficiency of electricity generation and transmission, typically about 40%. Since a heat pump moves 3 to 5 times more heat energy than the electric energy it consumes, the total energy output is much greater than the input. This results in net thermal efficiencies greater than 100% for most electricity sources. Traditional combustion furnaces and electric heaters can never exceed 100% efficiency, but heat pumps provide extra energy by extracting it from the ground.

Geothermal heat pumps can reduce energy consumption— and corresponding air pollution emissions—up to 44% compared to air source heat pumps and up to 72% compared to electric resistance heating with standard air-conditioning equipment.

The dependence of net thermal efficiency on the electricity infrastructure tends to be an unnecessary complication for consumers and is not applicable to hydroelectric power, so performance of heat pumps is usually expressed as the ratio of heating output or heat removal to electricity input. Cooling performance is typically expressed in units of BTU/hr/watt as the Energy Efficiency Ratio, (EER) while heating performance is typically reduced to dimensionless units as the Coefficient of Performance. (COP) The conversion factor is 3.41 BTU/hr/watt. Performance is influenced by all components of the installed system, including the soil conditions, the ground-coupled heat exchanger, the heat pump appliance, and the building distribution, but is largely determined by the "lift" between the input temperature and the output temperature.

For the sake of comparing heat pump appliances to each other, independently from other system components, a few standard test conditions have been established by the American Refrigerant Institute (ARI) and more recently by the International Organization for Standardization. Standard ARI 330 ratings were intended for closed loop ground-source heat pumps, and assumes secondary loop water temperatures of 77 °F (25 °C) for air conditioning and 32 °F (0 °C) for heating. These temperatures are typical of installations in the northern USA. Standard ARI 325 ratings were intended for open loop ground-source heat pumps, and include two sets of ratings for groundwater temperatures of 50 °F (10 °C) and 70 °F (21 °C). ARI 325 budgets more electricity for water pumping than ARI 330. Neither of these standards attempt to account for seasonal variations. Standard ARI 870 ratings are intended for direct exchange ground-source heat pumps. ASHRAE transitioned to ISO 13256-1 in 2001, which replaces ARI 320, 325 and 330. The new ISO standard produces slightly higher ratings because it no longer budgets any electricity for water pumps.

Efficient compressors, variable speed compressors and larger heat exchangers all contribute to heat pump efficiency. Residential ground source heat pumps on the market today have standard COPs ranging from 2.4 to 5.0 and EERs ranging from 10.6 to 30. To qualify for an Energy Star label, heat pumps must meet certain minimum COP and EER ratings which depend on the ground heat exchanger type. For closed loop systems, the ISO 13256-1 heating COP must be 3.3 or greater and the cooling EER must be 14.1 or greater.

Actual installation conditions may produce better or worse efficiency than the standard test conditions. COP improves with a lower temperature difference between the input and output of the heat pump, so the stability of ground temperatures is important. If the loop field or water pump is undersized, the addition or removal of heat may push the ground temperature beyond standard test conditions, and performance will be degraded. Similarly, an undersized blower may allow the plenum coil to overheat and degrade performance.

Soil without artificial heat addition or subtraction and at depths of several meters or more remains at a relatively constant temperature year round. This temperature equates roughly to the average annual air-temperature of the chosen location, usually 7–12 °C (45–54 °F) at a depth of six meters in the northern USA. Because this temperature remains more constant than the air temperature throughout the seasons, geothermal heat pumps perform with far greater efficiency during extreme air temperatures than air conditioners and air-source heat pumps.

Standards ARI 210 and 240 define Seasonal Energy Efficiency Ratio (SEER) and Heating Seasonal Performance Factors (HSPF) to account for the impact of seasonal variations on air source heat pumps. These numbers are normally not applicable and should not be compared to ground source heat pump ratings. However, Natural Resources Canada has adapted this approach to calculate typical seasonally adjusted HSPFs for ground-source heat pumps in Canada. The NRC HSPFs ranged from 8.7 to 12.8 BTU/hr/watt (2.6 to 3.8 in nondimensional factors, or 255% to 375% seasonal average electricity utilization efficiency) for the most populated regions of Canada. When combined with the thermal efficiency of electricity, this corresponds to net average thermal efficiencies of 100% to 150%.

## *Environmental impact*

The U.S. Environmental Protection Agency (EPA) has called ground source heat pumps the most energy-efficient, environmentally clean, and cost-effective space conditioning systems available. Heat pumps offer significant emission reductions potential, particularly where they are used for both heating and cooling and where the electricity is produced from renewable resources.

Ground-source heat pumps have unsurpassed thermal efficiencies and produce zero emissions locally, but their electricity supply includes components with high greenhouse gas emissions, unless the owner has opted for a 100% renewable energy supply. Their environmental impact therefore depends on the characteristics of the electricity supply.

Annual greenhouse gas savings from using a ground source heat pump instead of a high-efficiency furnace in a detached residence (assuming no specific supply of renewable energy)

| Country | Electricity $CO_2$ Emissions Intensity | GHG savings relative to | | |
|---|---|---|---|---|
| | | **natural gas** | **heating oil** | **electric heating** |
| Canada | 223 ton/GWh | 2.7 ton/yr | 5.3 ton/yr | 3.4 ton/yr |
| Russia | 351 ton/GWh | 1.8 ton/yr | 4.4 ton/yr | 5.4 ton/yr |
| USA | 676 ton/GWh | -0.5 ton/yr | 2.2 ton/yr | 10.3 ton/yr |
| China | 839 ton/GWh | -1.6 ton/yr | 1.0 ton/yr | 12.8 ton/yr |

The GHG emissions savings from a heat pump over a conventional furnace can be calculated based on the following formula:

$$GHG\ Savings = HL\left(\frac{FI}{AFUE \times 1000\frac{kg}{ton}} - \frac{EI}{COP \times 3600\frac{sec}{hr}}\right)$$

- HL = seasonal heat load ≈ 80 GJ/yr for a modern detached house in the northern USA
- FI = emissions intensity of fuel = 50 kg($CO_2$)/GJ for natural gas, 73 for heating oil, 0 for 100% renewable energy such as wind, hydro, photovoltaic or solar thermal
- AFUE = furnace efficiency ≈ 95% for a modern condensing furnace
- COP = heat pump coefficient of performance ≈ 3.2 seasonally adjusted for northern USA heat pump
- EI = emissions intensity of electricity ≈ 200-800 ton($CO_2$)/GWh, depending on region

Ground-source heat pumps always produce less greenhouse gases than air conditioners, oil furnaces, and electric heating, but natural gas furnaces may be competitive depending on the greenhouse gas intensity of the local electricity supply. In countries like Canada and Russia with low emitting electricity infrastructure, a residential heat pump may save 5 tons of carbon dioxide per year relative to an oil furnace, or about as much as taking an average passenger car off the road. But in countries like China or USA that are highly reliant on coal for electricity production, a heat pump may result in 1 or 2 tons more carbon dioxide emissions than a natural gas furnace.

The fluids used in closed loops may be designed to be biodegradable and non-toxic, but the refrigerant used in the heat pump cabinet and in direct exchange loops was, until recently, chlorodifluoromethane, which is an ozone depleting substance. Although harmless while contained, leaks and improper end-of-life disposal contribute to enlarging the ozone hole. This refrigerant is being phased out in favor of ozone-friendly R410A for new construction. The EcoCute water heater is an air-source heat pump that uses Carbon Dioxide as its working fluid instead of Chlorofluorocarbons.

Open loop systems that draw water from a well and drain to the surface may contribute to aquifer depletion, water shortages, groundwater contamination, and subsidence of the soil. A geothermal heating project in Staufen im Breisgau, Germany, is suspected to have caused considerable damage to buildings in the city center. The ground has subsided by up to eight millimeters under the city hall while other areas have been uplifted by a few millimeters.

Ground-source heat pump technology, like building orientation, is a natural building technique (bioclimatic building).

### *Economics*

Ground source heat pumps are characterized by high capital costs and low operational costs compared to other HVAC systems. Their overall economic benefit depends primarily on the relative costs of electricity and fuels, which are highly variable over time and across the world. Based on recent prices, ground-source heat pumps currently have lower operational costs than any other conventional heating source almost everywhere in the world. Natural gas is the only fuel with competitive operational costs, and only in a handful of countries where it is exceptionally cheap, or where electricity is exceptionally expensive. In general, a homeowner may save anywhere from 20% to 60% annually on utilities by switching from an ordinary system to a ground-source system. However, many family size installations are reported to use much more electricity then their owners had expected from advertisements. This is often partly due to bad design or installation: Heat exchange capacity with groundwater is often too small, heating pipes in house floors are often too thin and too few, or heated floors are covered with wooden panels or carpets.

Capital costs and system lifespan have received much less study, and the return on investment is highly variable. One study found the total installed cost for a system with 10 kW (3 ton) thermal capacity for a detached rural residence in the USA averaged $8000–$9000 in 1995 US dollars. More recent studies found an average cost of $14,000 in 2008 US dollars for the same size system. The US Department of Energy estimates a price of $7500 on its website, last updated in 2008. Prices over $20,000 are quoted in Canada, with one source placing them in the range of $30,000-$34,000 Canadian dollars. The rapid escalation in system price has been accompanied by rapid improvements in efficiency and reliability. Capital costs are known to benefit from economies of scale, particularly for open loop systems, so they are more cost-effective for larger commercial buildings and harsher climates. The initial cost can be two to five times that of a conventional heating system in most residential applications, new construction or existing. In retrofits, the cost of installation is affected by the size of living area, the home's age, insulation characteristics, the geology of the area, and location of the home/property. Proper duct system design and mechanical air exchange should be considered in the initial system cost.

Payback period for installing a ground source heat pump in a detached residence

| **Country** | **Payback period for replacing** | | |
|---|---|---|---|
| | **natural gas** | **heating oil** | **electric heating** |
| Canada | 13 years | 3 years | 6 years |
| USA | 12 years | 5 years | 4 years |
| Germany | net loss | 8 years | 2 years |

Notes:

- Highly variable with energy prices.
- Government subsidies not included.
- Climate differences not evaluated.

Capital costs may be offset by substantial subsidies from many governments, for example totaling over $7000 in Ontario for residential systems installed in the 2009 fiscal year. Some electric companies offer special rates to customers who install a ground-source heat pump for heating/cooling their building. This is due to the fact that electrical plants have the largest loads during summer months and much of their capacity sits idle during winter months. This allows the electric company to use more of their facility during the winter months and sell more electricity. It also allows them to reduce peak usage during the summer (due to the increased efficiency of heat pumps), thereby avoiding costly construction of new power plants. For the same reasons, other utility companies have started to pay for the installation of ground-source heat pumps at customer residences. They lease the systems to their customers for a monthly fee, at a net overall savings to the customer.

The lifespan of the system is longer than conventional heating and cooling systems. Good data on system lifespan is not yet available because the technology is too recent, but many early systems are still operational today after 25–30 years with routine maintenance. Most loop fields have warranties for 25 to 50 years and are expected to last at least 50 to 200 years. Ground-source heat pumps use electricity for heating the house. The higher investment above conventional oil, propane or electric systems may be returned in energy savings in 2–10 years for residential systems in the USA. If compared to natural gas systems, the payback period can be much longer or non-existent. The payback period for larger commercial systems in the USA is 1–5 years, even when compared to natural gas.

Ground source heat pumps are recognized as one of the most efficient heating and cooling systems on the market. They are often the second-most cost effective solution in extreme climates, (after co-generation), despite reductions in thermal efficiency due to ground temperature. (The ground source is warmer in climates that need strong air conditioning, and cooler in climates that need strong heating.)

Commercial systems maintenance costs in the USA have historically been between $0.11 to $0.22 per $m^2$ per year in 1996 dollars, much less than the average $0.54 per $m^2$ per year for conventional HVAC systems.

Governments that promote renewable energy will likely offer incentives for the consumer (residential), or industrial markets. For example, in the United States, incentives are offered both on the state and federal levels of government.

### *Installation*

Because of the technical knowledge and equipment needed to properly design and size the system (and install the piping if heat fusion is required), a GSHP system installation requires a professional's services. The International Ground Source Heat Pump Association (IGSHPA), Geothermal Exchange Organization (GEO) and the Canadian GeoExchange Coalition maintain listings of qualified installers in the USA and Canada.

Chapter 7

# Heatable Glass and Hand Warmer

## Heatable Glass

**Electrically heatable glass** and windows are relatively new products, which help to find solutions while designing buildings and vehicles. The idea of heating glass is based on usage of energy-efficient low-emissive glass which is generally simple silicate glass with special metallic oxides covering. Low-emissive covering decreases the loss of heat approximately by 30 %. Heatable glass can be used in all kinds of standard glazing systems, made of wood, plastic, aluminum or steel.

For the first time the heatable glass based on low-emissive coverings was produced in high volume in the beginning of 1980s. Nowadays heating glass is used in construction of many kinds of buildings and in production of serial vehicles, ships and trains. Heatable glass takes away discomfort and other disadvantages induced by low heat-insulating features of silicate glass. The effect of "cold glass" disappears when the surface of the glass is heated, there is no more condensation, ice crusts and snow covering, the window's heat losses are compensated and that is why there is an atmosphere of comfort in the room. Heatable glass can be used as the principal system of heating and can combine with floor and ceiling heating. This kind of combination helps to reduce the total rate of heat losses of the building thereby lowers the expenses for heating. Besides, having heating glass windows you can use the active area of the room more efficient, because you do not have to install massive window-sill radiators. Initially the heating glass was produced by sputtering the ordinary glass and it could not guarantee the quality stability of the product. The technological breakthrough took place in 1989 when the mass production of low-emissive glass began. The glass was coated during the process of manufacturing and thanks to that the quality of innovative product grew very high and this innovative product became the ideal component for heatable glass production.

## *Standard Windows*

- **Window construction**

Windows play a significant role in creation of comfortable atmosphere in the room. That is why the area of glazing of buildings is constantly being increased. Window technologies always in progress and it is common today to use low-emissive glass. In spite of progress the low temperature of glass surface is still the problem of constructive glazing. Heatable glass helps to solve problems concerning low surface temperature and increase the level of comfort in the room significantly. Heatable glass can be used in practically all kinds of glazing systems made of wood, plastic or aluminum. Heatable glass and multiple glass panes can be used both in blind and openable constructions. Multiple glass panes made of heating glass can have one or two chambers. The advantages of multiple glass panes are their hermiticity and ability to decrease heat transfer significantly.

- **Optical transmission and heat losses of windows**

If the temperature in the building is higher than the temperature outside, the heat leaks through the elements of construction. Windows are usually the most vulnerable elements of the building in terms of heat losses. So the heat loss though window constructions is about 20-25% of total heat loss. Heat insulation of translucent constructions can be improved by increase of the number of glasses and chambers of multiple glass panes; but it will result in increase of construction's cost and decrease of rate of optical transmission. The reasonable alternative is the usage of low-emissive glass, which is practically the same as ordinary glass in terms of optical transmission, but it also reflects the heat radiation back into the room. The major indicator which characterizes the ability of glass to reflect heat radiation is its emissivity (E) or the "emission factor". The emission factor of ordinary glass is 0.83; the factor of low-emissive can reach 0.03, so more than 90% of accumulated heat will be reflected back into the room. The lower the emission factor is, the more effective is the material to reflect the heat, and the more heat it will accumulate. To compare, the emission factor of multiple glass pane with two chambers, which is made of ordinary glass, is the same as the emission factor of multiple glass pane with one chamber, which was produced with usage of low-emissive glass. Besides energy-efficient functions in cold seasons of the year, low-emissive glass possesses the ability to reflect the excess of outside heat energy in summer seasons; the optical transmission coefficient is affected insignificantly in this way. The additional factor of reduce of heat transfer of multiple glass panes is the usage of low thermal conductivity gases – Ar or Kr – to fill the chambers. In present-day multiple glass panes Ar is more often used, which helps to reduce heat losses by 10-20%, though the cost of multiple glass panes is insignificantly increased.

- **Influence of window surface temperature on comfort**

There are two reasons why people feel discomfort when they are close to cold window surface. First, cold window is the reason of outflow of heat, which is produced by the cutaneous covering of individual. Second, cold window provokes the circulation of air, which is felt like draft. In order to reduce these factors the heating radiators are always places under window sills. As far as people can feel cold and heat, the actual temperature of environment is not the only factor which defines the total level of comfort. In reality, the heat radiation of surrounding surfaces has a greater influence than air temperature. If the window surface is cold then to maintain the comfort atmosphere it is necessary to increase the heating temperature, but it will also increase energy consumption. The problem of cold window can be solved effectively with the help of heatable glass. These windows allow to maintain the optimal comfort level and temperature of the room. The air temperature can be decreased at least by 1 degree if the temperature of surrounding surfaces has the same significance. You also do not have to install heating radiators and free the additional space for that. Besides, when turned off the multiple glass panes made of heatable glass act like ordinary low-emissive glass.

## *Heatable glass and multiple glass panes made of heating glass*

- **Structure of heatable glass**

The idea of heatable glass is based on usage of energy-efficient low-emissive glass, where the coating plays the role of heating element. It can be used both in production of multiple glass panes and as a part of triplex, which has also the function of protective glazing. The technological process of production of multiple glass panes made of heatable glass is practically the same as the process of ordinary multiple glass panes production. The main difference is the presence of power supply and, if necessary, temperature sensor. The temperature sensor allows to track the temperature of heating glass and eliminates the possibility of overheating of the product. In order to prevent shocks, the conductive coating is always placed inside the multiple glass pane or laminated unit. Only safe tempered glass, the strength of which is a lot higher than the strength of ordinary glass, is used in production of heatable glass. When the hardened glass is destructed there are safe splittings. Also the current-carrying coating loses its integrity and the automatic fuse, which turns off the power supply of the glass, is activated. The electrodes are placed inside the lamination and no one can reach them without destruction of the product.

- **Usage of heatable glass**

Alarm Glass

Transport Glass

Heating glass is mostly used for heating of windows. It is especially useful for rooms where people spend much time by the windows, at home or at work. The most common usage of heating glass—windows of cottages, office buildings and also big areas—leaded panes, translucent roofing, garret windows, canopies and so on.

Heating glass is used for defogging and prevention of frosting of windows of pools, saunas and other buildings of such kind. Insofar as heatable glass has a current-carrying coating, it can be used as the sensor of alarm systems. When the glass is destructed the system of protection is activated and it results in activation of alarm system. This kind of products is widely used on objects of tightened standards in questions of protection: nuclear power plants, stations of air navigation control, museums, special storehouses, etc. Heatable glass is also used in production of windows for different kinds of vehicles: electric and diesel locomotives, vessels and boats, various kinds of aircraft and automobiles. One of well-known examples of application of heating glass is armored windows, because the protective glazing is very thick and is disposed to frosting. The usage of heating glass is especially urgent in terms of being the part of armored multiple glass of Smart Glass of switchable transparency, because the heating significantly decreases the period of reaction of liquid crystals structure. The power consumed by products depends on the type of use. Power of about 50-100 watts per square meter of the window is generally enough for maintenance of comfort temperature in the room and for maintenance of glass surface temperature at the rate from +20 degrees to +30 degrees. When the heatable glass is used as the only resource of heat it is necessary to maintain the glass surface temperature at the rate from +30 degrees to -45 degrees and provide the power of 100 to 300 watt for 1 square meter of the window. The power needed for vehicle windows reaches 1.5 kilowatts per square meter or more, which is why there are such tight standards in terms of sputtering of current-carrying components. Heat power of about 500-700 watts per square meter of glazing is necessary for snow unloading and taking ice-covering off the outside protective translucent constructions in low temperatures and windy environments.

## *Technology of production*

Heatable glass is produced by lamination of two or more sheets of silicate glass. The most widespread technologies are the following technologies of panel production according to the type of materials used:

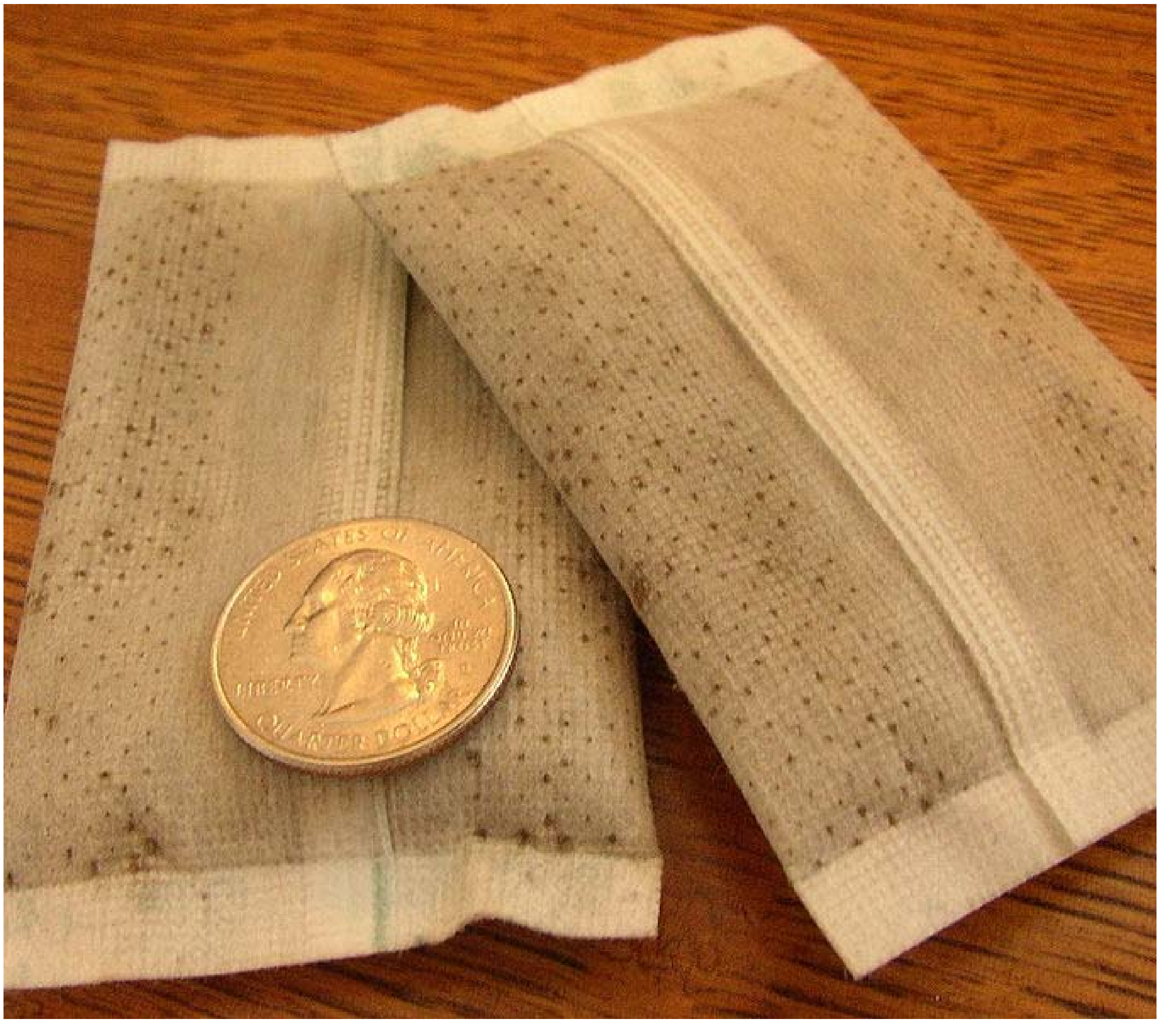
- EVA - ethylene-vinyl-acetate film with good adhesion to glass. Major advantages: low cost of both film and equipment. One needs only a primitive furnace with vacuum bags for production. Disadvantages: high rate of opalescence, especially after multcoat lamination, with the lapse of time yellowness appears. EVA has low shear strength, especially in low temperatures; it results in delamination (layering).

- PVB - polyvinyl butyral film with high rate of adhesion to glass. Major advantages: low cost of mass production of laminated glass, insignificant rate of opalescence, high quality of product. Disadvantages: high initial cost of equipment, it is necessary to have autoclave, press for preliminary hot pressing, “clean” room, and qualified personnel. Besides that, triplex made with the help of PVB technology can not be use in wet environment.

- TPU - thermoplastic polyurethane film with very high rate of adhesion to glass. Major advantages: insignificant rate of opalescence, insensible to humidity, mechanical effects and severe atmosphere; very high quality of the product. Disadvantages: high cost of film and equipment, it is necessary to have autoclave, “clean” room, and qualified personnel.

- Photocurable polymers (resins) – so-called “filling technology”. Major advantages: low cost of both resin and equipment. Only an ultraviolet furnace and a minimum of additional equipment is needed to produce laminated glass. Disadvantages: it is necessary to have qualified personnel for the work. Heating laminated glass that is produced with the help of this technology is insensible to humidity and temperature influence, has high shear strength.

# Hand Warmer



A pair of air-activated disposable hand warmers, US quarter to scale

*Hand warmers* are small (mostly disposable) packets which are held in the hand and produce heat on demand to warm cold hands. They are commonly used in outdoor activities such as hiking and skiing to keep extremities warm and assist insulated clothing. Other types of warmers are available to provide soothing heat for muscular or joint aches.

On one side the packets often have adhesive strips so they can be stuck to the underwear (never directly onto the skin as this can cause burns) to keep the lower back warm, for example. There are also types that can be inserted into the shoes or stuck to the socks.

Depending on the type and the source of heat, hand warmers last between 30 minutes (recrystallisation) to 12–24 hours (platinum catalyst).

## *Types*

### Air activated (iron)

Some hand warmers contain cellulose, iron, water, activated carbon (to speed up reaction), vermiculite (water reservoir) and salt (catalyst) and produce heat from the exothermic oxidation of iron when exposed to air.


Crystallization-type hand warmer with scale showing metal disc trigger

### Supersaturated solution (crystallization-type)

A second type generate heat through exothermic crystallisation of supersaturated solutions (typically sodium acetate) and are usually reusable. These can be recharged by boiling the heaters and allowing them to cool. Heating of these pads is triggered by snapping a small metal device buried in the pad, which generates nucleation centers that initiate crystallisation. Heat is required to dissolve the salt in its own water of crystallisation and it is this heat that is released when crystallisation is initiated.

This type typically has a shorter heat duration of 20 minutes to 2 hours.

Lighter fuel warmer

## Lighter fuel

Another type uses lighter fluid (lighter fuel) or LPG which is reacted with a platinum catalyst to release heat by oxidation reactions. These can be used on many occasions by simply refuelling.

## Battery

There is also a battery operated handwarmer. In this type, electrically resistive heating devices are used to convert electrical energy in the battery to thermal energy. Some use disposable batteries, but others are rechargeable, like cellphones, and can be used for many hundreds of cycles with the same battery. This type is not disposable. Typically they can last from up to 6 hours, one of the main benefits is that there are no fumes or other mess with this type.

## Charcoal

One of the older and perhaps less used types of handwarmer are made hot through the burning of charcoal in a special case. These can last up to 6 hours and become comfortably hot. The cases for these usually have felt on the outside and have materials inside that do not burn, but spread the heat evenly such as metal. To activate, one or both ends of a stick of charcoal are lit and then quickly extinguished to create a hot ember. The smoldering stick is then placed inside the case and the case is tightly shut. The charcoal sticks are available from most outdoor activity shops and are fairly inexpensive.

# Chapter 8

# Radiator (Heating) and Infrared Heater

## Radiator (Heating)

**Radiators** and **convectors** are heat exchangers designed to transfer thermal energy from one medium to another for the purpose of space heating. The heating radiator was invented by Franz San Galli, a Polish-born Russian businessman living in St. Petersburg, between 1855–1857.

### *Radiation vs. convection*

In practice, the term "radiator" refers to any of a number of devices in which a fluid circulates through exposed pipes (often with fins or other means of increasing surface area), notwithstanding that such devices tend to transfer heat mainly by convection and might logically be called convectors.

The term convection heater or *convector* refers to a class of devices in which the source of heat is not directly exposed. As domestic safety and the supply from water heaters keeps temperatures relatively low, radiation is inefficient in comparison to convection.

For homes with radiators, Energy Star recommends placing heat-resistant reflectors between radiators and exterior walls to help retain heat in a room.

## *Types*

A cast iron household radiator

## Hot water

A hot-water radiator consists of a sealed hollow metal container filled with hot water by gravity feed, a pressure pump, or convection. As it gives out heat the hot water cools and sinks to the bottom of the radiator and is forced out of a pipe at the other end. Anti-hammer devices are often installed to prevent or minimize knocking in hot water radiator pipes.

### Hot water baseboard

Traditional cast iron radiators are no longer common in new construction, replaced mostly with forced hot water baseboard style radiators. They consist of copper pipes which have aluminum fins to increase their surface area. In the U.K., modern domestic radiators tend to be of sheet steel construction (often with steel fins), though copper/aluminium is often found in industrial Air Handling System heat exchangers.

### Steam

Single-pipe steam radiator

Steam has the advantage of flowing through the pipes under its own pressure without the need for pumping. For this reason, it was adopted earlier, before electric motors and pumps became available. Steam is also far easier to distribute than hot water throughout large, tall buildings like skyscrapers. However, the higher temperatures at which steam systems operate make them inherently less efficient, as unwanted heat loss is inevitably greater.

Steam pipes and radiators are prone to producing banging sounds often incorrectly called water hammer. The bang is created when some of the steam condenses into water in a horizontal section of the steam piping. Subsequently, steam picks up the water, forms a "slug" and hurls it at high velocity into a pipe fitting, creating a loud hammering noise and greatly stressing the pipe. This condition is usually caused by a poor condensate drainage strategy and is often caused by buildings settling and the resultant pooling of condensate in pipes and radiators that no longer tilt slightly back towards the boiler.

## Fan assisted heat exchanger

A fan-assisted radiator contains a heat exchanger fed by hot water from the heating system. A thermostatic switch energises an electric fan which blows air over the heat exchanger to circulate it in a room. Its advantages are small relative size and even distribution of heat. Disadvantages are fan noise and the need for both a source of heat and a separate electrical supply.

## Underfloor

In underfloor heating, tubing is placed on the floor throughout the room and later covered with a concrete layer during construction.

Underfloor heating uses a network of pipes, tubing or heating cables is buried in or attached beneath a floor to allow heat to rise into the room. Best results are had with conductive flooring materials such as tile. The large surface area of such room-sized radiators allows them to be kept just a few degrees above desired room temperature, minimizing convection. Underfloor heating is more expensive in new construction than less efficient systems. It also is generally difficult to retrofit into existing buildings.

The Roman hypocaust employed a similar principle of operation.

### Electric baseboard

Similar in configuration to forced hot water baseboard - low profile units running along the base of a wall with a central heating element surrounded by radiating fins - electric baseboard heaters are inexpensive to produce and install. They offer instant heat and great reliability, but may be more or less cost-effective relative to other forms of heat depending on electricity prices.

### Portable

Electrically powered portable radiators come in two basic forms:

- Electric elements, which either heat directly or radiate heat to a heat-conducting solid such as quartz
- Liquid filled, which employ an electric element to warm a fluid such as oil held within metal tubing, which circulates via convection.

# Infrared Heater

An **infrared heater** is a body with a higher temperature which transfers energy to a body with a lower temperature through electromagnetic radiation. Depending on the temperature of the emitting body, the wavelength of the infrared radiation ranges from 780 nm to 1 mm. The relationship between temperature and wavelength is expressed by the Wien's displacement law. No contact or medium between the two bodies is needed for the energy transfer. A rough classification of infrared heaters is connected to wavelength bands of major emission of the energy: short wave or near infrared for the range from 780 nm to 1400 nm, these emitters are also named bright because still some visible light with glare is emitted; medium infrared for the range between 1400 nm and 3000 nm; far infrared or dark emitters for everything above 3000 nm.

A household infrared electric heater

## *Elements of infrared heaters*

Infrared heaters use either a fuel to heat an emitter, or an electrically heated filament as the emitting body. An infrared lamp will protect the filament with a heat-resistant quartz glass tube. Some heat lamps used halogen lamps. These emitters use the same materials and principle as an incandescent light bulb.

The most common filament material used for electrical infrared heaters is tungsten wire, which is coiled to provide more surface area. Low temperature alternatives for tungsten are carbon, or alloys of iron, chromium and aluminum (brand name ‘kanthal’). While carbon filaments are more fickle to produce, they heat up much quicker than a comparable medium-wave heater based on a FeCrAl filament.

Industrial infrared heaters sometimes use a gold coating on the quartz tube that reflects the infrared radiation and directs it towards the product to be heated. Consequently the infrared radiation impinging on the product is virtually doubled. Gold is used because of its oxidation resistance and very high IR reflectivity of approximately 95%.

## *Types of infrared heaters*

Infrared heaters are commonly used in infrared modules (or emitter banks) combining several heaters to achieve larger heated areas.

Infrared heaters are usually classified by the wavelength they emit. Near infrared (NIR) or short-wave infrared heaters operate at high filament temperatures above 1800 °C and when arranged in a field reach high power densities of some 100s of kW/m². Their peak wavelength is well below the absorption spectrum for water, making them unsuitable for many drying applications. They are well suited for heating of silica where a deep penetration is needed.

Medium-wave and carbon (CIR) infrared heaters operate at filament temperatures of around 1000 °C. They reach maximum power densities of up to 60 kW/m² (medium-wave) and 150 kW/m² (CIR).

Far infrared heaters are typically used in low-temperature infrared saunas.

## *Heat lamps*

A **heat lamp** is an incandescent light bulb that is used for the principal purpose of creating heat. The spectrum of black body radiation emitted by the lamp is shifted to produce more infrared light. Many heat lamps include a red filter to minimize the amount of visible light emitted. Heat lamps often include an internal reflector.

Heat lamps are commonly used in shower and bathrooms to warm bathers and in food-preparation areas of restaurants to keep food warm before serving. They are also commonly used for animal husbandry. Lights used for poultry are often called brooding lamps. Aside from young birds, other types of animals which can benefit from heat lamps include reptiles, amphibians, insects, arachnids, and the young of some mammals.

The sockets used for heat lamps are usually ceramic because plastic sockets can melt or burn when exposed to the large amount of waste heat produced by the lamps, especially when operated in the "base up" position. The shroud or hood of the lamp is generally metal. There may be a wire guard over the front of the shroud, to prevent touching the hot surface of the bulb.

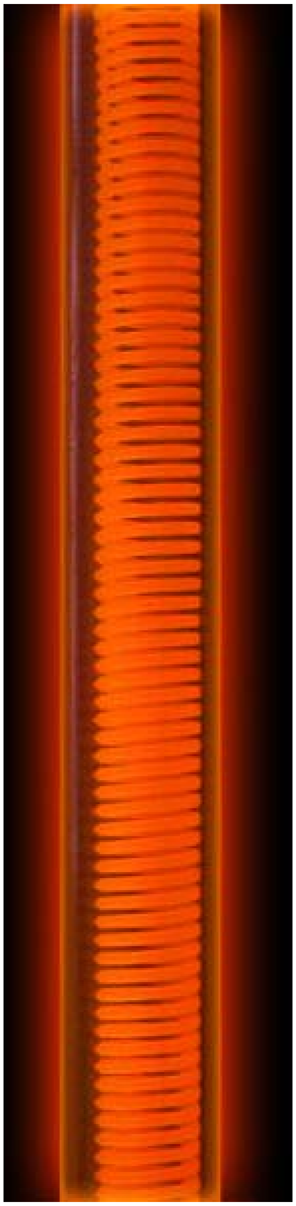
Ordinary household white incandescent bulbs can also be used as heat lamps, but red and blue bulbs are sold for use in brood lamps and reptile lamps. 250 watt heat lamps are commonly packaged in the "R40" (5" reflector lamp) form factor with an intermediate screw base.

Heat lamps can be used as a medical treatment to provide dry heat when other treatments are ineffective or impractical.

## *Quartz heat lamps*

Tubular infrared lamps in quartz bulbs produce useful infrared radiation in wavelengths shorter than 5 microns. The enclosed filament operates at around 2500 K, producing more shorter-wavelength radiation than open wire-coil sources. Developed in the 1950s at General Electric, these lamps produce about 100 watts/inch (4 w/mm) and can be combined to radiate 500 watts per square foot (54000 watts/square m). To achieve even higher power densities, halogen lamps were used. Quartz infrared lamps are used in highly-polished reflectors to direct radiation in a uniform and concentrated pattern.

Quartz heat lamps are used in food processing, chemical processing, paint drying, and thawing of frozen materials. They can also be used for comfort heating in cold areas, in incubators, and in other applications for heating, drying, and baking. During development of space re-entry vehicles, banks of quartz infrared lamps were used to test heat shield materials at power densities as high as 28 kW/ square foot (300 kW/square meter).



Clear Quartz Element Example

Most common designs consist of either a satin milky-white quartz glass tube or clear quartz with an electrically resistant element, usually a tungsten wire, or a thin coil of iron-chromium-aluminum alloy. The atmospheric air is removed and filled with inert gases such as nitrogen and argon then sealed. In quartz halogen lamps a small amount of halogen gas is added to prolong the heater's operational life.

Much of the infrared and visible energy released is caused by the direct heating of the quartz material, 97% of the near infrared is absorbed by the silica quartz glass tube causing the temperature of the tube wall to increases, this causes the silicon-oxygen bond to radiate far infrared rays.

Quartz glass heating elements were originally designed for lighting applications, but when a lamp is at full power less than 5% of the emitted energy is in the visible spectrum.

Quartz heater

### *Gas-fired infrared heaters*

There are two basic types of infrared radiant heaters.

- Luminous of High Intensity
- Radiant Tube Heaters

Radiant tube gas-fired heaters used for industrial and commercial building space heating use combustion of a fuel gas such as natural gas or propane to heat a steel emitter tube. Gas is released from a valve, and is either pushed or pulled through a cup burner, or in the case of more technologically advanced units, through a venturi. Once the proper air-fuel ratio is achieved, the gas is then ignited, which heats the emitter tube. As the tube heats, radiant energy from the tube strikes floors and other objects in the area, warming them. The advantage of this form of heating is maintained warmth even when a large volume of cold air is suddenly introduced, such as in maintenance garages for vehicles. The efficiency of an Infrared heater is a rating of the total energy consumed by the heater compared to the amount of Infrared energy generated. While there will always be some amount of convective heat generated through the process, any introduction of air motion across the heater will reduce its Infrared conversion efficiency

### *Efficiency of infrared heaters*

Electrically-heated infrared heaters radiate up to 86% of their input as radiant energy. Nearly all the electrical energy input is converted into infrared radiant heat in the filament and directed onto the product by reflectors. Some energy is lost due to conduction or convection.

For practical applications, the efficiency of the infrared heater depends on matching the emitted wavelength and the absorption spectrum of the material to be heated.

For example, the absorption spectrum for water has its peak at around 3000 nm. This means that emission from medium-wave or carbon infrared heaters are much better absorbed by water and water-based coatings than NIR or short-wave infrared radiation.

The same is true for many plastics like PVC or polyethylene. Their peak absorption is around 3500 nm. On the other hand, some metals absorb only in the short-wave range and show a strong reflectivity in the medium and far infrared. This makes a careful selection of the right infrared heater type important for energy efficiency in the heating process.

Ceramic elements operate in the temperature of 300°C to 700°C (572°F - 1292°F) producing infrared wavelengths in the 2 - 10 micron range. Most plastics and many other materials absorb infrared best in this range, which makes the ceramic heater most suited for this task.

## *Applications of infrared heaters*

Infrared heater cooking döner kebab

IR heaters are used in industrial manufacturing processes including curing of coatings, shrink tunnels, heating of plastic prior to forming, plastic welding, processing glass,and cooking and browning food. They are used when high temperatures are required, fast responses or temperature gradients are needed or products need to be heated in certain areas in a targeted way. Their application is difficult for objects with undercuts.

They are also used to provide warmth to suckling animals whose mother cannot or will not provide them with natural warmth as well as to captive animals in zoos or veterinary clinics, especially for lizards and other reptiles, and tropical animals such as birds.

Another recent use is in house heating, various companies sell infrared heaters for house use, claiming some medical benefits due to better circulation also infrared saunas claim same benefits.

## *Health effects*

In addition to the dangers of touching the hot bulb or element, infrared heaters may cause indirect thermal burns when the skin is exposed for too long or the heater is positioned too close to the subject. Individuals exposed to large amounts of infrared radiation over an extended period of time may develop depigmentation of the iris and opacity of the aqueous humor, so exposure should be moderated.

# Chapter 9

# Air Source Heat Pumps

An **air source heat pump** uses outside air as a heat source or heat sink. A compressor, condenser and refrigerant system is used to absorb heat at one place and release it at another.

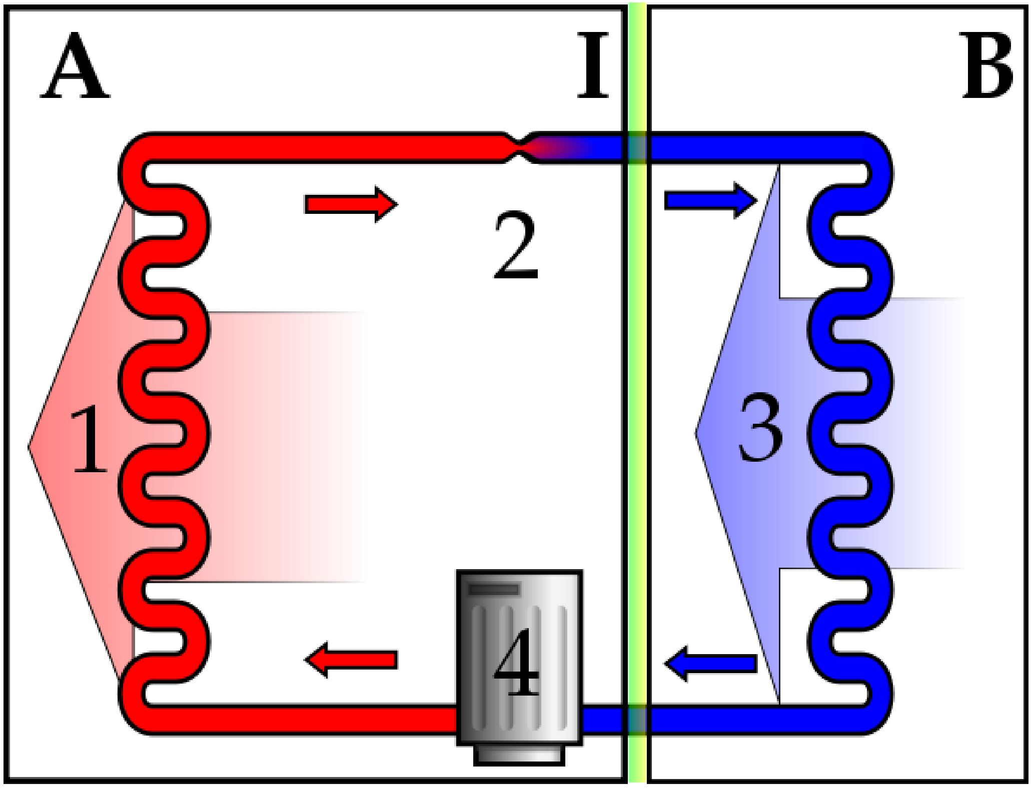
## *General*

Outside air, necessarily existing at some temperature above absolute zero, is a heat container. An air-source heat pump moves ("pumps") some of this heat to provide hot water or household heating. This can be done in either direction, to cool or heat the interior of a building.

The main components of an air-source heat pump are:

- a heat exchanger, over which outside air is blown, to extract the heat from the air
- a compressor, which acts like a refrigerator but in reverse and raises the temperature from the outside air
- a way to transfer the heat into a hot water tank or heating system, such as radiators or under-floor heating tubes

### *How air source heat pumps work*




A: indoor compartment, B: outdoor compartment, I: insulation, 1: condenser, 2: expansion valve, 3: evaporator, 4: compressor

Heating and cooling is accomplished by moving a refrigerant through the heat pump's various indoor and outdoor coils and components. A compressor, condenser, expansion valve and evaporator are used to change states of the refrigerant from a liquid to hot gas and from a gas to a cold liquid. The refrigerant is used to heat or cool coils in a building or room and fans pull the room air over the coils. An external outdoor heat exchanger is used to heat or cool the refrigerant. This use of outside air has led to the term "Air Source" Heat Pump. The overall operation uses the concepts described in classic vapor compression refrigeration.

When the liquid refrigerant at a low temperature passes through the outdoor evaporator coils, the temperature of the outside air causes the liquid to boil. This change of state from liquid to a vapor requires a considerable amount of energy or "latent heat" which is provided by outside air passing over the coils.

This vapor is then drawn into the compressor where the temperature of the vapor is boosted to well over 100 degrees Celsius. At this point we have used heat from the outside air to change the liquid refrigerant to a gas and added an amount of compression "work" to raise the temperature of the vapor. The vapor now enters the condenser heat exchanger coils where it begins to transfer heat to the air being drawn across the coils. As the vapor cools, it condenses back to a liquid and in so doing releases and transfers considerable latent heat to the air passing over the condenser unit coils. We have used the heat energy of outside air to change the phase of the refrigerant and then released this heat for heating, a typical heat pump operation.

At this stage we now have a very cold liquid refrigerant compressed to a high pressure. The refrigerant is next passed through an expansion valve which turns it back to a low pressure cold liquid ready to re-enter the evaporator to begin a new cycle.

The heat pump can also operate in a cooling mode where the cold refrigerant is moved through the indoor coils to cool the room air.

## *Efficiency*

The 'Efficiency' of air source heat pumps is measured by the Coefficient of performance (COP). In simple terms, a COP of 3 means the heat pump produces 3 units of heat energy for every 1 unit of electricity it consumes. In mild weather, the COP of an air source heat pump can be up to 4. However, on a very cold winter day, it takes more work to move the same amount of heat indoors than on a mild day. The heat pump's performance is limited by the Carnot cycle and will approach 1.0 as the outdoor-to-indoor temperature difference increases at around −18 °C (0 °F) outdoor temperature for air source heat pumps. Within most normal temperature ranges of say -3°C to 10°C heat pump performance and thus the COP for many machines is fairly stable at 3-3.5. However, heat pump construction methods that enable use of carbon dioxide refrigerant extend the figure downward to -30 °C (-22 °F). A Geothermal heat pump will have less change in COP as the ground temperature from which they extract heat is more constant than outdoor air temperature.

Seasonally adjusted heating and cooling efficiencies are given by the heating seasonal performance factor (HSPF) and seasonal energy efficiency ratio (SEER) respectively.

The efficiency of a heat pump can be significantly affected by its original design. Many air source heat pumps began life as air conditioning units, designed for summer temperatures. In designing a heat pump as a heat pump from inception great COPs and life cycles can be attained. The principal changes are in the scale and type of compressor and evaporator to allow COP of greater than 2 even down to -20°C.

## *Advantages and disadvantages*

### Advantages

- Typically draws approximately 1/3 to 1/4 of the electricity of a standard resistance heater for the same amount of heating, reducing utility bills. This typical efficiency compares to 70-95% for a fossil fuel-powered boiler.

- Few moving parts, reducing maintenance requirements. However, it should be ensured that the outdoor heat exchanger and fan is kept free from leaves and debris. Moreover, it must be borne in mind that a heat pump will have significantly more moving parts than an equivalent electric resistance heater or fuel burning heater.
- As an electric system, no flammable or potentially asphyxiating fuel is used at the point of heating, reducing the potential danger to users, and removing the need to obtain gas or fuel supplies (except for electricity).
- May be used to heat air, or water.
- The same system may be used for air conditioning in summer, as well as a heating system in winter.
- Lower running costs, the compressor being the thing that uses most power - when in comparison with traditional electrical resistance heaters..
- When correctly specified an ASHP can offer a full central heating solution and domestic hot water up to 80°C. This can in theory be down to well below -10°C if the unit is large enough.

## Disadvantages

The following disadvantages are associated with all air source heat pump designs:

- Air source heat pumps require electricity for operation. Electricity generation accounts for a significant amount of emissions pollutants and greenhouse gases.
- External space needs to be found for the outside condenser unit which can be somewhat noisy(comparable to an air conditioner unit) and possibly unsightly.
- The cost of installation is high (though less than a Ground Source heat pump because a ground source heat pump requires installation of a ground loop).
- The outdoor section on some units may "frost up" when outdoor temperatures are between 0°C and 5°C (between 32°F and 41°F respectively) and there is sufficient moisture in the air which causes restriction of air flow across the outdoor coil. These units employ a time/delay or demand defrost cycle where the system a) switches to "A/C" mode for up to 10 minutes or more to move heat from the home to the outdoor section to melt the ice and b) turns on the supplemental heater (resistance electric, gas, etc.) in the indoor section to temper the cold air being distributed. The defrost cycle reduces the efficiency of the heat pump significantly, although the newer (demand) systems are more intelligent and need to defrost less. As temperatures drop below freezing the tendency for frosting of the outdoor section decreases due to reduced humidity in the air. An air source heat pump switching out of defrost mode in normal operation emits a characteristic "whoosh" sound from the outdoor section..
- Air source heat pumps lose their efficiency as the external temperatures fall below 5 degrees Celsius (about 41 degrees Fahrenheit). In colder climates, the system needs to be installed with an auxiliary source of heat to supplement the heat pump in extremely cold temperatures or when it is simply too cold for the heat pump to work at all. When this happens, the heat pump will simply cease to function, and the system will operate solely on "Emergency Heat." The Auxiliary

Heat/Emergency Heat can also be used if the heat pump is malfunctioning and/or being repaired. In Northern climates, split-system heat pumps matched with gas or oil furnaces will work just fine in extremely cold temperatures. However, all-electric heat pump systems in colder Northern climates be considerably more expensive to operate when the system is operating solely on the electric heat. All-electric heat pump systems have an electric furnace or electric resistance heat, or strip heat, which typically consists of rows of electric coils that heat up. A fan blows over the heated coils and circulates warm air throughout the home. This serves as an adequate heating source, but as temperatures go down, the utility bill will go up. As mentioned above, the gas, oil, or electric heating system will also kick in when the heat pump is defrosting. In milder climates, and regions where heat is rarely needed, an all-electric system is usually all that is needed. Some homes in regions where heat is rarely needed (like South Florida) do not even have heat pumps, and instead have cool-only central air-conditioners with electric strip/resistance heat.
- Retrofit is difficult when used with conventional heating systems using radiators, hot water baseboard heaters, or radiant panels. The lower Heat Pump output temperatures would mean radiators would have to be increased in size or a low temperature underfloor heating system be installed instead.

The following disadvantages are associated with units charged with HFC refrigerants:

- Usually marketed as low energy or a sustainable technology, the HFCs have the potential to contribute to global warming. The effect the refrigerant could have is measured in global warming potential (GWP) and ozone depletion potential (ODP). However, recent government mandates have seen the phase-out of R-22 refrigerant and its replacement with more environmentally sound R410a refrigerant.
- The COP is reduced when heat pumps are used to reach over 60°C for heating domestic water or in conventional central heating systems using radiators to distribute heat (instead of an underfloor heating array).

## *Conclusions*

Air source heat pumps can provide fairly low cost space heating. A high efficiency heat pump can provide four times the heat compared to an electric heater..

Air source heat pumps are sometimes used to provide hot water from a pressurized system up to temperatures of 55°C. To minimize the risk from Legionellosis it is advised that hot water is heated to above 60°C.

The overall lifetime costs for using air source heat pumps should be considered carefully as gas (where available) may be cheaper than electricity (although it has higher carbon emissions).

Air source heat pumps should last for over 20 years with low maintenance requirements. There are numerous heat pumps from the 1970s and 1980s that are still in service as of 2011, even in Northern states where winters seasons are extremely cold.

## Chapter 10

# Thermostat


Honeywell's iconic "The Round" model T87 thermostat, one of which is in the Smithsonian.

A **thermostat** is a device for regulating the temperature of a system so that the system's temperature is maintained near a desired *setpoint* temperature. The name is derived from the Greek words thermos "hot" and statos "a standing". The thermostat does this by switching heating or cooling devices on or off, or regulating the flow of a heat transfer fluid as needed, to maintain the correct temperature.

A thermostat may be a control unit for a heating or cooling system or a component part of a heater or air conditioner. Thermostats can be constructed in many ways and may use a variety of sensors to measure the temperature. The output of the sensor then controls the heating or cooling apparatus.

The first electric room thermostat was invented in 1883 by Warren S. Johnson. Early technologies included mercury thermometers with electrodes inserted directly through the glass, so that when a certain (fixed) temperature was reached the contacts would be closed by the mercury. These were accurate to within a degree of temperature.

Common sensor technologies in use today include:

- Bimetallic mechanical or electrical sensors
- Expanding wax pellets
- Electronic thermistors and semiconductor devices
- Electrical thermocouples

These may then control the heating or cooling apparatus using:

- Direct mechanical control
- Electrical signals
- Pneumatic signals


A Honeywell electronic thermostat in a retail store

## *Mechanical*

This covers only devices which both sense and control using purely mechanical means.

### Bimetal

Domestic water and steam based central heating systems have traditionally been controlled by bi-metallic strip thermostats, and this is dealt with later here. Purely mechanical control has been localised steam or hot-water radiator bi-metallic thermostats which regulated the individual flow. However, Thermostatic Radiator Valves (TRV) are now being widely used.

Purely mechanical thermostats are used to regulate dampers in some rooftop turbine vents, reducing building heat loss in cool or cold periods.

Some automobile passenger heating systems have a thermostatically controlled valve to regulate the water flow and temperature to an adjustable level. In older vehicles the thermostat controls the application of engine vacuum to actuators that control water valves and flappers to direct the flow of air. In modern vehicles, the vacuum actuators may be operated by small solenoids under the control of a central computer.

### Wax pellet

#### Automotive

Car engine thermostat

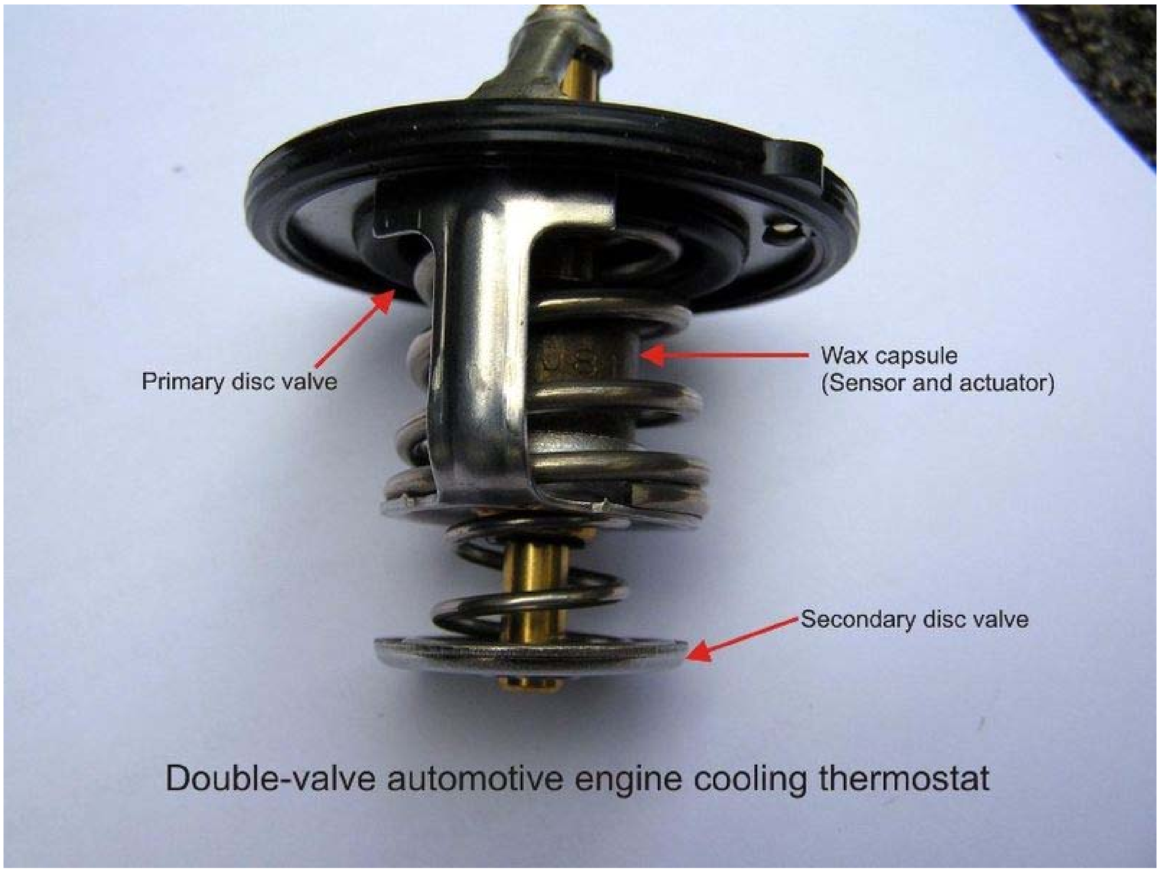
Perhaps the best example of purely mechanical technology in widespread use today is the internal combustion engine cooling thermostat. These are used to maintain the core temperature of the engine at its optimum operating temperature by regulating the flow of coolant to an external heat sink, usually an air cooled radiator. Also, research in the 1920s showed that cylinder wear was aggravated by condensation of fuel when it contacted a cool cylinder wall which removed the oil film, and the development of the automatic thermostat in the 1930s provided a solution to this problem by ensuring fast engine warm-up.

This type of thermostat operates mechanically. It makes use of a wax pellet inside a sealed chamber. The wax is solid at low temperatures but as the engine heats up the wax melts and expands. The sealed chamber has an expansion provision that operates a rod which opens a valve when the operating temperature is exceeded. The operating temperature is fixed, but is determined by the specific composition of the wax, so thermostats of this type are available to maintain different temperatures, typically in the range of 70 to 90°C (160 to 200°F). Modern engines run hot, that is, over 80°C (180°F), in order to run more efficiently and to reduce the emission of pollutants. Most thermostats have a small bypass hole to vent any gas that might get into the system, *e.g.*, air introduced during coolant replacement, which also allows a small flow of coolant past the thermostat when it is closed. This bypass flow ensures that the thermostat experiences the temperature change in the coolant as the engine heats up; without it a stagnant region of coolant around the thermostat could shield it from temperature changes in the coolant adjacent to the combustion chambers and cylinder bores.

While the thermostat is closed, there is no flow of coolant in the radiator loop, and water flow is instead redirected back through the engine, allowing it to warm up rapidly while also avoiding hotspots within the engine. The thermostat stays closed until the coolant temperature reaches the nominal thermostat opening temperature. The thermostat then progressively opens as the coolant temperature increases to the optimum operating temperature, increasing the coolant flow to the radiator. Once the optimum operating temperature is reached, the thermostat progressively increases or decreases its opening in response to temperature changes, dynamically balancing the coolant recirculation flow and coolant flow to the radiator to maintain the engine temperature in the optimum range as engine heat output, vehicle speed, and outside ambient temperature change. Under normal operating conditions the thermostat is open to about half of its stroke travel, so that it can open further or reduce its opening to react to changes in operating conditions. A correctly designed thermostat will never be fully open or fully closed while the engine is operating normally, or overheating or overcooling would occur. For instance,

- If more cooling is required, *e.g.*, in response to an increase in engine heat output which causes the coolant temperature to rise, the thermostat will increase its opening to allow more coolant to flow through the radiator and increase engine cooling. If the thermostat were already fully open, then it would not be able to increase the flow of coolant to the radiator, hence there would be no more cooling capacity available, and the increase in heat output by the engine would result in overheating.

- If less cooling is required, *e.g.*, in response to decrease in ambient temperature which causes the coolant temperature to fall, the thermostat will decrease its opening to restrict the coolant flow through the radiator and reduce engine cooling. If the thermostat were already fully closed, then it would not be able to reduce cooling in response to the fall in coolant temperature, and the engine temperature would fall below the optimum operating range.




Double valve engine thermostat

Engines which require a tighter control of temperature, as they are sensitive to "Thermal shock" caused by surges of coolant, may use a "constant inlet temperature" system. In this arrangement the inlet cooling to the engine is controlled by double-valve thermostat which mixes a re-circulating sensing flow with the radiator cooling flow. These employ a single capsule, but have two valve discs. Thus a very compact, and simple but effective, control function is achieved.

The wax product used within the thermostat requires a specific process to produce. Unlike a standard paraffin wax, which has a relatively wide range of carbon chain lengths, a wax used in the thermostat application has a very narrow range of carbon molecule chains. The extent of the chains is usually determined by the melting characteristics demanded by the specific end application. To manufacture a product in this manner requires very precise levels of distillation, which is difficult or impossible for most wax refineries.

**Shower and other hot water controls**

These use wax pellets to control the mixing of hot and cold water see thermostatic mixing valve (TMV).

## Gas expansion

Thermostats are sometimes used to regulate gas ovens. It consists of a gas-filled bulb connected to the control unit by a slender copper tube. The bulb is normally located at the top of the oven. The tube ends in a chamber sealed by a diaphragm. As the thermostat heats up the gas expands applying pressure to the diaphragm which reduces the flow of gas to the burner.

## Pneumatic

A pneumatic thermostat is a thermostat that controls a heating and/or cooling system via a series of air-filled control tubes. This "control air" system responds to the pressure changes (due to temperature) in the control tube to activate heating or cooling when required. The control air typically is maintained on "mains" at 15-18psi (although usually operable up to 20psi). Pneumatic thermostats typically provide output/ branch/ post-restrictor(for single-pipe operastion) pressures of 3-15psi which is piped to the end device (valve/ damper actuator/ Pneumatic-Electric switch, etc.)

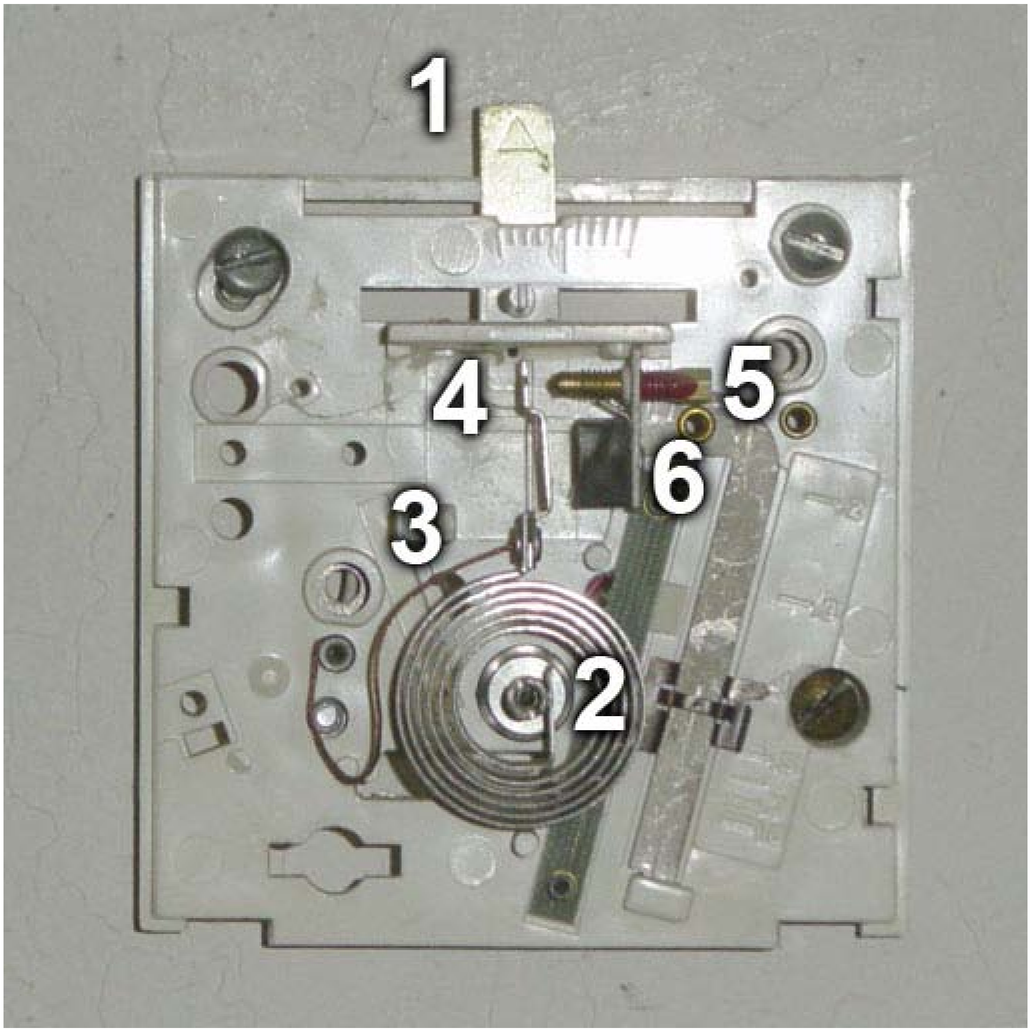
## *Electrical*

### Bimetallic switching thermostats


Bimetallic thermostat for buildings.

Water and steam based central heating systems have traditionally had overall control by wall-mounted bi-metallic strip thermostats. These sense the air temperature using the differential expansion of two metals to actuate an on/off switch. Typically the central system would be switched on when the temperature drops below the set point on the thermostat, and switched off when it rises above, with a few degrees of hysteresis to prevent excessive switching. Bi-metallic sensing is now being superseded by electronic sensors. A principal use of the bi-metallic thermostat today is in individual electric convection heaters, where control is on/off, based on the local air temperature and the set point desired by the user. These are also used on air-conditioners, where local control is required.

## Simple two wire thermostats




Milivolt thermostat mechanism

The illustration is the interior of a common two wire heat-only household thermostat, used to regulate a gas-fired heater via an electric gas valve. Similar mechanisms may also be used to control oil furnaces, boilers, boiler zone valves, electric attic fans, electric furnaces, electric baseboard heaters, and household appliances such as refrigerators, coffee pots, and hair dryers. The power through the thermostat is provided by the heating device and may range from millivolts to 240 volts in common North American construction, and is used to control the heating system either directly (electric baseboard heaters and some electric furnaces) or indirectly (all gas, oil and forced hot water systems). *Due to the variety of possible voltages and currents available at the thermostat, caution must be taken when selecting a replacement device.*

1. Set point control lever. This is moved to the right for a higher temperature. The round indicator pin in the center of the second slot shows through a numbered slot in the outer case.

2. Bimetallic strip wound into a coil. The center of the coil is attached to a rotating post attached to lever (1). As the coil gets colder the moving end — carrying (4) — moves clockwise.
3. Flexible wire. The left side is connected via one wire of a pair to the heater control valve.
4. Moving contact attached to the bimetal coil.thence to the heater's controller.
5. Magnet. This ensures a good contact when the contact closes. It also provides hysteresis to prevent short heating cycles, as the temperature must be raised several degrees before the contacts will open. As an alternative, some thermostats instead use a mercury switch on the end of the bimetal coil. The weight of the mercury on the end of the coil tends to keep it there, also preventing short heating cycles. However, this type of thermostat is banned in many countries due to its highly and permanently toxic nature if broken. When replacing these thermostats they must be regarded as chemical waste.
6. Fixed contact screw. This is adjusted by the manufacturer. It is connected electrically by a second wire of the pair to the thermocouple and the heater's electrically operated gas valve.

Not shown in the illustration is a separate bimetal thermometer on the outer case to show the actual temperature at the thermostat.

**Millivolt thermostats**

As illustrated in the use of the thermostat above, the power is provided by a thermocouple, heated by the pilot light. This produces little power and so the system must use a low power valve to control the gas. This type of device is generally considered obsolete as pilot lights waste a surprising amount of gas (in the same way a dripping faucet can waste a large amount of water over an extended period), and are also no longer used on stoves, but are still to be found in many gas water heaters and gas fireplaces. (Their poor efficiency is acceptable in water heaters, since most of the energy "wasted" on the pilot light is still being coupled to the water and therefore helping to keep the tank warm). It also makes it unnecessary for an electrical circuit to be run to the water heater. For tankless (on demand) water heaters, pilot ignition is preferable because it is faster than hot-surface ignition and more reliable than spark ignition.)

Some programmable thermostats will control these systems.

**24 volt thermostats**

The majority of modern heating/cooling/heat pump thermostats operate on low voltage (typically 24 volts AC) control circuits. The source of the 24 volt AC power is a control transformer installed as part of the heating/cooling equipment. The advantage of the low voltage control system is the ability to operate multiple electromechanical switching devices such as relays, contactors, and sequencers using inherently safe voltage and current levels. Built into the thermostat is a provision for enhanced temperature control using anticipation. A heat anticipator generates a small amount of additional heat to the

sensing element while the heating appliance is operating. This opens the heating contacts slightly early to prevent the space temperature from greatly overshooting the thermostat setting. A mechanical heat anticipator is generally adjustable and should be set to the current flowing in the heating control circuit when the system is operating. A cooling anticipator generates a small amount of additional heat to the sensing element while the cooling appliance is not operating. This causes the contacts to energize the cooling equipment slightly early, preventing the space temperature from climbing excessively. Cooling anticipators are generally non-adjustable.
Electromechanical thermostats use resistance elements as anticipators. Most electronic thermostats use either thermistor devices or integrated logic elements for the anticipation function. In some electronic thermostats, the thermistor anticipator may be located outdoors, providing a variable anticipation depending on the outdoor temperature.
Thermostat enhancements include outdoor temperature display, programmability, and system fault indication. While such 24 volt thermostats are incapable of operating a furnace when the mains power fails, most such furnaces require mains power for heated air fans (and often also hot-surface or electronic spark ignition) so no functionality is lost. In other circumstances such as piloted wall and "gravity" (fanless) floor and central heaters the low voltage system described previously may be capable of remaining functional when electrical power is unavailable.

**Ignition sequences in modern systems**

- Gas

  1. Start drafting fan (if the furnace is relatively recent) to create a column of air flowing up the chimney
  2. Heat ignitor or start spark-ignition system
  3. Open gas valve to ignite main burners
  4. Wait (if furnace is relatively recent) until the heat exchanger is at proper operating temperature before starting main blower fan or circulator pump

- Oil

  1. Similar to gas, except rather than opening a valve, the furnace will start an oil pump to inject oil into the burner

- Electric

  1. The blower fan or circulator pump will be started, and a large electromechanical relay or TRIAC will turn on the heating elements

- Coal (including grains such as corn, wheat, and barley, or pellets made of wood, bark, or cardboard)

1. Generally rare today (though grains and pellets are increasing in popularity); similar to gas, except rather than opening a valve, the furnace will start a screw to drive coal/grain/pellets into the firebox

With non-zoned (typical residential, one thermostat for the whole house) systems, when the thermostat's R (or Rh) and W terminals are connected, the furnace will go through its startup rituals and produce heat.

With zoned systems (some residential, many commercial systems — several thermostats controlling different "zones" in the building), the thermostat will cause small electric motors to open valves or dampers and start the furnace or boiler if it's not already running.

Most programmable thermostats will control these systems.

**Line voltage thermostats**

Line voltage thermostats are most commonly used for electric space heaters such as a baseboard heater or a direct-wired electric furnace. If a line voltage thermostat is used, system power (in the United States, 120 or 240 volts) is directly switched by the thermostat. With switching current often exceeding 40 amperes, using a low voltage thermostat on a line voltage circuit will result at least in the failure of the thermostat and possibly a fire. Line voltage thermostats are sometimes used in other applications, such as the control of fan-coil (fan powered from line voltage blowing through a coil of tubing which is either heated or cooled by a larger system) units in large systems using centralized boilers and chillers, or to control circulation pumps in hydronic heating applications.

Some programmable thermostats are available to control line-voltage systems. Baseboard heaters will especially benefit from a programmable thermostat which is capable of continuous control (as are at least some Honeywell models), effectively controlling the heater like a lamp dimmer, and gradually increasing and decreasing heating to ensure an extremely constant room temperature (continuous control rather than relying on the averaging effects of hysteresis). Systems which include a fan (electric furnaces, wall heaters, etc.) must typically use simple on/off controls.

## Combination heating/cooling regulation

Depending on what is being controlled, a forced-air air conditioning thermostat generally has an external switch for heat/off/cool, and another on/auto to turn the blower fan on constantly or only when heating and cooling are running. Four wires come to the centrally-located thermostat from the main heating/cooling unit (usually located in a closet, basement, or occasionally in the attic): One wire supplies a 24 volts AC power connection to the thermostat, while the other three supply control signals from the thermostat, one for heat, one for cooling, and one to turn on the blower fan. The power is supplied by a transformer, and when the thermostat makes contact between power and another wire, a relay back at the heating/cooling unit activates the corresponding function of the unit.

A thermostat, when set to "cool", will only turn on when the ambient temperature of the surrounding room is above the set temperature. Thus, if the controlled space has a temperature normally above the desired setting when the heating/cooling system is off, it would be wise to keep the thermostat set to "cool", despite what the temperature is outside. On the other hand, if the temperature of the controlled area falls below the desired degree, then it is advisable to turn the thermostat to "heat".

### *Heat pump regulation*

The heat pump is a refrigeration based appliance which reverses refrigerant flow between the indoor and outdoor coils. This is done by energizing a reversing valve (also known as a "4-way" or "change-over" valve). During cooling, the indoor coil is an evaporator removing heat from the indoor air and transferring it to the outdoor coil where it is rejected to the outdoor air. During heating, the outdoor coil becomes the evaporator and heat is removed from the outdoor air and transferred to the indoor air through the indoor coil. The reversing valve, controlled by the thermostat, causes the change-over from heat to cool. Residential heat pump thermostats generally have an "O" terminal to energize the reversing valve in cooling. Some residential and many commercial heat pump thermostats use a "B" terminal to energize the reversing valve in heating. The heating capacity of a heat pump decreases as outdoor temperatures fall. At some outdoor temperature (called the balance point) the ability of the refrigeration system to transfer heat into the building falls below the heating needs of the building. A typical heat pump is fitted with electric heating elements to supplement the refrigeration heat when the outdoor temperature is below this balance point. Operation of the supplemental heat is controlled by a second stage heating contact in the heat pump thermostat. During heating, the outdoor coil is operating at a temperature below the outdoor temperature and condensation on the coil may take place. This condensation may then freeze onto the coil, reducing its heat transfer capacity. Heat pumps therefore have a provision for occasional defrost of the outdoor coil. This is done by reversing the cycle to the cooling mode, shutting off the outdoor fan, and energizing the electric heating elements. The electric heat in defrost mode is needed to keep the system from blowing cold air inside the building. The elements are then used in the "reheat" function. Although the thermostat may indicate the system is in defrost and electric heat is activated, the defrost function is not controlled by the thermostat. Since the heat pump has electric heat elements for supplemental and reheats, the heat pump thermostat provides for use of the electric heat elements should the refrigeration system fail. This function is normally activated by an "E" terminal on the thermostat. When in emergency heat, the thermostat makes no attempt to operate the compressor or outdoor fan.

**Digital**


Residential digital thermostat


Lux Products' Model TX900TS Touch Screen Thermostat.

Newer digital thermostats have no moving parts to measure temperature and instead rely on thermistors or other semiconductor devices such as a resistance thermometer (resistance temperature detector). Typically one or more regular batteries must be installed to operate it, although some so-called "power stealing" digital thermostats use the common 24 volt AC circuits as a power source, but will not operate on thermopile powered "millivolt" circuits used in some furnaces. Each has an LCD screen showing the current temperature, and the current setting. Most also have a clock, and time-of-day and even day-of-week settings for the temperature, used for comfort and energy conservation. Some advanced models have touch screens, or the ability to work with home automation or building automation systems.

Digital thermostats use either a relay or a semiconductor device such as triac to act as switch to control the HVAC unit. Units with relays will operate millivolt systems, but often make an audible "click" noise when switching on or off.

More expensive models have a built-in PID controller, so that the thermostat knows ahead how the system will react to its commands. For instance, setting it up that temperature in the morning at 7 a.m. should be 21°C, makes sure that at that time the temperature will be 21°C, where a conventional thermostat would just start working at that time. The PID controller decides at what time the system should be activated in order to reach the desired temperature at the desired time. It also makes sure that the temperature is very stable (for instance, by reducing overshoots).

Most digital thermostats in common residential use in North America and Europe are programmable thermostats, which will typically provide a 30% energy savings if left with their default programs; adjustments to these defaults may increase or reduce energy savings. The programmable thermostat article provides basic information on the operation, selection and installation of such a thermostat.

### Household thermostat location

The thermostat should be located away from the room's cooling or heating vents or device, yet exposed to general airflow from the room(s) to be regulated. An open hallway may be most appropriate for a single zone system, where living rooms and bedrooms are operated as a single zone. If the hallway may be closed by doors from the regulated spaces then these should be left open when the system is in use. If the thermostat is too close to the source controlled then the system will tend to "short cycle", and numerous starts and stops can be annoying and in some cases shorten equipment life. A multiple zoned system can save considerable energy by regulating individual spaces, allowing unused rooms to vary in temperature by turning off the heating and cooling.

## *Dummy thermostats*

It has been reported that many thermostats in office buildings are non-functional dummy devices, installed to give tenants' employees an illusion of control. These dummy thermostats are in effect a type of placebo button.

## Chapter 11

# Insulated Shipping Container and Thermostatic Radiator Valve

# Insulated shipping container

**Insulated shipping containers** are a type of packaging used to ship temperature sensitive products such as foods, pharmaceuticals, and chemicals. They are used as part of a cold chain to help maintain product freshness and efficacy. The term can also refer to insulated intermodal containers or insulated swap bodies.

### *Construction*

An insulated shipping container might be constructed of:

1. a vacuum flask, similar to a "thermos" bottle
2. fabricated thermal blankets or liners
3. molded expanded polystyrene foam (EPS, styrofoam, etc), similar to a cooler
4. other molded foams such as polyurethane, polyethylene, etc
5. sheets of foamed plastics
6. reflective materials: (metallised film, etc)
7. bubble wrap or other gas filled panels
8. other packaging materials and structures

Some are designed for single use while others are returnable for reuse. Some empty containers are sent to the shipper disassembled or "knocked down", assembled and used, then knocked down again for easier return shipment.

### *Use*

Insulated shipping containers are part of a comprehensive cold chain which controls and documents the temperature of a product through its entire distribution cycle. The containers may be used with a refrigerant or coolant such as :

- block or cube ice, slurry ice, etc
- dry ice

- Gel or ice packs (often formulated for specific temperature ranges)
- Some products (such as frozen meat) have sufficient thermal mass to contribute to the temperature control
- etc

A temperature data logger or time temperature indicator is often enclosed to monitor the temperature inside the container for its entire shipment.

Labels and appropriate documentation (internal and external) are usually required.

Personnel throughout the cold chain need to be aware of the special handling and documentation required for some controlled shipments. With some regulated products, complete documentation is required.

## *Design and Evaluation*

The use of "off the shelf" insulated shipping containers does not necessarily guarantee proper performance. Several factors need to be considered :

- the sensitivity of the product to temperatures (high and low) and to time at temperatures
- the specific distribution system being used: the expected (and worst case) time and temperatures
- regulatory requirements
- the specific combination of packaging components and materials being used
- etc

In specifying an insulated shipping container, the two primary characteristics of the material will be the insulation properties of the matieral known as the "K Value" and the thickness of the material. These two attributies determine that majority of the functionality of the component. One should attempt to control the latent heat of any insultated shipping container when is use, as this will affect the overall performance of the component when integrated into a system (closed system with refrigerant & product).

It is wise (and sometimes mandatory) to have formal verification of the performance of the insulated shipping container. Laboratory package testing might include ASTM D3103-07, Standard Test Method for Thermal Insulation Performance of Packages, ISTA Guide 5B: Focused Simulation Guide for Thermal Performance Testing of Temperature Controlled Transport Packaging, and others. In addition, validation of field performance is extremely useful.

Specialists in design and testing of packaging for temperature sensitive products are often needed. These may be consultants, independent laboratories, universities, or reputable vendors.

# Thermostatic radiator valve

A **Thermostatic Radiator Valve** (TRV) is a self-regulating valve fitted to hot water heating system radiators. The TRV controls the temperature of a room by regulating the flow of hot water to the radiator. Thermostatic radiator valves (air vent valves) also exist for steam radiators.

### *Short history of the TRV*

Many years ago the first ideas for heating controls saw the light of day, but it was not until 1943 when Mads Clausen, founder of Danfoss, invented the first radiator thermostat that the development of TRVs became serious. However, from the first invention to mass production to the European market it took almost 15 years, and it was not until 1973 when the first oil crisis hit the world that the installation of TRVs really took speed.

Today TRVs have a wide market distribution and acceptance worldwide as an energy efficient and competitive technology. In spite of this there is still a huge potential for further implementation of TRVs as replacement of old manual valves to benefit the environment and reduce the energy costs for people around the world.

### *Product design and functionality*

A TRV consists of two parts: a valve that opens or closes to control the hot water flow and a sensor that controls the opening of the valve. The sensor contains an actuator with a sensing substance, which adjusts the valve opening based on the temperature in the room and via a physical connection between the actuator-spindle and the valve-spindle/cone.

The sensors are for the most part made of plastic in many different designs and shapes. The actuator usually contains a sensing substance, such as wax, liquid or gas.

The valves are mainly made by brass or bronze and have different sizes, shapes and connections to the radiator. The majority of valves are mounted on the piping connected to the radiator; however, the valves may also be mounted as an integrated part of the radiator.

## *Operation*

TRVs are self-regulating devices, which control the temperature in the room based on an individually set temperature and heat load. TRVs can work together with outdoor temperature controls, supply flow temperature controls, pressure controls and time set-back devices.

The self-regulating principle is shown in this animation. The overall principle can be described in this way:

1. The actuating device in the sensor is a steel container containing a sensing substance, either wax, liquid or gas. All three substances expand or contract depending on the temperature in the room.
2. A spindle system in the sensor transfers the axial movement from the actuator to the valve by interaction between the sensor spindle and the valve spindle. In the valve a rubber cone fixed on the valve spindle interacts with the valve seat and thereby regulates and controls the flow of hot water through the valve to the radiator inlet.

The process is completely self-contained and without complex electronic controls. The TRV keeps the room temperature at a desired level even through fairly wide swings in indoor temperature due to external conditions such as sudden temperature drops, solar radiation, wind velocity or wind direction.

After installing TRVs, owners have to get used to the self-regulating principle which means that they do not have to turn the thermostat up and down. When room temperatures vary, the valve automatically opens or closes to regulate the flow of hot water until the desired temperature is achieved. Only if the desired room temperature has to be changed or if windows are opened or closed for ventilation does the sensor setting need to be adjusted.

A TRV should not be fitted on a radiator where it is in the same room as the main house/rooms thermostat, as this can lead to inaccurate overall house temperature control. Refer to BS5449 or equivalent.

## *Applications and $CO_2$ savings*

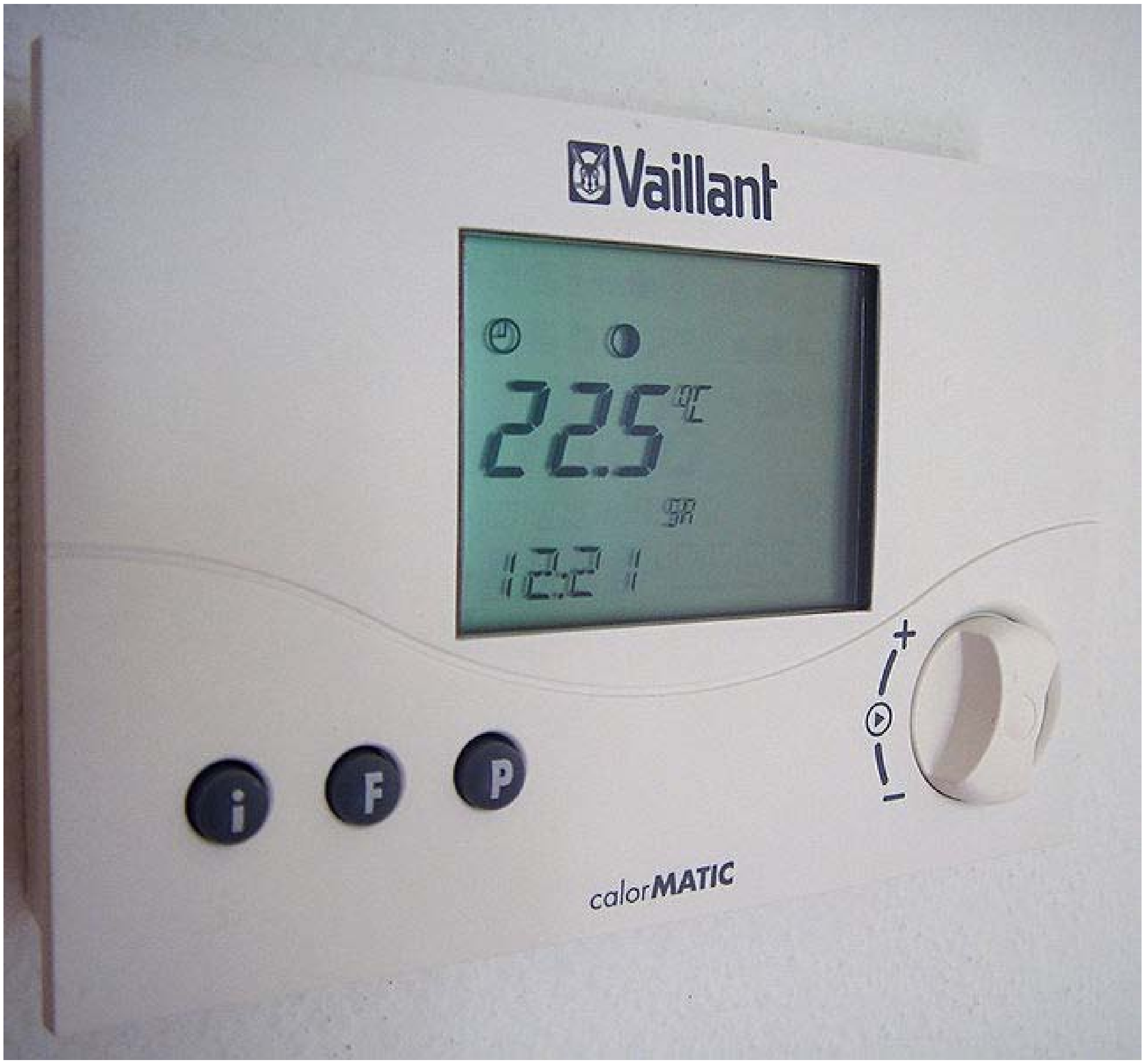
TRVs are suitable for all kind of radiator systems, radiators, convectors and towel dryers. Designs of the sensors can be tailored to suit the specific applications. TRVs are cheap and easy solutions with a significant potential for energy savings and $CO_2$ reductions from heating installations. In fact the replacement of a manual heating control with a TRV can save at least 100 kg $CO_2$ per year.

When dimensioning a heating system in a building, it is necessary to perform a precise calculation of the total system. As part of this calculation it is important to secure proper hydraulic balancing of the complete heating system. For this balancing, the presetting feature in the valve or a special hydraulic balancing valve can be used.

## Chapter 12

# Programmable Thermostat


Lux Products' Model TX900TS Touch Screen Thermostat.




Vaillant digital room thermostat

A **programmable thermostat** is a thermostat which is designed to adjust the temperature according to a series of programmed settings that take effect at different times of the day. Programmable thermostats may also be called **setback thermostats** or **clock thermostats**.

## *Benefits*


Honeywell electronic thermostat in a store

Heating and cooling losses from a building (or any other container) become greater as the difference in temperature increases. A programmable thermostat allows reduction of these losses by allowing the temperature difference to be reduced at times when the reduced amount of heating or cooling would not be objectionable.

For example, during cooling season, a programmable thermostat used in a home may be set to allow the temperature in the house to rise during the workday when no one will be at home. It may then be set to turn on the air conditioning before the arrival of occupants, allowing the house to be cool upon the arrival of the occupants while still having saved air conditioning energy during the peak outdoor temperatures. The reduced cooling required during the day also decreases the demands placed upon the electrical supply grid.

Conversely, during the heating season, the programmable thermostat may be set to allow the temperature in the house to drop when the house is unoccupied during the day and also at night after all occupants have gone to bed, re-heating the house prior to the occupants arriving home in the evening or waking up in the morning. Since most people sleep better when a room is cooler and the temperature differential between the interior and exterior of a building will be greatest on a cold winter night, this reduces energy losses.

Similar scenarios are available in commercial buildings, with due consideration of the building's occupancy patterns.

## *Construction and features*

### Clock thermostats


Honeywell office thermostat

The most basic clock thermostats may only implement one program with two periods (a hotter period and a colder period), and the same program is run day after day. More sophisticated clock thermostats may allow four or more hot and cold periods to be set per day. Usually, only two distinct temperatures (a hotter temperature and a colder temperature) can be set, even if multiple periods are permitted. The hotter and colder temperatures are usually established simply by sliding two levers along an analogue temperature scale, much the same as in a conventional (non-clock) thermostat.

This design, while simple to manufacture and relatively easy to program, sacrifices comfort on weekends since the program is repeated each of the seven days of the week with no variation. To overcome this deficit, a push-button is sometimes provided to allow the user to explicitly switch (once) the current period from hot period to a cold period or vice-versa; the usual use of this button is to over-ride a "set back" that takes place during the workday when the home is normally unoccupied.

The clock mechanism is electrical, and two methods have commonly been used to drive it:

- A separate, continuous source of 24 volts AC is provided to the thermostat, or
- A rechargeable battery in the thermostat operates the clock. The battery charges when the thermostat is not calling for heat and 24 VAC is available across the thermostat's terminals, and discharges to operate the clock when the thermostat is commanding heating or cooling.

### Digital thermostats


A touch-screen programmable thermostat in programming mode.

Digital thermostats may implement the same functions, but most provide more versatility. For example, they commonly allow setting temperatures for two, four, or six periods each day, and rather than being limited to a single "hotter" temperature and a single "colder" temperature, digital thermostats usually allow each period to be set to a unique temperature. The periods are commonly labeled "Morning", "Day", "Evening", and "Night", although nothing constrains the time intervals involved. Digital thermostats usually allow the user to override the programmed temperature for the period, automatically resuming programmed temperatures when the next period begins. A function to "hold" (lock-in) the current temperature is usually provided as well; in this case, the override temperature is maintained until the user cancels the hold or a programmed event occurs to resume the normal program. More-sophisticated models will allow for the release of the hold to take place at a set time in the future.

As with clock thermostats, basic digital thermostats may have just one cycle that is run every day of the week. More-sophisticated thermostats may have a weekday schedule and a separate weekend schedule (so-called "5-2" setting) or separate Saturday and Sunday schedules (so-called "5-1-1" settings), while other thermostats will offer a separate schedule for each day of the week ("7 day" settings). The selection of which days are defined as the "weekend" is arbitrary, depending on the user's heating and cooling schedule requirements. Often, a manufacturer will sell three similar thermostats offering each of those levels of functionality, and there is no obvious difference in the thermostats other than the factory programming and the price.

Most digital thermostats have separate programs for heating and cooling, and may feature a digital or manual switch to turn on the furnace blower for air circulation, even when the system isn't heating or cooling. More-sophisticated models may be programmed to run the circulating fan for a brief 5-10 minute period in the event a heating or cooling cycle has not taken place during the previous hour. This is particularly useful in buildings subject to stratification where without frequent air circulation, hot air rises and separates from the cooler air that falls.

Digital thermostats may also have a user-programmable air filter change reminder; this counts the accumulated run-time of the heating/cooling system and reminds the user when it is time to change the filter. The feature often displays the accumulated run-time either as an aggregate of both heating and cooling or displaying each time separately.

Some digital thermostats have the capability of being programmed using a touch-tone telephone or over the Internet.

Digital thermostats are usually powered one of three ways:

- A sophisticated power circuit operates from the 24 VAC supply when the thermostat is *not* calling, and operates from the current flowing in the thermostat circuit when the thermostat *is* calling. A battery is used to provide back-up during power failures.
- A rechargeable battery operates the thermostat just as in the clock thermostat, charging when the thermostat is not calling and discharging while the thermostat is calling.
- A non-rechargeable battery always powers the thermostat. To limit the amount of power drawn from the battery, such thermostats use an impulse relay that does not require the continuous application of power to the relay's coil. These thermostats can be used on millivolt circuits, as well as conventional 24 VAC circuits. Battery life is typically one to two years.

## Digital thermostats with PID controller

More expensive models have a built-in PID controller, so that the thermostat learns how the system will react to its commands. Programming the morning temperature to be 21° C at 7:00 AM, for instance, makes sure that at that time the temperature will be 21° C. A standard programmable thermostat would simply start working toward 21° at 7:00 AM. The PID controller decides at what time the system should be activated in order to reach the desired temperature at the desired time. It knows this by remembering the past behavior of the room, and the current temperature of the room. This is called optimal start.

It also makes sure that the temperature is very stable (for instance, by reducing overshoots at the end of the heating cycle) so that the comfort level is increased.

## Commercial thermostats

In commercial applications, the thermostat may not contain any clock mechanism. Instead, another means may be used to select between the "hotter" and "colder" settings. For example, if the thermostat uses pneumatic controls, a change in the air pressure supplied to the thermostat may select between the "hotter" and "colder" settings, and this air pressure is determined by a central regulator. With electronic controls, a specific signal may indicate whether to operate at the "hotter" or "colder" setting.

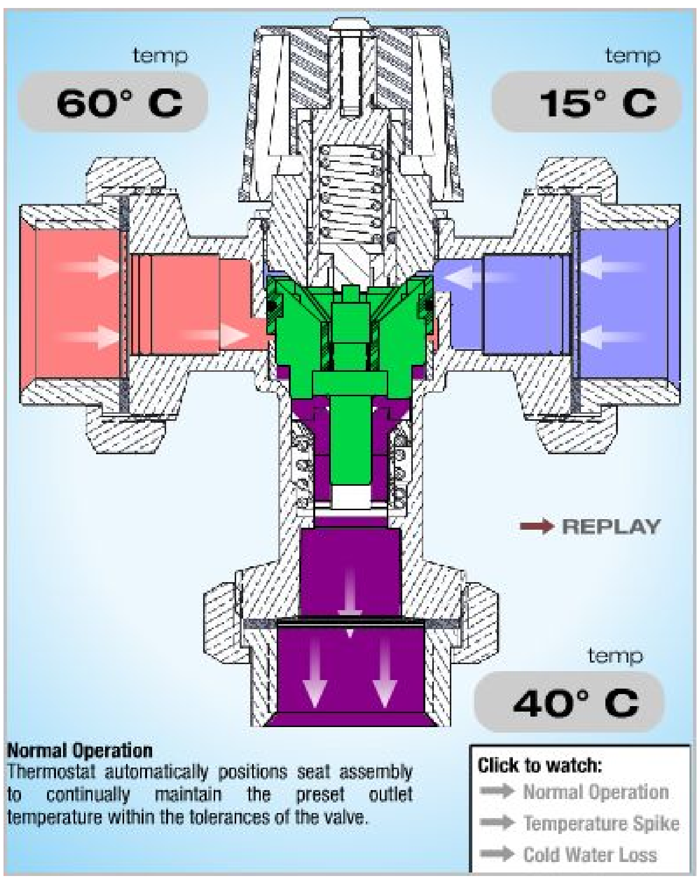
## Terminal types

| Terminal Code | Color | Description |
|---|---|---|
| R | Red | 24 volt |
| RH / RC | Red | 24 volt HEAT / COOL load |
| C / X | | 24 volt Common |
| W / W1 | White | Heat |
| W2 | White | Backup Heat |
| Y / Y1 | Yellow | Cool |
| G | Green | Fan |
| O / OB | Orange | Reversing valve (Heat Pump) |
| E | | Emergency Heat (Heat Pump) |

Chapter 13

# Thermostatic Mixing Valve and Wax Thermostatic Element

## Thermostatic mixing valve




A **Thermostatic Mixing Valve** (TMV) is a valve that blends hot water with cold water to ensure constant, safe outlet temperatures preventing scalding.

The storage of water at high temperature removes one possible breeding ground for Legionella; the use of a thermostat rather than a static mixing valve provides increased safety against scalding, and increased user comfort because the hot-water temperature remains constant.

Many TMVs use a wax thermostat for regulation. They also shut-off rapidly in the event of a hot or cold supply failure to prevent scalding or thermal shock.

It is increasingly common practice around the world to regulate the storage water temperature to above 60 °C (140 °F), and to circulate or distribute water at a temperature less than 50 °C (122 °F). Water above these temperatures can cause scald injuries. Many countries, states, or municipalities now require that the temperature of all bath water in new build and extensively refurbished domestic properties be controlled to a maximum of 48 °C (118 °F). Installing Thermostatic Mixing Valves (TMVs) can ensure that water is delivered at the required temperature thereby reducing the risk of scalding accidents; it also reduces hot water consumption relative to a supply that is maintained at a higher temperature.

There are three main categories for water temperature controlling devices: Heat Source, Group Control, and Point of Use.

Heat Source:

These are used with central heating systems that use water as a medium.

- tempering valves for use on hot water heat distribution systems
- High flow rates suitable for use in under floor (radiant) heating applications
- Allows water to be stored at a higher temperature

Group Control:

These provide a uniform distribution temperature for all hot water outlets in a household.

- Designed for multi-point applications
- High flow rates (from 14gpm to 51gpm at 45psi)
- Temperature stability

Point of Use:

These are single Outlet Thermostatic Mixing Valves, often called "thermostatic faucets", "thermostat taps" or "thermostat valves".

- Designed for single point applications such as Individual Showering, Hand Wash Basin Mixers, Bath or Tub fillers
- High level protection against scalding and thermal shock

# Wax thermostatic element

The **wax thermostatic element** was invented by Sergius Vernet (USA) in 1936 . The principal application of the wax element technology is for the production of automotive thermostats. The first applications of this technology in the plumbing and heating industries were in Sweden (1970) and in Switzerland (1971).

Wax thermostatic elements permit the transforming of thermal energy into mechanical energy. Their working principle is based on the large increase in the thermal expansion of waxes when they pass from the solid to the liquid state. The range of application includes but is not limited to the automotive industry, military and civil aviation, domestic heating (eg. thermostatic radiator valves), plumbing, industrial, fire, and agriculture.

## *Types of elements*

### Flat diaphragm element

The temperature sensing material contained in the cup transfers pressure to the piston by means of the diaphragm and the plug, held tightly in position by the guide. On cooling, the initial position of the piston is obtained by means of a return spring. Flat diaphragm elements are particularly noted for their high level of accuracy, and therefore mainly used in sanitary installations and heating.

### Squeeze-push elements

Squeeze-Push elements contain a synthetic rubber sleeve-like component shaped like the 'finger of a glove' which surrounds the piston. As the temperature increases, pressure from the expansion of the thermostatic material moves the piston with a lateral squeeze and a vertical push. As with the flat diaphragm element, the piston returns to its initial position by means of a return spring. These elements are slightly less accurate but provide a more powerful stroke.

## *Piston stroke*

The stroke is the movement of the piston in relation to its starting point. The ideal stroke corresponds to the temperature range of the elements. According to the type of element, it can vary from 1.5 mm to 16 mm.

## *Temperature range*

The temperature range lies between the minimum and maximum operating temperature of the element. Elements can cover temperatures ranging from -15°C to +120°C.

The temperature curve represents the movement of the piston in relation to the temperature. It can be a continuous or broken line. The angle varies according to the composition of the waxes.

### *Hysteresis*

Hysteresis is the difference noted between the upstroke and down stroke curve (i.e. heating and cooling of the element). Hysteresis is caused by the thermal inertia of the element and by the friction between the parts in motion.

# Chapter 14

# OpenTherm

**OpenTherm** (short: OT) is a protocol used in central heating systems between a central heating boiler and a thermostat or controller. It is a point to point protocol where one device (thermostat) is the master and the other the slave (boiler). Multiple devices can be linked by using the Multi Point to Point specification.

OpenTherm is manufacturer independent. A controller of manufacturer A can be used to control a boiler of manufacturer B.

## *How OpenTherm works*

Communication is digital and bi-directional between the thermostat (master) and the boiler (slave), many different commands, status reports and requests for information between the two devices is possible. However the most basic command is to control the boiler water temperature. The boiler when it has received a temperature control setpoint command will modulate (reduce or increase the heating power) to maintain this temperature setpoint. The thermostat constantly calculates what temperature the boiler water should be to maintain control of the room temperature, this results in a greater energy efficiency.

## *Communications media*

Physically OpenTherm is a 2 wire connection allowing the existing wiring to be re-used. OpenTherm not polarity sensitive: wires can be swapped. The maximum wiring length is 50m up to maximum 2 x 5 ohm resistance.

## *OpenTherm/Plus (OT/+)*

When referring to OpenTherm/Plus (OT/+) most of the time the “Plus OT+” part is left out.

The two wires are used for both communications and power supply. In this point-to-point connection the controller is the master and the boiler the slave. The master requests by changing the voltage level, and the slave responds by changing the current. Power supply for the controller is supplied by the slave. The minimal available power is 35 mW. When using OpenTherm Smart Power this can, by master request, also be 136 mW (medium power) or 255 mW (high power).

When short circuiting the OpenTherm connection on the boiler, the boiler will start heating.

OpenTherm specifies a minimal communications interval of one second. The data in the communication packet is functionally specified and is called OpenTherm-ID (OT-ID). 256 OT-IDs are available, 128 are reserved for OEM use. The other 128 are reserved, 90 of them are functionally specified. (OT specification v3.0)

### *OpenTherm/Lite (OT/-)*

When OT/- is used the master generates a PWM voltage signal, representing the boiler water temperature set point. The boiler current signal indicates the status of the boiler: error, no error.

When short circuiting the OpenTherm connection on the boiler, the boiler will start heating.

Due to the limited possibilities OT/- is hardly used.

### *OpenTherm Smart Power*

On June 16 2008 OpenTherm specification 3.0 is approved by the association. This version introduces OpenTherm Smart Power. The master can request the slave to change the available power to low, medium or high power. With this master manufacturers can add more functionality to their products (backlight or extra sensors).

### *Multi Point to Point*

Specification 3.0 also describes how more than two devices can be connected by OpenTherm. Whilst OpenTherm is a point-to-point connection, an extra device (gateway) is added between the master and the slave. This gateway has 1 slave and 1 (or more) master interfaces. The gateway controls which data is passed to each slave. An application example is a room temperature controller connected to a heat recovery unit, which is connected to a boiler. The heat recovery unit is then functioning as gateway.

## *Certifying products*

Manufacturers are allowed to market OpenTherm products when they comply with some rules of the OpenTherm association. Most importantly the manufacturer has to be an OpenTherm member, and the product must be tested by an independent testing body.

By handing over the test report and a Declaration of Conformity to the association, the manufacturer is allowed to use the OpenTherm logo.

## *History*

OpenTherm was founded because multiple manufacturers needed a simple-to-use communicating system between room controller and boiler. It had to run, like the existing controllers, over the existing two wires, not polarity sensitive, without the use of batteries.

For one British Pound, Honeywell sold the first specification to the OpenTherm Association on November 1996. Shortly after the first products appeared on the market. The Association has grown since then to around 42 members (2008) and has regularly updated and improved the specification. Furthermore, the Association is also active in lobbying for the interests of its members and is also present at exhibitions like the ISH (Frankfurt) and the Mostra Convegno (Milan)

## *Specification documents*

The protocol specifications document: **Protocol specification** (v2.2).

Document used for certification: **Test Specification**.

The document **Application Functional Specification** describes different applications and how the OpenTherm ID's are to be used. In addition implementation tips are given.

# Chapter 15

# Storage Heater

A **storage heater** is an electrical home appliance which stores thermal energy during the evening, or at night when base load electricity is available at lower cost, and releases the heat during the day as required. Heat banks may be composed of clay bricks or other ceramic material, of concrete walls, or of water containers

In Australia, storage heaters are often called *heat banks*.

## *Application*

Storage heaters are usually used in conjunction with a two-tariff electricity meter which records separately the electricity used during the off-peak period so that it can be billed at a lower rate. In order to derive any benefit from a storage heater, the house must be on a special electricity tariff. In the United Kingdom the Economy 7 tariff is appropriate.

Storage heaters usually have two controls - a charge control (often called "input"), which controls the amount of heat stored, and the draught control (often called "output"), which controls the rate at which heat is released. These controls may be controlled by the user, or may operate automatically once the user selects the target room temperature on a thermostat.

Storage heaters may also incorporate an electric heater (utilizing either resistance heaters or heat pumps), which can be used to increase heat output. Such added heating is expensive, as it occurs during the high-tariff time of day.

## *Advantages*

- Storage heaters allow electrical heating, which is often more expensive than equivalent gas- or oil-fired heating systems, to be used without as much operating cost

- If the storage heater is incorporated into the building's floorplan (i.e. as dividing walls between areas, or underfloor), they take up less area than a gas- or oil-fired heating system
- Users of gas central heating & some other systems often turn off the heating during the night as an economy measure, with the result that the house is cold at night and early morning; but because night storage heaters are on at night, the house is still warm at those times
- Using storage heaters allows houses to be sited in areas where natural-gas distribution systems are not available, without forcing the homeowners to pay high electrical-heating bills
- The capital cost of night storage heating is relatively low; and installation is far easier than the initial installation of gas fired boilers, piping and radiators
- As compared to gas central heating systems, night storage heaters require next to no maintenance, with a consequent reduction in running costs.

### *Disadvantages*

- Sizing a storage heater is a compromise between the maximum expected cold-spell intensity and duration, and the cost and space requirement of the heater. If the heater is too large, its cost will be excessive and it will impact on the building's available area; if too small, the cost of supplemental (daytime) electrical heating will be excessive
- The heat stored during the night will be released into the living area during the next day, regardless of need (due to the inevitable heat transfer through the storage heater's insulation). Thus if the homeowner is unexpectedly absent that day (and therefore does not need the house to be warmed) or is only at home for a small part of the day, the heat has already been purchased and is already there, and eventually comes out
- Many users do not fully understand the controls, and a common error is leaving the output (or boost) control open at night, so that the heaters dissipate heat when they should be storing it, with a consequent increase in electricity consumption and cost
- Storage heaters are very heavy and somewhat bulky, due to the material used to store heat

### *Using storage heaters*

Storage heaters can be cost-effective if used properly, but they require more attention than fuel-fired systems.

## Power switches


Off peak and peak power supplies to storage heater

Storage heaters usually provide two power circuits, one for on-peak and one for off-peak electricity, and two power switches, which are switched off during the summer when heat is not required. During other months the off-peak switch can be left on at all times, with the on-peak switch being used when insufficient energy has been stored during off-peak times. The amount of heat that is stored can be altered using the controls on the storage heater unit. Normally the on-peak will have a fuse as it is part of another circuit. The off-peak will just be a switch as it has a dedicated circuit.

## Basic controls


Input and Output switches on a basic storage heater

Basic storage heaters have an input switch, and an output switch, called *heat boost* on some models.

The position of the input switch should be changed to reflect how cold the next day is predicted to be. The input switch is normally thermostatic, controlling the maximum temperature that the bricks will be heated to overnight. The exact setting needed will depend on the size of the storage heater, the desired room temperature, the number of hours that this needs to be maintained, and the room's rate of heat loss under a given set of circumstances. Some experimenting may be needed to find the relationship between forecast outside temperature and best input setting for a particular room. Most storage heater users follow simpler guidelines; for example, in the middle of winter, it is often appropriate to turn the input switch to its maximum setting. There is no need to touch the input switch on a daily basis if the same sort of weather prevails for weeks at a time. There is no need to touch the input switch during the day, as storage heaters only use electricity at night.

The output switch does require attention throughout the day. Before going to bed, the operator should switch the output to its minimum setting. This keeps as much heat in the bricks as possible. Enough will leak out into the room to make it warm in the morning. Only in exceptionally cold circumstances will the operator require output overnight. The operator may wish to slowly increase the output switch during the day to try and maintain the temperature in the house. Increasing the output will allow the heat to convect out of the heater. If the house is empty during the day because the operator is at work, the output should be left at a minimum all day and then switched up when returning from work in order to let more heat escape into the house.

### Thermostatic controls


Thermostatic controls on a more advanced storage heater

A thermostatic storage heater will automatically regulate the temperature in a room throughout the day. However, the operator may wish to switch the thermostatic switch to the minimum setting overnight to lower the room temperature. If the room is empty during the day, it is better to keep the thermostat at the mimimum setting and then increase the setting when the room is occupied in the evening. Some thermostatic heaters also make use of on-peak electricity when there is not enough stored heat to maintain the requested temperature; the user may wish to be aware of this and lower the settings.

## *Environmental aspects*

In common with other forms of direct electric heating, storage heaters are not normally considered environmentally friendly because most electricity is generated remotely using fossil fuels, with up to two-thirds of energy in the fuel lost at the power station and in transmission losses. In Sweden the use of direct electric heating has been restricted since the 1980s for this reason, and there are plans to phase it out entirely - while Denmark has banned the installation of electric space heating in new buildings for similar reasons. In the UK, a storage heater earns a "Poor" rating for Environmental Performance on an Energy Performance Certificate. Many progressive countries are developing their electricity generating system, principally, to incorporate 'greener', more sustainable and renewable energy sources.

In some countries, the current design of the electrical generating system may result in a surplus of electricity from base load power stations during off-peak periods, and storage heaters may then be able to make use of this surplus to increase the net efficiency of the system as a whole. However, future changes in supply and demand - for example as a result of energy conservation measures or a more responsive generating system - may then reverse this situation, with storage heaters preventing a reduction in the national base load. Other future technologies may incorporate electricity-supply-sensitive electronics to sense when there is a change in supply and demand. Thereby, they ensure that these loads only use off-peak electricity. Further advances in supply technology could provide for a more bespoke 'supply and demand' tariff system to make these sensing technologies a more viable financial prospect.

Compared to other forms of electric heating, storage heaters are cheaper to run and they impose lower peak loads. The highest peak loads come from instantaneous electric heating, such as immersion water heaters, which create heavy loads for short durations, although instantaneous water heaters may use less electricity overall. High-efficiency ground source heat pumps are able to use up to 66% less electricity than storage heaters in heating by recovering heat from the ground, and are regarded as preferable even though they use electricity throughout the day. These are not to be confused with air conditioning (A/C) heat pumps which are now considered to be an environmental liability in some, (in particular hotter climate), countries.

Where alternatives to electricity exist, hot-water central heating systems can use water heated in or close to the building using high-efficiency condensing boilers, biofuels, heat pumps or district heating. Ideally wet underfloor heating should be used. This can be converted in the future to use developing technologies such as solar panels, so also providing future-proofing. In the case of new buildings, low-energy buildings such as those built to the Passive House standard can eliminate the need for conventional space heating systems.