Heat Pump Technologies

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Chapter 1

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.

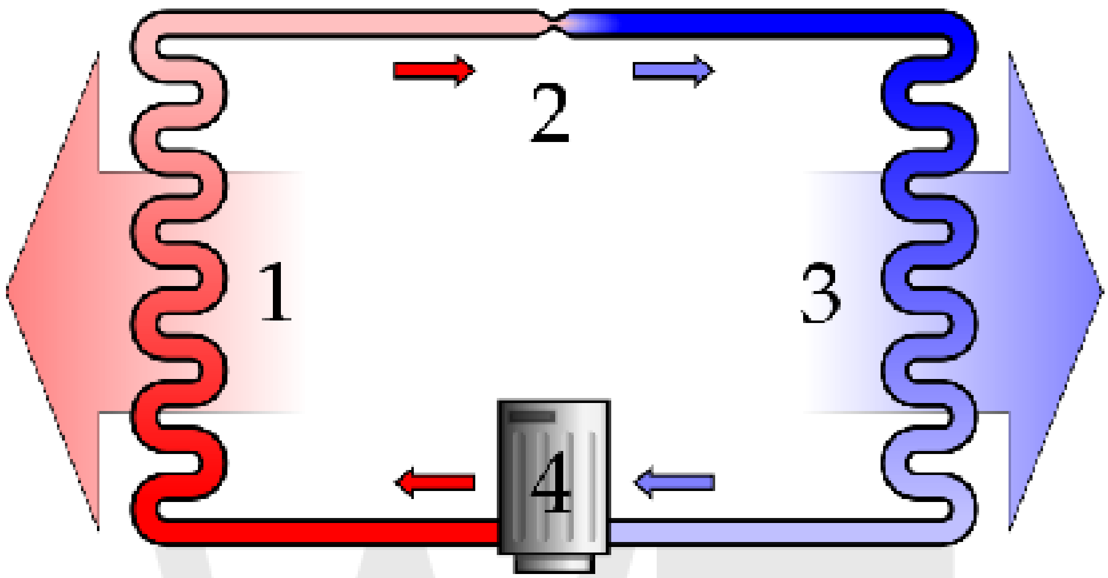
Overview

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:

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

where

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

COP and lift

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

		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 2

Heat Pump and Refrigeration Cycle

Thermodynamic **heat pump cycles** or **refrigeration cycles** are the conceptual and mathematical models for heat pumps and refrigerators. 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. Thus a heat pump may be thought of a "heater" if the objective is to warm the heat sink (as when warming the inside of a home on a cold day), or a "refrigerator" if the objective is to cool the heat source (as in the normal operation of a freezer). In either case, the operating principles are identical. Heat is moved from a colder place to a warmer place.

Thermodynamic cycles

According to the second law of thermodynamics heat cannot spontaneously flow from a colder location to a hotter area; work is required to achieve this. An air conditioner does work to cool a living space, moving heat from the cooler interior (the heat source) to the warmer outdoors (the heat sink). Similarly, a refrigerator moves heat from inside the cold icebox (the heat source) to the warmer room-temperature air of the kitchen (the heat sink). The operating principle of the refrigeration cycle was described mathematically by Sadi Carnot in 1824 as a heat engine. A heat pump can be thought of as a heat engine which is operating in reverse.

Heat pump and refrigeration cycles can be classified as *vapor compression*, *vapor absorption*, *gas cycle*, or *Stirling cycle* types.

Vapor-compression cycle

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

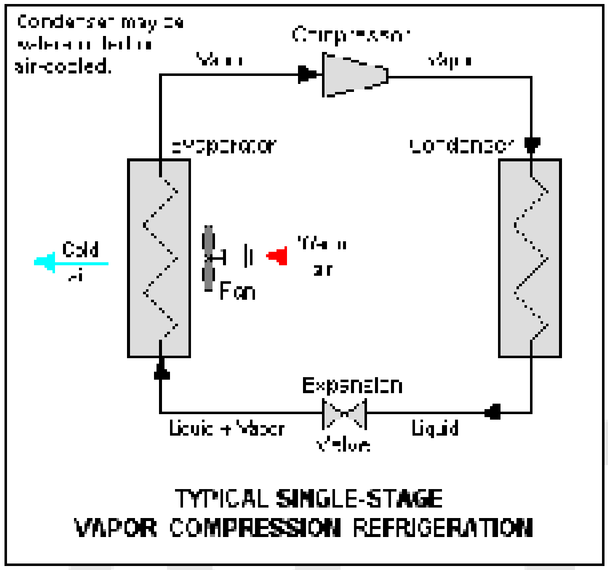


Figure 1: Vapor compression refrigeration

The thermodynamics of the cycle can be analyzed on a diagram as shown in Figure 2. In this cycle, a circulating refrigerant such as Freon enters the compressor as a vapor. The vapor is compressed at constant entropy and exits the compressor superheated. The superheated vapor travels through the condenser which first cools and removes the superheat and then condenses the vapor into a liquid by removing additional heat at constant pressure and temperature. The liquid refrigerant goes through the expansion valve (also called a throttle valve) where its pressure abruptly decreases, causing flash evaporation and auto-refrigeration of, typically, less than half of the liquid.

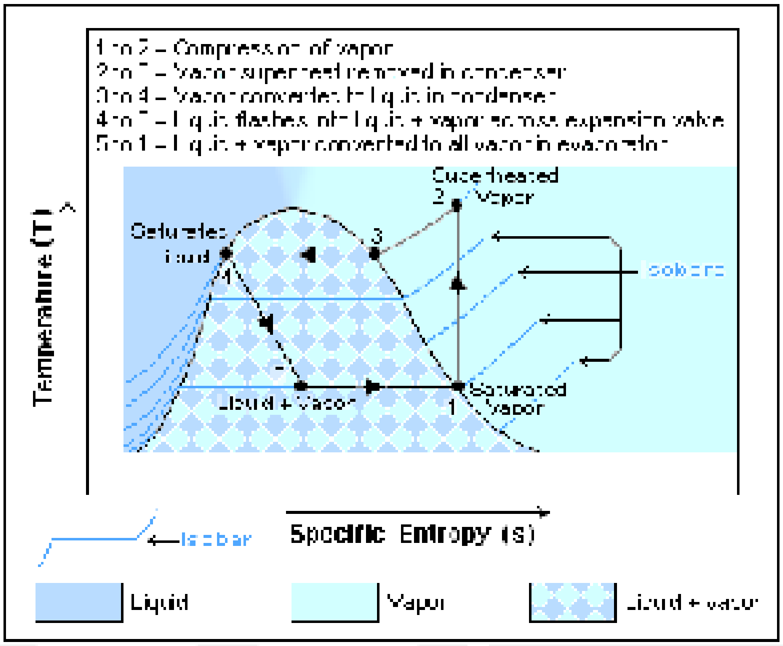


Figure 2: Temperature–Entropy diagram

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

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

Vapor absorption cycle

In the early years of the twentieth century, the vapor absorption cycle using water-ammonia systems was popular and widely used but, after the development of the vapor compression cycle, it lost much of its importance because of its low coefficient of performance (about one fifth of that of the vapor compression cycle). Nowadays, the vapor absorption cycle is used only where waste heat is available or where heat is derived from solar collectors.

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

Gas cycle

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

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

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

Stirling cycle

The Stirling cycle heat engine can be driven in reverse, using a mechanical energy input to drive heat transfer in a reversed direction (i.e. a heat pump, or refrigerator). There are several design configurations for such devices that can be built. Several such setups require rotary or sliding seals, which can introduce difficult tradeoffs between frictional losses and refrigerant leakage.

The Free Piston Stirling Cooler (FPSC) is an elegant, completely-sealed heat transfer system that has only two moving parts (a piston and a displacer), and uses helium as the working fluid. The piston is typically driven by an oscillating magnetic field that is the source of the power needed to drive the refrigeration cycle. The magnetic drive allows the piston to be driven without requiring any seals, gaskets, O-rings, or other compromises to the hermetically sealed system. Claimed advantages for the system include environmental friendliness, cooling capacity, light weight, compact size, precise controllability, and high efficiency.

The FPSC was invented in 1964 by William Beale, a professor of Mechanical Engineering at Ohio University in Athens, Ohio. He founded and continues to be associated with Sunpower Inc., which specializes primarily in researching and developing FPSC systems for a wide variety of military, aerospace, industrial, and commercial applications. Sunpower also makes cryocoolers and special pulse tube coolers capable of reaching below 40°K (around –390°F, or –230°C). A FPSC cooler made by Sunpower was used by NASA to cool instrumentation in satellites.

Since 2002. another leading supplier of FPSC technology has been the Twinbird Company in Japan, which also markets a broad line of household appliances. Both Sunpower and Twinbird appear to work in collaboration with Global Cooling NV, which is located in the Netherlands, but has a research center in Athens, Ohio.

For several years starting around 2004, the Coleman Company sold a version of the Twinbird "SC-C925 Portable Freezer Cooler 25L" under its own brand name, but it has since discontinued offering the product, in spite of favorable customer reviews on Amazon. The portable cooler can be operated more than a day, maintaining sub-freezing temperatures while powered only by an automotive battery. This cooler is still being manufactured and distributed worldwide, with Global Cooling now coordinating distribution to North America and Europe. Other variants offered by Twinbird include a portable deep freezer (to –80°C), collapsible coolers, and a special model for transporting blood and vaccine.

In addition to the technical information available on the websites referenced above, a step-by-step photographic teardown of the Coleman (Twinbird) FPSC cooler is viewable online.

Chapter 3

Absorption Refrigerator

An **absorption refrigerator** is a refrigerator that uses a heat source (e.g., solar, kerosene-fueled flame) to provide the energy needed to drive the cooling system. Absorption refrigerators are a popular alternative to regular compressor refrigerators where electricity is unreliable, costly, or unavailable, where noise from the compressor is problematic, or where surplus heat is available (e.g., from turbine exhausts or industrial processes, or from solar plants).

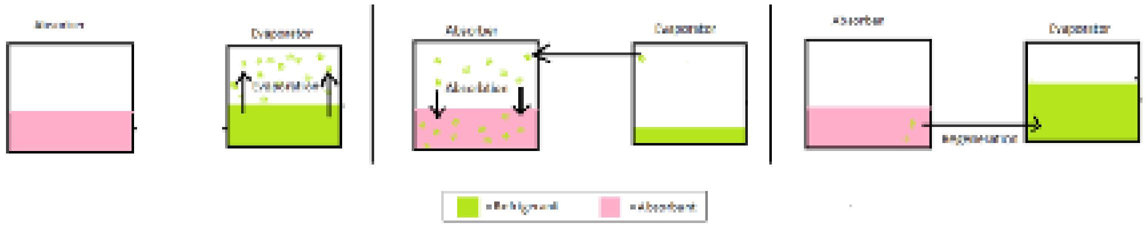
For example, absorption refrigerators powered by heat from the combustion of liquefied petroleum gas are often used for food storage in recreational vehicles. Absorptive refrigeration can also be used to air-condition buildings using the waste heat from a gas turbine or water heater. This use is very efficient, since the gas turbine produces electricity, hot water and air-conditioning (called Trigeneration).

Both absorption and compressor refrigerators use a refrigerant with a very low boiling point (less than 0 °F/−18 °C). In both types, when this refrigerant evaporates (boils), it takes some heat away with it, providing the cooling effect. The main difference between the two types is the way the refrigerant is changed from a gas back into a liquid so that the cycle can repeat. An absorption refrigerator changes the gas back into a liquid using a different method that needs only heat, and has no moving parts. The other difference between the two types is the refrigerant used. Compressor refrigerators typically use an HCFC or HFC, while absorption refrigerators typically use ammonia.

The standard for the absorption refrigerator is given by the ANSI/AHRI standard 560-2000.

Principles

Absorptive refrigeration uses a source of heat to provide the energy needed to drive the cooling process.



Absorption

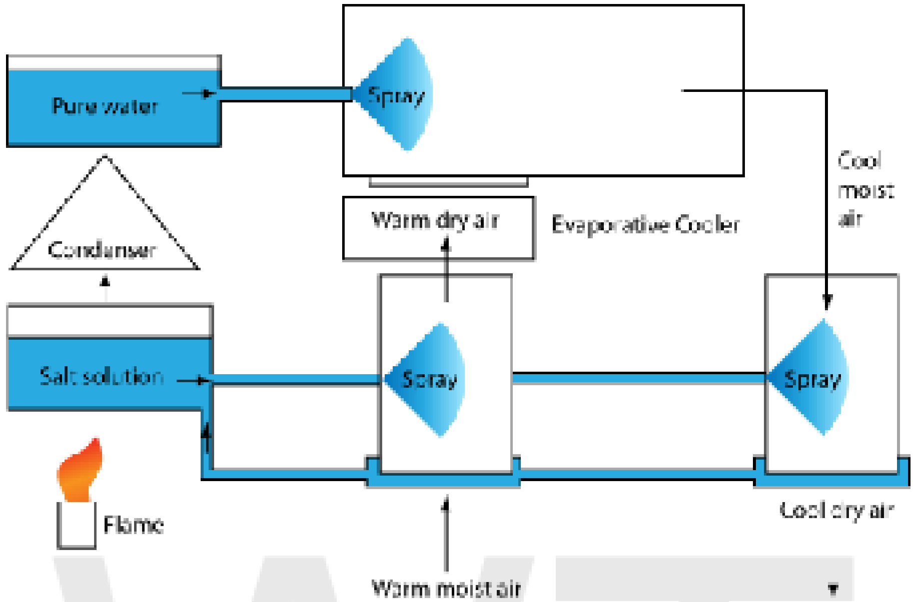
The absorption cooling cycle can be described in three phases:

1. Evaporation: A liquid refrigerant evaporates in a low partial pressure environment, thus extracting heat from its surroundings – the refrigerator.
2. Absorption: The gaseous refrigerant is absorbed – dissolved into another liquid - reducing its partial pressure in the evaporator and allowing more liquid to evaporate.
3. Regeneration: The refrigerant-laden liquid is heated, causing the refrigerant to evaporate out. It is then condensed through a heat exchanger to replenish the supply of liquid refrigerant in the evaporator.

Simple salt and water system

A simple absorption refrigeration system common in large commercial plants uses a solution of lithium bromide salt and water. Water under low pressure is evaporated from the coils that are being chilled. The water is absorbed by a lithium bromide/water solution. The water is driven off the lithium bromide solution using heat.

Water spray absorption refrigeration



Water Spray Absorption Refrigeration

Another variant, depicted to the right, uses air, water, and a salt water solution. The intake of warm, moist air is passed through a sprayed solution of salt water. The spray lowers the humidity but does not significantly change the temperature. The less humid, warm air is then passed through an evaporative cooler, consisting of a spray of fresh water, which cools and re-humidifies the air. Humidity is removed from the cooled air with another spray of salt solution, providing the outlet of cool, dry air.

The salt solution is regenerated by heating it under low pressure, causing water to evaporate. The water evaporated from the salt solution is re-condensed, and rerouted back to the evaporative cooler.

Single pressure absorption refrigeration

Labeled photo of a domestic absorption refrigerator.

A single-pressure absorption refrigerator uses three substances: ammonia, hydrogen gas, and water. At standard atmospheric conditions, ammonia is a gas with a boiling point of -33°C, but a single-pressure absorption refrigerator is pressurised to the point where the ammonia is a liquid. The cycle is closed, with all hydrogen, water and ammonia collected and endlessly reused.

The cooling cycle starts with liquefied ammonia entering the evaporator at room temperature. The ammonia is mixed in the evaporator with hydrogen. The partial pressure of the hydrogen is used to regulate the total pressure, which in turn regulates the vapour pressure and thus the boiling point of the ammonia. The ammonia boils in the evaporator, providing the cooling required.

The next three steps exist to separate the gaseous ammonia and the hydrogen. First, in the absorber, the mixture of gasses enters the bottom of an uphill series of tubes, into which water is added at the top. The ammonia dissolves in the water, producing a mixture of ammonia solution and hydrogen. The hydrogen is collected at the top of the absorber, with the ammonia solution collected at the bottom.

The second step is to separate the ammonia and water. In the generator, heat is applied to the solution, to distill the ammonia from the water. Some water remains with the ammonia, in the form of vapour and bubbles. This is dried in the final separation step, called the separator, by passing it through an uphill series of twisted pipes with minor obstacles to pop the bubbles, allowing the collected water to drain back to the generator.

Finally the pure ammonia gas enters the condenser. In this heat exchanger, the hot ammonia gas is cooled to room temperature and hence condenses to a liquid, allowing the cycle to restart.

History

Absorption cooling was invented by the French scientist Ferdinand Carré in 1858. The original design used water and sulfuric acid.

In 1922 Baltzar von Platen and Carl Munters, while they were still students at the Royal Institute of Technology in Stockholm, Sweden, enhanced the principle with a 3 fluids configuration. This "Platen-Munters" design can operate without a pump.

Commercial production began in 1923 by the newly formed company AB Arctic, which was bought by Electrolux in 1925. In the 60s the absorption refrigeration saw a renaissance due to the substantial demand for refrigerators for caravans. AB Electrolux established a subsidiary in the U.S, named Dometic Sales Corporation. The company marketed refrigerators for caravans under the **Dometic** brand. In 2001 Electrolux sold most of its Leisure Products line to the venture-capital company EQT. The Dometic Group was created.

In 1926 Albert Einstein and his former student Leó Szilárd proposed an alternative design known as Einstein refrigerator.

In 2007, Adam Grosser presented his research of a new, very small, "intermittent absorption" refrigeration system for use in third world countries at the TED Conference. The refrigerator is a small unit placed over a campfire, that can later be used to cool 3 gallons of water to just above freezing for 24 hours in a 30 degree Celsius environment.

Chapter 4

Coefficient of Performance

The **coefficient of performance** or COP (sometimes CP), of a heat pump is the ratio of the change in heat at the "output" (the heat reservoir of interest) to the supplied work.

Equation

The equation is:

$$COP = \frac{Q_H}{W}$$

where

- Q_H is the heat supplied to the hot reservoir
- W is the work consumed by the heat pump.

The COP for heating and cooling are thus different, because the heat reservoir of interest is different. When one is interested in how well a machine cools, the COP is the ratio of the heat removed from the cold reservoir to input work. However, for heating, the COP is the ratio of the heat removed from the cold reservoir plus the heat added to the hot reservoir by the input work to input work:

$$COP_{heating} = \frac{|Q_C| \quad W}{W}$$

$$COP_{cooling} = \frac{|Q_C|}{W}$$

where

- Q_C is the heat supplied to the cold reservoir.

Derivation

According to the first law of thermodynamics, in a reversible system we can show that $Q_{hot} = Q_{cold} + W$ and $W = Q_{hot} - Q_{cold}$, where Q_{hot} is the heat given off by the hot heat reservoir and Q_{cold} is the heat taken in by the cold heat reservoir.
Therefore, by substituting for W,

$$COP_{heating} = \frac{Q_{hot}}{Q_{hot} - Q_{cold}}$$

For a heat pump operating at maximum theoretical efficiency (i.e. Carnot efficiency), it can be shown that $\frac{Q_{hot}}{T_{hot}} = \frac{Q_{cold}}{T_{cold}}$ and $Q_{cold} = \frac{Q_{hot}T_{cold}}{T_{hot}}$, where T_{hot} and T_{cold} are the absolute temperatures of the hot and cold heat reservoirs respectively.

At maximum theoretical efficiency,

$$COP_{heating} = \frac{T_{hot}}{T_{hot} - T_{cold}}$$

Which is equal to the inverse of the ideal Carnot cycle efficiency because a heat pump is a heat engine operating in reverse. Similarly,

$$COP_{cooling} = \frac{Q_{cold}}{Q_{hot} - Q_{cold}} = \frac{T_{cold}}{T_{hot} - T_{cold}}$$

It can also be shown that $COP_{cooling} = COP_{heating} - 1$. Note that these equations must use the absolute temperature (the Kelvin or Rankine scale.)

$COP_{heating}$ applies to heat pumps and $COP_{cooling}$ applies to air conditioners or refrigerators. Values for actual systems will always be less than these theoretical maximums. In Europe, ground source heat pump units are standard tested at T_{hot} is 35 Celsius (95 Fahrenheit) and T_{cold} is 0 Celsius (32 Fahrenheit). According to the above formula, the maximum achievable COP would be 7.8. Test results of the best systems are around 4.5. When measuring installed units over a whole season and one also counts the energy needed to pump water through the piping systems, then seasonal COP's are around 3.5 or less. This indicates room for improvement.

Improving COP

As the formula shows, to improve the COP of a heat pump system, one needs to reduce the temperature gap T_{hot} minus T_{cold} at which the system works. For a heating system this would mean two things. One is to reduce output temperature to around 30 Celsius (86 Fahrenheit) which requires piped floor- or wall- or ceiling heating, or oversized water to air heaters. The other is to increase input temperature (by using an oversized ground source). For an air cooler, COP could be improved by using ground water as an input instead of air, and by reducing temperature drop on output side through increasing air flow. For both systems, also increasing the size of pipes and air canals would help to reduce noise and the energy consumption of pumps (and ventilators).

Also the heat pump itself can be improved a lot. The two most simple ways to improve heat pump units, is to double the size of the internal heat exchangers relative to the power of the compressor, and to reduce the system's internal temperature gap over the compressor. This last measure however, makes such heat pumps unsuitable to produce output above roughly 40 Celsius (104 Fahrenheit) which means that a separate machine is needed for producing hot tap water.

One reason that heat pump manufacturers often show little interest into making such improvements, is that they often also earn a lot of money in producing boilers, turbines and transformers for electricity plants. More efficient heat pumps would mean that less growth can be achieved in the industrial boilers and turbines sector.

For the same reason, there is little progress in engineering small heat pumps, driven on oil or piped gas. Such systems can also produce electricity, and, especially when combined with seasonally storing excess heat underground, they would be even more energy efficient then electricity driven heat pumps, because they cut away the heat wastage of central electricity production, by using exhaust and cool water heat for house warming. However, they would also vastly reduce the need for centrally produced electricity.

Example

A geothermal heat pump operating at $COP_{heating}$ 3.5 provides 3.5 units of heat for each unit of energy consumed (i.e. 1 kWh consumed would provide 3.5 kWh of output heat). The output heat comes from both the heat source and 1 kWh of input energy, so the heat-source is cooled by 2.5 kWh, not 3.5 kWh.

A heat pump of $COP_{heating}$ 3.5, such as in the example above, could be less expensive to use than even the most efficient gas furnace.

A heat pump cooler operating at $COP_{cooling}$ 2.0 removes 2 units of heat for each unit of energy consumed (e.g. an air conditioner consuming 1 kWh would remove 2 kWh of heat from a building's air).

Given the same energy source and operating conditions, a higher COP heat pump will consume less purchased energy than one with a lower COP. The overall environmental impact of a heating or air conditioning installation depends on the source of energy used as well as the COP of the equipment. The operating cost to the consumer depenends on the cost of energy as well as the COP or efficiency of the unit. Some areas provide two or more sources of energy, for example, natural gas and electricity. A high COP of a heat pump may not entirely overcome a relatively high cost for electicity compared with the same heating value from natural gas.

For example, the 2009 US average price per therm (100,000 BTU) of electricity was $3.38 while the average price per therm of natural gas was $1.16. Using these prices, a heat pump with a COP of 3.5 in moderate climate would cost $0.97 to provide one therm of heat, while a high efficiency gas furnace with 95% efficiency would cost $1.22 to provide one therm of heat. With these average prices, the heat pump costs 20% less to provide the same amount of heat. At 0 fahrenheit (-18 Celsius) COP is much lower. Then, the same system costs as much to operate as an efficient gas heater. The yearly savings will depend on the actual cost of electricity and natural gas, which can both vary widely.

However, a COP may help make a determination of system choice based on carbon contribution. Although a heat pump may cost more to operate than a conventional natural gas or electric heater, depending on the source of electricity generation in one's area, it may contribute less net carbon dioxide to the environment than burning natural gas or heating fuel. If locally no green electricity is available, then carbon wise the best option would be to drive a heat pump on piped gas or oil, to store excess heat in the ground source for use in winter, while using the same machine also for producing electricity with a built-in Sterling engine.

Conditions of use

While the COP is partly a measure of the efficiency of a heat pump, it is also a measure of the conditions under which it is operating: the COP of a given heat pump will rise as the input temperature increases or the output temperature decreases because it is linked to a warm temperature distribution system like underfloor heating.

Chapter 5

EcoCute and Fluidyne Engine

EcoCute

Domestic EcoCute outdoor unit (front) and hot water storage tank (back)

The **EcoCute** is an energy efficient electric heat pump, water heating and supply system that uses heat extracted from the air to heat water for domestic, industrial and commercial use. Instead of the more conventional ammonia or haloalkane gases, EcoCute uses carbon dioxide as a refrigerant. The technology offers a means of energy conservation and reduces the emission of greenhouse gas.

Etymology

The name of the EcoCute comes from the Japanese phrase *Shizen Reibai Hīto Ponpu Kyūtō-ki* (自然冷媒ヒートポンプ給湯機?), which literally means "natural refrigerant heat pump water heater". *Eco* is a contraction of either Ecology or Economical and *Cute* also means *kyūtō* (給湯?); literally "supply hot water."

History

Modern chemical refrigeration techniques developed after the proposal of the Carnot cycle in 1824. Jacob Perkins invented an ice-making machine that used ether in 1843, and *Edmond Carré* built a refrigerator that used water and sulfuric acid in 1850. In Japan, Fusanosuke Kuhara, founder of Hitachi, Ltd., made an air conditioner for his own home use using compressed CO_2 as a refrigerant.

In 1930 Thomas Midgley, Jr. discovered dichlorodifluoromethane, a chlorinated fluorocarbon (CFC) known as Freon. CFCs rapidly replaced traditional refrigerant substances, including CO_2 (which proved hard to compress for domestic use), for use in heat pumps and refrigerators. But from the 1980s CFCs began to lose favor as refrigerant when their damaging effects on the ozone layer were discovered. An alternative type of refrigerant, Hydro fluoro compounds (HFC), also lost favour when they were identified as greenhouse gases. The Vienna Convention for the Protection of the Ozone Layer, the Montreal Protocol and the Kyoto Protocol call for the complete abandonment of such refrigerants by 2030.

In 1989, amid international concern about the effects of chlorofluorocarbons (CFC and HFC) on the ozone layer, scientist Gustav Lorentzen and SINTEF patented a method for using CO_2 as a refrigerant in heating and cooling. Further research into CO_2 refrigeration was then conducted at Shecco (Sustainable Heating and Cooling with CO_2) in Brussels, Belgium, leading to increasing use of CO_2 refrigerant technology in Europe.

In 1993 the Japanese company Denso, in collaboration with Gustav Lorentzen, developed an automobile air conditioner using CO_2 as a refrigerant. They demonstrated the invention at the June 1998 International Institute of Refrigeration/Gustav Lorentzen Conference. After the conference Denso were approached by CRIEPI (Central Research Institute of Electric Power Industry) and TEPCO (The Tokyo Electric Power Company) to develop a prototype air conditioner using natural refrigerant materials instead of Freon. Together they produced 30 prototype EcoCute units for a year-long experimental installation at locations throughout Japan, from the cold climate of Hokkaidō to hotter

Okinawa. After this successful feasibility study, Denso obtained a patent to compress CO_2 refrigerant for use in a heat pump from SINTEF in September 2000.

The first commercial domestic EcoCute was marketed in Japan by CORONA Corp. in May 2001, and several manufacturers sold 1.5 million units there by October, 2008.

FEPC reported 2 million units of EcoCute had been delivered by end of October 2009, and its equivalents CO_2 absorption is 9400 km² of forest.

Features and demand

In Japan in 1998, water heating (Kyuto (給湯 *kyūtō*)) accounted for 33.8% of typical domestic energy consumption, with air conditioner and kerosene heater heating accounting for another 26.9% and cooling by air conditioner another 2.3%. Most of the remaining 37% was spent on electrical home appliances, a field where 21st century innovations in energy conservation began to make considerable energy savings. This left hot water supply as the most difficult area for energy conservation, leaving a gap in the market for the EcoCute. By January 2005, 26 Japanese companies were producing more than 450 models of EcoCute machines, and sales of domestic units increased 130-150% each year between 2001 and 2005.

Denso first introduced the EcoCute outside Japan at the COP9 Milan, Italy on December 9, 2003. From 2007, Denso began concentrating on marketing the EcoCute in the EU. In Japan, the Japanese government incorporated the EcoCute into its CO_2 reduction program under the Kyoto Protocol, mandating the installation of 5.2 million units in commercial and domestic properties by 2010. The cost of EcoCute is approximately 500 thousand Japanese yen as of February - March 2009.

EcoCute machine basics

An EcoCute machine or system consists of a heat pump and hot water storage unit. The components are serially concatenated with sealing refrigerant CO_2 gas in circulation.

1. At the first stage, a heat exchanger collects heat from the air outside to use as energy for the refrigerant. Air flow is usually obtained using a centrifugal fan; in cold areas with ambient temperatures around -20 to -25 ℃ an auxiliary fan heater is attached.
2. A gas compressor is used to heat the gas CO_2 refrigerant to around 100℃ under pressure of 10MPa via adiabatic compression. The carbon dioxide becomes a supercritical fluid. Several types of compressor can be used, including dual layer cylindrical compressors, scroll compressors, and dual stage rotary compressors
3. At the second stage a heat exchanger transfers energy from the hot refrigerant into water to produce hot water. Water temperatures around 5℃ and up are suitable at this stage.

4. Finally, ejector or expansion valves reduce pressure on the refrigerant, letting it cool via adiabatic expansion and revert to CO_2 gas.

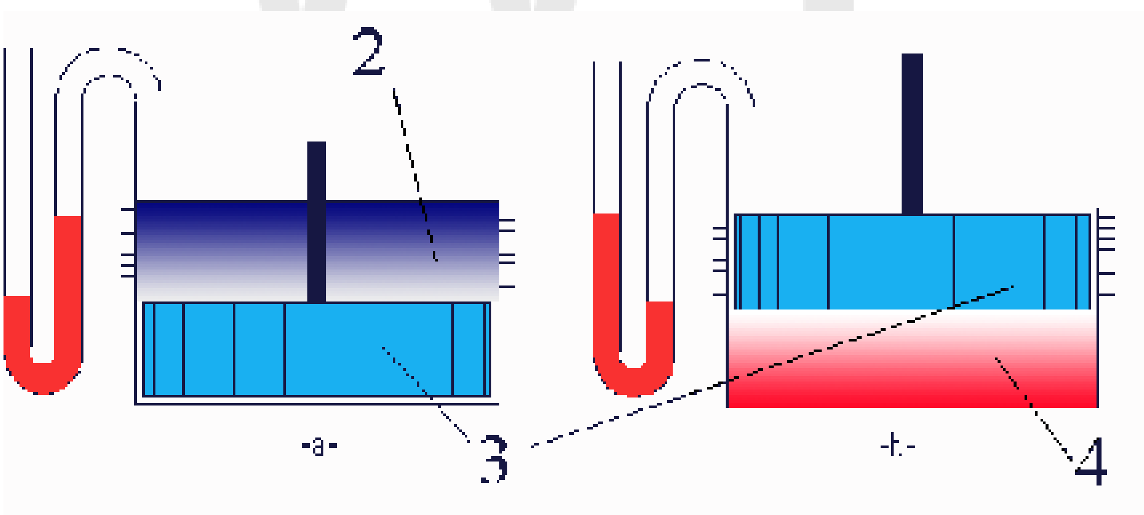
The EcoCute derives two units of energy from ambient air temperature for every unit of electrical power it requires. Each of these **one unit plus two cost free units** produces more than three units of hot water energy, resulting in reduced CO_2 emissions compared to water heating via electricity or town gas. To produce 90℃ hot water, an EcoCute consumes 66% less energy than an electric water heater, and costs 80% less than heating water via town gas in Japan. Also, by reducing use of fossil fuels, the EcoCute results in more than 50% reductions in CO_2 emissions

The EcoCute's COP is 3.8 in industrial use, while electric power water heating is 1.0, and gas boiler is 0.88 including pilot light loss.

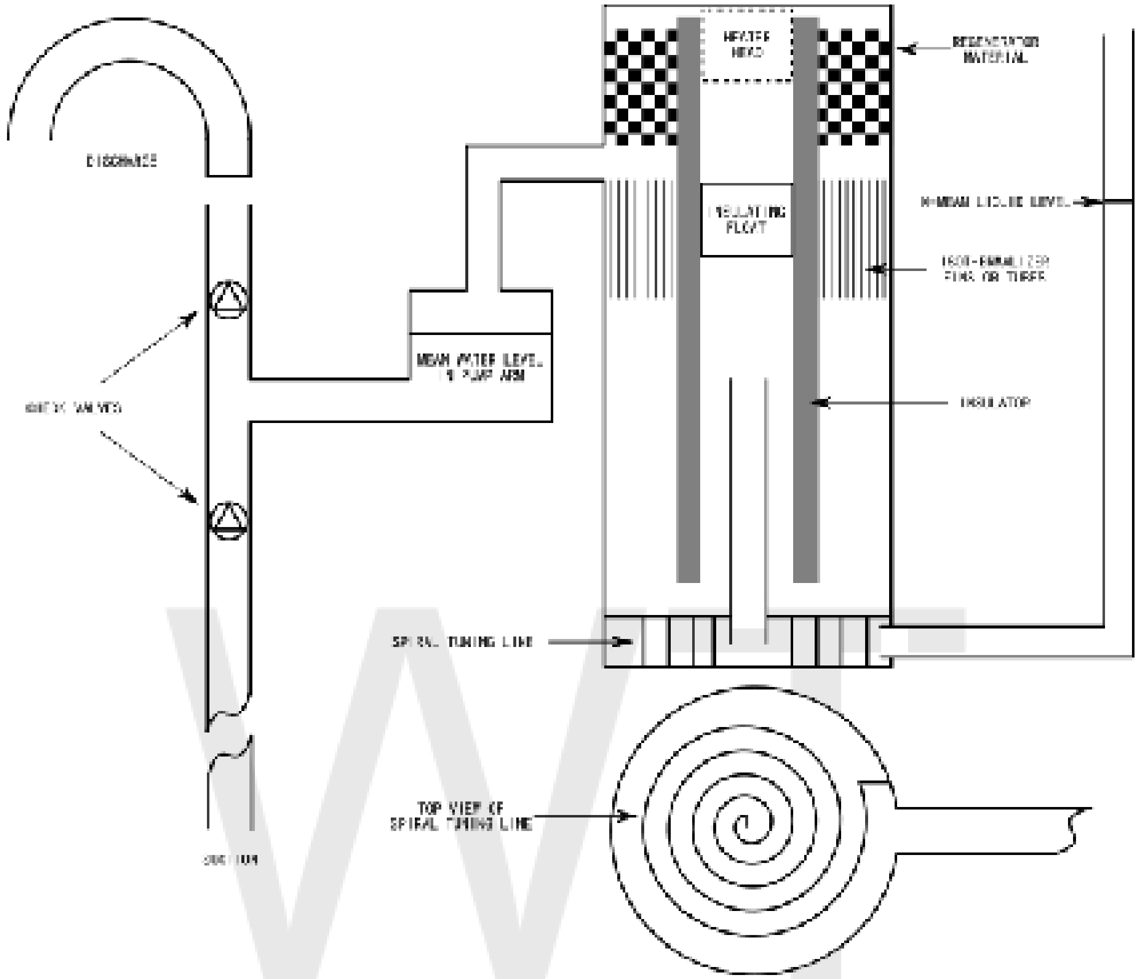
Others

EcoCute (エコキュート *ekokyūto*) is a registered trademark (No. 4575216 - Japan) of Kansai Electric Power Company, but the term is also used generically to refer to water heaters designed for energy conservation or greenhouse gas emission reduction.

Fluidyne Engine



This is a Fluidyne variant with a solid displacer piston (3). In figure -a-, as the displacer moves from the cold compression space (2), to the hot expansion space (4) in figure -b-, the temperature of the gaseous working fluid is increased. This increases the pressure of the gaseous working fluid, and as it expands, work is done on the (red) liquid piston as it is pushed through the tube.



A Concentric-cylinder Fluidyne Pumping engine

A **Fluidyne engine** is an alpha or gamma type Stirling engine with one or more liquid pistons. It contains a working gas (often air), and either two liquid pistons or one liquid piston and a displacer.

Engine operation

Working gas in the engine is heated, and this causes it to expand and push on the water column. This expansion cools the air which contracts, at the same time being pushed back by the weight of the displaced water column. Cycle then repeats.

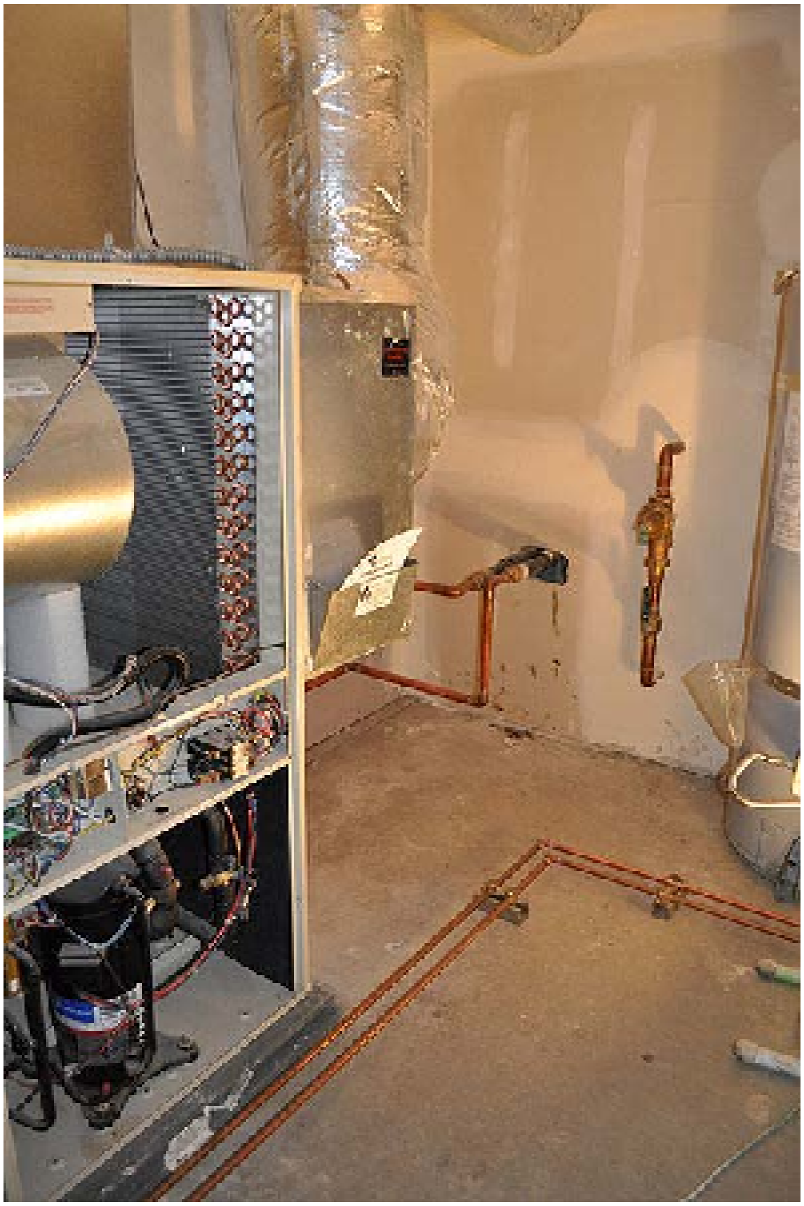
Engine as a pump

In the classic configuration, the work produced via the water pistons is integrated with a water pump. The simple pump is external to the engine, and consists of two check valves, one on the intake and one on the outlet. In the engine, the loop of oscillating liquid can be thought of as acting as a displacer piston. The liquid in the single tube extending to the pump acts as the power piston. Traditionally the pump is open to the atmosphere, and the hydraulic head is small, so that the absolute engine pressure is close to atmospheric pressure.

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

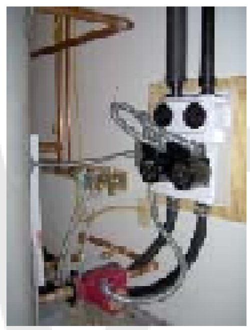
The Direct exchange geothermal heat pump is the oldest type of geothermal heat pump technology. It is also the simplest and easiest to understand. The ground-coupling is achieved through a single loop circulating refrigerant in direct thermal contact with the ground (as opposed to a combination of a 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.

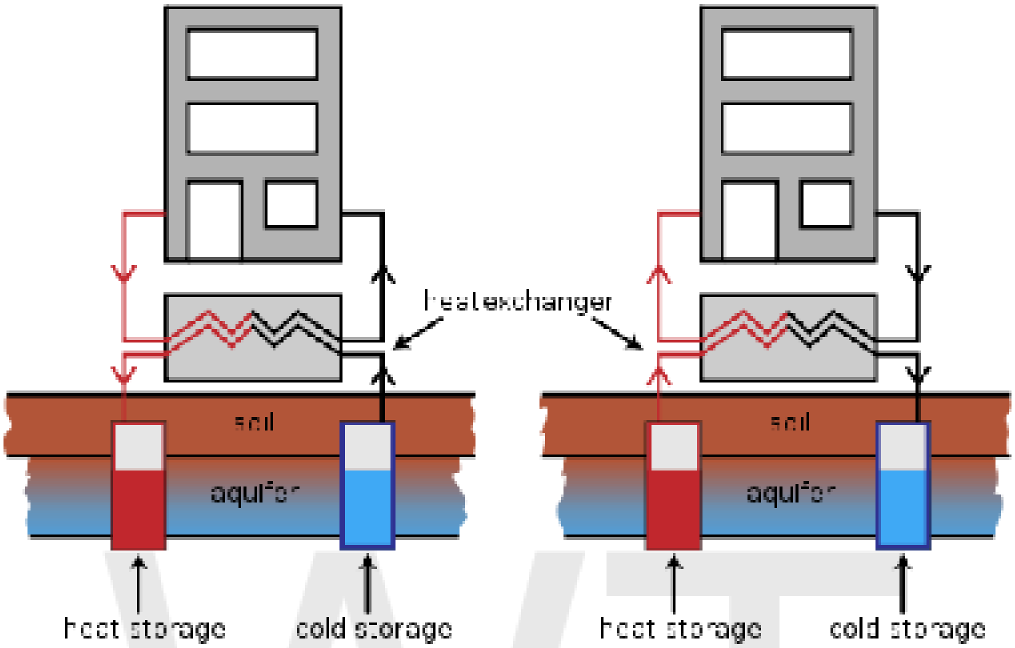
Liquid-to-water heat pump

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:

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

- 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

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.

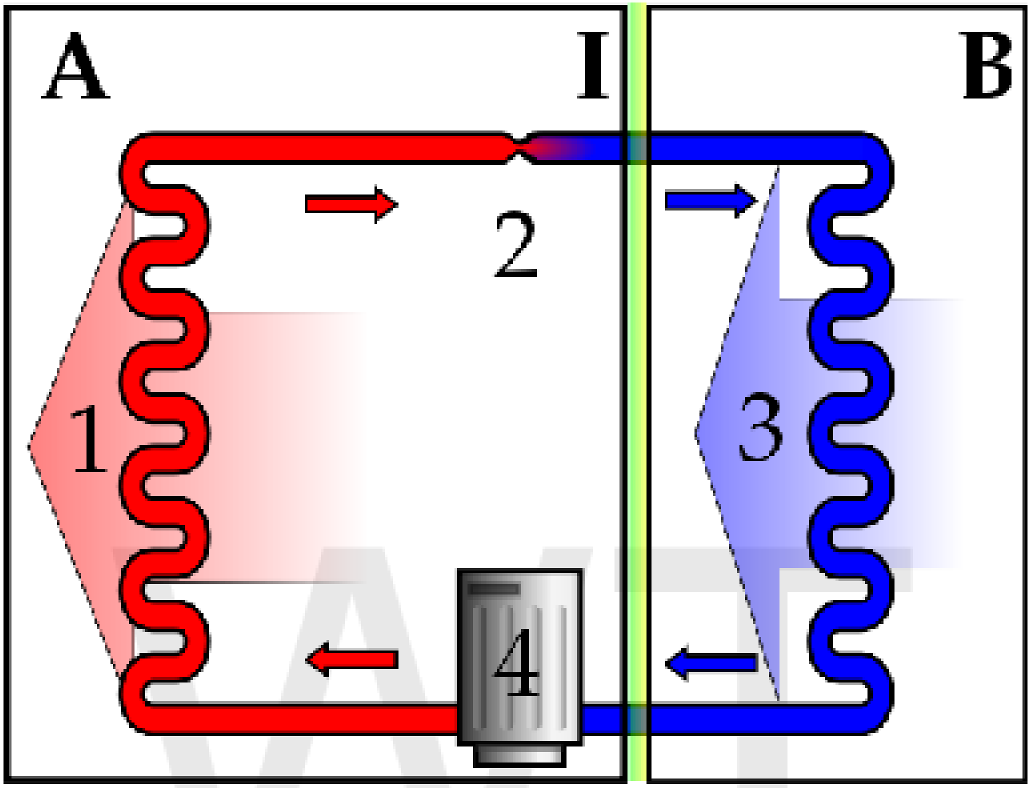
General

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 8

Geothermal Heating

Geothermal heating is the direct use of geothermal power for heating applications. Humans have taken advantage of geothermal heat this way since the Paleolithic era. Approximately seventy countries made direct use of a total of 270 PJ of geothermal heating in 2004. As of 2007, 28 GW of geothermal heating capacity is installed around the world, satisfying 0.07% of global primary energy consumption. Thermal efficiency is high since no energy conversion is needed, but capacity factors tend to be low (around 20%) since the heat is mostly needed in the winter.

Geothermal energy originates from the heat retained within the Earth since the original formation of the planet, from radioactive decay of minerals, and from solar energy absorbed at the surface. Most high temperature geothermal heat is harvested in regions close to tectonic plate boundaries where volcanic activity rises close to the surface of the Earth. In these areas, ground and groundwater can be found with temperatures higher than the target temperature of the application. However, even cold ground contains heat, below 10' or 3 Meters, the ground is consistently 12.8°C (55°F), and it may be extracted with a geothermal heat pump. Due to recent advances in heat pump performance, this is now a rapidly growing market in the US.

Briefly and Simply Explained

Geothermal heating relies on an energy exchange between the air within the building being heated and the ground. Below ten feet the earth's temperature is fairly constant, generally between ~10°C (~50°F). During the summer when the ambient temperature of the building exceeds that of the ground heat pumps are used to pump heat from the building in to the transfer medium (typically water with small amounts of ethanol or glycol) and is subsequently pumped through narrow pipes into the ground so that the heat can be dissipated in the earth. When the ambient temperature falls below the ground temperature the process works in reverse. Heat pumps extract heat from the ground and use it to heat the building.

Applications

Country	Production PJ/yr	Capacity GW	Capacity Factor	Dominant applications
China	45.38	3.69	39%	bathing
Sweden	43.2	4.2	33%	heat pumps
USA	31.24	7.82	13%	heat pumps
Turkey	24.84	1.5	53%	district heating
Iceland	24.5	1.84	42%	district heating
Japan	10.3	0.82	40%	bathing (onsens)
Hungary	7.94	0.69	36%	spas/greenhouses
Italy	7.55	0.61	39%	spas/space heating
New Zealand	7.09	0.31	73%	industrial uses
63 others	71	6.8		
Total	**273**	**28**	**31%**	**space heating**

Top countries using the most geothermal heating in 2005

There are a wide variety of applications for cheap geothermal heat. In 2004 more than half of direct geothermal heat was used for space heating, and a third was used for spas. The remainder was used for a variety of industrial processes, desalination, domestic hot water, and agricultural applications. The cities of Reykjavík and Akureyri pipe hot water from geothermal plants under roads and pavements to melt snow. Geothermal desalination has been demonstrated.

Geothermal systems tend to benefit from economies of scale, so space heating power is often distributed to multiple buildings, sometimes whole communities. This technique, long practiced throughout the world in locations such as Reykjavik, Iceland, Boise, Idaho, and Klamath Falls, Oregon is known as district heating.

Extraction

Some parts of the world, including substantial portions of the western USA, are underlain by relatively shallow geothermal resources. Similar conditions exist in Iceland, parts of Japan, and other geothermal hot spots around the world. In these areas, water or steam may be captured from natural hot springs and piped directly into radiators or heat exchangers. Alternatively, the heat may come from waste heat supplied by co-generation from a geothermal electrical plant or from deep wells into hot aquifers. Direct geothermal heating is far more efficient than geothermal electricity generation and has less demanding temperature requirements, so it is viable over a large geographical range. If the shallow ground is hot but dry, air or water may be circulated through earth tubes or downhole heat exchangers which act as heat exchangers with the ground.

In areas where the shallow ground is too cold to provide comfort directly, it is still warmer than the winter air. The thermal inertia of the shallow ground retains solar energy accumulated in the summertime, and seasonal variations in ground temperature disappear completely below 10m of depth. That heat can be extracted with a geothermal heat pump more efficiently than it can be generated by conventional furnaces. Geothermal heat pumps are economically viable essentially anywhere in the world. One geothermal district heating system at Drake Landing enhances storage of solar energy in the ground to such an extent that no heat pumps are needed.

Geothermal heat pumps

Even in regions without large high temperature geothermal resources, a geothermal heat pump can still provide space heating and air conditioning. Like a refrigerator or air conditioner, these systems use a heat pump to force the transfer of heat from the ground to the application. 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 or ground water (typically starting at 10–12 °C, 50–54 °F) as a source of heat, thus taking advantage of its seasonally moderate temperatures. In contrast, an air-source heat pump draws heat from the colder outside air and thus requires more energy.

Closed loop geothermal heat pumps circulate a carrier fluid (usually a water/antifreeze mix) through pipes buried in the ground. As the fluid circulates underground it absorbs heat from the ground and, on its return, the now warmer fluid passes through the heat pump which uses electricity to extract the heat from the fluid. The re-chilled fluid is sent back through the ground thus continuing the cycle. The heat extracted and that generated by the heat pump appliance as a byproduct is used to heat the house. The addition of the ground heating loop in the energy equation means that more heat is generated than if electricity alone had been used directly for heating. Switching the direction of heat flow, the same system can be used to circulate the cooled water through the house for cooling in the summer months. The heat is exhausted to the same relatively cool soil (or groundwater) rather than delivering it to the hot outside air as an air conditioner does. As a result, the heat is pumped across a smaller temperature difference and this leads to higher efficiency and lower energy use.

This technology makes geothermal heating economically viable in any geographical location. In 2004, an estimated million geothermal heat pumps with a total capacity of 15 GW extracted 88 PJ of geothermal energy for space heating. Global geothermal heat pump capacity is growing by 10% annually.

History

The oldest known pool fed by a hot spring, built in the Qin dynasty in the 3rd century BC.

Hot springs have been used for bathing at least since Paleolithic times. The oldest known spa is a stone pool on China's Lisan mountain built in the Qin dynasty in the 3rd century BC, at the same site where the Huaqing Chi palace was later built. In the first century AD, Romans conquered Aquae Sulis and used the hot springs there to feed public baths and underfloor heating. The admission fees for these baths probably represents the first commercial use of geothermal power. The world's oldest geothermal district heating system in Chaudes-Aigues, France, has been operating since the 14th century. The earliest industrial exploitation began in 1827 with the use of geyser steam to extract boric acid from volcanic mud in Larderello, Italy.

In 1892, America's first district heating system in Boise, Idaho was powered directly by geothermal energy, and was soon copied in Klamath Falls, Oregon in 1900. A deep geothermal well was used to heat greenhouses in Boise in 1926, and geysers were used to heat greenhouses in Iceland and Tuscany at about the same time. Charlie Lieb developed the first downhole heat exchanger in 1930 to heat his house. Steam and hot water from the geysers began to be used to heat homes in Iceland in 1943.

By this time, Lord Kelvin had already invented the heat pump in 1852, and Heinrich Zoelly had patented the idea of using it to draw heat from the ground in 1912. But it was not until the late 1940s that the geothermal heat pump was successfully implemented. The earliest one was probably Robert C. Webber's home-made 2.2 kW direct-exchange system, but sources disagree as to the exact timeline of his invention. J. Donald Kroeker designed the first commercial geothermal heat pump to heat the Commonwealth Building (Portland, Oregon) and demonstrated it in 1946. Professor Carl Nielsen of Ohio State University built the first residential open loop version in his home in 1948. The technology became popular in Sweden as a result of the 1973 oil crisis, and has been growing slowly in worldwide acceptance since then. The 1979 development of polybutylene pipe greatly augmented the heat pump’s economic viability. As of 2004, there are over a million geothermal heat pumps installed worldwide providing 12 GW of thermal capacity. Each year, about 80,000 units are installed in the USA and 27,000 in Sweden.

Economics

Geothermal drill machine.

Geothermal energy is a type of renewable energy that encourages conservation of natural resources. According to the U.S. Environmental Protection Agency, geo-exchange systems save homeowners 30-70 percent in heating costs, and 20-50 percent in cooling costs, compared to conventional systems. Geo-exchange systems also save money because they require much less maintenance. In addition to being highly reliable they are built to last for decades.

Some utilities, such as Kansas City Power and Light, offer special, lower winter rates for geothermal customers, offering even more savings.

Subsidence

In geothermal heating projects the underground is penetrated by trenches or drillholes. Large projects may cause problems if the geology of the area is poorly understood as with all underground work. In connection with a geothermal heating project for the historical city hall of Staufen im Breisgau, Germany, subsidence of the ground up to eight millimeters has occurred while other areas have been uplifted by a few millimeters. A relation to the geothermal wells is suspected. The subsidence has caused considerable damage to buildings in the city center.

Chapter 9

Vapor-Compression Refrigeration

Vapor-compression refrigeration is one of the many refrigeration cycles available for use. It has been and is the most widely used method for air-conditioning of large public buildings, offices, private residences, hotels, hospitals, theaters, restaurants and automobiles. It is also used in domestic and commercial refrigerators, large-scale warehouses for chilled or frozen storage of foods and meats, refrigerated trucks and railroad cars, and a host of other commercial and industrial services. Oil refineries, petrochemical and chemical processing plants, and natural gas processing plants are among the many types of industrial plants that often utilize large vapor-compression refrigeration systems.

Refrigeration may be defined as lowering the temperature of an enclosed space by removing heat from that space and transferring it elsewhere. A device that performs this function may also be called a *heat pump*.

Description of the vapor-compression refrigeration system

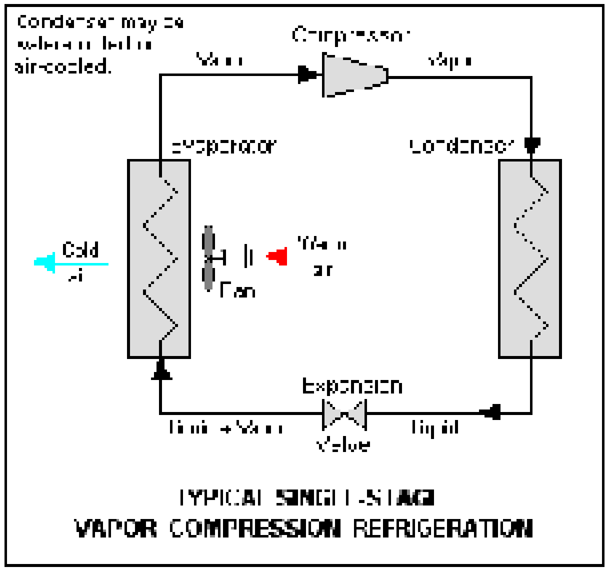


Figure 1: Vapor compression refrigeration

The vapor-compression uses a circulating liquid refrigerant as the medium which absorbs and removes heat from the space to be cooled and subsequently rejects that heat elsewhere. Figure 1 depicts a typical, single-stage vapor-compression system. All such systems have four components: a compressor, a condenser, a Thermal expansion valve (also called a throttle valve), and an evaporator. Circulating refrigerant enters the compressor in the thermodynamic state known as a saturated vapor and is compressed to a higher pressure, resulting in a higher temperature as well. The hot, compressed vapor is then in the thermodynamic state known as a superheated vapor and it is at a temperature and pressure at which it can be condensed with typically available cooling water or cooling air. That hot vapor is routed through a condenser where it is cooled and condensed into a liquid by flowing through a coil or tubes with cool water or cool air flowing across the coil or tubes. This is where the circulating refrigerant rejects heat from the system and the rejected heat is carried away by either the water or the air (whichever may be the case).

The condensed liquid refrigerant, in the thermodynamic state known as a saturated liquid, is next routed through an expansion valve where it undergoes an abrupt reduction in pressure. That pressure reduction results in the adiabatic flash evaporation of a part of the liquid refrigerant. The auto-refrigeration effect of the adiabatic flash evaporation lowers the temperature of the liquid and vapor refrigerant mixture to where it is colder than the temperature of the enclosed space to be refrigerated.

The cold mixture is then routed through the coil or tubes in the evaporator. A fan circulates the warm air in the enclosed space across the coil or tubes carrying the cold refrigerant liquid and vapor mixture. That warm air evaporates the liquid part of the cold refrigerant mixture. At the same time, the circulating air is cooled and thus lowers the temperature of the enclosed space to the desired temperature. The evaporator is where the circulating refrigerant absorbs and removes heat which is subsequently rejected in the condenser and transferred elsewhere by the water or air used in the condenser.

To complete the refrigeration cycle, the refrigerant vapor from the evaporator is again a saturated vapor and is routed back into the compressor.

Refrigerants

"Freon" is a trade name for a family of haloalkane refrigerants manufactured by DuPont and other companies. These refrigerants were commonly used due to their superior stability and safety properties: they were not flammable nor obviously toxic as were the fluids they replaced, such as sulfur dioxide. Unfortunately, these chlorine-bearing refrigerants reach the upper atmosphere when they escape. In the stratosphere, CFCs break up due to UV-radiation, releasing their chlorine atoms. These chlorine atoms act as catalysts in the breakdown of ozone, thus causing severe damage to the ozone layer that shields the Earth's surface from the Sun's strong UV radiation. The chlorine will remain active as a catalyst until and unless it binds with another particle, forming a stable molecule. CFC refrigerants in common but receding usage include R-11 and R-12. Newer refrigerants that have reduced ozone depletion effect include HCFCs (R-22, used in most homes today) and HFCs (R-134a, used in most cars) have replaced most CFC use. HCFCs in turn are being phased out under the Montreal Protocol and replaced by hydrofluorocarbons (HFCs), such as R-410A, which lack chlorine. However, CFCs, HCFCs, and HFCs all have large global warming potential.

Newer refrigerants are currently the subject of research, such as supercritical carbon dioxide, known as R-744. These have similar efficiencies compared to existing CFC and HFC based compounds, and have many orders of magnitude lower **global warming potential**.

Thermodynamic analysis of the system

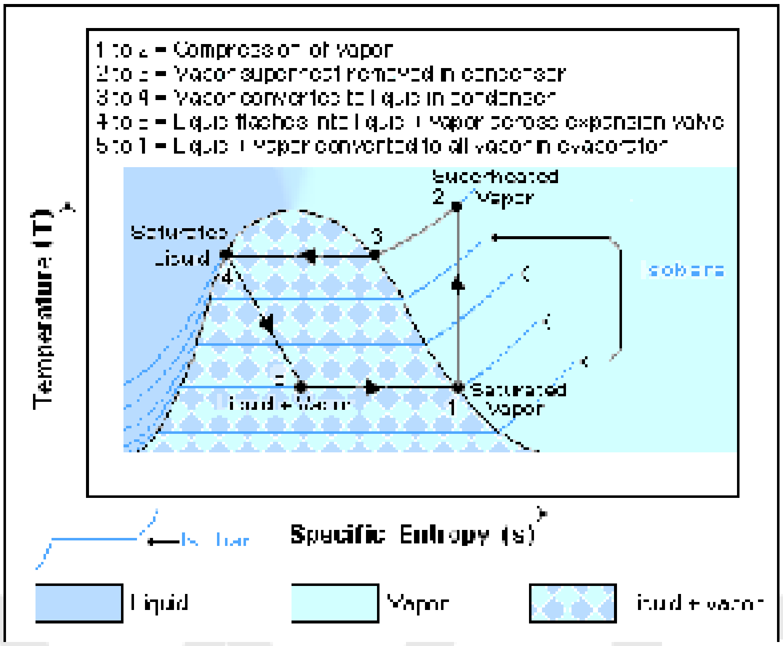


Figure 2: Temperature–Entropy diagram

Types of gas compressors

The most common compressors used in chillers are reciprocating, rotary screw, centrifugal, and scroll compressors. Each application prefers one or another due to size, noise, efficiency and pressure issues. Compressors are often described as being either open, hermetic, or semi-hermetic, to describe how the compressor and/or motor is situated in relation to the refrigerant being compressed. Variations of motor/compressor types can lead to the following configuations:

- Hermetic motor, hermetic compressor
- Hermetic motor, semi-hermetic compressor
- Open motor (belt driven or close coupled), hermetic compressor
- Open motor (belt driven or close coupled), semi-hermetic compressor

Typically in hermetic, and most semi-hermetic compressors (sometimes known as accessible hermetic compressors), the compressor and motor driving the compressor are integrated, and operate within the refrigerant system. The motor is hermetic and is designed to operate, and be cooled by, the refrigerant being compressed. The obvious disadvantage of hermetic motor compressors is that the motor drive cannot be maintained in situ, and the entire compressor must be removed if a motor fails. A further disadvantage is that burnt out windings can contaminate whole refrigeration systems requiring the system to be entirely pumped down and the refrigerant replaced.

An open compressor has a motor drive which is outside of the refrigeration system, and provides drive to the compressor by means of an input shaft with suitable gland seals.

Open compressor motors are typically air cooled and can be fairly easily exchanged or repaired without degassing of the refrigeration system. The disadvantage of this type of compressor is a failure of the shaft seals, leading to loss of refrigerant.

Open motor compressors are generally easier to cool (using ambient air) and therefore tend to be simpler in design and more reliable, especially in high pressure applications where compressed gas temperatures can be very high. However the use of liquid injection for additional cooling can generally overcome this issue in most hermetic motor compressors.

Reciprocating compressors

Reciprocating compressors are piston-style, positive displacement compressors.

Rotary screw compressors

Figure 3: Screw Compressors

Rotary screw compressors are also positive displacement compressors. Two meshing screw-rotors rotate in opposite directions, trapping refrigerant vapor, and reducing the volume of the refrigerant along the rotors to the discharge point.

Centrifugal compressors

Centrifugal compressors are dynamic compressors. These compressors raise the pressure of the refrigerant by imparting velocity or dynamic energy, using a rotating impeller, and converting it to pressure energy.

Scroll compressors

Figure 4: Operating principle of a Scroll Compressor

Scroll compressors are also positive displacement compressors. The refrigerant is compressed when one spiral orbits around a second stationary spiral, creating smaller and smaller pockets and higher pressures. By the time the refrigerant is discharged, it is fully pressurized.

Compressor Lubrication

In order to lubricate the moving parts of the compressor, an oil is added to the refrigerant during installation or commissioning. The type of oil may be mineral or synthetic to suit the compressor type, and also chosen so as not to react with the refrigerant type and other components in the system. In small refrigeration systems the oil is allowed to circulate throughout the whole circuit, but care must be taken to design the pipework and components such that oil can drain back under gravity to the compressor. In larger more distributed systems, especially in retail refrigeration, then oil is normally captured at an oil separator immediately after the compressor, and is in turn re-delivered, by an oil level management system, back to the compressor(s). Oil separators are not 100% efficient so system pipework must still be designed so that oil can drain back by gravity to the oil separator or compressor.

Some newer compressor technologies use magnetic bearings and require no lubrication, for example the Danfoss Turbocor range of centrifugal compressors. Avoiding the need for oil lubrication and the design requirements and ancillaries associated with it, simplifies the design of the refrigerant system and reduces maintenance requirements.

Control

In simple commercial refrigeration systems the compressor is normally controlled by a simple pressure switch, with the expansion performed by a capillary tube or simple thermostatic expansion valve. In more complex systems, including multiple compressor installations, the use of electronic controls is typical, with adjustable set points to control the pressure at which compressors cut in and cut out, and temperature control by the use of electronic expansion valves.

In addition to the operational controls, separate high pressure and low pressure switches are normally utilised to provide secondary protection to the compressors and other components of the system from operating outside of safe parameters.

In more advanced electronic control systems the use of floating head pressure, and proactive suction pressure, control routines allow the compressor operation to be adjusted to accurately meet differing cooling demands whilst reducing energy consumption.

Other features and facts of interest

The schematic diagram of a single-stage refrigeration system shown in Figure 1 does not include other equipment items that would be provided in a large commercial or industrial vapor compression refrigeration system, such as:

- A horizontal or vertical pressure vessel, equipped internally with a demister, between the evaporator and the compressor inlet to capture and remove any residual, entrained liquid in the refrigerant vapor because liquid may damage the compressor. Such vapor-liquid separators are most often referred to as "suction line accumulators". (In other industrial processes, they are called "compressor suction drums" or "knockout drums".)

- Large commercial or industrial refrigeration systems may have multiple expansion valves and multiple evaporators in order to refrigerate multiple enclosed spaces or rooms. In such systems, the condensed liquid refrigerant may be routed into a pressure vessel, called a receiver, from which liquid refrigerant is withdrawn and routed through multiple pipelines to the multiple expansion valves and evaporators.

- Filter Dryers, installed before the compressors to catch any moisture or contaminents in the system and thus protect the compressors from internal damage

- Some refrigeration units may have multiple stages which requires the use of multiple compressors in various arrangements.

The cooling capacity of refrigeration systems is often defined in units called "tons of refrigeration". The most common definition of that unit is: 1 ton of refrigeration is the rate of heat removal required to freeze a short ton (i.e., 2000 pounds) of water at 32 °F in 24 hours. Based on the heat of fusion for water being 144 Btu per pound, 1 ton of refrigeration = 12,000 Btu/h = 12,660 kJ/h = 3.517 kW. Most residential air conditioning units range in capacity from about 1 to 5 tons of refrigeration.

A much less common definition is: 1 tonne of refrigeration is the rate of heat removal required to freeze a metric ton (i.e., 1000 kg) of water at 0 °C in 24 hours. Based on the heat of fusion being 334.9 kJ/kg, 1 tonne of refrigeration = 13,954 kJ/h = 3.876 kW. As can be seen, 1 tonne of refrigeration is 10 percent larger than 1 ton of refrigeration.

Applications

Refrigeration application	Short descriptions	Typical refrigerants used
Domestic refrigeration	Appliances used for keeping food in dwelling units	R-600a, R-134a
Commercial refrigeration	Holding and displaying frozen and fresh food in retail outlets	R-134a, R-404A, R-507
Food processing and cold storage	Equipment to preserve, process and store food from its source to the wholesale distribution point	R-134a, R-407C, R-410A, R-507
Industrial refrigeration	Large equipment, typically 25 kW to 30 MW, used for chemical processing, cold storage, food processing, building and district heating and cooling	R-134a, R-404A, R-407C, R-507, R-717
Transport refrigeration	Equipment to preserve and store goods, primarily foodstuffs, during transport by road, rail, air and sea	R-134a, R-407C, R-410A
Electronic cooling	Low-temperature cooling of CMOS circuitry and other components in large computers and servers	R-134a, R-404A, R-507
Medical refrigeration		R-134a, R-404A, R-507
Cryogenic refrigeration		Ethylene, Helium

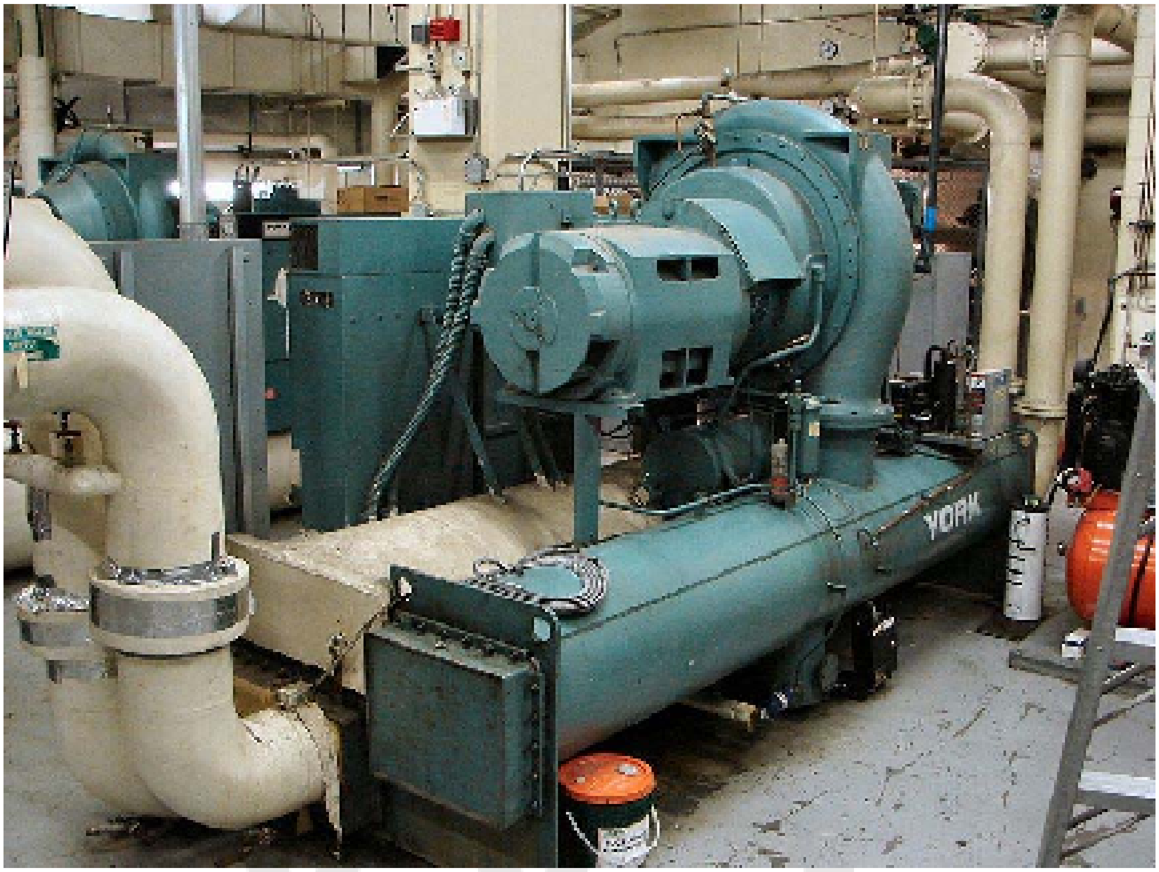


Figure 5: Commercial water cooled liquid chiller installation for building air conditioning

Economic analysis

Advantages

- Very mature technology.
- Relatively inexpensive.
- Can be driven directly using mechanical energy (water, car/truck motor) or with electrical energy.
- Efficient up to 60% of Carnot's theoretical limit (as evaluated in ASHRAE testing conditions: evaporation temperature of -23.3 °C, condensing temperature of 54.4°C, and ambient temperature of 32°C) based on some of the best compressors produced by Danfoss, Matsushita, Copeland, Embraco, Bristol and Tecumseh compressor manufacturers. However, many refrigeration systems use compressors having lower efficiencies of between 40-55%, since the 60% efficient ones cost almost twice as much as the lower efficiency ones.

Disadvantages

Many systems still use HCFC refrigerants, which contribute to depletion of the Earth's ozone layer. In countries adhering to the Montreal Protocol, HCFCs are due to be phased out and are largely being replaced by ozone-friendly HFCs. However, systems using HFC refrigerants tend to be slightly less efficient than systems using HCFCs. HFCs also have an extremely large global warming potential (GWP) because they remain in the atmosphere for many years and trap heat more effectively than carbon dioxide.

With disruption of the status quo already a certainty, alternative non-haloalkane refrigerants are gaining popularity. In particular, once-abandoned refrigerants such as hydrocarbons (HCs, such as butane) and CO_2 are coming back into broader use. For example, Coca-Cola's vending machines at the 2006 FIFA World Cup in Germany used refrigeration utilizing CO_2

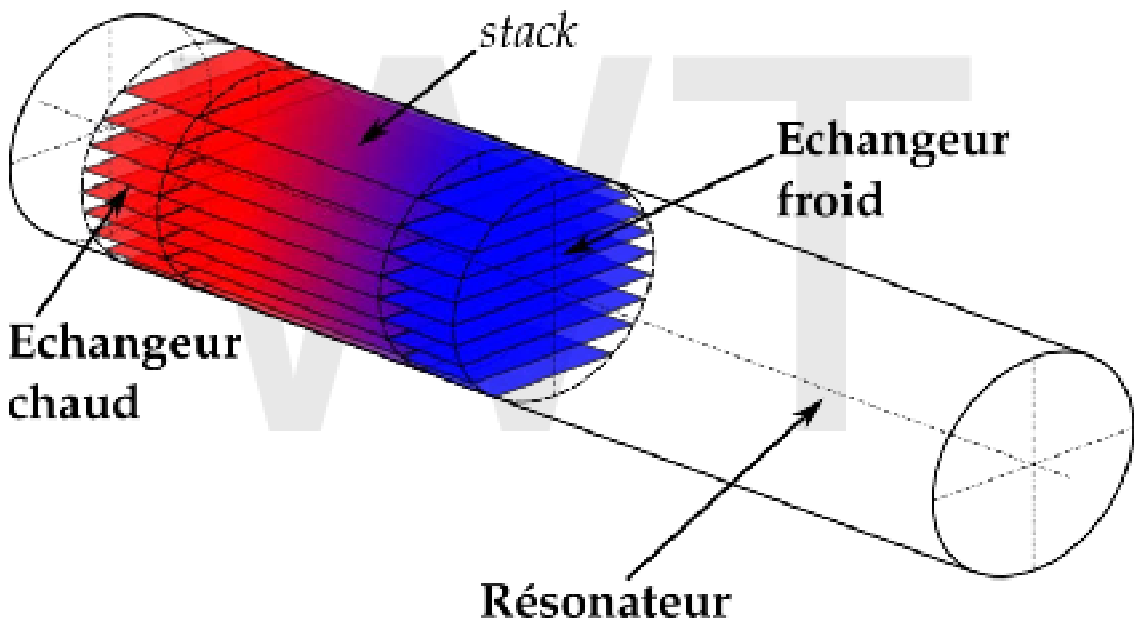
History

Jacob Perkins received a patent for the first refrigeration machine in 1836 using the vapor-compression cycle, based on an 1834 machine he built. Perkins had improved upon the design of Oliver Evans, who conceived of the idea in 1805 but never built a refrigerator. John Gorrie received US patent 8,080 in 1851 for work he began in 1845 on ice machines.

Alexander Twining received a patent in 1853 for an ice maker, US Patent 10221. James Harrison of Australia received a patent in 1855 for an ice maker. Both inventors used ether as the working fluid in their vapor-compression refrigeration cycle, but Harrison was the first to develop a practical refrigeration system which could be used in the brewing and meat-packing industries in Geelong, Victoria.

Chapter 10

Thermoacoustic Hot Air Engine



A schematic representation of a thermoacoustic hot air engine. *Echangeur chaud* is French for the heat exchanger (heat bridge not shown) that conducts heat to or from a hot heat reservoir - and *Echangeur froid* is French for the heat exchanger (cold bridge not shown) that conducts heat to or from a cold heat reservoir. The acoustic-electric transducer, e.g. a loudspeaker, is not shown.

Thermoacoustic engines are thermoacoustic devices which use high-amplitude sound waves to pump heat from one place to another, or use a heat difference to induce high-amplitude sound waves. In general, thermoacoustic engines can be divided in standing wave and travelling wave devices. These two types of thermoacoustics devices can again be divided in two thermodynamic classes, a prime mover (or simply heat engine), and a heat pump. The prime mover creates work using heat and a heat pump creates or moves heat using work.

Operation

Overview of device

A thermoacoustic device basically consists of heat exchangers, a resonator, and a stack (on standing wave devices) or regenerator (on travelling wave devices). Depending on the type of engine a driver or loudspeaker might be used as well to generate sound waves.

Consider a tube closed at both ends. Interference can occur between two waves traveling in opposite directions at certain frequencies. The interference causes resonance creating a standing wave. Resonance only occurs at certain frequencies called resonance frequencies, and these are mainly determined by the length of the resonator.

The stack is a part consisting of small parallel channels. When the stack is placed at a certain location in the resonator, while having a standing wave in the resonator, a temperature difference can be measured across the stack. By placing heat exchangers at each side of the stack, heat can be moved. The opposite is possible as well, by creating a temperature difference across the stack, a sound wave can be induced. The first example is a simple heat pump, while the second is a prime mover.

Heat pumping

To be able to create or move heat, work must be done, and the acoustic power provides this work. When a stack is placed inside a resonator a pressure drop occurs. Interference between the incoming and reflected wave is now imperfect since there is a difference in amplitude causing the standing wave to travel little, giving the wave acoustic power.

When looking at the acoustic wave, parcels of gas are adiabatic compressed and decompressed. Pressure and temperature change simultaneously; when pressure reaches a maximum or minimum, so does the temperature. Heat pumping along a stack in a standing wave device can now be described using the Brayton cycle.

Below is the counter-clockwise Brayton cycle consisting of four processes for a refrigerator when a parcel of gas is followed between two plates of a stack.

1. *Adiabatic compression of the gas.* When a parcel of gas is displaced from its rightmost position to its leftmost position, the parcel is adiabatic compressed and thus the temperature increases. At the leftmost position the parcel now has a higher temperature than the warm plate.
2. *Isobaric heat transfer.* The parcels temperature is higher than that of the plate causing it to transfer heat to the plate at constant pressure losing temperature.
3. *Adiabatic expansion of the gas.* The gas is displaced back from the leftmost position to the rightmost position and due to adiabatic expansion the gas is cooled to a temperature lower than that of the cold plate.

4. *Isobaric heat transfer*. The parcels temperature is now lower than that of the plate causing heat to be transferred from the cold plate to the gas at a constant pressure, increasing the parcels temperature back to its original value.

Travelling wave devices can be described using the Stirling cycle.

Temperature gradient

A prime mover and heat pump both typically use a stack and heat exchangers. The boundary between a prime mover and heat pump is given by the temperature gradient operator, which is the mean temperature gradient divided by the critical temperature gradient.

$$I \quad \frac{\nabla T_m}{\nabla T_{crit}}$$

The mean temperature gradient is the temperature difference across the stack divided by the length of the stack.

$$\nabla T_m = \frac{\Delta T_m}{\Delta x_{stack}}$$

The critical temperature gradient is a value depending on certain characteristics of the device like frequency, cross-sectional area and gas properties.

If the temperature gradient operator exceeds one, the mean temperature gradient is larger than the critical temperature gradient and the stack operates as a prime mover. If the temperature gradient operator is less than one, the mean temperature gradient is smaller than the critical gradient and the stack operates as a heat pump.

Efficiency

In thermodynamics the highest achievable efficiency is the Carnot efficiency. The efficiency of thermoacoustic engines can be compared to Carnot efficiency using the temperature gradient operator.

The efficiency of a thermoacoustic prime mover is given by

$$\eta = \frac{\eta_c}{1}$$

The coefficient of performance of a thermoacoustic heat pump is given by

$$COP = 1 \cdot COP_c$$

Derivations

Using the Navier-Stokes equations for fluids, Rott was able to derive equations specific for thermoacoustics. Swift continued with these equations, deriving expressions for the acoustic power in thermoacoustic devices.

Efficiency

The *most* efficient thermoacoustic devices built to date have an efficiency approaching 40% of the Carnot limit, or about 20% to 30% overall (depending on the heat engine temperatures). The efficiency of high-end TA engine is comparable with an average internal combustion engine, or with low-end domestic vapor compression systems (a high-end compressor by itself will yield efficiencies of up to 65% for the compression process alone, however the overall cycle efficiency will be much less, due to the Carnot limit).

Higher hot-end temperatures may be possible with thermoacoustic devices because there are no moving parts, thus allowing the Carnot efficiency to be higher. This may partially offset their lower efficiency, compared to conventional heat engines, as a percentage of Carnot, thus yielding overall efficiencies similar to conventional heat engines.

"...the engine's 30% [absolute] efficiency and high reliability may make medium-sized natural-gas liquefaction plants (with a capacity of up to a million gallons per day) and residential cogeneration economically feasible..."

Advantages

Thermoacoustic device have several advantages. Compared to vapor refrigerators, thermoacoustic refrigerators have no ozone-depleting or toxic coolant and few or no moving parts. Thermoacoustic devices consist of very simple and easy to manufacture parts as well.

Research in thermoacoustics

Modern research and development of thermoacoustic systems is largely based upon the work of Rott (1980) and later Steven Garrett, and Greg Swift (1988), in which linear thermoacoustic models were developed to form a basic quantitative understanding, and numeric models for computation. Commercial interest has resulted in niche applications such as small to medium scale cryogenic applications. The technology is also suitable for air-conditioning for homes, commercial buildings, vehicles and other cooling and heating applications.

Historical

The history of thermoacoustic hot air engines start about 1887, where Lord Rayleigh discusses the possibility of pumping heat with sound. Little further research occurred until Rott's work in 1969.

A very simple thermoacoustic hot air engine is the Rijke tube invented/discovered by Pieter Rijke, that converts heat into acoustic energy. This device however uses natural convection.

An older thermoacoustic hot air engine, where the speaker is replaced by a working piston, is the *Laminar Flow engine* or Laminar Flow Beta Stirling engine

Current research

Orest Symko began a research project in 2005 called *Thermal Acoustic Piezo Energy Conversion* (TAPEC). The research group has built several prototypes, including a ring-shaped model designed by student Ivan Rodriguez that currently has the highest efficiency.

The development of a combined electrical generator, refrigerator based on two coupled thermoacoustic Stirling engines, has recently been disclosed. The name is *SCORE* (*Stove for Cooking, Refrigeration and Electricity*). Score was awarded £2M in March 2007 to research a cooking Stove that will produce electricity and cooling using the Thermo-acoustic effect for use in developing countries.

Q-Drive is also engaged in developing thermoacoustic devices for refrigeration.

Cool Sound Industries, Inc. is developing an air-conditioning system that uses thermoacoustic techology. The unit has No freon and No compressor.

Chapter 11

Applications of the Stirling Engine

Applications of the Stirling engine range from heating and cooling to underwater power systems. A Stirling engine is a heat engine operating by cyclic compression and expansion of air or other gas, the "working fluid", at different temperature levels such that there is a net conversion of heat energy to mechanical work.

Heating and cooling

If supplied with mechanical power, a Stirling engine can function in reverse as a heat pump for heating or cooling. Experiments have been performed using wind power driving a Stirling cycle heat pump for domestic heating and air conditioning. In the late 1930s, the Philips Corporation of the Netherlands successfully utilized the Stirling cycle in cryogenic applications.

Combined heat and power

Thermal power stations on the electric grid use fuel to produce electricity, however there are large quantities of waste heat produced which often go unused. In other situations, high-grade fuel is burned at high temperature for a low temperature application. According to the second law of thermodynamics, a heat engine can generate power from this temperature difference. In a CHP system, the high temperature primary heat enters the Stirling engine heater, then some of the energy is converted to mechanical power in the engine, and the rest passes through to the cooler, where it exits at a low temperature. The "waste" heat actually comes from engine's main *cooler*, and possibly from other sources such as the exhaust of the burner, if there is one.

In a combined heat and power (CHP) system, mechanical or electrical power is generated in the usual way, however, the waste heat given off by the engine is used to supply a secondary heating application. This can be virtually anything that uses low temperature heat. It is often a pre-existing energy use, such as commercial space heating, residential water heating, or an industrial process.

The power produced by the engine can be used to run an industrial or agricultural process, which in turn creates biomass waste refuse that can be used as free fuel for the engine, thus reducing waste removal costs. The overall process can be efficient and cost effective.

Disenco, a UK based company are going through the final stages of development of their HomePowerPlant. Unlike other m-CHP appliances coming to market the HPP generates 3 kW of electrical and 15 kW of thermal energy, making this appliance suitable for both the domestic and SME markets.

WhisperGen, a New Zealand firm with offices in Christchurch, has developed an "AC Micro Combined Heat and Power" Stirling cycle engine. These microCHP units are gas-fired central heating boilers which sell unused power back into the electricity grid. WhisperGen announced in 2004 that they were producing 80,000 units for the residential market in the United Kingdom. A 20 unit trial in Germany started in 2006.

Solar power generation

Placed at the focus of a parabolic mirror a Stirling engine can convert solar energy to electricity with an efficiency better than non-concentrated photovoltaic cells, and comparable to Concentrated Photo Voltaics. On August 11, 2005, Southern California Edison announced an agreement with Stirling Energy Systems to purchase electricity created using over 30,000 Solar Powered Stirling Engines over a twenty year period sufficient to generate 850 MW of electricity. These systems, on an 8,000 acre (19 km^2) solar farm will use mirrors to direct and concentrate sunlight onto the engines which will in turn drive generators. "In January, 2010, four months after breaking ground, Stirling Energy partner company Tessara Solar completed the 1.5 MW Maricopa Solar power plant in Peoria, Arizona, just outside Phoenix. The power plant is comprised of 60 SES SunCatchers." The SunCatcher is described as "a large, tracking, concentrating solar power (CSP) dish collector that generates 25 kilowatts (kW) of electricity in full sun. Each of the 38-foot-diameter collectors contains over 300 curved mirrors (heliostats) that focus sunlight onto a power conversion unit, which contains the Stirling engine. The dish uses dual-axis tracking to follow the sun precisely as it moves across the sky." There have been disputes over the project due to concerns of environmental impact on animals living on the site.

Stirling cryocoolers

Any Stirling engine will also work in reverse as a heat pump; when a motion is applied to the shaft, a temperature difference appears between the reservoirs. The essential mechanical components of a Stirling cryocooler are identical to a Stirling engine. In both the engine and the heat pump, heat flows from the expansion space to the compression space; however, input work is required in order for heat to flow against a thermal gradient, specifically when the compression space is hotter than the expansion space. The external side of the expansion-space heat exchanger may be placed inside a thermally insulated compartment such as a vacuum flask. Heat is in effect pumped out of this compartment, through the working gas of the cryocooler and into the compression space. The compression space will be above ambient temperature, and so heat will flow out into the environment.

One of their modern uses is in cryogenics, and to a lesser extent, refrigeration. At typical refrigeration temperatures, Stirling coolers are generally not economically competitive with the less expensive mainstream Rankine cooling systems, because they are less energy efficient. However, below about −40° to −30 °C, Rankine cooling is not effective because there are no suitable refrigerants with boiling points this low. Stirling cryocoolers are able to "lift" heat down to −200 °C (73 K), which is sufficient to liquefy air (oxygen, nitrogen and argon). They can go as low as 40–60 K, depending on the particular design. Cryocoolers for this purpose are more or less competitive with other cryocooler technologies. The coefficient of performance at cryogenic temperatures is typically 0.04–0.05 (corresponding to a 4–5% efficiency). Empirically, the devices show a linear trend, where typically the $COP = 0.0015 \times T_c - 0.065$, where T_c is the cryogenic temperature. At these temperatures, solid materials have lower values for specific heat, so the regenerator must be made out of unexpected materials, such as cotton.

The first Stirling cycle cryocooler was developed at Philips in the 1950s and commercialized in such places as liquid air production plants. The Philips Cryogenics business evolved until it was split off in 1990 to form the Stirling Cryogenics BV, The Netherlands. This company is still active in the development and manufacturing of Stirling cryocoolers and cryogenic cooling systems.

A wide variety of smaller size Stirling cryocoolers are commercially available for tasks such as the cooling of electronic sensors and sometimes microprocessors. For this application, Stirling cryocoolers are the highest performance technology available, due to their ability to lift heat efficiently at very low temperatures. They are silent, vibration-free, and can be scaled down to small sizes, and have very high reliability and low maintenance. As of 2009, cryocoolers are considered to be the only commercially successful Stirling devices.

Heat pump

A Stirling heat pump is very similar to a Stirling cryocooler, the main difference being that it usually operates at room temperature and its principal application to date is to pump heat from the outside of a building to the inside, thus cheaply heating it.

As with any other Stirling device, heat flows from the expansion space to the compression space; however, in contrast to the Stirling engine, the expansion space is at a lower temperature than the compression space, so instead of producing work, an input of mechanical work is required by the system (in order to satisfy the second law of thermodynamics). When the mechanical work for the heat pump is provided by a second Stirling engine, then the overall system is called a "heat-driven heatpump".

The expansion side of the heat pump is thermally coupled to the heat source, which is often the external environment. The compression side of the Stirling device is placed in the environment to be heated, for example a building, and heat is "pumped" into it. Typically there will be thermal insulation between the two sides so there will be a temperature rise inside the insulated space.

Heat pumps are by far the most energy-efficient types of heating systems. Stirling heat pumps also often have a higher coefficient of performance than conventional heat pumps. To date, these systems have seen limited commercial use; however, use is expected to increase along with market demand for energy conservation, and adoption will likely be accelerated by technological refinements.

Marine engines

Swedish shipbuilder Kockums has built 8 successful Stirling powered submarines since the late 1980s. They carry compressed oxygen to allow fuel combustion submerged, providing heat for the Stirling engine. They are currently used on submarines of the *Gotland* and *Södermanland* classes. They are the first submarines in the world to feature Stirling air-independent propulsion (AIP), which extends their underwater endurance from a few days to two weeks. This capability has previously only been available with nuclear powered submarines.

Nuclear power

There is a potential for nuclear-powered Stirling engines in electric power generation plants. Replacing the steam turbines of nuclear power plants with Stirling engines might simplify the plant, yield greater efficiency, and reduce the radioactive byproducts. A number of breeder reactor designs use liquid sodium as coolant. If the heat is to be employed in a steam plant, a water/sodium heat exchanger is required, which raises some concern as sodium reacts violently with water. A Stirling engine eliminates the need for water anywhere in the cycle. This would have advantages for nuclear installations in dry regions.

United States government labs have developed a modern Stirling engine design known as the Stirling Radioisotope Generator for use in space exploration. It is designed to generate electricity for deep space probes on missions lasting decades. The engine uses a single displacer to reduce moving parts and uses high energy acoustics to transfer energy. The heat source is a dry solid nuclear fuel slug and the heat sink is space itself.

Automotive engines

It is often claimed that the Stirling engine has too low a power/weight ratio, too high a cost, and too long a starting time for automotive applications. They also have complex and expensive heat exchangers. A Stirling cooler must reject twice as much heat as an Otto engine or Diesel engine radiator. The heater must be made of stainless steel, exotic alloy or ceramic to support high heater temperatures needed for high power density, and to contain hydrogen gas that is often used in automotive Stirlings to maximize power. The main difficulties involved in using the Stirling engine in an automotive application are startup time, acceleration response, shutdown time, and weight, not all of which have ready-made solutions. However, a modified Stirling engine has been recently introduced that uses concepts taken from a patented internal-combustion engine with a sidewall combustion chamber (U.S. patent 7,387,093) that promises to overcome the deficient power-density and specific-power problems, as well as the slow acceleration-response problem inherent in all Stirling engines. However, it could be possible to use these in co-generation systems that use waste heat from a conventional piston or gas turbine engine's exhaust and use this either to power the ancillaries (e.g.: the alternator) or even as a turbo-compound system that adds power and torque to the crankshaft.

At least two automobiles exclusively powered by Stirling engines were developed by NASA, as well as earlier projects by the Ford Motor Company using engines provided by Philips and American Motors Corporation. The NASA vehicles were designed by contractors and designated MOD I and MOD II. The MOD II replaced the normal spark-ignition engine in a 1985 4-door Chevrolet Celebrity Notchback. In the 1986 MOD II Design Report (Appendix A) the results show that highway gas mileage was increased from 40 to 58 mpg and urban mileage from 26 to 33 mpg with no change in vehicle gross weight. Startup time in the NASA vehicle maxed out at 30 seconds, while Ford's research vehicle used an internal electric heater to jump-start the vehicle, allowing it to start in only a few seconds.

Electric vehicles

Stirling engines as part of a hybrid electric drive system may be able to bypass the design challenges or disadvantages of a non-hybrid Stirling automobile.

In November 2007, a prototype hybrid car using solid biofuel and a Stirling engine was announced by the Precer project in Sweden.

The Manchester Union Leader reports that Dean Kamen has developed a series plug-in hybrid car using a Ford Think. DEKA, Kamen's technology company in the Manchester Millyard, has recently demonstrated an electric car, the DEKA Revolt, that can go approximately 60 miles (97 km) on a single charge of its lithium battery.

Aircraft engines

Stirling engines may hold theoretical promise as aircraft engines, if high power density and low cost can be achieved. They are quieter, less polluting, gain efficiency with altitude due to lower ambient temperatures, are more reliable due to fewer parts and the absence of an ignition system, produce much less vibration (airframes last longer) and safer, less explosive fuels may be used. However, the Stirling engine often has low power density compared to the commonly used Otto engine and Brayton cycle gas turbine. This issue has been a point of contention in automobiles, and this performance characteristic is even more critical in aircraft engines.

Underwater power systems

The Stirling engine could be well suited for underwater power systems where electrical work or mechanical power is required on a intermitted or continuous level. General Motors has actually done a considerable amount of work on advanced stirling – cycle engines which include thermal storage for underwater applications. At United Stirling, Malmo, a experimental development of a four –cylinder engine using hydrogen peroxide as an oxidant in underwater power systems, is in progress. The SAGA (Submarine assistance Great autonomy) submarine, became operational in the 1990s and is driven by two stirling engines supplied with diesel and liquid oxygen.

Low temperature difference engines

A low temperature difference Stirling Engine shown here running on the heat from a warm hand

A low temperature difference (Low Delta T, or LTD) Stirling engine will run on any low temperature differential, for example the difference between the palm of a hand and room temperature or room temperature and an ice cube. A record of only 0.5 K was achieved in 1990. Usually they are designed in a gamma configuration, for simplicity, and without a regenerator, although some have slits in the displacer typically made of foam, for partial regeneration. They are typically unpressurized, running at pressure close to 1 atmosphere.

The power produced is less than 1 W, and they are intended for demonstration purposes only. They are sold as toys and educational models. Larger (typically 1 m square) low temperature engines have been built for pumping water using direct sunlight with minimal or no magnification.

Other recent applications

Acoustic Stirling Heat Engine

Los Alamos National Laboratory has developed an "Acoustic Stirling Heat Engine" with no moving parts. It converts heat into intense acoustic power which (quoted from given source) "can be used directly in acoustic refrigerators or pulse-tube refrigerators to provide heat-driven refrigeration with no moving parts, or ... to generate electricity via a linear alternator or other electro-acoustic power transducer".

MicroCHP

WhisperGen, a New Zealand based company has developed Stirling engines that can be powered by natural gas or diesel. Recently an agreement has been signed with Mondragon Corporación Cooperativa, a Spanish firm, to produce WhisperGen's microCHP and make them available for the domestic market in Europe. Some time ago E.ON UK announced a similar initiative for the UK. Stirling engines would supply the client with hot water, space heating and a surplus electric power that could be fed back into the electric grid.

Based on the companies published performance specifications of the off-grid diesel fueled unit for combined heat (5.5kw heat) and electric (800w electric) from a unit being feed 0.75 liters of automotive grade diesel fuel per hour. Whipsergen units can operate as a combined co-generation unit reaching as high as ~80% operating efficiency.

However the preliminary results of an Energy Saving Trust review of the performance of the WhisperGen microCHP units suggested that their advantages were marginal at best in most homes. However another author shows that that Stirling engined microgeneration is the most cost effective of various microgeneration technologies in terms of reducing CO_2.

Chip cooling

MSI (Taiwan) recently developed a miniature Stirling engine cooling system for personal computer chips that uses the waste heat from the chip to drive a fan.

Chapter 12

Reversing Valve and Direct Exchange Geothermal Heat Pump

Reversing Valve

A reversing valve removed from an HVAC heat pump for replacement.

A **reversing valve** a type of valve and is a component in a heat pump, that changes the direction of refrigerant flow. By reversing the flow of refrigerant, the heat pump refrigeration cycle is changed from cooling to heating or vice versa. This allows a residence or facility to be heated and cooled by a single piece of equipment, by the same means, and with the same hardware.

Operation

The reversing valve has two states, relaxed and energized. The energized state is typically achieved by applying 24 volts of alternating current, which is commonly used in HVAC . The heat pump can be designed by the manufacturer to produce cooling or heating with the reversing valve in the relaxed state. When the reversing valve is energized, it will produce the opposite conditioning. In other words, a reversing valve installed in such a way as to produce cooling when relaxed will produce heating when energized. Likewise, a reversing valve installed to produce heating when relaxed will produce cooling when energized.

Control

Depending on the construction and use of the heat pump, the reversing valve may be driven by the heat pump through the use of a control board, or it may be driven directly by a thermostat (typically from the "O" terminal).

Replacement

Reversing valves are built into the heat pump by the manufacturer, and must be replaced by an HVAC technician if they fail.

Direct Exchange Geothermal Heat Pump

A **direct exchange (DX) geothermal heat pump** system is a geothermal heat pump system in which the refrigerant circulates through copper tubing placed in the ground. The refrigerant exchanges heat directly with the soil through the walls of the copper tubing. This eliminates the plastic water pipe and water pump to circulate water found in a water-source geothermal heat pump. This simplicity allows the system to reach high efficiencies while using a relatively shorter and smaller set of buried tubing, reducing installation cost. DX systems, like water-source systems, can also be used to heat water in the house for use in radiant heating applications and for domestic hot water, as well as for cooling applications.

History

The first geothermal heat pump was a DX system built in the late 1940s by Robert C. Webber. Later designs incorporated an additional plastic pipe loop to circulate water in deep wells in an effort to gather sufficient heat for large industrial applications such as cement plants. Thus water-source technology advanced due to industrial interest while DX, more suited to smaller projects such as small businesses and private homes, lagged behind.

Gradually developing since the 1970s, DX technology is now experiencing a surge in popularity among homeowners and small businesses due to high energy costs. There is also increasing awareness of environmental and energy issues among urban and suburban residents with limited space in which to install a system.

Applications

Typical drill rig for DX installation, length 8 ft

Typical drill rig for water source installation, length 22 ft

Because of their small earth loop size, DX systems can be installed in relatively small areas and in relatively shallow soil. This provides a flexibility of installation that is useful in allowing many properties to be served by geothermal that could not be served otherwise. A direct exchange system ground loop can be drilled with a small drill rig that can fit into small side yards and gardens under existing trees. It can be drilled in areas where rock is found 50 foot (15 m) to 100 foot (30 m) below ground without the need for actually drilling into rock.

Because DX derives its efficiency from the direct heat exchange between refrigerant and ground, the compressor unit cannot be placed at great distance from the earth loops. This can limit some DX applications. However, the use of multiple distributed compressor units on a single project can allow DX systems to serve large buildings.

Ground loop configuration

The copper tubing consists of a line set, a pair of manifolds, and several earth loops. The line set is the pair of main copper pipes coming from the heat pump compressor unit, usually located indoors. One line is for the liquid refrigerant, the other is for gaseous refrigerant. The line set runs through the building wall and runs underground to the location of the manifolds. Each manifold (one for gas and one for liquid) serves to allow a main pipe to be attached to the earth loops which exchange heat with the ground.

The earth loops can be installed vertically, diagonally or horzontally 6 foot (1.8 m) deep and laying the earth loops on the bottom of the pit before installation is done by drilling several boreholes radiating outward from the manifolds and placing an earth loop into each of the boreholes. After the earth taps are placed, the boreholes are then filled with grout for good thermal contact between loop and soil.

The boreholes are drilled to a length of 50, 75 or 100 ft (15, 22 or 30 m) with a diameter of 3 inches (76 mm). A total of 100 feet (30 m) to 140 feet (43 m) of drilling is needed for each ton (3.5 kW_{th}) of system capacity.

Because copper is a naturally-occurring metal that survives in the ground for thousands of years in most soil conditions, the copper loops have a very long lifetime in most soil conditions. Corrosion of the copper earth loop in acidic soil can be eliminated through installation of a sacrificial anode.

System sizing

DX systems are currently manufactured in sizes from 1.5 tons (5.25 kW_{th}) to 6 tons (21 kW_{th}). Larger projects can be accomplished through installation of multiple units.