

Temperature Control Technologies



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Introduction

Temperature control is a process in which change of temperature of a space (and objects collectively therewithin) is measured or otherwise detected, and the passage of heat energy into or out of the space is adjusted to achieve a desired average temperature.

Control loops

A home thermostat is an example of a closed control loop: It constantly assesses the current room temperature and controls a heater and/or air conditioner to increase or decrease the temperature according to user-defined setting(s). A simple (low-cost, cheap) thermostat merely switches the heater or air conditioner either on or off, and temporary overshoot and undershoot of the desired average temperature must be expected. A more expensive thermostat varies the amount of heat or cooling provided by the heater or cooler, depending on the difference between the required temperature (the "setpoint") and the actual temperature. This minimizes over/undershoot. The process is called PID and is implemented using a PID Controller.

Energy balance

An object's or space's temperature increases when heat energy moves into it, increasing the average kinetic energy of its atoms, e.g., of things and air in a room. Heat energy leaving an object or space lowers its temperature. Heat flows from one place to another (always from a higher temperature to a lower one) by one or more of three processes: conduction, convection and radiation. In conduction, energy is passed from one atom to another by direct contact. In convection, heat energy moves by conduction into some movable fluid (such as air or water) and the fluid moves from one place to another, carrying the heat with it. At some point the heat energy in the fluid is usually transferred to some other object by means conduction again. The movement of the fluid can be driven by negative-buoyancy, as when cooler (and therefor denser) air drops and thus upwardly displaces warmer (less-dense) air (natural convection), or by fans or pumps (forced convection). In radiation, the heated atoms make electromagnetic emissions absorbed by remote other atoms, whether nearby or at astronomical distance. For example, the Sun radiates heat as both invisible and visible electromagnetic energy. What we know as "light" is but a narrow region of the electromagnetic spectrum.

If, in a place or thing, more energy is received than is lost, its temperature increases. If the amount of energy coming in and going out are exactly the same, the temperature stays constant—there is thermal balance, or thermal equilibrium.

Chapter 1

Thermostat



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

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

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

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

Common sensor technologies in use today include:

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

These may then control the heating or cooling apparatus using:

- Direct mechanical control
- Electrical signals
- Pneumatic signals



A Honeywell electronic thermostat in a retail store

Mechanical

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

Bimetal

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

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

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

Wax pellet

Automotive



Car engine thermostat

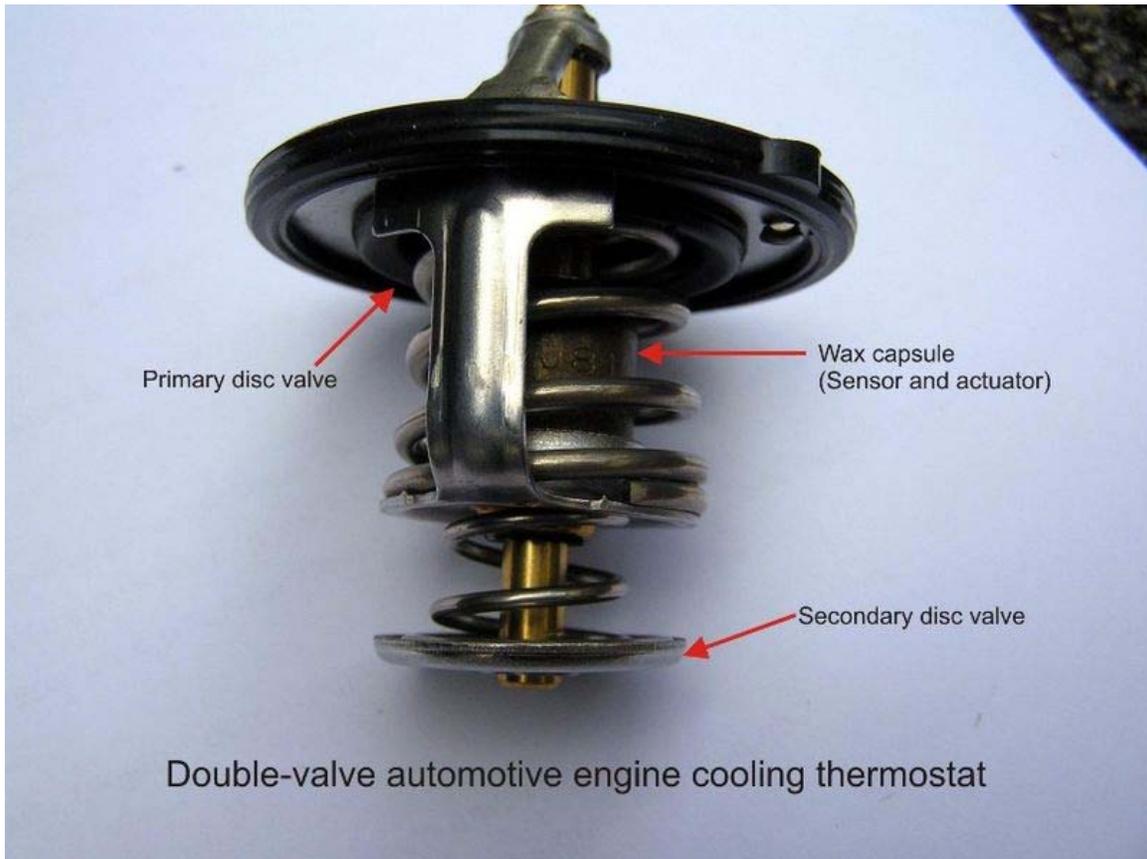
Perhaps the best example of purely mechanical technology in widespread use today is the internal combustion engine cooling thermostat. These are used to maintain the core temperature of the engine at its optimum operating temperature by regulating the flow of coolant to an external heat sink, usually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

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

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

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

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



Double valve engine thermostat

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

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

this manner requires very precise levels of distillation, which is difficult or impossible for most wax refineries.

Shower and other hot water controls

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

Gas expansion

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

Pneumatic

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

Electrical

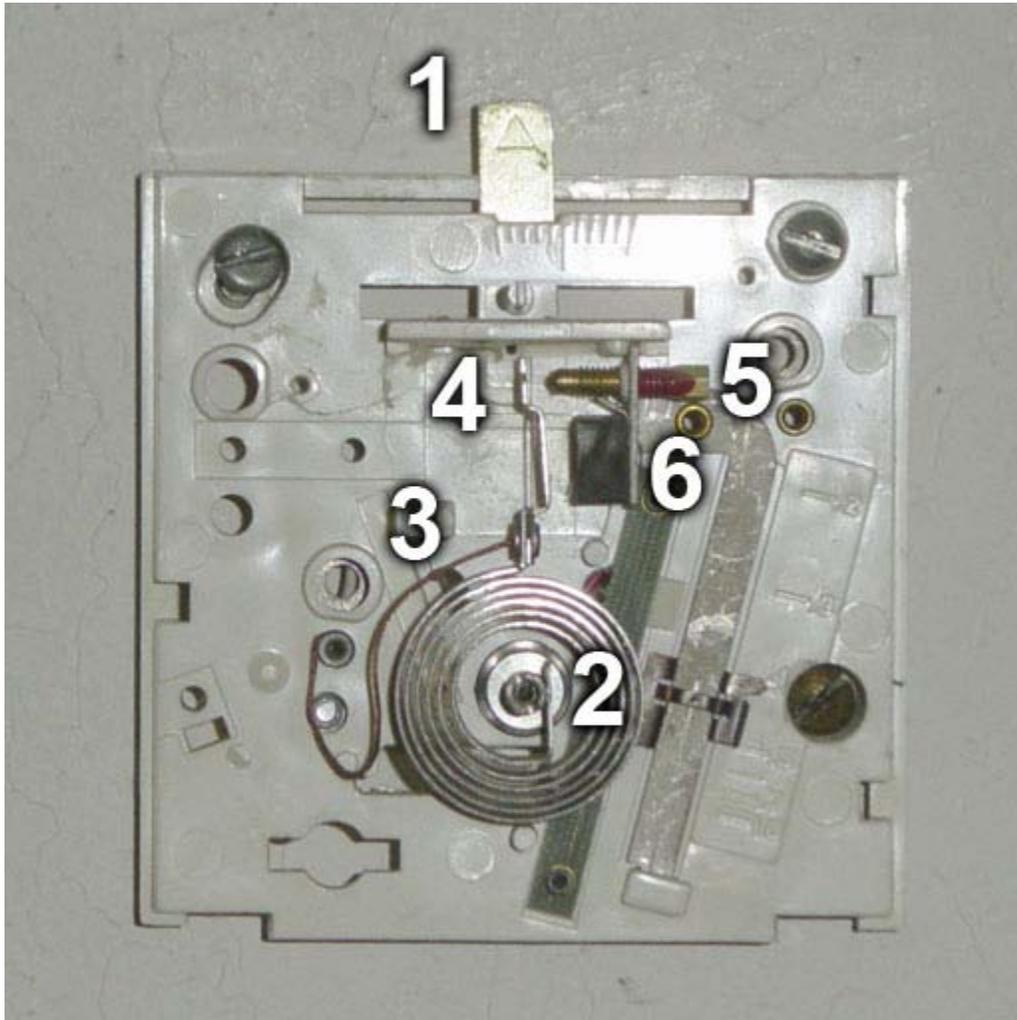
Bimetallic switching thermostats



Bimetallic thermostat for buildings.

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

Simple two wire thermostats



Milivolt thermostat mechanism

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

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

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

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

Millivolt thermostats

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

Some programmable thermostats will control these systems.

24 volt thermostats

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

sensing element while the heating appliance is operating. This opens the heating contacts slightly early to prevent the space temperature from greatly overshooting the thermostat setting. A mechanical heat anticipator is generally adjustable and should be set to the current flowing in the heating control circuit when the system is operating. A cooling anticipator generates a small amount of additional heat to the sensing element while the cooling appliance is not operating. This causes the contacts to energize the cooling equipment slightly early, preventing the space temperature from climbing excessively. Cooling anticipators are generally non-adjustable.

Electromechanical thermostats use resistance elements as anticipators. Most electronic thermostats use either thermistor devices or integrated logic elements for the anticipation function. In some electronic thermostats, the thermistor anticipator may be located outdoors, providing a variable anticipation depending on the outdoor temperature. Thermostat enhancements include outdoor temperature display, programmability, and system fault indication. While such 24 volt thermostats are incapable of operating a furnace when the mains power fails, most such furnaces require mains power for heated air fans (and often also hot-surface or electronic spark ignition) so no functionality is lost. In other circumstances such as piloted wall and "gravity" (fanless) floor and central heaters the low voltage system described previously may be capable of remaining functional when electrical power is unavailable.

Ignition sequences in modern systems

- Gas
 1. Start drafting fan (if the furnace is relatively recent) to create a column of air flowing up the chimney
 2. Heat ignitor or start spark-ignition system
 3. Open gas valve to ignite main burners
 4. Wait (if furnace is relatively recent) until the heat exchanger is at proper operating temperature before starting main blower fan or circulator pump
- Oil
 1. Similar to gas, except rather than opening a valve, the furnace will start an oil pump to inject oil into the burner
- Electric
 1. The blower fan or circulator pump will be started, and a large electromechanical relay or TRIAC will turn on the heating elements
- Coal (including grains such as corn, wheat, and barley, or pellets made of wood, bark, or cardboard)

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

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

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

Most programmable thermostats will control these systems.

Line voltage thermostats

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

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

Combination heating/cooling regulation

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

another wire, a relay back at the heating/cooling unit activates the corresponding function of the unit.

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

Heat pump regulation

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

Digital



Residential digital thermostat



Lux Products' Model TX900TS Touch Screen Thermostat.

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

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

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

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

Household thermostat location

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

Dummy thermostats

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

Chapter 2

Heat Exchanger



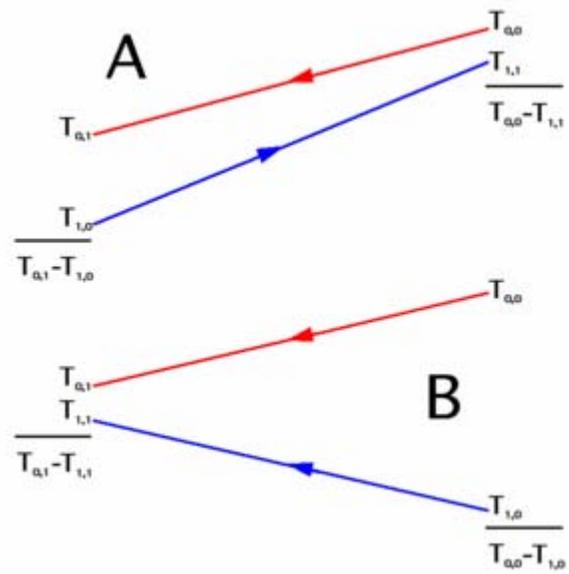
An interchangeable plate heat exchanger



Tubular heat exchanger.

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

Flow arrangement



Countercurrent (A) and parallel (B) flows

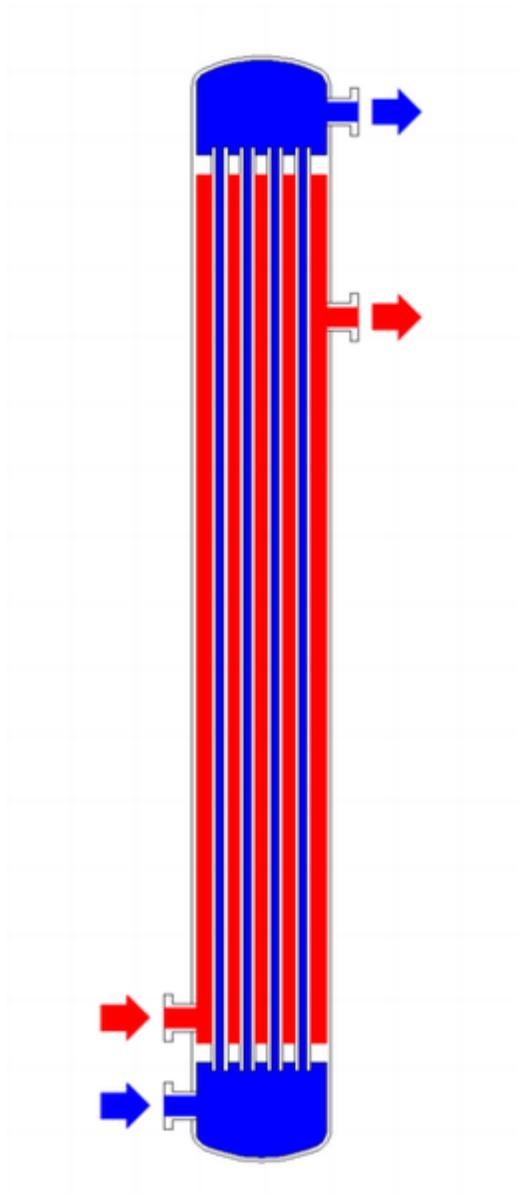


Fig. 1: Shell and tube heat exchanger, single pass (1-1 parallel flow)

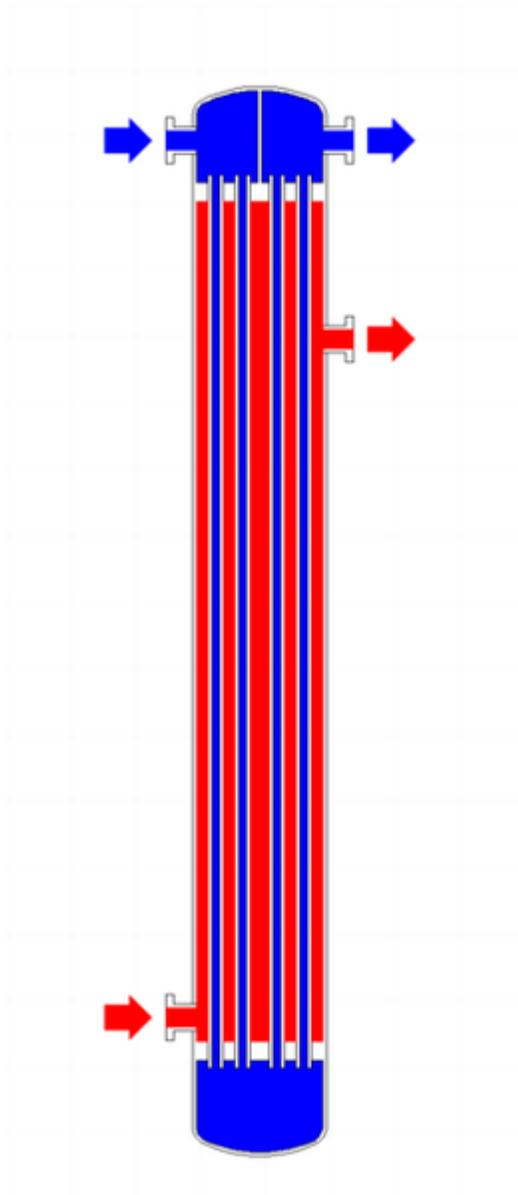


Fig. 2: Shell and tube heat exchanger, 2-pass tube side (1-2 crossflow)

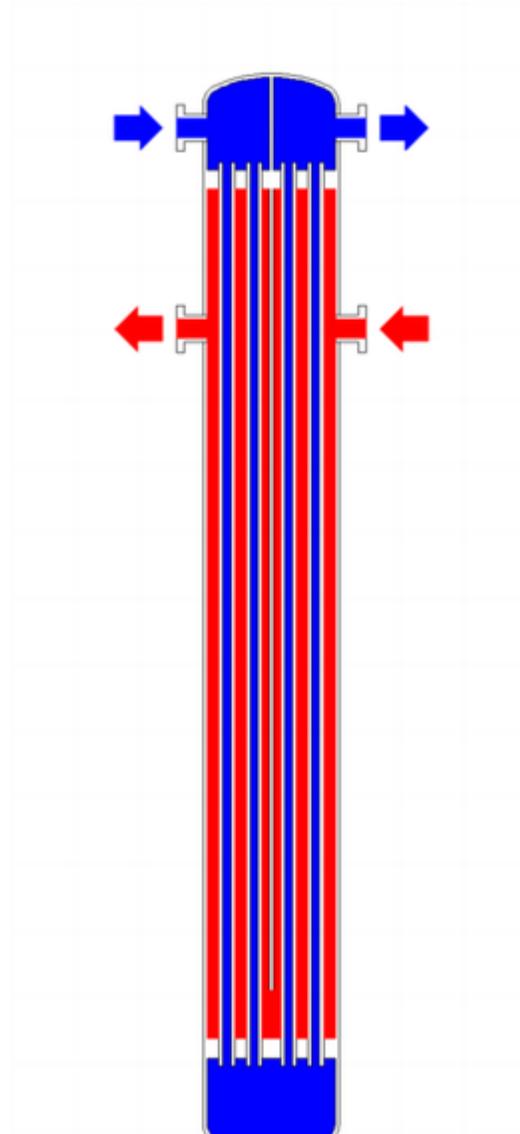


Fig. 3: Shell and tube heat exchanger, 2-pass shell side, 2-pass tube side (2-2 countercurrent)

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

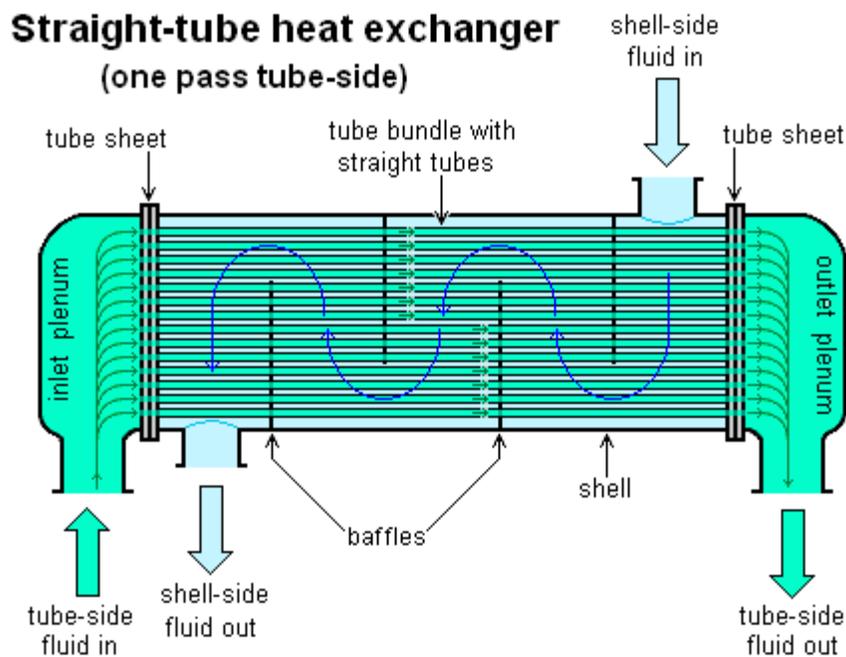
For efficiency, heat exchangers are designed to maximize the surface area of the wall between the two fluids, while minimizing resistance to fluid flow through the exchanger.

The exchanger's performance can also be affected by the addition of fins or corrugations in one or both directions, which increase surface area and may channel fluid flow or induce turbulence.

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

Types of heat exchangers

Shell and tube heat exchanger



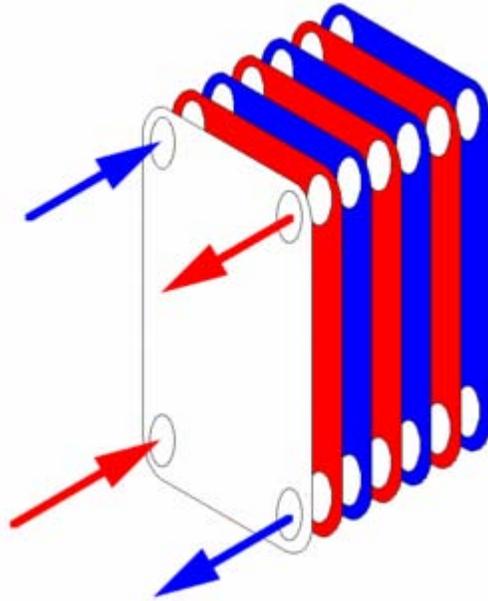
A Shell and Tube heat exchanger

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

There are several thermal design features that are to be taken into account when designing the tubes in the shell and tube heat exchangers. These include:

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

redirection. Consequently having the baffles spaced too far apart means that there may be cooler spots in the corners between baffles. It is also important to ensure the baffles are spaced close enough that the tubes do not sag. The other main type of baffle is the disc and donut baffle which consists of two concentric baffles, the outer wider baffle looks like a donut, whilst the inner baffle is shaped as a disk. This type of baffle forces the fluid to pass around each side of the disk then through the donut baffle generating a different type of fluid flow.



Conceptual diagram of a plate and frame heat exchanger.



A single plate heat exchanger



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

Plate heat exchanger

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

loop applications such as refrigeration. Plate heat exchangers also differ in the types of plates that are used, and in the configurations of those plates. Some plates may be stamped with "chevron" or other patterns, where others may have machined fins and/or grooves.

Adiabatic wheel heat exchanger

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

Plate fin heat exchanger

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

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

Advantages of plate and fin heat exchangers:

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

Disadvantages of plate and fin heat exchangers:

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

Pillow plate heat exchanger

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

The pillow plate is constructed using a thin sheet of metal spot-welded to the surface of another thicker sheet of metal. The thin plate is welded in a regular pattern of dots or with

a serpentine pattern of weld lines. After welding the enclosed space is pressurized with sufficient force to cause the thin metal to bulge out around the welds, providing a space for heat exchanger liquids to flow, and creating a characteristic appearance of a swelled pillow formed out of metal.

Fluid heat exchangers

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

Waste heat recovery units

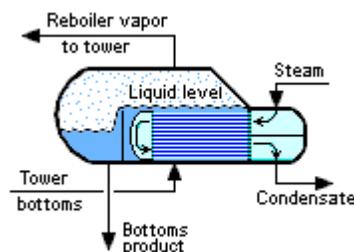
A Waste Heat Recovery Unit (WHRU) is a heat exchanger that recovers heat from a hot gas stream while transferring it to a working medium, typically water or oils. The hot gas stream can be the exhaust gas from a gas turbine or a diesel engine or a waste gas from industry or refinery.

Dynamic scraped surface heat exchanger

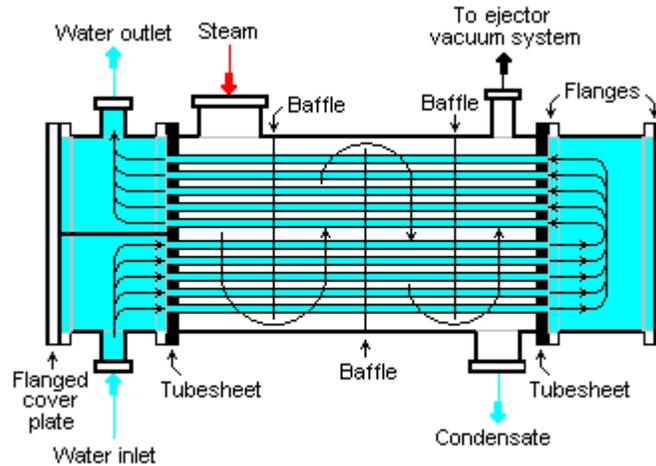
Another type of heat exchanger is called "(dynamic) scraped surface heat exchanger". This is mainly used for heating or cooling with high-viscosity products, crystallization processes, evaporation and high-fouling applications. Long running times are achieved due to the continuous scraping of the surface,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

The formula used for this will be $Q=A*U*LMTD$, whereby Q = amount of heat transferred; U = heat transfer coefficient; A =Heat Transfer Area; $LMTD$ = Log mean temperature differential.

Phase-change heat exchangers



Typical kettle reboiler used for industrial distillation towers



Typical water-cooled surface condenser

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

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

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

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

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

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

Direct contact heat exchangers

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

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

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

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

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

HVAC air coils

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

On the liquid side of these heat exchangers, the common fluids are water, a water-glycol solution, steam, or a refrigerant. For *heating coils*, hot water and steam are the most common, and this heated fluid is supplied by boilers, for example. For *cooling coils*, chilled water and refrigerant are most common. Chilled water is supplied from a chiller

that is potentially located very far away, but refrigerant must come from a nearby condensing unit. When a refrigerant is used, the cooling coil is the evaporator in the vapor-compression refrigeration cycle. HVAC coils that use this direct-expansion of refrigerants are commonly called *DX coils*.

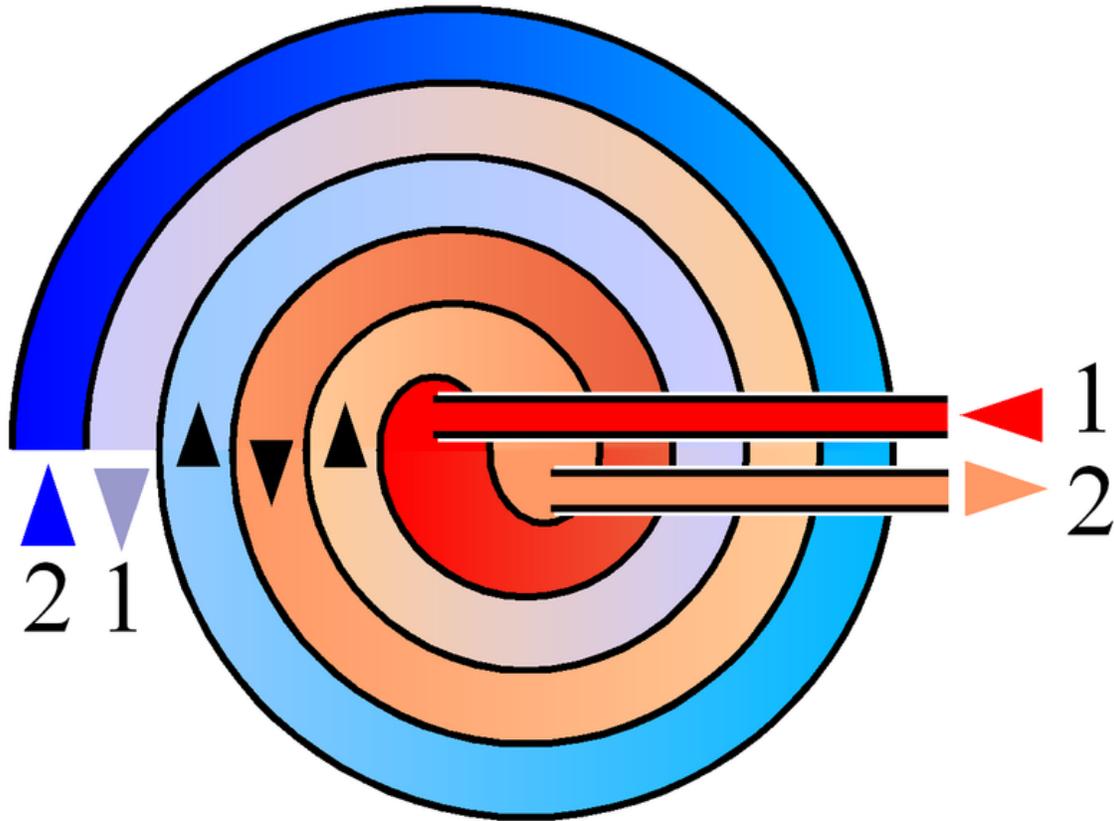
On the air side of HVAC coils a significant difference exists between those used for heating, and those for cooling. Due to psychrometrics, air that is cooled often has moisture condensing out of it, except with extremely dry air flows. Heating some air increases that airflow's capacity to hold water.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

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

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

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

Spiral heat exchangers



Schematic drawing of a spiral heat exchanger.

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

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

Construction

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

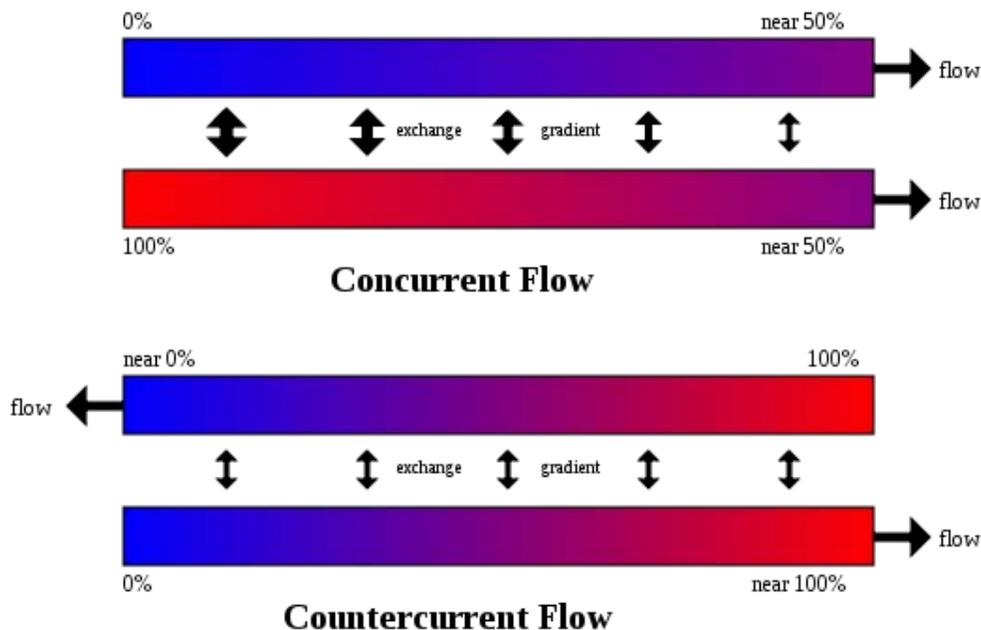
leakage happens, it will be from the periphery cover to the atmosphere, or to a passage containing the same fluid.

Self cleaning

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

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

Flow Arrangements



Concurrent and countercurrent flow.

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

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

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

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

Applications

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

Selection

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

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

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

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

cooling. With sufficient knowledge of heat exchanger types and operating requirements, an appropriate selection can be made to optimise the process.

Monitoring and maintenance

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

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

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

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

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

Fouling



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

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

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

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

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

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

Maintenance

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

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

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

In nature

Humans

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

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

Birds, fish, marine mammals

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

In industry

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

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

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

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

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

In aircraft

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

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

A model of a simple heat exchanger

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

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

$$\begin{aligned}\frac{du_1}{dt} &= \gamma(T_2 - T_1) \\ \frac{du_2}{dt} &= \gamma(T_1 - T_2)\end{aligned}$$

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

$$\frac{du_1}{dt} = J_1 \frac{dT_1}{dx}$$

$$\frac{du_2}{dt} = J_2 \frac{dT_2}{dx}$$

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

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

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

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

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

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

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

$$\bar{T}_1 = \frac{1}{L} \int_0^L T_1(x) dx$$

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

Using the solutions above, these temperatures are:

$$T_{10} = A - \frac{Bk_1}{k} \quad T_{20} = A + \frac{Bk_2}{k}$$

$$T_{1L} = A - \frac{Bk_1}{k} e^{-kL} \quad T_{2L} = A + \frac{Bk_2}{k} e^{-kL}$$

$$\bar{T}_1 = A - \frac{Bk_1}{k^2 L} (1 - e^{-kL}) \quad \bar{T}_2 = A + \frac{Bk_2}{k^2 L} (1 - e^{-kL}).$$

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

$$\frac{dU_1}{dt} = \int_0^L \frac{du_1}{dt} dx = J_1(T_{1L} - T_{10}) = \gamma L(\bar{T}_2 - \bar{T}_1)$$

$$\frac{dU_2}{dt} = \int_0^L \frac{du_2}{dt} dx = J_2(T_{2L} - T_{20}) = \gamma L(\bar{T}_1 - \bar{T}_2).$$

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

Chapter 3

Insulated Shipping Container and Thermostatic Radiator Valve

Insulated shipping container

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

Construction

An insulated shipping container might be constructed of:

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

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

Use

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

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

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

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

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

Design and Evaluation

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

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

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

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

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

Thermostatic radiator valve

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





Short history of the TRV

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

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

Product design and functionality

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

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

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

Operation

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

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

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

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

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

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

Applications and CO₂ savings

TRVs are suitable for all kind of radiator systems, radiators, convectors and towel dryers. Designs of the sensors can be tailored to suit the specific applications. TRVs are cheap and easy solutions with a significant potential for energy savings and CO₂ reductions

from heating installations. In fact the replacement of a manual heating control with a TRV can save at least 100 kg CO₂ per year.

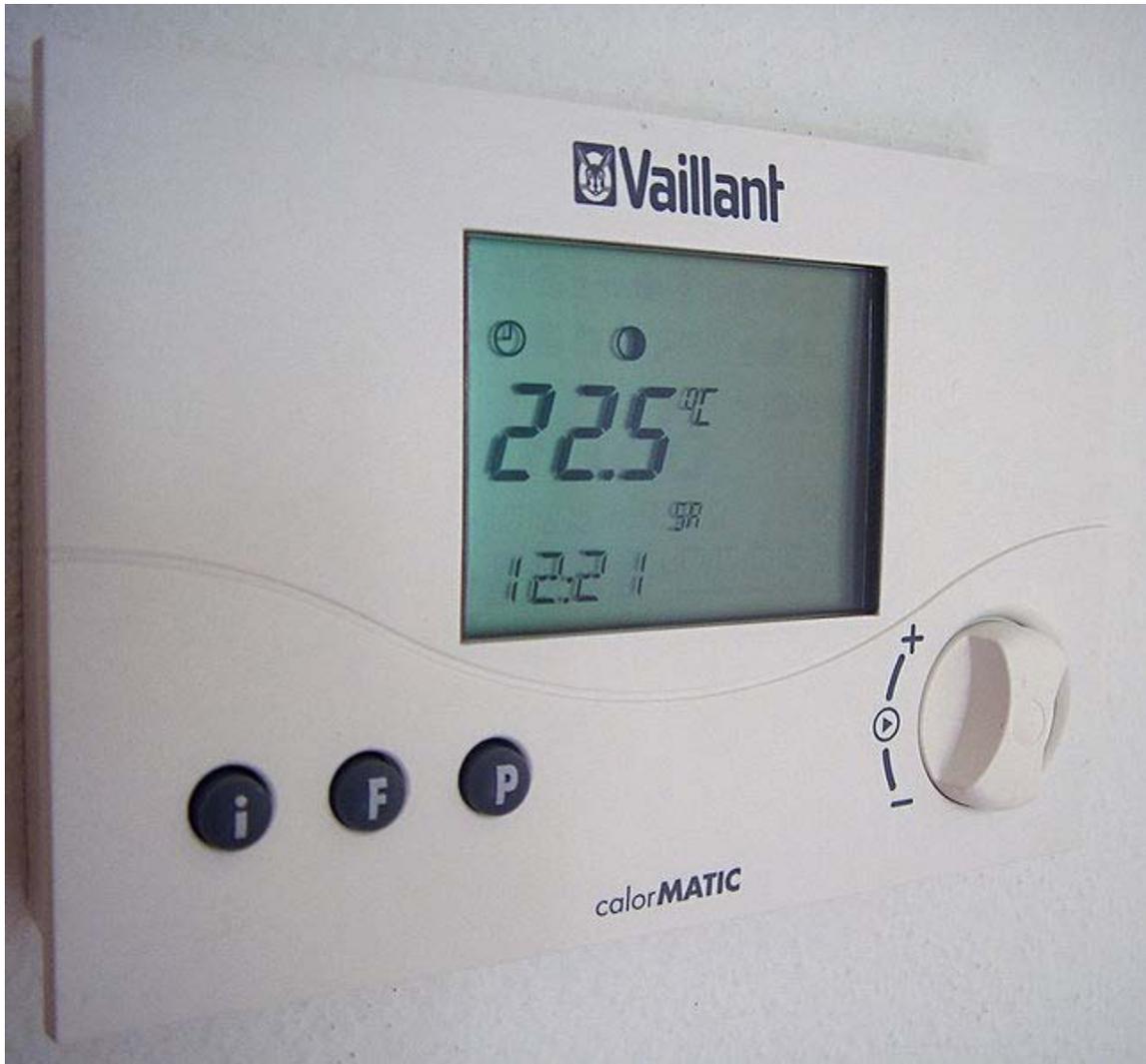
When dimensioning a heating system in a building, it is necessary to perform a precise calculation of the total system. As part of this calculation it is important to secure proper hydraulic balancing of the complete heating system. For this balancing, the presetting feature in the valve or a special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

Chapter 4

Programmable Thermostat



Lux Products' Model TX900TS Touch Screen Thermostat.



Vaillant digital room thermostat

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

Benefits



Honeywell electronic thermostat in a store

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

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

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

and exterior of a building will be greatest on a cold winter night, this reduces energy losses.

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

Construction and features

Clock thermostats



Honeywell office thermostat

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

This design, while simple to manufacture and relatively easy to program, sacrifices comfort on weekends since the program is repeated each of the seven days of the week with no variation. To overcome this deficit, a push-button is sometimes provided to allow the user to explicitly switch (once) the current period from hot period to a cold period or

vice-versa; the usual use of this button is to over-ride a "set back" that takes place during the workday when the home is normally unoccupied.

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

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

Digital thermostats



A touch-screen programmable thermostat in programming mode.

Digital thermostats may implement the same functions, but most provide more versatility. For example, they commonly allow setting temperatures for two, four, or six periods each day, and rather than being limited to a single "hotter" temperature and a single "colder" temperature, digital thermostats usually allow each period to be set to a unique temperature. The periods are commonly labeled "Morning", "Day", "Evening", and "Night", although nothing constrains the time intervals involved. Digital thermostats usually allow the user to override the programmed temperature for the period,

automatically resuming programmed temperatures when the next period begins. A function to "hold" (lock-in) the current temperature is usually provided as well; in this case, the override temperature is maintained until the user cancels the hold or a programmed event occurs to resume the normal program. More-sophisticated models will allow for the release of the hold to take place at a set time in the future.

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

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

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

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

Digital thermostats are usually powered one of three ways:

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

Digital thermostats with PID controller

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

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

Commercial thermostats

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

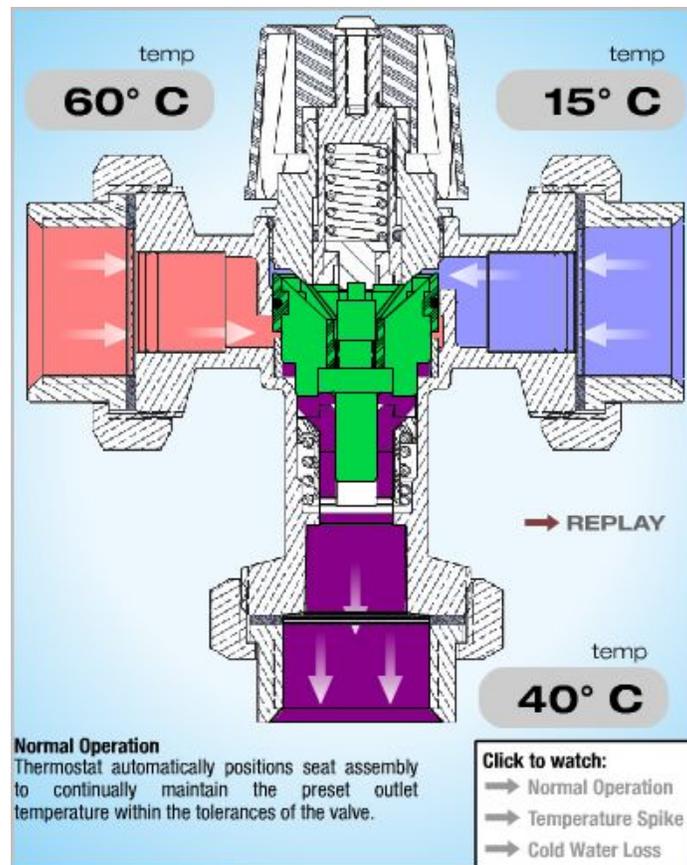
Terminal types

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

Chapter 5

Thermostatic Mixing Valve and Wax Thermostatic Element

Thermostatic mixing valve



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

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

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

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

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

Heat Source:

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

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

Group Control:

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

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

Point of Use:

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

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

Wax thermostatic element

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

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

Types of elements

Flat diaphragm element

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

Squeeze-push elements

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

Piston stroke

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

Temperature range

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

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

Hysteresis

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

Chapter 6

OpenTherm

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

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

How OpenTherm works

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

Communications media

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

OpenTherm/Plus (OT/+)

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

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

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

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

OpenTherm/Lite (OT/-)

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

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

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

OpenTherm Smart Power

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

Multi Point to Point

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

Certifying products

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

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

History

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

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

Specification documents

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

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

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

Chapter 7

Radiator (Heating)

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

Radiation vs. convection

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

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

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

Types



A cast iron household radiator

Hot water

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

Hot water baseboard

Traditional cast iron radiators are no longer common in new construction, replaced mostly with forced hot water baseboard style radiators. They consist of copper pipes which have aluminum fins to increase their surface area. In the U.K., modern domestic

radiators tend to be of sheet steel construction (often with steel fins), though copper/aluminium is often found in industrial Air Handling System heat exchangers.

Steam



Single-pipe steam radiator

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

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

Fan assisted heat exchanger

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

Underfloor



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

Underfloor heating uses a network of pipes, tubing or heating cables is buried in or attached beneath a floor to allow heat to rise into the room. Best results are had with

conductive flooring materials such as tile. The large surface area of such room-sized radiators allows them to be kept just a few degrees above desired room temperature, minimizing convection. Underfloor heating is more expensive in new construction than less efficient systems. It also is generally difficult to retrofit into existing buildings.

The Roman hypocaust employed a similar principle of operation.

Electric baseboard

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

Portable

Electrically powered portable radiators come in two basic forms:

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

Chapter 8

Storage Heater

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

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

Application

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

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

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

Advantages

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

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

Disadvantages

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

Using storage heaters

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

Power switches



Off peak and peak power supplies to storage heater

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

Basic controls



Input and Output switches on a basic storage heater

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

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

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

Thermostatic controls



Thermostatic controls on a more advanced storage heater

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

Environmental aspects

In common with other forms of direct electric heating, storage heaters are not normally considered environmentally friendly because most electricity is generated remotely using fossil fuels, with up to two-thirds of energy in the fuel lost at the power station and in transmission losses. In Sweden the use of direct electric heating has been restricted since the 1980s for this reason, and there are plans to phase it out entirely - while Denmark has

banned the installation of electric space heating in new buildings for similar reasons. In the UK, a storage heater earns a "Poor" rating for Environmental Performance on an Energy Performance Certificate. Many progressive countries are developing their electricity generating system, principally, to incorporate 'greener', more sustainable and renewable energy sources.

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

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

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

Chapter 9

Underfloor Heating

Underfloor heating and cooling is a form of central heating and cooling which achieves indoor climate control for thermal comfort using conduction, radiation and convection. The terms *radiant heating* and *radiant cooling* are commonly used to describe this approach because radiation is responsible for a significant portion of the resulting thermal comfort but this usage is technically correct only when radiation composes more than 50% of the heat exchanged between the floor and the rest of the space.

History

Underfloor heating has a long history extending back into the Neoglacial and Neolithic periods. Archeological digs in Asia and the Aleutian islands of Alaska reveal how the inhabitants drafted smoke from fires through stone covered trenches which were excavated in the floors of their subterranean dwellings. The hot smoke heated the floor stones which then radiated into the living spaces. These early forms have evolved into modern systems using fluid filled pipes or electrical cables and mats. Below is a chronological overview of under floor heating from around the world.

Time period, c. BC	Description
10,000	From China, the word kang, can be traced back to the 11th century B.C. and originally meant, “to dry” before it became known as a heated bed.
5,000	Evidence of “baked floors” are found foreshadowing early forms of kang and dikang “heated floor” later ondol meaning “warm stone” in China and Korea respectively.
3,000	Korean fire hearth, was used both as kitchen range and heating stove.
1,000	Ondol type system used in the Aleutian islands, Alaska and in Unggi, Hamgyeongbuk-do (present-day North Korea).

1,000	More than two hearths were used in one dwelling; one hearth located at the center was used for heating, the others at the perimeter was used for cooking throughout the year. This perimeter hearth is the initial form of the budumak (meaning kitchen range), which composes combustion section of the traditional ondol in Korea.
500	Greeks and later Romans scale up the use of conditioned surfaces (floors and walls) with the hypocausts.
200	Central hearth developed into gudeul (meaning heat releasing section of ondol) and perimeter hearth for cooking became more developed and budumak was almost established in Korea.
50	China, Korea and Roman Empire use kang, dikang/ondol and hypocaust respectively.

Time period, c. AD

Description

500	Asia continues to use conditioned surfaces but the application is lost in Europe where it is replaced by the open fire or rudimentary forms of the modern fireplace. Anecdotal literary reference to radiant cooling system in the Middle East using snow packed wall cavities.
700	More sophisticated and developed gudeul was found in some palaces and living quarters of upper class people in Korea. Countries in the Mediterranean Basin (Iraq, Algeria, Turkey, Afghanistan et al.) use various forms of hypocaust type heating in public baths and homes (ref.: tabakhana, atishkhana, sandali) but also use heat from cooking (see:tandoor, also tanur) to heat the floors.
1000	Ondol continues to evolve in Asia. The most advanced true ondol system was established. The fire furnace was moved outside and the room was entirely floored with ondol in Korea. Europe uses various forms of the fireplace with the evolution of drafting combustion products with chimneys.
1400	Hypocaust type systems used to heat Turkish Baths of the Ottoman Empire.
1500	Attention to comfort and architecture in Europe evolves; China and Korea continue to apply floor heating with wide scale adoption.
1600	In France, heated flues in floors and walls are used in greenhouses.
1700	Benjamin Franklin studies the French and Asian cultures and makes note of their respective heating system leading to the development of the Franklin stove. Steam based radiant pipes are used in France. Hypocaust type system used to heat public bath (Hammam) in the citadel town of Erbil located in modern day Iraq.
1800	Beginnings of the European evolution of the modern water heater/boiler and water based piping systems including studies in thermal conductivities and specific heat of materials and emissivity/reflectivity of surfaces (Watt/Leslie/Rumford). Reference to the use of small bore pipes used in the John Soane house and museum.

- 1864 Ondol type system used at Civil War hospital sites in America. Reichstag building in Germany uses the thermal mass of the building for cooling and heating.
- 1899 The earliest beginnings of polyethylene-based pipes occur when German scientist, Hans von Pechmann, discovered a waxy residue at the bottom of a test tube, colleagues Eugen Bamberger and Friedrich Tschirner called it polymethylene but it was discarded as having no commercial use at the time.
- 1904 Liverpool Cathedral in England is heated with system based on the hypocaust principles.
- 1905 Frank Lloyd Wright makes first trip to Japan, later incorporates various early forms of radiant heating in his projects.
- 1907 England, Prof. Barker granted Patent No. 28477 for panel warming using small pipes. Patents later sold to the Crittal Company who appointed representatives across Europe. A.M. Byers of America promotes radiant heating using small bore water pipes. Asia continues to use traditional ondol and kang—wood is used as the fuel, combustion gases sent under floor.
- 1930 Oscar Faber in England uses water pipes used to radiant heat and cool several large buildings.
- 1933 Explosion at England's Imperial Chemical Industries (ICI) laboratory during a high pressure experiment with ethylene gas results in a wax like substance—later to become polyethylene and the re-beginnings of PEX pipe.
- 1937 Frank Lloyd Wright designs the radiant heated Herbert Jacobs house, the first Usonian home.
- 1939 First small scale polyethylene plant built in America.
- 1945 American developer William Levitt builds large scale developments for returning GI's. Water based (copper pipe) radiant heating used throughout thousands of homes. Poor building envelopes on all continents require excessive surface temperatures leading in some cases to health problems. Thermal comfort and health science research (using hot plates, thermal manikins and comfort laboratories) in Europe and America later establishes lower surface temperature limits and development of comfort standards.
- 1950 Korean War wipes out wood supplies for ondol, population forced to use coal. Developer Joseph Eichler in California begins the construction of thousands of radiant heated homes.
- 1951 Dr. J. Bjorksten of Bjorksten Research Laboratories in Madison, WI, announces first results of what is believed to be the first instance of testing three types of plastic tubing for radiant floor heating in America. Polyethylene, vinyl chloride copolymer, and vinylidene chloride were tested over three winters.
- 1953 The first Canadian polyethylene plant is built near Edmonton, Ab.

- 1960 NRC researcher from Canada installs underfloor heating in his home and later remarks, "Decades later it would be identified as a passive solar house. It incorporated innovative features such as the radiant heating system supplied with hot water from an automatically stoked anthracite furnace."
- 1965 Thomas Engel patents method for stabilizing polyethylene by cross linking molecules using peroxide (PEX-A) and in 1967 sells license options to a number of pipe producers.
- 1970 Evolution of Korean architecture leads to multistory housings, flue gases from coal based ondol results in many deaths leading to the removal of the home based flue gas system to a central water based heating plants. Oxygen permeation becomes corrosion issue in Europe leading to the development of barriered pipe and oxygen permeation standards.
- 1980 The first standards for floor heating are developed in Europe. Water-based ondol system is applied to almost all of residential buildings in Korea.
- 1985 Floor heating becomes a traditional heating systems in residential buildings in Middle Europe and Nordic countries and increasing applications in non-residential buildings.
- 1995 The application of floor cooling and thermal active building systems (TABS) in residential and commercial buildings are widely introduced into the market.
- 2000 The use of embedded radiant cooling systems in middle of Europe becomes a standard system with many parts of the world applying radiant based HVAC systems as means of using low temperatures for heating and high temperatures for cooling.
- 2010 Radiant conditioned Pearl River Tower in Guangzhou, China, topped out at 71-stories.

Description

Modern underfloor heating systems use either electrical resistance elements ("electric systems") or fluid flowing in pipes ("hydronic systems") to heat the floor. Either type can be installed as the primary, whole-building heating system or as localized floor heating for thermal comfort. Electrical resistance can only be used for heating so when space cooling is also required, hydronic systems are used. Other applications for which either electric or hydronic systems are suited include snow/ice melting for walks, driveways and landing pads, turf conditioning of football and soccer fields and frost prevention in freezers and skating rinks.

Electric heating elements or hydronic piping can be cast in a concrete floor slab ("poured floor system" or "wet system"). They can also be placed under the floor covering ("dry system") or attached directly to a wood sub floor ("sub floor system" or "dry system").

Some commercial buildings are designed to take advantage of thermal mass which is heated or cooled during off peak hours when utility rates are lower. With the

heating/cooling system turned off during the day, the concrete mass and room temperature drift up or down within the desired comfort range. Such systems are known as thermally activated building systems or TABS.

Hydronic systems

Hydronic systems use water or a mix of water and anti-freeze such as propylene glycol as the heat transfer fluid in a "closed loop" that is recirculated between the floor and the boiler.

Various types of pipes are available specifically for hydronic underfloor heating and cooling systems and are generally made from polyethylene including PEX, PEX-Al-PEX and PERT. Older materials such as Polybutylene (PB) and copper or steel pipe are still used in some locales or for specialized applications.

Hydronic systems require skilled designers and tradespeople familiar with boilers, circulators, controls, fluid pressures and temperature. The use of modern factory assembled sub-stations, used primarily in district heating and cooling, can greatly simplify design requirements and reduce the installation and commissioning time of hydronic systems.

Hydronic systems can use a single source or combination of energy sources to help manage energy costs. Hydronic system **energy source** options are:

- Boilers (heaters) including Combined heat and power plants¹ heated by:
 - Natural gas, coal, oil or waste oil
 - Electricity
 - Solar thermal
 - wood or other biomass
 - bio-fuels

- Heat pumps and chillers powered by:
 - Electricity
 - Natural gas



Underfloor heating pipes, before they are covered by the screed



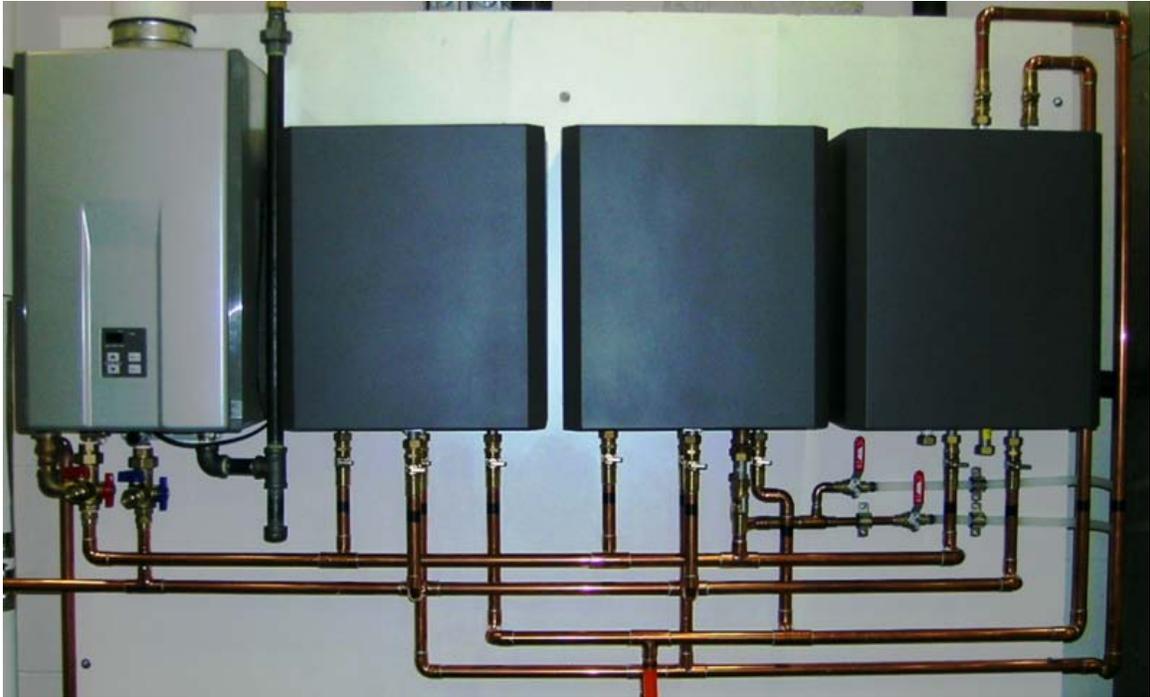
Underfloor heating pipes, before they are covered by a concrete garage slab



Radiant tubing layout, Project: BCIT Aerospace Hangar, Vancouver, British Columbia, Canada



Manifold assembly



Modern factory assembled hydronic control appliances for underfloor heating and cooling, shown with covers on.



Modern factory assembled hydronic control appliances for underfloor heating and cooling, shown with covers off.

Electric systems



Electric floor heating installation, cement being applied

Electric systems are used only for heating and employ non-corrosive, flexible heating elements including cables, pre-formed cable mats, bronze mesh, and carbon films. Due to their low profile they can be installed in a thermal mass or directly under floor finishes. Electric systems can also take advantage of time-of-use electricity metering and are frequently used as carpet heaters, portable under area rug heaters, under laminate floor heaters, under tile heating, under wood floor heating, and floor warming systems, including under shower floor and seat heating. Large electric systems also require skilled designers and tradespeople but this is less so for small floor warming systems. Electric systems use fewer components and are simpler to install and commission than hydronic systems. Some electric systems use line voltage technology while others use low voltage technology. Power consumption of an electric system is not based on voltage but rather wattage output produced by the heating element.

Features

Thermal comfort quality

As defined by ANSI/ASHRAE Standard 55 – Thermal Environmental Conditions for Human Occupancy, thermal comfort is, “that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation.” Relating specifically to underfloor heating, thermal comfort is influenced by floor surface temperature and associated elements such as radiant asymmetry, mean radiant temperature and operative temperature. Research by Nevins, Rohles, Gagge, P. Ole Fanger et al. show that humans at rest with clothing typical of light office and home wear, exchange over 50% of their sensible heat via radiation.

Underfloor heating influences the radiant exchange by thermally conditioning the interior surfaces with low temperature long wave radiation. The heating of the surfaces suppresses body heat loss resulting in a perception of heating comfort. This general sensation of comfort is further enhanced through conduction (feet on floor) and through convection by the surface's influence on air density. Underfloor cooling works by absorbing both short wave and long wave radiation resulting in cool interior surfaces. These cool surfaces encourage the loss of body heat resulting in a perception of cooling comfort. Localized discomfort due to cold and warm floors wearing normal foot wear and stocking feet is addressed in the ISO 7730 and ASHRAE 55 standards and ASHRAE Fundamentals Handbooks and can be corrected or regulated with floor heating and cooling systems.

Indoor air quality

Underfloor heating can have a positive effect on the quality of indoor air by facilitating the choice of otherwise perceived cold flooring materials such as tile, slate, terrazzo and concrete. These masonry surfaces typically have very low VOC emissions (volatile organic compounds) in comparison to other flooring options. In conjunction with moisture control, floor heating also establishes temperature conditions that are less favorable in supporting mold, bacteria, viruses and dust mites. By removing the sensible heating load from the total HVAC (Heating, Ventilating, and Air Conditioning) load, ventilation, filtration and dehumidification of incoming air can be accomplished with dedicated outdoor air systems having less volumetric turnover to mitigate distribution of airborne contaminants. There is recognition from the medical community relating to the benefits of floor heating especially as it relates to allergens.

Sustainability—energy

Under floor radiant systems are evaluated for sustainability through the principles of efficiency, entropy, exergy and efficacy. When combined with high performance buildings, under floor systems operate with low temperatures in heating and high temperatures in cooling in the ranges found typically in geothermal and solar thermal systems. When coupled with these non combustible, renewable energy sources the sustainability benefits include reduction or elimination of combustion and green house gases produced by boilers and power generation for heat pumps and chillers, as well as reduced demands for non renewables and greater inventories for future generations. This has been supported through simulation evaluations and though research funded by the U.S. Department of Energy, Canada Mortgage and Housing Corporation, Fraunhofer Institute as well as ASHRAE.

Safety

Low temperature underfloor heating is embedded in the floor or placed under the floor covering. As such it occupies no wall space and creates no burn hazards, nor is it a hazard for physical injuries due to accidental contact leading to tripping and falling. This has been referenced as a positive feature in healthcare facilities including those serving

elderly clients and those with dementia. Anecdotally, under similar environmental conditions, heated floors will speed evaporation of wetted floors (showering, cleaning, and spills). Additionally, underfloor heating with fluid filled pipes is useful in heating and cooling explosion proof environments where combustion and electrical equipment can be located remotely from the explosive environment.

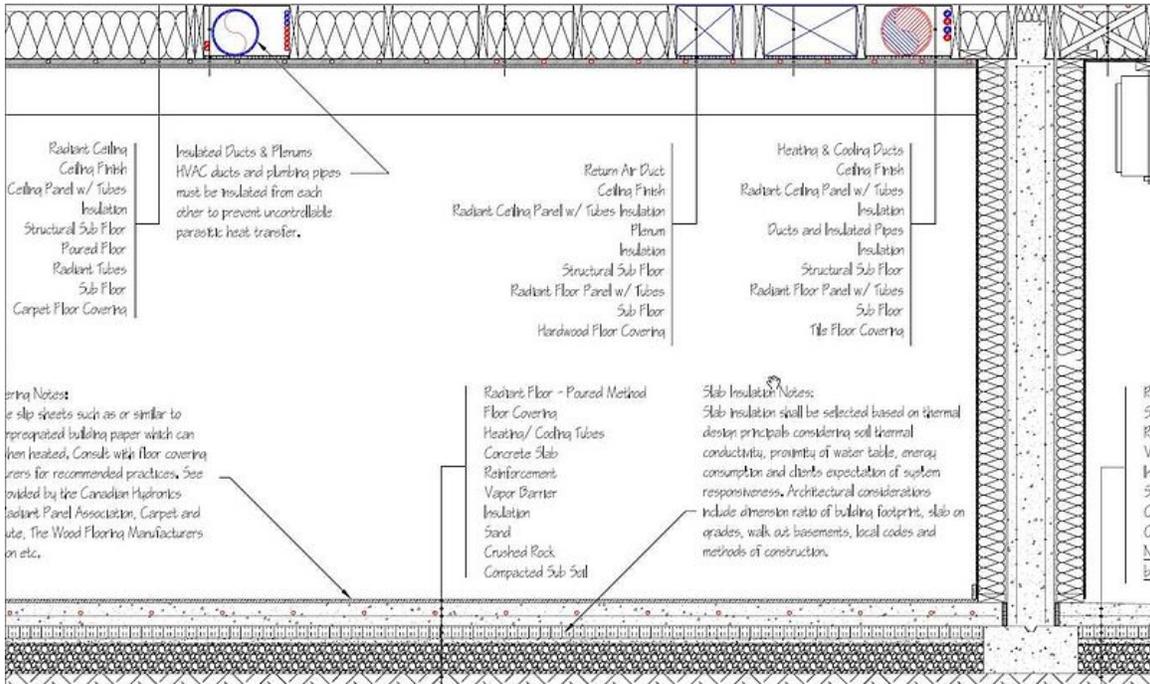
Longevity, maintenance and repair

Equipment maintenance and repair is the same as for other water or electrical based HVAC systems except when pipes, cables or mats are embedded in the floor. Early trials (for example homes built by Levitt and Eichler, c. 1940-70's) experienced failures in embedded copper and steel piping systems as well as failures assigned by the courts to Shell, Goodyear and others for polybutylene and EPDM materials. There also have been a few publicized claims of failed electric heated gypsum panels from the mid 90's.

Failures associated with most installations are attributable to job site neglect, installation errors and product mishandling such as exposure to ultraviolet radiation. Pre-pour pressure tests required by concrete installation standards and good practice guidelines for the design, construction, operation and repair of radiant heating and cooling systems mitigate problems resulting from improper installation and operation.

Fluid based systems using Cross-linked polyethylene (PE-x) a product developed in the 1930s and its various derivatives such as PE-rt, have demonstrated reliable long term performance in harsh cold-climate applications such as bridge decks, aircraft hangar aprons and landing pads. Since the materials are produced from polyethylene and its bonds are cross-linked, it is highly resistant to corrosion or the temperature and pressure stresses associated with typical fluid based HVAC systems.

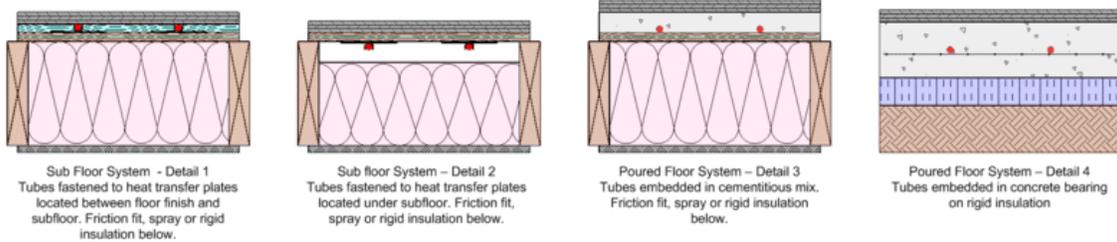
Typical installation details



General considerations for placing radiant heating and cooling pipes in flooring assemblies where other HVAC and plumbing components may be present.

Typical Under Floor Heating and Cooling - Floor Section Details

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Note: Local practices, codes, standards and fire regulations will determine actual assembly methods and materials

Typical under floor heating and cooling assemblies. Local practices, codes, standards, best practices and fire regulations will determine actual materials and methods.

Design and installation considerations

The engineering of underfloor cooling and heating systems is governed by industry standards and guidelines.

Technical design

The amount of heat exchanged from or to an underfloor system is based on the combined radiant and convective heat transfer coefficients.

- Radiant heat transfer is constant based on the Stefan–Boltzmann constant.
- Convective heat transfer changes over time depending on
 - the air's density and thus its buoyancy. Air buoyancy changes according to surface temperatures and
 - forced air movement due to fans and the motion of people and objects in the space.

Convective heat transfer with underfloor systems is much greater when the system is operating in a heating rather than cooling mode. Typically with underfloor heating the convective component is almost 50% of the total heat transfer and in underfloor cooling the convective component is less than 10%.

Heat and moisture considerations

When heated and cooled pipes or heating cables share the same spaces as other building components, parasitic heat transfer can occur between refrigeration appliances, cold storage areas, domestic cold water lines, air conditioning and ventilation ducts. To control this, the pipes, cables and other building components must all be well insulated.

With underfloor cooling, condensation may collect on the surface of the floor. To prevent this, air humidity is kept low, below 50%, and floor temperatures are maintained above the dew point, 66°F(19°C).

Building systems and materials

- Heat losses to below grade
 - The thermal conductivity of soil will influence the conductive heat transfer between the ground and heated or cooled slab-on-grade floors.
 - Soils with moisture contents greater than 20% can be as much as 15 times more conductive than soils with less than 4% moisture content.
 - Water tables and general soil conditions should be evaluated.
 - Suitable underslab insulation such as rigid extruded or expanded polystyrene is required by Model National Energy Codes.
- Heat losses at the exterior floor framing
 - The heated or cooled sub-floor increases the temperature difference between the outdoors and the conditioned floor.
 - The cavities created by the framing timbers such as headers, trimmers and cantilevered sections must then be insulated with rigid, batt or spray type insulations of suitable value based on climate and building techniques.
- Masonry and other hard flooring considerations

- Concrete floors must accommodate shrinkage and expansion due to curing and changes in temperature.
- Curing times and temperatures for poured floors (concrete, lightweight toppings) must follow industry standards.
- Control and expansion joints and crack suppression techniques are required for all masonry type floors including;
 - Tile
 - Slate
 - Terrazzo
 - Stone
 - Marble
 - Concrete, stained, textured and stamped
- Wood flooring
 - The dimensional stability of wood is based primary on moisture content, however, other factors can mitigate the changes to wood as it is heated or cooled, including;
 - Wood species
 - Milling techniques, quarter sawn or plane sawn
 - Acclimation period
 - Relative humidity within the space
- Piping standards

Control system

Underfloor heating and cooling systems can have several control points including the management of:

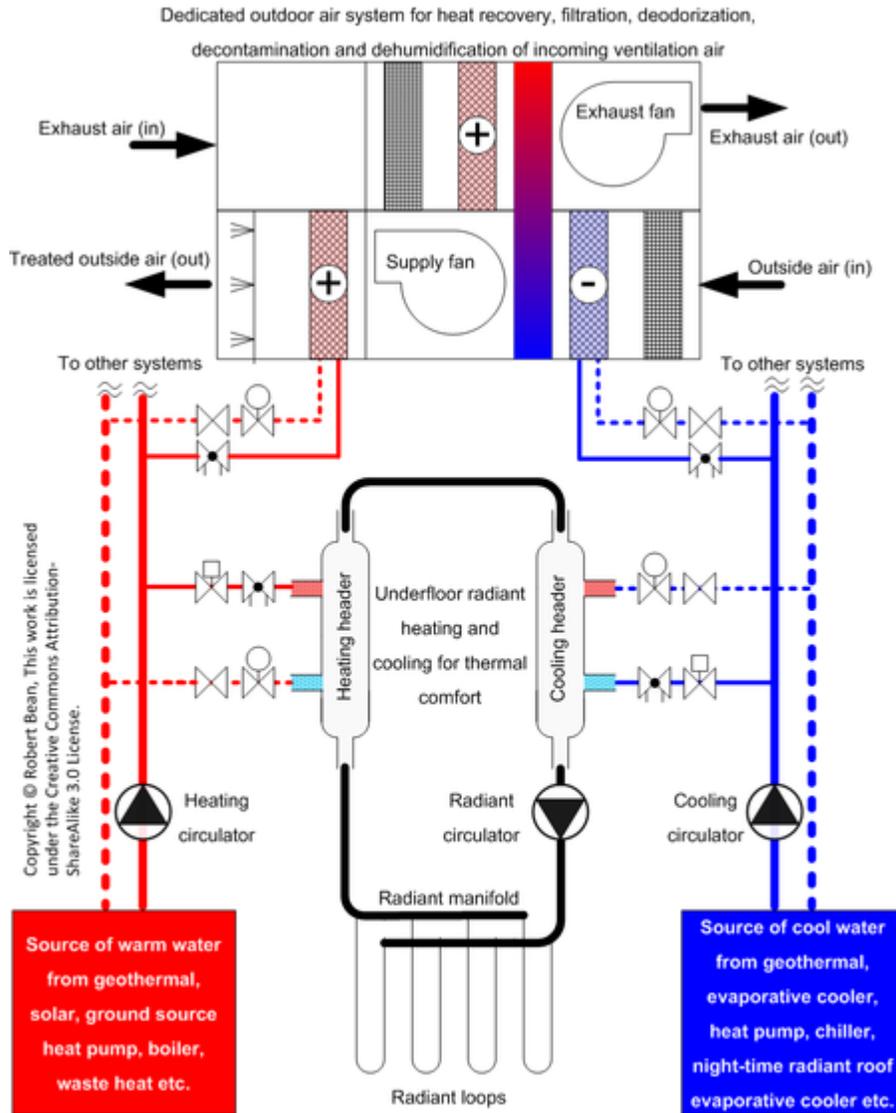
- Fluid temperatures in the heating and cooling plant (e.g. boilers, chillers, heat pumps).
 - Influences the efficiency
- Fluid temperatures in distribution network between the plant and the radiant manifolds.
 - Influences the capital and operating costs
- Fluid temperatures in the PE-x piping systems, which is based on;
 - Heating and cooling demands
 - Tube spacing

- Upward and downward losses
- Flooring characteristics

- Operative temperature
 - Incorporates the mean radiant and dry bulb

- Surface temperatures for;
 - Comfort
 - Health and safety
 - Material integrity
 - Dew point (for floor cooling).

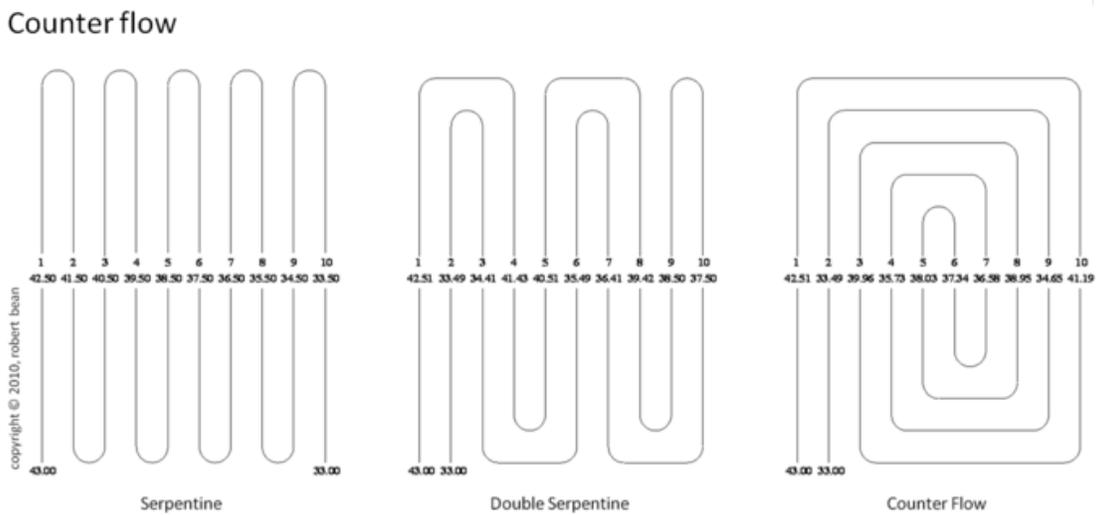
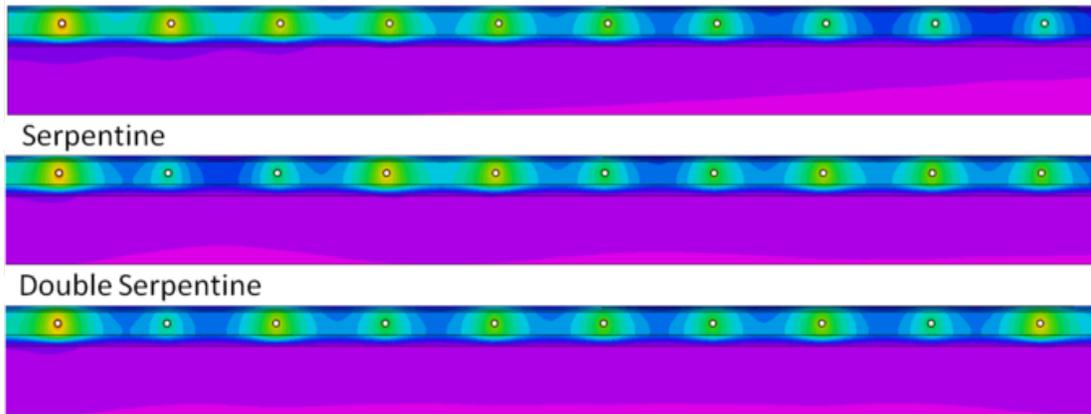
Sample - mechanical schematic



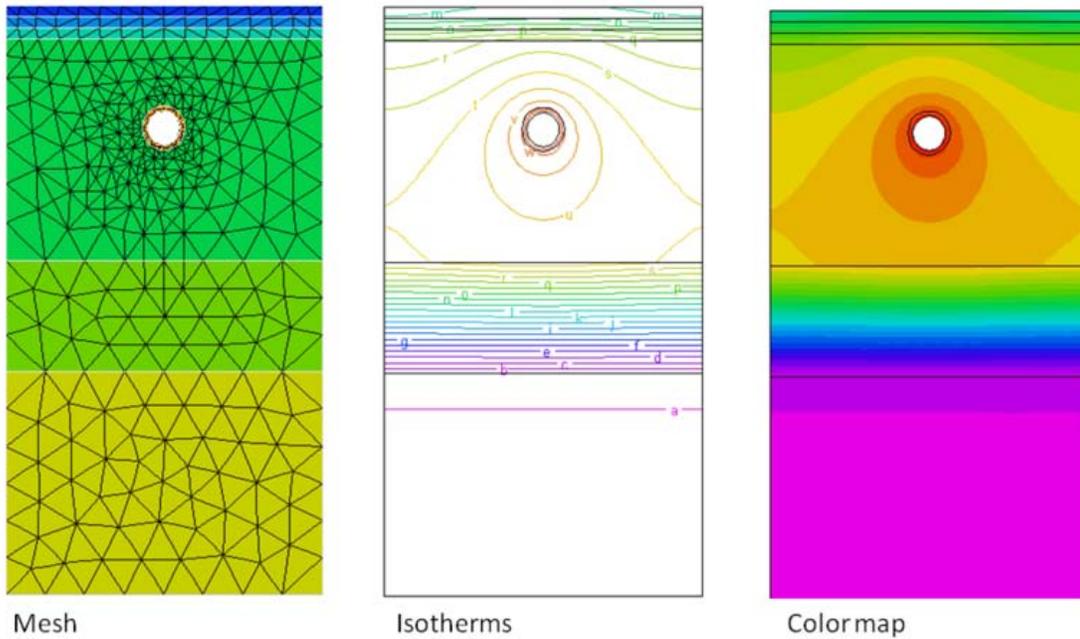
Example of a radiant based HVAC schematic.

Illustrated is a simplified mechanical schematic of an underfloor heating and cooling system for thermal comfort quality with a separate air handling system for indoor air quality. In high performance residential homes of moderate size (e.g. under 3000 ft² (278 m²) total conditioned floor area), this system using manufactured hydronic control appliances would take up about the same space as a three or four piece bathroom.

Modeling piping patterns with finite element analysis



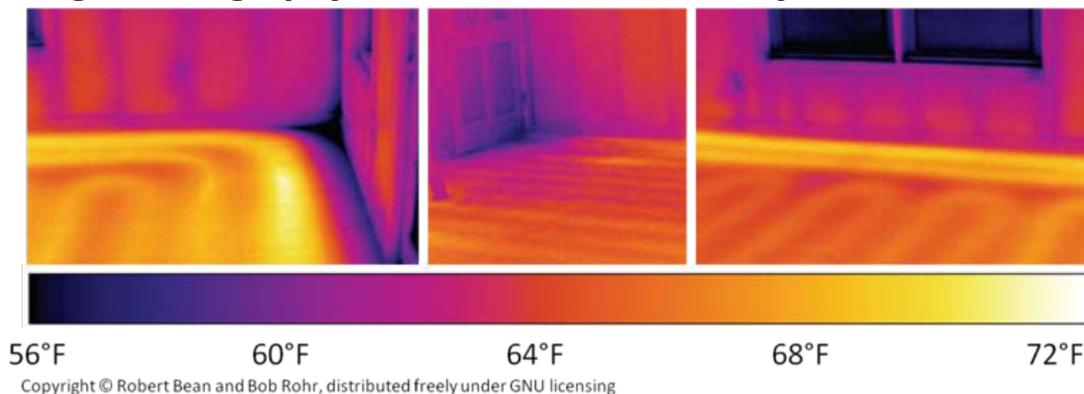
Thermal diffusions and surface temperature quality (efficacy) of various piping layouts



Typical FEA output screen shots of wire mesh, thermal isotherms and color-coded mapping

Modeling radiant piping (also tube or loop) patterns with finite element analysis(FEA) predicts the thermal diffusions and surface temperature quality or efficacy of various loop layouts. The performance of the model (left image above) and image to the right are useful to gain an understanding in relationships between flooring resistances, conductivities of surrounding mass, tube spacing's, depths and fluid temperatures. As with all FEA simulations, they depict a snap shot in time for a specific assembly and may not be representative of all floor assemblies nor for system that have been operative for considerable time in a steady state condition. The practical application of FEA for the engineer is being able to assess each design for fluid temperature, back losses and surface temperature quality. Through several iterations it is possible to optimize the design for the lowest fluid temperature in heating and the highest fluid temperature in cooling which enables combustion and compression equipment to achieve its maximum rated efficiency performance.

Using thermography to observe underfloor systems



Thermographic images of a room heated with low temperature radiant heating shortly after starting up the system.

Thermography is a useful tool to see the actual thermal efficacy of an underfloor system from its start up (as shown) to its operating conditions. In a startup it is easy to identify the tube location but less so as the system moves into a steady state condition. It is important to interpret thermographic images correctly. As is the case with finite element analysis (FEA), what is seen, reflects the conditions at the time of the image and may not represent the steady conditions. For example, the surfaces viewed in the images shown, may appear ‘hot’, but in reality are actually below the nominal temperature of the skin and core temperatures of the human body and the ability to ‘see’ the pipes does not equate to ‘feel’ the pipes. Thermography can also point out flaws in the building enclosures (left image, corner intersection detail), thermal bridging (right image, studs) and the heat losses associated with exterior doors (center image).

Economics

There is a wide range of pricing for underfloor systems based on regional differences, application and project complexity. It is widely adopted in the Nordic, Asian and European communities consequently the market is more mature and systems relatively more affordable than North America where market share for fluid based systems remains between 3% to 7% of HVAC systems (ref. Statistics Canada and U.S. Census Bureau).

In energy efficiency buildings such as Passive House, R-2000 or Net Zero Energy, simple thermostatic radiator valves can be installed along with a single compact circulator and small condensing heater controlled without or with basic hot water reset control. Economical electric resistant based systems also are useful in small zones such as bathrooms and kitchens, but also for entire buildings where heating loads are very low and preferably where photovoltaic’s, wind or hydro is the generating source of electricity. Larger structures will need more sophisticated systems to deal with cooling and heating needs, and often requiring building management control systems to regulate the energy use and control the overall indoor environment.

Low temperature radiant heating and high temperature radiant cooling systems lend themselves well to district energy systems (community based systems) due to the temperature differentials between the plant and the buildings which allow small diameter insulated distribution networks and low pumping power requirements. The low return temperatures in heating and high return temperatures in cooling enable the district energy plant to achieve maximum efficiency. The principles behind district energy with underfloor systems can also be applied to stand alone multi story buildings with the same benefits. Additionally, underfloor radiant systems are ideally suited to renewable energy sources including geothermal and solar thermal systems or any system where waste heat is recoverable.

In the global drive for sustainability, long term economics supports the need to eliminate where possible, compression for cooling and combustion for heating. It will then be necessary to use low quality heat sources for which radiant underfloor heating and cooling is well suited.

System efficiency

System efficiency and energy use analysis takes into account building enclosure performance, efficiency of the heating and cooling plant, system controls and the conductivities, surface characteristics, tube/element spacing and depth of the radiant panel, operating fluid temperatures and wire to water efficiency of the circulators. The efficiency in electric systems is analyzed by similar processes and includes the efficiency of electricity generation.

Though the efficiency of radiant systems is under constant debate with no shortage of anecdotal claims and scientific papers presenting both sides, the low return fluid temperatures in heating and high return fluid temperatures in cooling enable condensing boilers, chillers and heat pumps to operate at or near their maximum engineered performance. The greater efficiency of 'wire to water' versus 'wire to air' flow due to water's significantly greater heat capacity favors fluid based systems over air based systems. Both field application and simulation research have demonstrated significant electrical energy savings with radiant cooling and dedicated outdoor air systems based in part on the previous noted principles.

In Passive Houses, R-2000 homes or Net Zero Energy buildings the low temperatures of radiant heating and cooling systems present significant opportunities to exploit exergy.

Efficiency considerations for flooring surface materials

System efficiency is also affected by the floor covering serving as the radiational boundary layer between the floor mass and occupants and other contents of the conditioned space. For example, carpeting has a greater resistance or lower conductance than tile. Thus carpeted floors need to operate at higher internal temperatures than tile which can create lower efficiencies for boilers and heat pumps. However, when the floor covering is known at the time the system is installed then the internal floor temperature

required for a given covering can be achieved through proper tube spacing without sacrificing plant efficiency (though the higher internal floor temperatures may result in increased heat loss from the non-room surfaces of the floor).

The emissivity, reflectivity and absorptivity of a floor surface are critical determinants of its heat exchange with the occupants and room. Unpolished flooring surface materials and treatments have very high emissivity's (0.85 to 0.95) and therefore make good heat radiators.

With underfloor heating and cooling ("reversible floors") flooring surfaces with high absorbance and emissivity and low reflectivity are most desirable.

Global examples of large modern buildings using radiant heating and cooling

- Manitoba Hydro Place, Canada
- California Academy of Science, United States
- Copenhagen Opera House, Denmark
- Post Tower, Germany
- Ewha Womans University, Korea
- NREL Research Support Facility, United States
- Suvarnabhumi International Airport, Bangkok
- la Defense Office, Netherlands
- Pearl River Tower, China
- 41 Cooper Square, United States
- Hearst Tower (New York City), United States
- Akron Art Museum, United States
- BMW Welt, Germany
- David Brower Center, United States

Chapter 10

Concentric Tube Heat Exchanger and Plate Heat Exchanger

Concentric tube heat exchanger

Concentric Tube (or Pipe) Heat Exchangers are used in a variety of industries for purposes such as material processing, food preparation and air-conditioning. They create a temperature driving force by passing fluid streams of different temperatures parallel to each other, separated by a physical boundary in the form of a pipe. This induces forced convection, transferring heat to/from the product.

Theory and application

The thermodynamic behaviour of concentric tube heat exchangers can be described by both empirical and numerical analysis. The simplest of these involve the use of correlations to model heat transfer; however the accuracy of these predictions varies depending on the design. For turbulent, non-viscous fluids the Dittus-Boelter Equation can be used to determine the heat transfer coefficient for both the inner and outer streams; given their diameters and velocities (or flow rates). For conditions where thermal properties vary significantly, such as for large temperature differences, the Seider-Tate Correlation is used. This model takes into consideration the differences between bulk and wall viscosities. Both correlations utilize the Nusselt number and are only valid when the Reynolds number is greater than 10,000. While Dittus-Boelter requires the Prandtl number to be between 0.7 and 160, Seider-Tate applies to values between 0.7 and 16,700.

For calculations involving the outer stream, the equivalent diameter (or mean hydraulic radius) is used in place of the geometric diameter, as the cross-sectional area of the annulus is not circular. Equivalent diameters are also used for irregular shapes such as rectangular and triangular ducts. For concentric tubes, this relationship simplifies to the difference between the diameters of the shell and the outer surface of the inner tube.

Transfer mode	Amount of heat transferred	Thermal Resistance
Conduction	$Q = \frac{T_1 - T_2}{L/kA}$	L/kA
Convection	$Q = \frac{T_{surf} - T_{envr}}{1/h_{conv} \cdot A_{surf}}$	$\frac{1}{h_{conv} \cdot A_{surf}}$
Radiation	$Q = \frac{T_{surf} - T_{surv}}{1/h_r \cdot A_{surf}}$	$\frac{1}{h_r \cdot A}$ $h_r = \epsilon \sigma A_{surf} (T_{surf} + T_{surv})(T_{surf}^2 + T_{surv}^2)$

Table 1 Equations for different heat transfer modes and their thermal resistances

$$D_{eo} = \frac{4 \cdot Area}{WettedPerimeter}$$

After the heat transfer coefficients ($h_{\{i\}}$ and $h_{\{o\}}$) are determined, and knowing the resistance due to fouling and thermal conductivity of the boundary material ($k_{\{w\}}$), the Overall Heat Transfer coefficient ($U_{\{o\}}$) can be calculated.

$$\frac{1}{U_o} = R_{fo} + R_{fi} \cdot \frac{D_o}{D_i} + \frac{D_o}{2k_w} \cdot \ln \frac{D_o}{D_i} + \frac{1}{h_o} + \frac{1}{h_i} \cdot \frac{D_o}{D_i}$$

The length of heat exchanger required can then be expressed as a function of the rate of heat transfer:

$$A = \frac{Q}{U \Delta t}$$

Where A is the surface area available for heat transfer and ΔT is the log mean temperature difference. From these results, the NTU method can be performed to calculate the heat exchanger's effectiveness.

$$q_{max} \equiv C_{min}(T_{h,i} - T_{c,i})$$

where

$$E \equiv \frac{q}{q_{max}}$$

Concentric tube heat exchanger design

The primary advantage of a concentric configuration, as opposed to a plate or shell and tube heat exchanger, is the simplicity of their design. As such, the insides of both surfaces are easy to clean and maintain, making it ideal for fluids that cause fouling. Additionally, their robust build means that they can withstand high pressure operations. They also produce turbulent conditions at low flow rates, increasing the heat transfer coefficient, and hence the rate of heat transfer. There are significant disadvantages however, the two most noticeable being their high cost in proportion to heat transfer area; and the impractical lengths required for high heat duties. They also suffer from comparatively high heat losses via their large, outer shells.

The simplest form is composed of straight sections of tubing encased within the outer shell, however alternatives such as corrugated or curved tubing conserve space while maximising heat transfer area per unit volume. They can be arranged in series or in parallel depending on the heating requirements. Typically constructed from stainless steel, spacers are inserted to retain concentricity, while the tubes are sealed with O-rings, packing, or welded depending on the operating pressures.

While both co and counter configurations are possible, the countercurrent method is more common. The preference is to pass the hot fluid through the inner tube to reduce heat losses, while the annulus is reserved for the high viscosity stream to limit the pressure drop. Beyond double stream heat exchangers, designs involving triple (or more) streams are common; alternating between hot and cool streams, thus heating/cooling the product from both sides.

Plate heat exchanger



An interchangeable plate heat exchanger

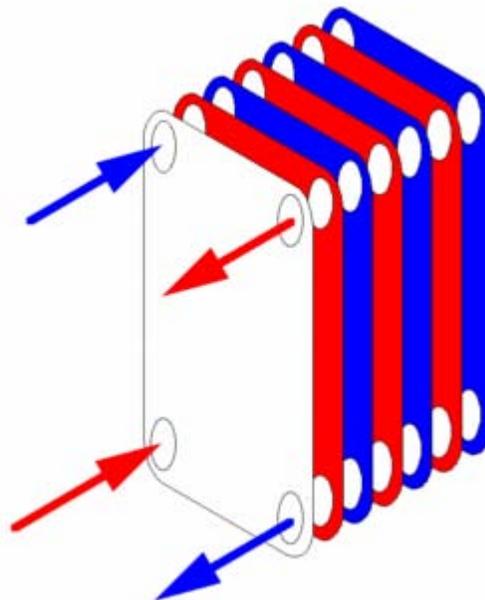
A **plate heat exchanger** is a type of heat exchanger that uses metal plates to transfer heat between two fluids. This has a major advantage over a conventional heat exchanger in that the fluids are exposed to a much larger surface area because the fluids spread out over the plates. This facilitates the transfer of heat, and greatly increases the speed of the temperature change. Plate heat exchangers are now common and very small brazed versions are used in the hot-water sections of millions of combination boilers. The high

heat transfer efficiency for such a small physical size has increased the domestic hot water (DHW) flowrate of combination boilers. The small plate heat exchanger has made a great impact in domestic heating and hot-water. Larger commercial versions use gaskets between the plates, smaller version tend to be brazed.

The concept behind a heat exchanger is the use of pipes or other containment vessels to heat or cool one fluid by transferring heat between it and another fluid. In most cases, the exchanger consists of a coiled pipe containing one fluid that passes through a chamber containing another fluid. The walls of the pipe are usually made of metal, or another substance with a high thermal conductivity, to facilitate the interchange, whereas the outer casing of the larger chamber is made of a plastic or coated with thermal insulation, to discourage heat from escaping from the exchanger.

The plate heat exchanger (PHE) was invented by Dr Richard Seligman in 1923 and revolutionised methods of indirect heating and cooling of fluids. Dr Richard Seligman founded APV in 1910 as the Aluminium Plant & Vessel Company Limited, a specialist fabricating firm supplying welded vessels to the brewery and vegetable oil trades.

Design of plate and frame heat exchangers



Schematic conceptual diagram of a plate and frame heat exchanger.



An individual plate for a heat exchanger

The plate heat exchanger (PHE) is a specialized design well suited to transferring heat between medium- and low-pressure fluids. Welded, semi-welded and brazed heat exchangers are used for heat exchange between high-pressure fluids or where a more compact product is required. In place of a pipe passing through a chamber, there are instead two alternating chambers, usually thin in depth, separated at their largest surface by a corrugated metal plate. The plates used in a plate and frame heat exchanger are obtained by one piece pressing of metal plates. Stainless steel is a commonly used metal for the plates because of its ability to withstand high temperatures, its strength, and its corrosion resistance. The plates are often spaced by rubber sealing gaskets which are cemented into a section around the edge of the plates. The plates are pressed to form troughs at right angles to the direction of flow of the liquid which runs through the channels in the heat exchanger. These troughs are arranged so that they interlink with the other plates which forms the channel with gaps of 1.3–1.5 mm between the plates.

The plates produce an extremely large surface area, which allows for the fastest possible transfer. Making each chamber thin ensures that the majority of the volume of the liquid contacts the plate, again aiding exchange. The troughs also create and maintain a turbulent flow in the liquid to maximize heat transfer in the exchanger. A high degree of turbulence can be obtained at low flow rates and high heat transfer coefficient can then be achieved.

A plate heat exchanger consists of a series of thin, corrugated plates which are mentioned above. These plates are gasketed, welded or brazed together depending on the application of the heat exchanger. The plates are compressed together in a rigid frame to form an arrangement of parallel flow channels with alternating hot and cold fluids.

As compared to shell and tube heat exchangers, the temperature approach in a plate heat exchangers may be as low as 1 °C whereas shell and tube heat exchangers require an approach of 5 °C or more. For the same amount of heat exchanged, the size of the plate

heat exchanger is smaller, because of the large heat transfer area afforded by the plates (the large area through which heat can travel). Expansion and reduction of the heat transfer area is possible in a plate heat exchanger.

Evaluating plate heat exchangers

All plate heat exchangers look similar on the outside. The difference lies on the inside, in the details of the plate design and the sealing technologies used. Hence, when evaluating a plate heat exchanger, it is very important not only to explore the details of the product being supplied, but also to analyze the level of research and development carried out by the manufacturer and the post-commissioning service and spare parts availability.

An important aspect to take into account when evaluating a heat exchanger are the forms of corrugation within the heat exchanger. There are two types: intermingling and chevron corrugations. In general, greater heat transfer enhancement is produced from chevrons for a given increase in pressure drop and are more commonly used than intermingling corrugations.

Advantages and disadvantages of plate heat exchangers

Advantages

- Compactness- The units in a plate heat exchanger occupy less floor space and floor loading by having a large surface area that is formed from a small volume. This in turn produces a high overall heat transfer coefficient due to the heat transfer associated with the narrow passages and corrugated surfaces.
- Flexibility- Changes can be made to heat exchanger performance by utilizing a wide range of fluids and conditions that can be modified to adapt to the various design specifications. These specifications can be matched with different plate corrugations.
- Low Fabrication Costs- Welded plates are relatively more expensive than pressed plates. Plate heat exchangers are made from pressed plates, which allow greater resistance to corrosion and chemical reactions.
- Ease of Cleaning- The heat exchanger can be easily dismantled for inspection and cleaning (especially in food processing) and the plates are also easily replaceable as they can be removed and replaced individually.
- Temperature Control- The plate heat exchanger can operate with relatively small temperature differences. This is an advantage when high temperatures must be avoided. Local overheating and possibility of stagnant zones can also be reduced by the form of the flow passage.

Disadvantages

- The main weakness of the plate and frame heat exchanger is the necessity for the long gaskets which holds the plates together. Although these gaskets are seen as

drawback, plate-and-frame heat exchangers have been successfully run at high temperatures and pressures.

- There is a potential for leakage. The leaks that occur are sent to the atmosphere and not between process streams.
- The pressure drop that occurs through a plate heat exchanger is relatively high and the running costs and capital of the pumping system should be considered.
- When loss of containment or loss of pressure occurs, it can take a long time to clean and reinitialise this type of exchanger as hundreds of plates are common in larger builds.
- The narrow spacing between plates can become blocked by particulate contaminants in the fluid, for example oxide and sludge particles found in central heating systems.
- for the reason above most manufacturers will only guarantee their units for 12 months, furthermore replacement plate and gasket sets can be as much as the plate to buy initially.

Plate heat transfer equation

The total rate of heat transfer between the hot and cold fluids passing through a plate heat exchanger may be expressed as: $Q = UA\Delta T_m$ where U is the overall heat transfer coefficient, A is the total plate area, and ΔT_m is the temperature difference. U is dependent upon the heat transfer coefficients in the hot and cold streams.

Chapter 11

Dynamic Scraped Surface Heat Exchanger and Thermal Wheel

Dynamic scraped surface heat exchanger

The **dynamic scraped surface heat exchanger** (DSSHE) was designed to face some problems found in other types of heat exchangers. They increase heat transfer by:

- removing the fouling layers,
- increasing turbulence in case of high viscosity flow,
- avoiding the generation of ice and other process by-products.

DSSHEs incorporate an internal mechanism which periodically removes the product from the heat transfer wall.

Introduction

The most important technologies for indirect heat transfer use tubes (shell-and-tube exchangers) or flat surfaces (plate exchangers). Their goal is to exchange the maximum amount of heat per unit area by generating as much turbulence as possible below given pumping power limits. Typical approaches to achieve this consist of corrugating the tubes or plates or extending their surface with fins.

However, these geometry conformation technologies, the calculation of optimum mass flows and other turbulence related factors become diminished when fouling appears, obliging designers to fit significantly larger heat transfer areas. There are several types of fouling, including particulate accumulation, precipitation (crystallization), sedimentation, generation of ice layers, etc.

Another factor posing difficulties to heat transfer is viscosity. Highly viscous fluids tend to generate deep laminar flow, a condition with very poor heat transfer rates and high pressure losses involving a considerable pumping power, often exceeding the exchanger

design limits. This problem becomes worsened frequently when processing non-newtonian fluids.

The dynamic scraped surface heat exchangers (DSSHE) have been designed to face the aforementioned problems. They increase heat transfer by:

- removing the fouling layers,
- increasing turbulence in case of high viscosity flow,
- avoiding the generation of ice and other process by-products.

Basic description

The dynamic scraped surface heat exchangers incorporate an internal mechanism which periodically removes the product from the heat transfer wall. The product side is scraped by blades attached to a moving shaft or frame. The blades are made of a rigid plastic material to prevent damage to the scraped surface. This material is FDA approved in the case of food applications.

Types of dynamic scraped surface heat exchangers

There are basically three types of DSSHEs depending on the arrangement of the blades:

1. *Rotating, tubular DSSHEs*. The shaft is placed parallel to the tube axis, not necessarily coincident, and spins at various frequencies, from a few dozen rpm to more than 1000 rpm. The number of blades oscillates between 1 and 4 and may take advantage of centrifugal forces to scrape the inner surface of the tube. Examples are the Waukesha Cherry-Burrell Votator II and the Alfa Laval Contherm.
2. *Reciprocating, tubular DSSHEs*. The shaft is concentric to the tube and moves longitudinally without rotating. The frequency spans between 10 and 60 strokes per minute. The blades may vary in number and shape, from baffle-like arrangements to perforated disk configurations.
3. *Rotating, plate DSSHEs*. The blades wipe the external surface of circular plates arranged in series inside a shell. The heating/cooling fluid runs inside the plates. The frequency is about several dozen rpm. An example is the HRS Spiratube T-Sensation.

Evaluation of dynamic scraped surface heat exchangers

Computational fluid dynamics (CFD) techniques are the standard tools to analyse and evaluate heat exchangers and similar equipment. However, for quick calculation purposes, the evaluation of DSSHEs are usually carried out with the help of ad-hoc (semi)empirical correlations based on the Buckingham π theorem:

$$Fa = Fa(Re, Re', n, \dots)$$

for pressure loss and

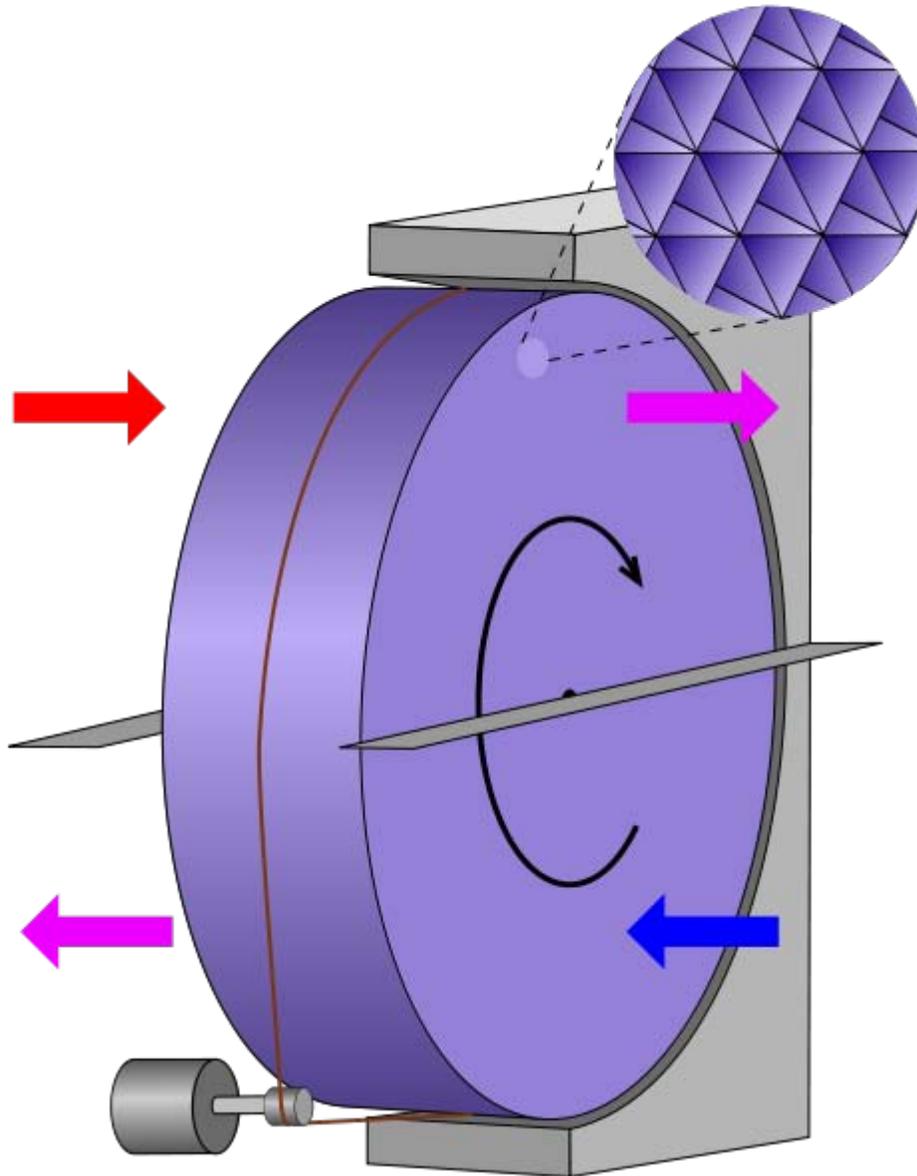
$$Nu = Nu(Re, Re', Pr, Fa, L/D, N, \dots)$$

for heat transfer, where Nu is the Nusselt number, Re is the standard Reynolds number based on the inner diameter of the tube, Re' is the specific Reynolds number based on the wiping frequency, Pr is the Prandtl number, Fa is the Fanning friction factor, L is the length of the tube, D is the inner diameter of the tube, n is the number of blades and the dots account for any other relevant dimensionless parameters.

Applications

The range of applications covers a number of industries, including food, chemical, petrochemical and pharmaceutical. The DSSHEs are appropriate whenever products are prone to fouling, very viscous, particulate, heat sensitive or crystallizing.

Thermal wheel



Diagrammatic operation of a thermal wheel

A **Thermal Wheel**, also known as a **Rotary heat exchanger**, or **Rotary air-to-air enthalpy wheel**, or **Heat recovery wheel**, is a type of energy recovery heat exchanger positioned within the supply and exhaust air streams of an air handling system, or in the exhaust gases of an industrial process, in order to recover the heat energy. Other variants include **Enthalpy wheels** and **Desiccant wheels**. A cooling-specific thermal wheel is sometimes referred to as a **Kyoto wheel**.

Description

A thermal wheel consists of a circular honeycomb matrix of heat absorbing material, which is slowly rotated within the supply and exhaust air streams of an air handling system. As the thermal wheel rotates heat is picked up from the exhaust air stream in one half of the rotation, and given up to the fresh air stream in the other half of the rotation. Thus waste heat energy from the exhaust air stream is transferred to the matrix material and then from the matrix material to the fresh air stream, raising the temperature of the supply air stream by an amount proportional to the temperature differential between air streams, or 'thermal gradient', and depending upon the efficiency of the device. The airstreams must be flowing in opposite directions or no beneficial heat exchange can occur. The principle of course works in reverse and 'coolth' energy can be recovered to the supply air stream if so desired and the temperature differential allows.

The heat exchange matrix is normally manufactured in aluminium, which has good heat transfer properties, but can also be manufactured from plastics and synthetic fibres. The heat exchanger is rotated by a small electric motor and belt drive system. The motors are often inverter speed controlled for improved control of the leaving air temperature. If no heat exchange is required then the motor can be stopped altogether.

Because of the nature of thermal wheels in the way that heat is transferred from the exhaust air stream to the supply air stream without having to pass directly through or via an exchange medium, the gross efficiencies are usually much higher than that of any other air-side heat recovery system. The shallower depth of the heat exchange matrix, as compared to that say for a plate heat exchanger, means that the pressure drop through the device is normally lower in comparison. Generally a thermal wheel will be selected for face velocities between 1.5 and 3.0 m/s, and with equal air volume flow rates gross 'sensible' efficiencies of 85% can be expected. Although there is a small extra energy requirement to rotate the wheel, the motor energy consumption is usually very low and has little affect upon the seasonal efficiency of the device. In addition, the ability to recover 'latent' heat, depending upon the materials and coatings used, can improve gross efficiencies by some 10% to 15%.

Energy transfer process

Normally the heat transfer between airstreams provided by the device is termed as 'sensible', which is the exchange of energy, or enthalpy, resulting in a change in temperature of the medium (air in this case), but with no change in moisture content. However, if moisture or relative humidity levels in the return air stream are high enough to allow condensation to take place in the device, then this will cause 'latent' heat to be released and the heat transfer material will be covered with a film of water. Despite a corresponding absorption of latent heat, as some of the water film is evaporated in the opposite airstream, the water will reduce the thermal resistance of the boundary layer of the heat exchanger material and thus improve the heat transfer coefficient of the device, and hence increase efficiency. The energy exchange of such devices now comprises both

sensible and latent heat transfer; in addition to a change in temperature, there is also a change in moisture content of the air streams.

However, the film of condensation will also slightly increase pressure drop through the device, and depending upon the spacing of the matrix material, this can increase resistance by up to 30%. This will increase fan energy consumption and reduce the seasonal efficiency of the device.

Aluminium matrices are also available with an applied hygroscopic coating, and the use of this, or the use of porous synthetic fibre matrices, allows for the adsorption and release of water vapour, at moisture levels much lower than that normally required for condensation and latent heat transfer to occur. The benefit of this is an even higher heat transfer efficiency, but it also results in the drying or humidification of airstreams, which may also be desired for the particular process being served by the supply air.

For this reason these devices are also commonly known as an **Enthalphy Wheel**

Use in Gas Turbines

During the automotive industry's interest in gas turbines for vehicle propulsion (around 1965), Chrysler invented a unique type of rotary heat exchanger that consisted of a rotary drum constructed from corrugated metal (similar in appearance to corrugated cardboard). This drum was continuously rotated by reduction gears driven by the turbine. The hot exhaust gasses were directed through a portion of the device, which would then rotate to a section that conducted the induction air, where this intake air was heated. This recovery of the heat of combustion significantly increased the efficiency of the turbine engine. This engine proved impractical for an automotive application due to its poor low-rpm torque. Even such an efficient engine, if large enough to deliver the proper performance, would have a low average fuel economy. Such an engine may at some future time be attractive when combined with an electric motor in a hybrid vehicle owing to its robust longevity and an ability to burn a wide variety of liquid fuels.

Desiccant Wheel

A **desiccant wheel** is very similar to a thermal wheel, but with a coating applied for the sole purpose of dehumidifying or 'drying' the air stream. The desiccant is normally Silica Gel. As the wheel turns, the desiccant passes alternately through the incoming air where the moisture is adsorbed, and through a "regenerating" zone where the desiccant is dried and the moisture expelled. The wheel continues to rotate and the adsorbent process is repeated. Regeneration is normally carried out by the use of a heating coil, such as a water or steam coil, or a direct-fired gas burner.

Thermal wheels and desiccant wheels are often used in series configuration to provide the required dehumidification as well as recovering the heat from the regeneration cycle.

Disadvantages

Thermal wheels are not suitable for use where total separation of supply and exhaust air streams is required, since air will bypass at the interface between the air streams at the heat exchanger boundary, and at the point where the wheel passes from one air stream to the other during its normal rotation. The former is reduced by brush seals, and the latter is reduced by a small purge section, formed by plating off a small segment of the wheel, normally in the exhaust air stream.

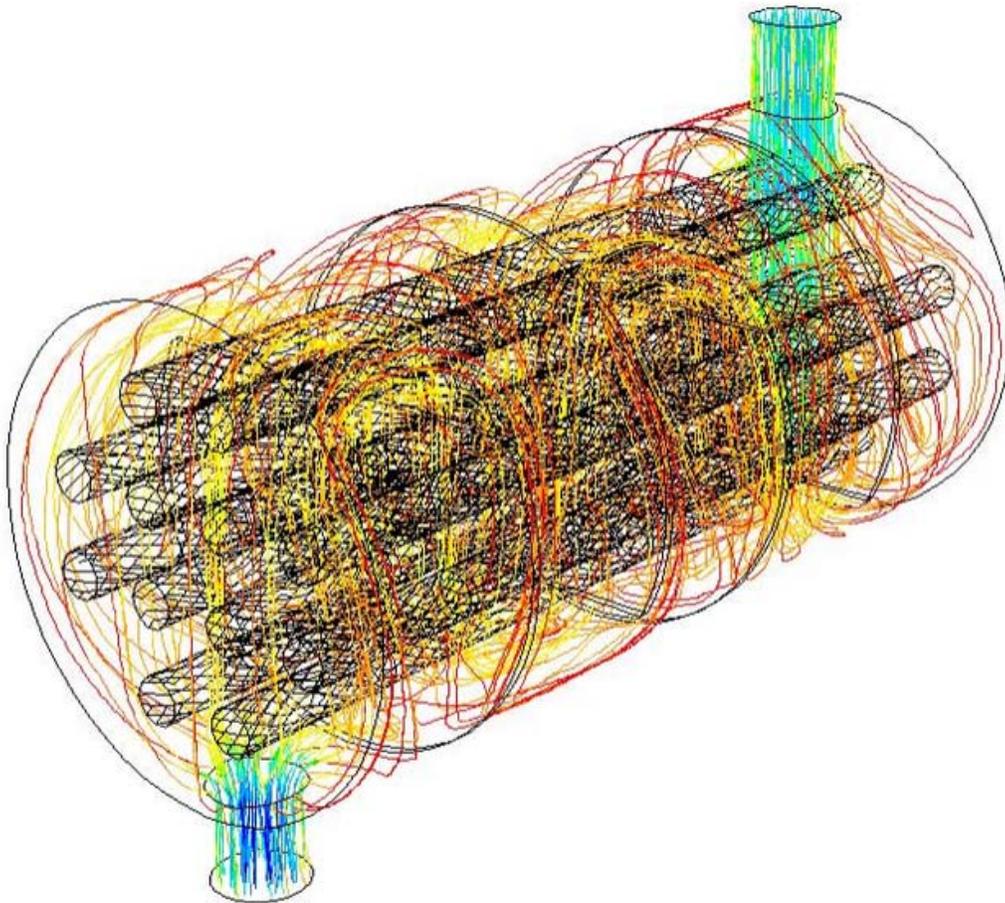
Matrices made from fibrous materials, or with hygroscopic coatings, for the transfer of latent heat, are far more susceptible to damage and degradation by 'fouling' than for plain metal or plastic materials, and are difficult or impossible to effectively clean if dirty. Care must be taken to properly filter the air streams on both exhaust and fresh air sided of the wheel.

Other types of air-to-air heat exchangers

- Run around coil
- Recuperator, or cross plate heat exchanger
- Heat pipe

Chapter 12

Shell and Tube Heat Exchanger



Fluid flow simulation for a shell and tube style exchanger; The shell inlet is at the top rear and outlet in the foreground at the bottom

A **shell and tube heat exchanger** is a class of heat exchanger designs. It is the most common type of heat exchanger in oil refineries and other large chemical processes, and is suited for higher-pressure applications. As its name implies, this type of heat exchanger

consists of a shell (a large pressure vessel) with a bundle of tubes inside it. One fluid runs through the tubes, and another fluid flows over the tubes (through the shell) to transfer heat between the two fluids. The set of tubes is called a tube bundle, and may be composed by several types of tubes: plain, longitudinally finned, etc.

Theory and Application

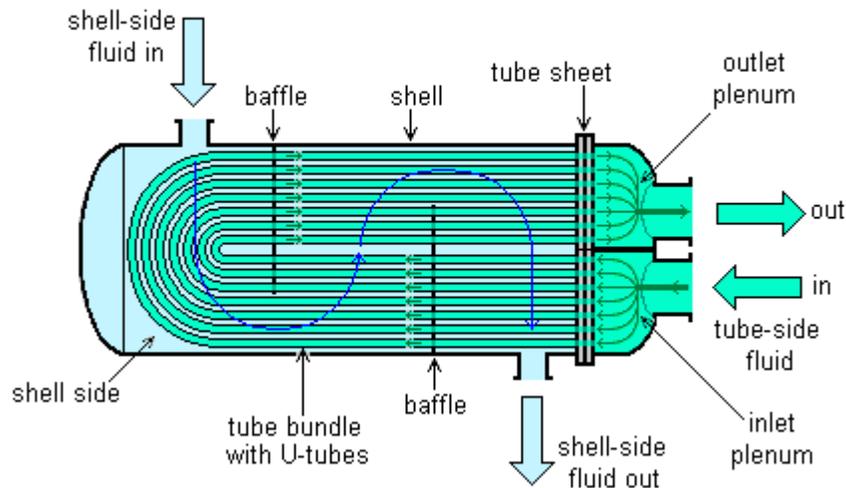
Two fluids, of different starting temperatures, flow through the heat exchanger. One flows through the tubes (the tube side) and the other flows outside the tubes but inside the shell (the shell side). Heat is transferred from one fluid to the other through the tube walls, either from tube side to shell side or vice versa. The fluids can be either liquids or gases on either the shell or the tube side. In order to transfer heat efficiently, a large heat transfer area should be used, leading to the use of many tubes. In this way, waste heat can be put to use. This is an efficient way to conserve energy.

Heat exchangers with only one phase (liquid or gas) on each side can be called one-phase or single-phase heat exchangers. Two-phase heat exchangers can be used to heat a liquid to boil it into a gas (vapor), sometimes called boilers, or cool a vapor to condense it into a liquid (called condensers), with the phase change usually occurring on the shell side. Boilers in steam engine locomotives are typically large, usually cylindrically-shaped shell-and-tube heat exchangers. In large power plants with steam-driven turbines, shell-and-tube surface condensers are used to condense the exhaust steam exiting the turbine into condensate water which is recycled back to be turned into steam in the steam generator.

Shell and tube heat exchanger design

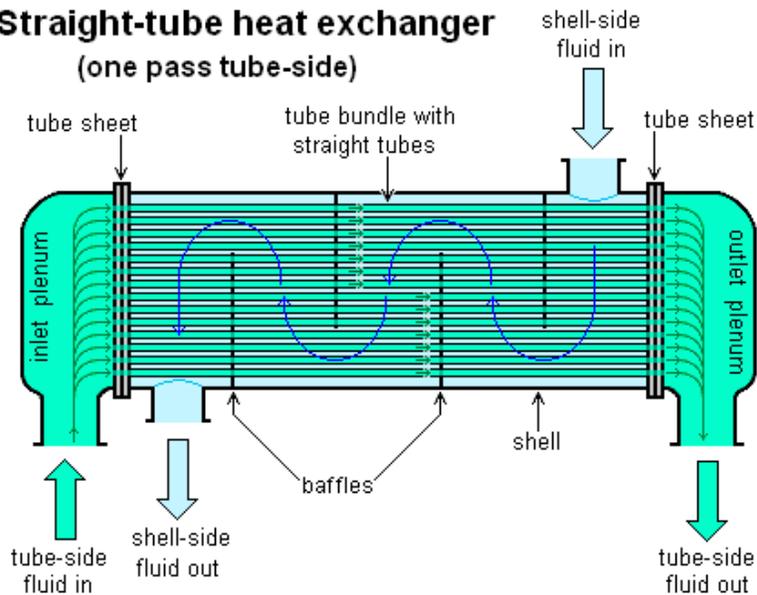
There can be many variations on the shell and tube design. Typically, the ends of each tube are connected to **plenums** (sometimes called **water boxes**) through holes in **tubesheets**. The tubes may be straight or bent in the shape of a U, called U-tubes.

U-tube heat exchanger

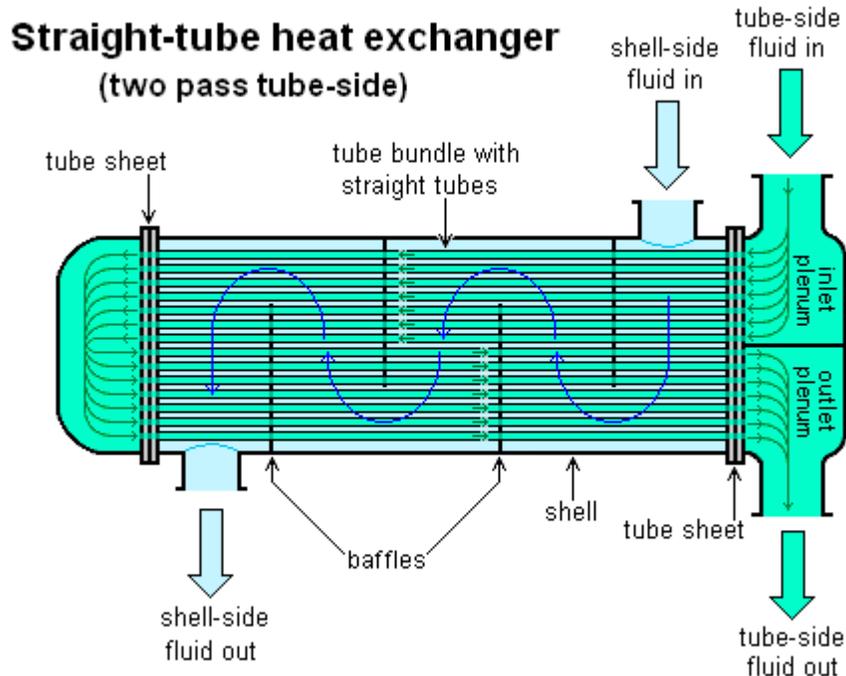


In nuclear power plants called pressurized water reactors, large heat exchangers called steam generators are two-phase, shell-and-tube heat exchangers which typically have U-tubes. They are used to boil water recycled from a surface condenser into steam to drive a turbine to produce power. Most shell-and-tube heat exchangers are either 1, 2, or 4 pass designs on the tube side. This refers to the number of times the fluid in the tubes passes through the fluid in the shell. In a single pass heat exchanger, the fluid goes in one end of each tube and out the other.

Straight-tube heat exchanger (one pass tube-side)



Surface condensers in power plants are often 1-pass straight-tube heat exchangers. Two and four pass designs are common because the fluid can enter and exit on the same side. This makes construction much simpler.



There are often baffles directing flow through the shell side so the fluid does not take a short cut through the shell side leaving ineffective low flow volumes.

Counter current heat exchangers are most efficient because they allow the highest log mean temperature difference between the hot and cold streams. Many companies however do not use single pass heat exchangers because they can break easily in addition to being more expensive to build. Often multiple heat exchangers can be used to simulate the counter current flow of a single large exchanger.

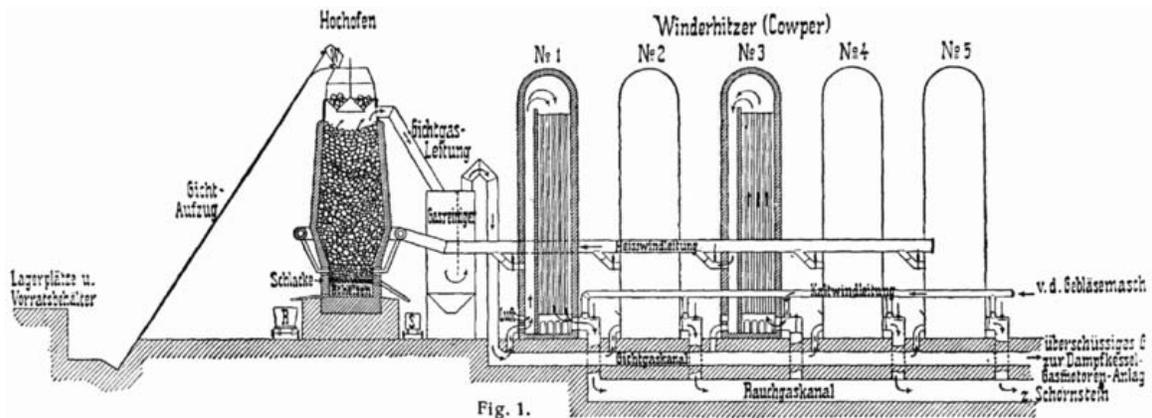
Selection of tube material

To be able to transfer heat well, the tube material should have good thermal conductivity. Because heat is transferred from a hot to a cold side through the tubes, there is a temperature difference through the width of the tubes. Because of the tendency of the tube material to thermally expand differently at various temperatures, thermal stresses occur during operation. This is in addition to any stress from high pressures from the fluids themselves. The tube material also should be compatible with both the shell and tube side fluids for long periods under the operating conditions (temperatures, pressures, pH, etc.) to minimize deterioration such as corrosion. All of these requirements call for careful selection of strong, thermally-conductive, corrosion-resistant, high quality tube materials, typically metals, including copper alloy, stainless steel, carbon steel, non-ferrous copper alloy, Inconel, nickel, Hastelloy and titanium. Poor choice of tube material could result in a leak through a tube between the shell and tube sides causing fluid cross-contamination and possibly loss of pressure.

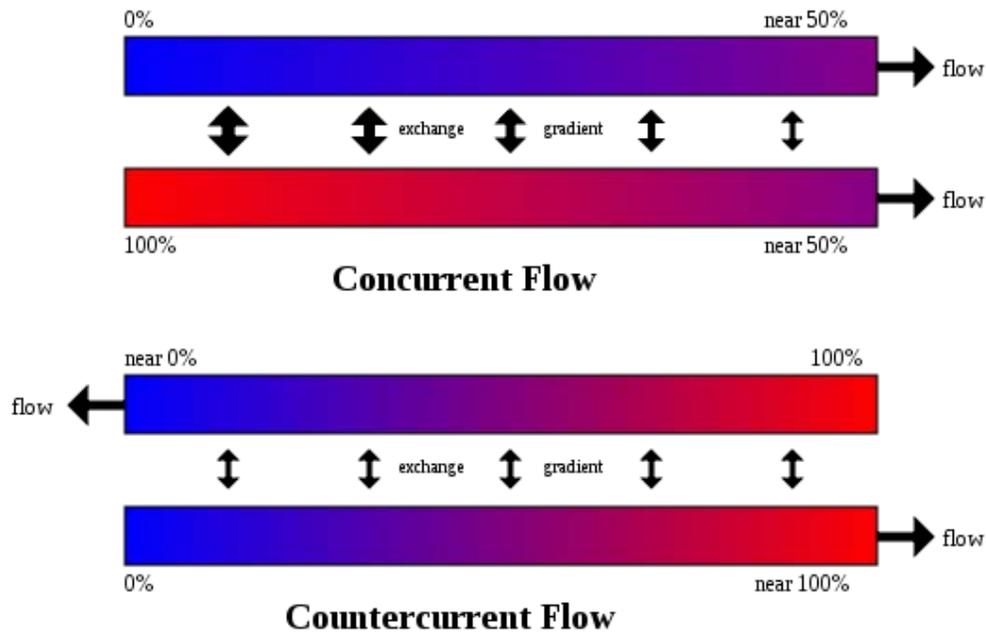
Chapter 13

Regenerative Heat Exchanger

A **regenerative heat exchanger**, or more commonly a **regenerator**, is a type of heat exchanger where the flow through the heat exchanger is cyclical and periodically changes direction. It is similar to a countercurrent heat exchanger. However, a regenerator mixes the two fluid flows while a countercurrent exchanger maintains them separated. The temperature profile remains at a nearly constant temperature, and this includes the fluid entering and exiting each end.



Five Cowper's regenerative heat exchanger placed in series.



Regenerative heat exchangers use counter-current exchange to minimize loss of heat while permitting flow.

In regenerative heat exchangers, the fluid on either side of the heat exchanger is nearly always the same fluid. The fluid is cycled through the heat exchanger, often reaching high temperatures. The fluid may go through an external processing step, and then it is flowed back through the heat exchanger in the opposite direction for further processing. Usually the application will use this process cyclically or repetitively. Thus, in regenerative heat exchangers, a fluid incoming to a process is heated using the energy contained in the fluid exiting this process.

The regenerative heat exchanger gives a considerable net savings in energy, since most of the heat energy is reclaimed nearly in a thermodynamically reversible way. This type of heat exchanger can have a thermal efficiency of over 90%, transferring almost all the relative heat energy from one flow direction to the other. Only a small amount of extra heat energy needs to be added at the hot end, and dissipated at the cold end, even to maintain very high or very low temperatures.

History

The regenerator was invented by Rev. Robert Stirling in 1816, and is commonly found as a component of his Stirling engine. The simplest Stirlings, and most models, use a less efficient but simpler to construct, *displacer* instead.

Types of regenerators

In **rotary regenerators** the matrix rotates continuously through two counter-flowing streams of fluid. In this way, the two streams are mostly separated but the seals are generally not perfect. Only one stream flows through each section of the matrix at a time; however, over the course of a rotation, both streams eventually flow through all sections of the matrix in succession. Each portion of the matrix will be nearly isothermal, since the rotation is perpendicular to both the temperature gradient and flow direction, and not through them. The two fluid streams flow counter-current. The fluid temperatures vary across the flow area; however the local stream temperatures are not a function of time.

In a **fixed matrix regenerator**, a single fluid stream has cyclical, reversible flow; it is said to flow "counter-current". This regenerator may be part of a valveless system, such as a Stirling engine. In another configuration, the fluid is ducted through valves to different matrices in alternate operating periods P_h and P_c resulting in outlet temperatures that vary with time.

Another type of regenerator is called a **micro scale regenerative heat exchanger**. It has a multilayer grating structure in which each layer is offset from the adjacent layer by half a cell which has an opening along both axes perpendicular to the flow axis. Each layer is a composite structure of two sublayers, one of a high thermal conductivity material and another of a low thermal conductivity material. When a hot fluid flows through the cell, heat from the fluid is transferred to the cell wells, and stored there. When the fluid flow reverses direction, heat is transferred from the cell walls back to the fluid.

A third type of regenerator is called a "*Rothemuhle*" regenerator. This type has a fixed matrix in a disk shape, and streams of fluid are ducted through rotating hoods. The *Rothemuhle* regenerator is used as an air preheater in some power generating plants. The thermal design of this regenerator is the same as of other types of regenerators.

Biology

We use our nose and throat as a regenerative heat exchanger when we breathe. The cooler air coming in is warmed, so that it reaches the lungs as warm air. On the way back out, this warmed air deposits much of its heat back onto the sides of the nasal passages, so that these passages are then ready to warm the next batch of air coming in.

Cryogenics

Regenerator heat exchangers are made up of materials with high volumetric heat capacity and low thermal conductivity in the longitudinal (flow) direction. At cryogenic (very low) temperatures around 20 K, the specific heat of metals are low, and so a regenerator must be larger for a given heat load.

Advantages of regenerators

The advantages of a regenerator over a recuperating (counter-flowing) heat exchanger is that it has a much higher surface area for a given volume, which provides a reduced exchanger volume for a given energy density, effectiveness and pressure drop. This makes a regenerator more economical in terms of materials and manufacturing, compared to an equivalent recuperator.

The design of inlet and outlet headers used to distribute hot and cold fluids in the matrix is much simpler in counter flow regenerators than recuperators. The reason behind this is that both streams flow in different sections for a rotary regenerator and one fluid enters and leaves one matrix at a time in a fixed-matrix regenerator. Furthermore flow sectors for hot and cold fluids in rotary regenerators can be designed to optimize pressure drop in the fluids. The matrix surfaces of regenerators also have self-cleaning characteristics, reducing fluid-side fouling and corrosion. Finally properties such as small surface density and counter-flow arrangement of regenerators make it ideal for gas-gas heat exchange applications requiring effectiveness exceeding 85%. The heat transfer coefficient is much lower for gases than for liquids, thus the enormous surface area in a regenerator greatly increases heat transfer.

Disadvantages of regenerators

The major disadvantage of a regenerator is that there is always some mixing of the fluid streams, and they can not be completely separated. There is an unavoidable carryover of a small fraction of one fluid stream into the other. In the rotary regenerator, the carryover fluid is trapped inside the radial seal and in the matrix, and in a fixed-matrix regenerator, the carryover fluid is the fluid that remains in the void volume of the matrix. This small fraction will mix with the other stream in the following half-cycle. Therefore regenerators are only used when it is acceptable for the two fluid streams to be mixed. Mixed flow is common for gas-to-gas heat and/or energy transfer applications, and less common in liquid or phase-changing fluids since fluid contamination is often prohibited with liquid flows.