Hydronic Heating: A Practical Overview

TR-114793

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REPORT SUMMARY

This booklet is a hydronic-heating primer for utility representatives, contractors, and homeowners. Its purpose is to foster a general knowledge and interest in modem hydronic heating.

Background

Hydronic heating uses water or steam as the source for heat transfer. Driven by the comfort benefits of hydronic radiant heat, this technique has seen a resurgence in the United States. Well-insulated homes and radiant-floor heating permit use of low-temperature water. Combined with new energy efficient models of hydronic heat pumps and combustion boilers, radiant heat offers a high level of comfort and energy efficiency. New piping materials, improved pumps and valves, and a variety of versatile control systems have made hydronics the heating choice of many home buyers.

Objectives

- To introduce consumers, designers, and builders to the advantages and disadvantages of hydronic heating systems.
- To explain the process of designing and installing hydronic systems.

Approach

The project team used existing reference material coupled with extensive site visits and discussions with hydronic system installers to develop a firm background in hydronic system technology. The draft material was then reviewed by hydronic practitioners for accuracy and completeness.

Results

This booklet discusses how hydronic systems work and briefly compares them with forced-air heating. It describes hydronic heat pumps, electric boilers, electric thermal storage, and fossil-fuel boilers. Selecting heat emitters is detailed, with descriptions of baseboard convectors, fan coils, panel radiators, and radiant floors. The booklet covers key elements in designing distribution and control systems. Also covered are domestic hot water, cooling, and installation issues.

EPRI Perspective

Hydronic heating has many virtues and advantages—including comfort, energy efficiency, and durability—but is generally more expensive and complex to design and install than forced-air heating. If design and planning are adequate, however, an experienced hydronic-heating contractor can install a system that will give customers a heating system generally superior to more conventional forced-air systems. This booklet introduces designers and builders to the process of designing and installing hydronic systems.

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Keywords
Residential energy use
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ABSTRACT

Hydronic heating has enjoyed a resurgence in the United States, driven by the comfort benefits of hydronic radiant heat. Well-insulated homes and radiant-floor heating allow the use of low-temperature water. Combined with new energy-efficient models of hydronic heat pumps and combustion boilers, radiant heat offers a high level of comfort and energy efficiency. New piping materials, improved pumps and valves, and a variety of versatile control systems make hydronics the heating choice of many discriminating home buyers. Domestic water heating is easy to integrate with the modern hydronic system. Cooling is still a challenge to integrate with hydronic heating and commonly requires the addition of an air handler with ducts. However, a radiant floor combined with room-sized fan-coils will provide effective cooling in well-designed homes, where indoor relative humidity can be closely controlled.

ACKNOWLEDGMENTS

Most of the information contained in this booklet originates from just a few sources. John Siegenthaler has chronicled this field better than anyone else in his text*, Modern Hydronic Heating* and in the *1999 Standard Guidelines* for the Radiant Panel Association (RPA) and in the RPA's book, *Radiant Basics*. John is an experienced and inventive engineer, whose talent for technical communication is a great benefit to the hydronics industry.

Dale Pickard answered a host of practical questions and loaned his expert technical review to this document. His 15 years of experience installing hydronic systems was a great help to the author. Thanks also to Dale's partner Bob Knebel for answering questions and arranging site visits. Many of the photographs in this booklet come from the files of Radiant Engineering.

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FOREWORD

This booklet is a hydronic-heating primer for utility representatives, contractors and homeowners. Its purpose is to encourage a general knowledge and interest in modern hydronic heating.

Hydronic heating has been used extensively for over 100 years. The word hydronic refers to central heating that employs a hot-water or steam distribution system. Steam is considered obsolete for heating buildings because of its excessive cycle losses and its hot radiators that resulted in room air stratification.

Both hydronic hot-water and steam heating were popular choices for central heating in the early part of the 20th century. In the 1950s forced-air heating gained the dominant market share when the modern furnace was introduced. Furnaces and ducts can be installed less expensively than a boiler and pipes.

In the past 15 years, hydronic hot-water heating has been gaining back some market share from forced-air heating. New system components, pioneered in Europe, are leading the way. Modern hydronic systems feature: easy-to-install plastic pipe, innovative valve designs, and electronic controls that can provide superior comfort and energy efficiency, when installed correctly.

CONTENTS

1.0 Choosing hydronics

The primary purpose of this booklet is to introduce consumers, designers, and builders to the advantages and disadvantages of hydronic heating systems, and also, to explain the process of designing and installing hydronic systems. Hydronic heating uses water or steam as the source of heat transfer. This booklet discusses hydronic heating with hot water only. (Hydronic cooling systems are also discussed, but to a lesser extent.)

Hydronic heating has many virtues and advantages, including comfort, energy efficiency, and durability, but it is generally more expensive and complex to design and install than forced-air heating. If the design and planning are adequate, however, an experienced hydronic-heating contractor can install a system that will give the customer a heating system generally superior to a more conventional forced-air system.

Cost is a key issue since hydronic heating is substantially more expensive than forced-air heating, and can vary widely depending on the choices made by the customer and designer. High-efficiency heat sources like condensing boilers and hydronic heat pumps are more expensive than conventional boilers. Radiant-floor heating is more labor-intensive and expensive than heating with baseboard convectors and wall-hung radiators. However, a growing number of consumers appear to believe that the benefits of a radiant floor outweigh the costs.

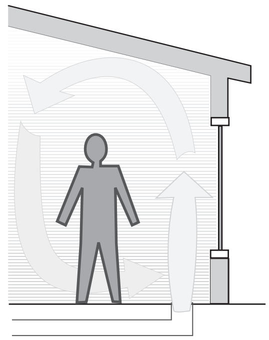
The best way to provide comfort is to create an indoor environment where the body effortlessly remains at thermal equilibrium with its surroundings. Thermal equilibrium means that the body is losing the required amount of heat—not too much or too little. Forced-air and radiant heating accomplish this goal in two different ways. Forced-air heating moves warm air throughout the living space, raising the air temperature and heating the objects in the room by convection. Radiant heat warms a building's contents and occupants, in turn, warming the air.

As we metabolize our food and operate our bodies in a relaxed way, we must release about 400

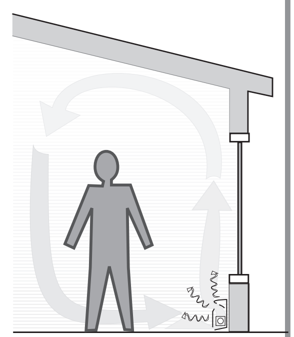
British thermal units per hour (Btuh) (117 watts) to remain at a constant 98.6° F (37.0° C). Almost half of this, or 190 Btuh (56 watts), is typically lost through radiation, with convection contributing about 120 Btuh and evaporation contributing 80 Btuh (23 watts). Radiant-heating experts profess that controlling the mean radiant temperature (MRT) is the most effective and efficient way to provide comfort because the human body's preferred heat-control mechanism is radiation. Every 1-degree Fahrenheit (0.6-degree Celsius) increase in MRT is equivalent to a 1.4°-F (0.8°-C) increase in air temperature.

The more a hydronic heating system relies on radiation, the more of these radiation-related benefits it provides. Large radiation surfaces like radiant floors theoretically provide the most comfort and efficiency advantages by reducing indoor temperature differences and temperature-induced air stratification common with forced-air heating and high-temperature hydronic convectors. The opportunity to use low-temperature water in radiant floors allows them to be coupled

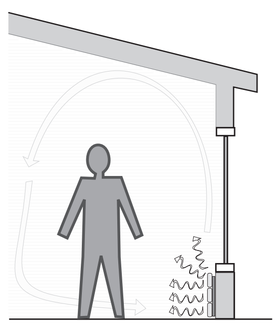
Convection versus radiation



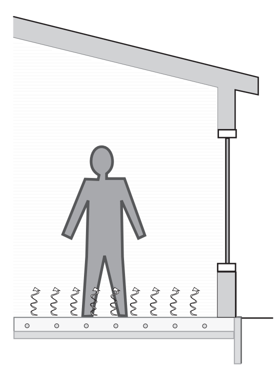
Forced-air heating depends exclusively on convection. The room's objects are warmed by moving air. Air stratification and cool floors can result. Windows are well dried by moving air, and window downdraft is overpowered by airflow from the register.



Hydronic radiant convectors heat primarily by convection with some radiation. Window downdrafts and condensation are prevented. Stratification and pressurization disadvantages can be avoided by using low water temperatures.



Panel radiators heat primarily by radiation with some convection to prevent most window downdrafts and condensation. Convection plays a lesser role, improving comfort.



Radiant floors heat exclusively by radiation. Radiant temperature controls bodily heat loss most comfortably. Radiant floors may need help from hydronic baseboard convectors to counteract sudden outdoor temperature changes, and to avoid condensation and downdrafts at large windows.

with condensing boilers and hydronic heat pumps to provide the most efficient heating systems available.

1.1 How a hydronic system works

Hydronic heating systems adjust temperature in a home with a combination of piped water and heat emitters. Hydronic systems often include domestic hot-water heating as part of the system. This document is almost entirely about hydronic heating because it is far more common than hydronic cooling. (See **Section 5.2** for a short discussion of hydronic cooling.)

The main component of a hydronic system is its heat source; the most common are combustion boilers and hydronic heat pumps. A combustion boiler burns gas or oil to produce the needed heat. A hydronic heat pump collects heat from the ground or from a water source, such as a well or lake.

Heat from the boiler or heat pump is circulated through the heat emitters by a pump or circulator. A circulator adds the mechanical energy needed to move the heated water through the heat emitters.

The most common heat emitter is the baseboard convector, although European-style wall-hung radiators are becoming more common. The popularity of radiant-floor heat is driving a revival of interest in hydronic systems, as evidenced by sales increases of these systems and their component parts.

Hydronic piping systems contain an expansion tank to allow the water to expand and contract as it's heated and cooled. Hydronic piping also contains vents to rid the system of air—a cause of corrosion and other problems.

1.2 Comparing hydronic heating with forced-air heating

The two main types of distribution systems for central heating are hydronic heating and forced-air heating. Forced-air heating uses ducts to distribute heated air from a furnace or air-source heat pump. Hydronic heat uses pipes and heat emitters to distribute heated water from a boiler or hydronic heat pump. Forced-air heating is the most popular residential application because of its lower initial cost and easier integration with central cooling compared to hydronic systems.

When properly designed and installed, hydronic heating offers the best comfort and the highest energy efficiency of any common heating system, although at higher cost and greater complexity. This cost-and-complexity disadvantage fades as a home gets larger, or with a multifamily building.

Advantages of hydronic heating include:

- Ability to zone rooms,
- More efficient use of space for pipes compared to ducts,
- Ability to control fluid temperature according to outdoor temperature,
- Ability to use low fluid temperatures in radiant floors, and
- Distributing heat more efficiently with pumps than fans.

Advantages of forced-air heating include:

- Less expense and complexity than hydronics,
- Easy and economical inclusion of cooling systems,
- Ready availability of high-efficiency furnaces that require no special installation procedures, and
- Reasonably priced electric heating and cooling from air-source heat pumps.

1.3 Energy efficiency

Forced-air and hydronic system efficiency varies widely, depending on design, equipment selection, and installation. Some forced-air systems are more efficient than their hydronic counterparts. However, hydronic systems usually have an energy-efficiency advantage over forced-air systems for the following reasons:

- Pipes waste less heat because of their smaller surface area and relative absence of leaks compared to ducts;
- Water moves heat many times more efficiently than air because water stores four times as much heat by weight and 3450 times as much heat by volume as air;
- Hydronic systems can be zoned far more easily and economically than forced-air systems;
- It’s far easier to adjust water temperature up

or down, according to both indoor and outdoor temperature, compared to air temperature; and

- A correctly designed hydronic system can avoid temperature-induced air stratification and room pressurization—energy problems commonly associated with forced-air heating.

A variety of design elements determine how close the hydronic system will come to its theoretical limit of energy efficiency:

- Matching the heat source to the load through multi-boiler systems or two-stage compressors in hydronic heat pumps;
- Designing piping systems to minimize hydraulic resistance without sacrificing operating effectiveness or control; and
- Using the lowest acceptable supply-water temperature by adjusting boiler-water temperature, valve setting, or pump speed, according to outdoor temperature.

These energy-saving advantages can be maximized, and can provide superior energy efficiency, if combined with an energy-efficient building shell.

1.4 The building shell

The performance of any heating system depends on the construction of the building shell. A well-insulated and airtight building will make almost any heating system shine. And conversely, a poorly insulated, drafty building may tarnish the performance of a well-designed and well-installed heating system. Flaws in the building shell have been the cause of many complaints to heating contractors about inadequate comfort. For this reason, many experts in the heating, ventilation, and air conditioning (HVAC) field are advising HVAC contractors to get involved in home heating and cooling projects early and to advise the building contractor and the customer to construct an energy-efficient building shell.

Air leakage through the shell is particularly difficult for a heating engineer or contractor to predict, and could range from 0.10 to 1.0 air changes per hour. Flaws in insulation can reduce the R-value of insulation by 15 to 30 percent, depending on their severity. Given this unpredictable variability, HVAC contractors often install a significantly oversized heating or cooling system. Installing oversized heating and cooling equipment costs the customer more initially, reduces system efficiency, and makes providing optimal comfort more difficult than installing a correctly sized system.

Home heat loss is divided between heat transmission and air leakage. The following are some simple thermal resistance standards to consider for minimizing heat transmission:

- U-0.40 or less window U factor;
- R-38 attic insulation with energy trusses that allow at least R-24 over top of outside walls;
- R-19 above-grade wall insulation;
- R-11 below-grade wall insulation;
- R-19 floor insulation between living spaces and uninsulated basement or crawl space; and
- Insulation should be installed touching the interior sheeting material. Batt insulation should be cut and sized very accurately, allowing no gaps or voids.

A home's air leakage must be measured, because experience shows it can't be estimated by visual inspection. If the air leakage is unknown and varies tenfold from one house to the next, how can a contractor or utility representative calculate the correct equipment size? Instruments called blower doors are used to measure air leakage, and the natural airflow rate is calculated from blower-door readings. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) has established a lower limit for air leakage in homes without mechanical ventilation systems. ASHRAE Standard 62-1989 states that a house should have 0.35 air changes of the complete house volume each hour under typical outdoor conditions. Homes with mechanical ventilation systems are allowed to be completely airtight, although it's rare for a home's leakage rate to be much less than 0.10 air changes per hour.

Planning an airtight home and mechanical ventilation system is safer and more realistic than expecting the building contractor to build the home "tight but not too tight." Most building scientists agree that airtight building-shell components protect a home from moisture-bearing air intrusion and resulting condensation damage. There is no accepted way of leaving gaps in floors, walls, or ceilings, to achieve the "tight but not too tight" specification. Recent scientific studies indicate that mechanical ventilation systems perform better in airtight homes than in looser homes. The same studies suggest that mechanical ventilation systems should have both fan-powered intake and exhaust to be effective at removing pollutants and keeping indoor air fresh.

1.5 Planning and design

The vast array of hydronic systems and components offers the contractor and customer abundant flexibility. However, the complexity and uniqueness of hydronic systems requires careful design and planning.

It's ideal to match a home's heating system to its design, and to include drawings and specifications for the heating system in the home's blueprints. Heating systems occupy space and require dedicated room or area. The heat source along with its circulators, valves, and controls need a dedicated space large enough to contain the equipment, while allowing extra working space for maintenance and repair. Baseboard convectors, wall-hung radiators, and fan coils also need some empty space around them to function properly, and should be located to minimize conflicts with furniture.

The home's heating load is determined by its climate, size, insulation levels, airtightness, and the energy efficiency of its windows and doors. The heating load is expressed in Btuh or kilowatts (kW), and is calculated using the design temperature of a particular climatic region. Design temperature is the temperature that a particular climate exceeds 97.5 percent of the time.

Better designers and contractors calculate both the total heating load for a home and the room-by-room heat loads needed to select the heat emitters and provide them with the proper flow rate and water temperature. These calculations are usually performed using a computer program designed for this purpose. Heat loads commonly range from 10 to 50 Btuh per square foot of floor space (32 to 158 watts per square meter), depending on climate and the characteristics of the building shell.

The design process continues with the designer and customers choosing the heat emitters and determining their location. Next the designer determines which heat emitters should be grouped together in zones. A piping diagram is next, combined with determination of hydraulic resistance for the heat emitters, piping, and fittings from the manufacturer's specifications. Each heat emitter, pipe, and fitting removes head or mechanical energy from the moving water, depending on its hydraulic resistance. Each of the system's piping circuits can be described by a graph of flow rate versus head loss. Head loss is the amount of mechanical energy removed from the water by a hydronic component or a whole piping circuit.

Planning, designing, and installing the system require the following tasks:

- Selecting the heater,
- Selecting the heat emitters,
- Designing the distribution and control system, and
- Installing and testing the heating system.

1.6 Quality installation

Planning and installing hydronic systems will tolerate few errors and omissions. A few minor service calls or failure of a single component could defeat the economic advantages anticipated by the customer. Simpler systems pose less potential problems and may be a better choice for less-experienced contractors.

Hydronic systems are often one-of-a-kind engineered systems. All components should be used only as recommended by the manufacturer. Pitfalls involving unsuitability or incompatibility of system components are more numerous than those found in forced-air systems.

Most hydronic systems have iron and steel components that will corrode if oxygen migrates into the system. There are two common ways oxygen gets in. The first is oxygen dissolved in makeup water. A design or installation flaw that allows water to escape through the pressure-relief valve or a leak will bring a steady supply of oxygen into the system through the makeup water valve. The second is too low pressure. If the circulator creates too great a suction within the valves and piping, oxygen from the air can be drawn in through vents or other openings.

A particular threat to boilers is condensation of water out of combustion gases that corrodes boilers and chimneys. The most common cause of this condensation is return water temperature to the boiler that is too cool. Control systems must be designed, installed, and adjusted to avoid this condition.

Selecting the proper pipe, fittings, and valves is critical to the system's durability. Mistakes in the application of these components have rendered new systems ineffective and in need of expensive modifications.

1.7 Choosing a fuel

The three fuels discussed in this book are electricity, gas, and oil. Price is a major concern to consumers, especially to those who have a choice of fuels. Natural gas and electricity have remained fairly stable in cost for about the past 15 years, with electricity about three times more expensive than natural gas per unit of heat. However, a hydronic heat pump with a Coefficient of Performance (COP) of between 3 and 4 is competitive with a condensing boiler with an *Annual Fuel Utilization Efficiency* (AFUE) of around 95 percent. (Efficiency comparisons are explained in **Section 2**.)

The efficiency of oil-fired boilers is about the same as gas-fired boilers, except that high-efficiency oil-fired condensing boilers aren't commonly available. Oil has experienced more cost increases and reductions than electricity and natural gas. However, it's anyone's guess how or if energy prices will change. Oil may rise and fall more than natural gas and electricity because oil is the leading transportation fuel and because the cost of oil is affected by politics of the oil-producing countries.

2.0 Selecting the heater

The heaters described here have one of three design types. They are fossil-fuel boilers, hydronic heat pumps, and electric boilers. Hydronic heat pumps and electric boilers have simple designs compared to fossil-fuel boilers, which have many different designs featuring various combustion systems, heat exchangers, and controls. Fossil-fuel boilers include those fired by oil, natural gas, and propane. Propane boilers are nearly identical to natural-gas boilers, except they have slightly different gas valves and burner orifices.

2.1 Hydronic heat pumps

Hydronic heat pumps use the refrigeration cycle to move heat from the earth or a body of water into the home during the heating season. Heat-pump systems that get their heat from a body of water, such as a well or lake, are called *open-loop systems* because the system is open to the atmosphere. *Closed-loop systems* extract heat from the earth using loops of buried pipe. These loops recirculate the same cold-water/antifreeze solution to move heat from the earth to the home.

The energy efficiency of a hydronic heat pump is expressed as a Coefficient of Performance (COP). Most hydronic heat pumps list a COP of between 3.0 and 3.5, meaning that they supply 3.0 to 3.5 kilowatt-hours (kWh) of heat for each kWh of electricity they consume.

Hydronic heat pumps can't produce the high temperatures required by most radiators and convectors. Radiant floors are a low-temperature heat emitter and are more compatible with hydronic heat pumps. Hydronic heat pumps offer the opportunity for both heating and cooling if matched to radiant floors, radiant walls or ceilings, fan coils, or air handlers with ducts.

Hydronic heat pumps, like air-source heat pumps, work best in well-insulated and airtight homes because they provide heat at a relatively low temperature.

2.1.1 Open-loop systems

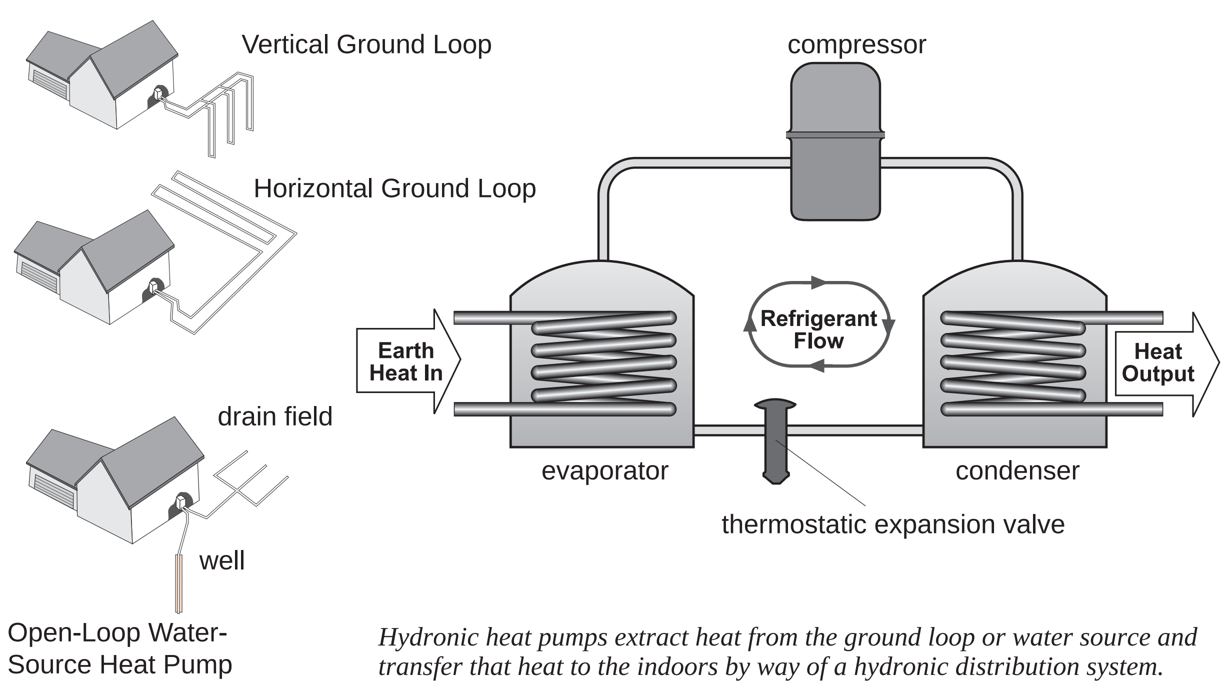
An open-loop system pumps water from a lake, pond, or underground aquifer through a water-to-refrigerant heat exchanger. Hydronic heat pumps require water flow of at least one gallon per minute (gpm) (0.13 liters per second [lps]) for each 6000 Btuh of heating capacity. Medium-to-large-sized systems may demand too much water for some wells. The well should have a verified flow rate of at least 10 gpm (0.63 lps) to handle the heat pump and domestic water. If you live in an area where well capacity varies from season to season or year to year, be sure to allow for this variation in your design. Also consider the electricity drawn by the water pump when comparing the heat pump's efficiency with other heat sources.

Water from lakes and wells must be returned to the ground unpolluted by water treatments. Lake and well water should be tested to analyze its potential to corrode the heat exchanger or deposit silt or minerals.

2.1.2 Closed-loop systems

The key to a successful closed-loop system is a contractor or engineer who understands the design of the ground loop. The ground loop's design and installation, including materials, soil type, and the loop's depth and configuration must be appropriate to the site, climate, and size of the

Components and functioning of a hydronic heat pump



Hydronic heat pumps extract heat from the ground loop or water source and transfer that heat to the indoors by way of a hydronic distribution system.

heating system. Piping materials and connections in particular will tolerate no compromise. A well-designed and well-installed ground loop will last decades, and a poorly designed and installed ground loop may never work properly, or fail in a few years.

2.2 Electric boilers and electric thermal storage

Although electricity as a fuel is typically two to four times as expensive as fossil fuels, electric boilers have some advantages over combustion boilers. Electric boilers have two or more heating elements that can be staged to match the load. And, electric boilers are tolerant of low return-water temperature, which can cause thermal shock or corrosion in fossil-fuel boilers. Electric boilers also eliminate the safety hazards involved with combustion, venting, and fuel storage.

Some electric utilities have lower rates for off-peak use than for on-peak use. Electric thermal-storage systems heat water with off-peak electricity and store this heat for on-peak use. The stored heat is provided by an electric boiler, a hydronic heat pump, or electric heating elements installed in a large, insulated storage tank.

2.3 Fossil-fuel boilers

Gas- and oil-fired boilers are by far the most popular heat sources for hydronic heating systems. Boilers are classified by the materials and design of their heat exchanger. Many gas and oil boiler designs are identical except for the burner—either oil or gas. The two dominant designs are cast-iron-sectional boilers and copper water-tube boilers.

2.3.1 Energy-efficient gas combustion

Boiler efficiency is measured in laboratories by a standard test procedure that yields an Annual Fuel Utilization Efficiency (AFUE). AFUE measures the efficiency of the combustion process and considers cycle losses and losses through the cabinet of the boiler. The most important advance made by newer, energy-efficient boilers over older, conventional models is the reduction of both combustion air and dilution air. Draft-producing blowers regulate combustion air to the heat exchanger, forcing combustion by-products through tighter spaces, where the heat is removed more effectively than in atmospherically vented boilers. Dilution air—chimney-balancing air that comes from the home—is reduced or eliminated because the boiler's blower regulates the venting of combustion products.

Technicians should use combustion-test equipment to verify the safe and efficient operation of new gas and propane boilers. Modern combustion test equipment measures excess combustion air, carbon monoxide, and flue-gas temperature to estimate efficiency and evaluate combustion safety.

Conventional boilers in existing buildings have AFUEs of 68 to 80 percent. Mid-efficiency boilers have AFUEs of 82 to 87 percent. And, high-efficiency gas boilers have AFUEs ranging from 90 to 96 percent. The boiler efficiency has increased because of a number of important innovations:

- Electronic ignition (no pilot light);
- Vent dampers to limit airflow through the heat exchanger when the burner is off;
- Heat exchangers made smaller, lighter, and of better materials;
- Fans that control combustion air more precisely than atmospheric draft; and
- Water vapor condensed from flue gases, yielding latent heat for extra efficiency in gas boilers (AFUEs of over 90 percent).

The continuous pilot lights in conventional gas boilers use about 3 percent of the boiler's total gas consumption. Intermittent ignition devices (IIDs) eliminate this waste and are featured on all new mid- and high-efficiency gas boilers. The least advanced type of mid-efficiency gas boiler has an IID and a vent damper that closes off the flue when the burner is not operating.

The more advanced mid-efficiency boilers have a draft-assisting fan in the flue just above the heat exchanger. The fan draws combustion air into the heat exchanger as it pulls exhaust gases out at a controlled rate. This greatly reduces excess combustion air that conveys heat from the combustion process up the chimney. The draft-assisting fan also reduces or eliminates dilution air that increases home air leakage by creating a slight vacuum. These mid-efficiency boilers are vented vertically through existing chimneys (assuming the chimney is properly lined) or horizontally, through an exterior wall, using a manufactured stainless-steel vent.

Mid-efficiency furnaces and boilers have had problems with condensation in their chimneys and heat exchangers. The condensing boilers (high efficiency) have the advantage of being designed to reclaim the latent heat from the condensation and to resist corrosion.

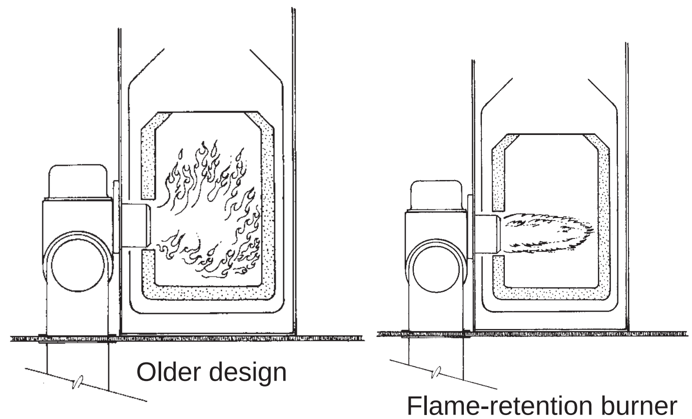
Natural-gas combustion produces large amounts of water vapor. About 12 percent of the total heat in the gas is tied up in the water vapor's latent heat. This accounts for the high-efficiency boilers' dramatic increase of AFUE from the mid-80 to the mid-90-percent range. The water vapor condenses in a corrosion-resistant section of the heat exchanger and flows to a drain. The combustion gases are so cool they exit through horizontal plastic pipe passing through a nearby outside wall.

2.3.2 Energy-efficient oil combustion

High-efficiency oil boilers have AFUEs of 80 to 87 percent, compared to conventional boilers with AFUEs of 68 to 80 percent. The high-efficiency oil boilers contain a number of important improvements over older models:

- Flame-retention oil burners provide better fuel-air mixing and a more efficient flame;
- Combustion gases travel more slowly through the combustion chamber and heat exchanger compared to older models;
- Interruptable igniters shut off once the flame is established instead of operating during the entire cycle;
- Solid-state igniters and controls reduce the burner's electrical consumption; and

Oil combustion evolution



Older oil gun-type burner design shown at left has been replaced by the flame-retention oil burner that swirls the oil-air mixture into a tighter, hotter tube of flame.

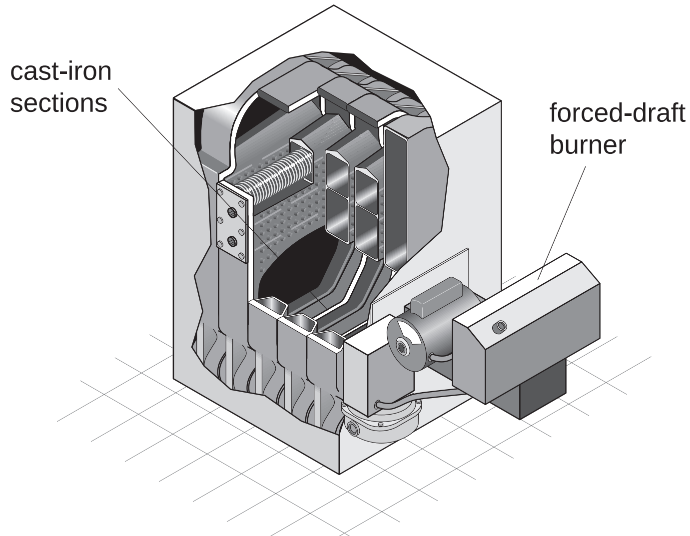
- Solenoid valves provide immediate oil shutoff, reducing oil drips after the flame is extinguished.

Oil burners can only reach their rated efficiency when adjusted using a combustion analyzer. Technicians use combustion analyzers to test the newly installed boiler and during yearly or bi-yearly service calls.

2.3.3 Cast-iron and steel boilers

Cast-iron sectional boilers have a series of boxlike cast-iron sections connected by watertight fittings. Hot combustion gases flow through spaces between the sections, heating the cast-iron and water. Cast-iron boilers are mass-produced and are the most common type of boiler for residential use, owing to their availability and reasonable cost.

Cast-iron sectional boiler



Cast-iron sectional boilers are available with gas or oil burners. Their efficiency has improved because of better burners and more efficient venting, along with the elimination of the pilot light.

Wet-base cast-iron boilers have become very popular because of their improved efficiency. Wet-base boilers have a cast-iron heat exchanger that surrounds the combustion chamber. The more traditional dry-base heat exchangers sit above the combustion chamber and miss the opportunity to collect heat that radiates sideways and downwards from the flame.

Steel fire-tube boilers have a steel tank with internal tubing. The tubes, which carry the combustion gases, may be oriented vertically or horizontally.

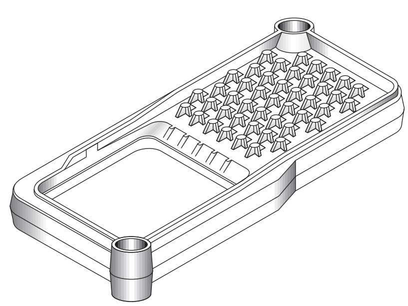
Both cast-iron and steel fire-tube boilers are high-mass boilers, weighing from 300 to 600 pounds (136 to 272 kilograms) when full of water. The boilers' metal and water require considerable energy to reheat to their operating temperature during each heating cycle. Much of this heat is lost up the chimney between cycles, a major disadvantage in using high-mass boilers. This cycling energy waste can be reduced by:

- Sizing the boiler accurately to a home's maximum heat loss;
- Installing a vent damper to minimize flue losses during the off-cycle; and
- Using a modular boiler system, composed of two or more smaller boilers.

Design and installation flaws can cause corrosion in cast-iron and steel boilers. If return water is below 130° F (54° C), acidic condensation can form on the heat exchanger and venting system and corrode these vital boiler parts. To protect the boiler from condensation, make sure the system has a control that temporarily shuts down the circulator if the water temperature gets too low. Radiant floors and other low-temperature heat emitters pose a threat to iron and steel boilers, if piped directly, because of low return-water temperature from the heat emitter. Designers use mixing valves or secondary piping circuits to provide boilers with protection against low return-water temperature.

Dissolved oxygen can corrode iron or steel parts such as heat exchangers or pump housings. The oxygen originally dissolved in the system's water isn't a problem, but oxygen continually introduced in makeup water or through air leaking into the system could eventually corrode and ruin the iron or steel boilers, pumps, and valves. Water leaks or discharges through the pressure relief valve cause makeup water to flow into the system, carrying a continual influx of oxygen. Air can be sucked in through air vents if the circulator drops the system's water pressure below atmospheric pressure. Finally, plastic pipe without an oxygen barrier can allow small amounts of oxygen into the system.

Wet-base boiler section



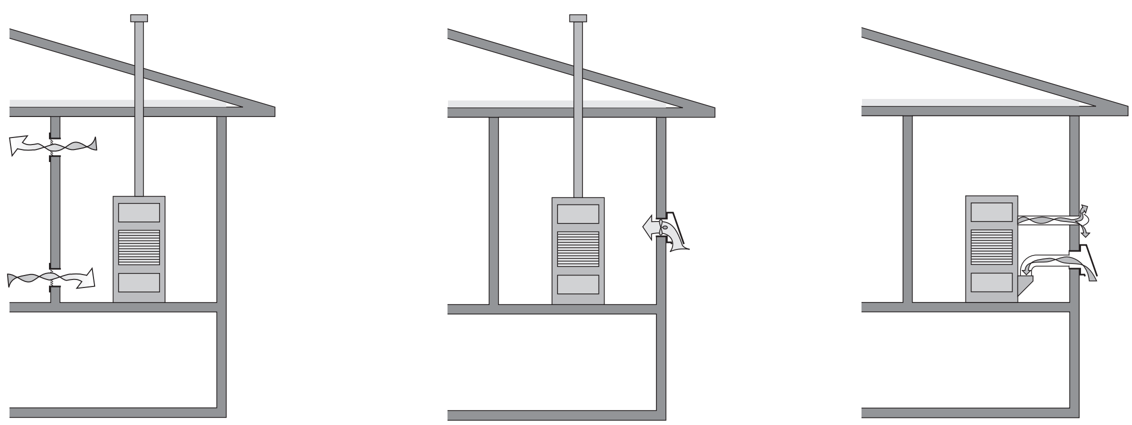
Another significant energy improvement to cast-iron boilers is the wet-base boiler. These boilers have cast-iron sections that wrap around the sides and bottom of the combustion chamber.

2.3.4 Low-mass and condensing boilers

Copper water-tube boilers are popular for central heating, pool heating, hot tubs, and domestic hot water. The copper is corrosion-resistant, but even copper boilers can corrode under a steady diet of oxygen. Copper water-tube boilers and other low-mass boilers can be quickly destroyed by thermal shock if water stops circulating while the burner is firing. The hydronic system's design must assure continuous circulation during firing and emergency burner shutoff.

The water vapor, formed by the combustion process, represents about 12 percent of the burner's heat. Several manufacturers make boilers that condense water out of the flue gases, reclaiming this heat. The condensing boiler's corrosion-resistant heat exchanger needs cool return water to actually condense the heat-laden water out of the flue gases. If the return water is above 130° F (54° C), there will be little condensation and the boiler's efficiency will be about the same as a mid-efficiency boiler. Condensing boilers are often paired with radiant floors because

Providing combustion air to boilers in confined mechanical rooms



Linking the confined space to a garage or the home's interior through high and low vents increases the availability of combustion air. This approach fulfills code requirements.

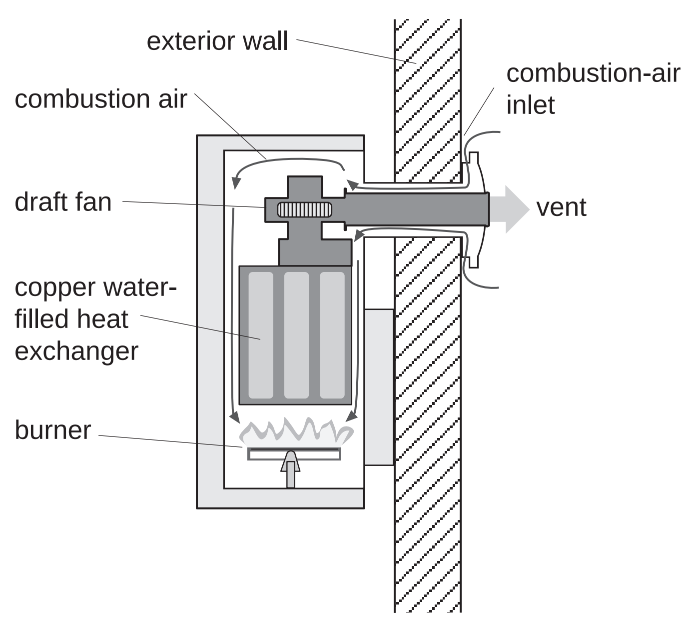
Providing the confined mechanical room with fan-powered combustion air is superior to passive vents because the fan can overpower most wind effects.

Sealed combustion provides the best safety and reliability of any combustion-air method.

radiant floors return low-temperature water. The lower the return-water temperature, the higher the condensing boiler's efficiency.

Manufacturers once underestimated the acidic condensate's corrosiveness and fire's ability to burn lightweight metal, and consequently many of the early condensing boilers failed. New condensing boilers, using stainless steel or electroplated coatings, are more reliable. Oil-fired condensing boilers aren't common because condensing flue gases doesn't raise their efficiency nearly as much as boilers designed for natural gas and propane. Oil doesn't have as much hydrogen as natural gas so there isn't as much water in the oil boiler's flue gases. Oil boilers' flue gases contain sulfur, as well, creating very corrosive sulfuric acid condensate.

Low-mass direct-vent boiler



Low-mass direct-vent boilers are usually variations of the water-tube boiler.

3.0 Selecting heat emitters

The heat emitters discussed here give off heat by convection and radiation—radiation providing generally better comfort. Each heat emitter has a Btuh (kW) rating depending on its length or size, the flow rate through it, and the supply-water temperature. Baseboard convectors are the most common type of heat emitter used in North America. Panel radiators are the most common type in Europe.

3.1 Baseboard convectors

Residential baseboard convectors, for years the mainstay of the industry, are usually 6 to 8 inches (15 to 20 centimeters) high. Of the heat emitters discussed here, baseboard convectors are the least expensive and most commonly used. Their element is a 1/2-inch (1.3-cm) or 3/4-inch (1.9-cm) copper tube fitted with rectangular aluminum fins. Baseboard convectors come in sections 2 to 10 feet (0.61 to 3.0 meters) long. The heating capacity of baseboard convectors generally ranges from 300 to 700 Btuh per linear foot (3.4 to 8.0 kW per meter), depending on the design, circulating water temperature, and water flow rate.

A minimum of 6 inches (15 cm) of clearance should be maintained in front of baseboard convectors to allow for air circulation. Baseboard convectors should never be installed where they will interfere with a swinging door.

Baseboard convection is advantageous because moving air reduces condensation on glass and counteracts cold downdrafts from windows. Rising air from the convectors blankets exterior walls, raising their radiant temperature. However, baseboard convectors may create temperature-induced air stagnation when they circulate high-temperature water. And, they may not provide acceptable comfort when used as the only heat emitter for rooms with high ceilings. Baseboard convectors are susceptible to mechanical damage and their steel housings rust in damp environments, such as bathrooms.

Baseboard convectors can be noisy, especially when the system is cycling frequently and circulating high-temperature water. This noise usually can be eliminated by purchasing good-quality convectors and limiting the water temperature with an effective control system.

Baseboard convectors vary in quality, cost, and design. One standard design includes a return pipe that doubles back inside the enclosure, allowing both connections to be made on one end. Another design has two tiers of finned tube, providing about double the heat output of the one-tiered design or the same heat output with half the length.

3.2 Fan coils

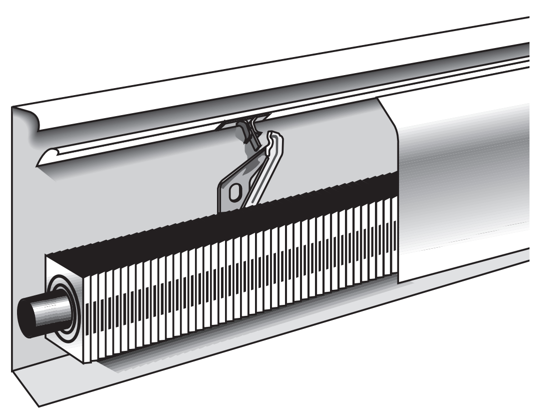
Fan coils can provide equivalent heating capacity to other heat emitters, while circulating cooler water and using less wall space. They can be used with lower temperature heat sources, such as condensing boilers and hydronic heat pumps. Since fan coils use copper pipe that doesn't readily oxidize, they can be used with both open and closed systems.

Fan coils require an electrical connection to power their fans. Dust accumulation on coils can significantly hinder fan-coil performance, particularly when the fan coil operates at a low temperature. Some units are equipped with filters that must be changed or cleaned regularly. Others need coil cleaning on a regular basis.

Kick-space heaters are specialty fan coils that fit under cabinets or into stair risers. Room air is sucked through the top of the kick-space heater's grill and changes direction in the fan. The air is then heated by the coil and pushed out the bottom of the grill. These heaters are especially prone to dust accumulation and must be installed with adequate access for cleaning.

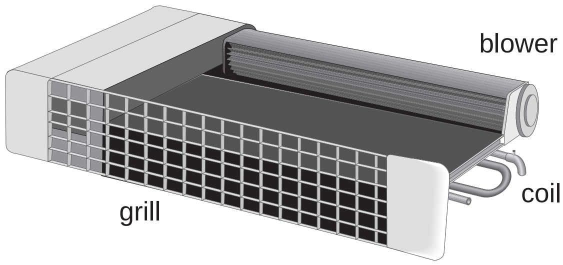
Larger fan coils, called air handlers, connect to supply and return ducts like a forced-air furnace. These hydronic air handlers may have an A-coil for cooling or a heat-recovery

Hydronic baseboard convectors



Baseboard convectors are the traditional hydronic heat emitter. They are inexpensive and readily available. Avoid using them in bathrooms, kitchens, and other high-traffic or moisture-prone areas.

Kick-space heater



Kickspace heaters are small fan coils designed for kitchens and large bathrooms. They preserve space and are installed under a cabinet, out of harm's way.

ventilator for whole-house ventilation.

Any fan coil equipped with a drip pan and drain tube can be used for summer cooling, when provided cold water from a hydronic heat pump or chiller. Combined with radiant floors, fan coils are being used to cool multifamily buildings, commercial buildings, and homes.

3.3 Panel radiators

Panel radiators have been used for years in Europe but have only recently become popular in America. Panel radiators are made from steel or aluminum panels welded or pressed together into flat sections. Radiators are vulnerable to corrosion and mineral build-up and so water quality is very important when using open hydronic systems.

Panel radiators are either designed primarily for radiation or for a combination of radiation and convection. The latter can provide a greater heat output than the former, given approximately equal space. The difference in design between radiators and radiator/convectors is the addition of steel fins mounted vertically to the back of the panel or between two panels.

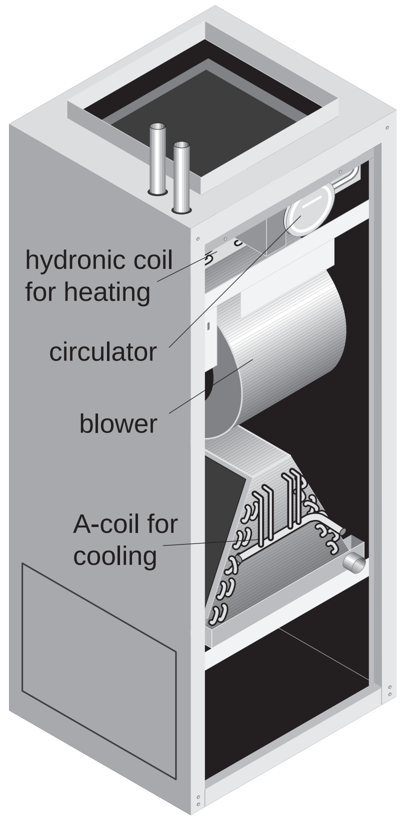
Panel radiators come in a wide variety of sizes and shapes, making them the most versatile type of heat emitter and especially well-suited for retrofit.

3.4 Radiant floors

Radiant floors give hydronic heating the ability to produce both the best comfort and the highest energy efficiency available from any central heating system. However, radiant floor heating is also the most demanding distribution system in terms of design, planning, and installation. Radiant floors offer the following advantages:

- The unbeatable comfort of low-temperature radiant heat;

Hydronic air handler



A hydronic air handler is the missing link to providing a highly effective heating, cooling, and ventilation system. Heat the home with radiant slabs. Then provide cooling and ventilation air through the air handler, delivered from ceiling registers that are very effective for cool-air delivery.

Panel radiators

This European-style panel radiator heats partly by radiation and partly by convection.

Runtal Radiators

Panel radiators are available in a variety of styles, including models that warm towels as an auxiliary feature.

- The efficiency advantage of low water temperature, 90° F (32° C) to 130° F (54° C) for radiant floors versus 130° F (54° C) to 180° F (93° C) for radiators and convectors; and
- The efficiency advantage of being able to use a condensing boiler or hydronic heat pump.

To achieve all three of these advantages requires an energy-efficient building shell and a well-designed and well-installed hydronic heating system.

A radiant floor can be hydronic piping buried in an insulated concrete slab or a layered wood floor that incorporates hydronic tubing. A concrete slab gives superior heat transfer and is the most economical type of radiant floor. Masonry tile is an ideal finish flooring material to enhance the concrete's heat-transfer capability. However, bare concrete or concrete with tile are considered too hard and unyielding by many home buyers.

Thin masonry slabs incorporate the conductivity of masonry with a more conventional wood floor.

Thin slabs are poured gypsum or concrete, installed over a wood subfloor. Gypsum slabs are installed by pumping the liquid gypsum mix through a hose onto the floor. Concrete is poured in the traditional way out of a truck from a batch plant. Pouring thin slabs carries a lot of water into the home. The slab and the surrounding building materials must have adequate time to dry before final finishes are applied and the home is occupied.

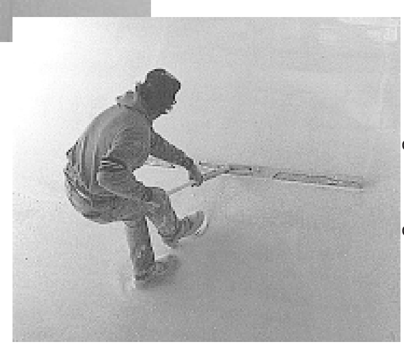
Either thin-slab system must be planned into the home design at an early stage so that preparations for cabinets, plumbing fixtures, door thresholds, and stair headroom can allow for the extra thickness of the slab. Waiting until construction has started to choose a thin slab can cause some major headaches, especially for the carpenters.

If the thin slab will have a wood finish floor, wood nailers must be installed on the wood subfloor before the thin slab is poured. The top side of the wood nailers is level with the slab and serves as a fastening surface for the wood flooring or underlayment for carpet.

Radiant floors require different water temperatures, depending on

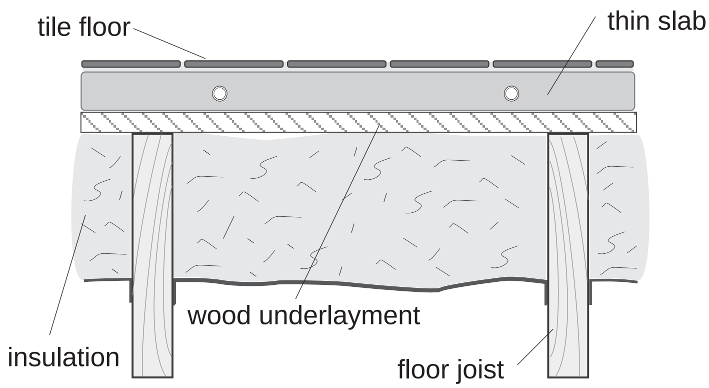
Radiant masonry slabs

Incorporating radiant heat into an insulated concrete slab provides the best comfort and energy efficiency of any type of radiant floor.

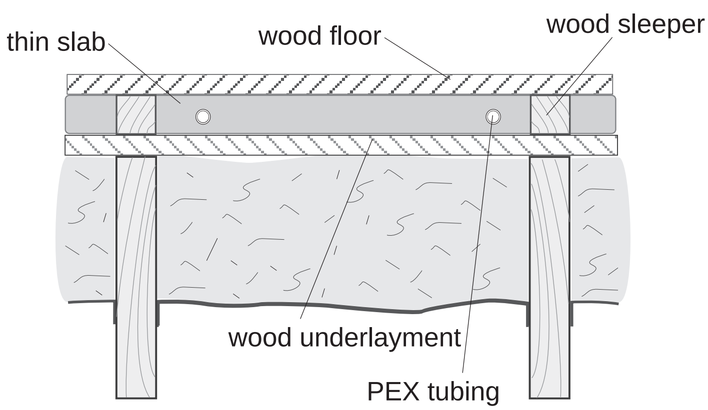


A workman first pours and then levels a thin gypsum slab. Thin gypsum or concrete slabs offer the best heat-transfer characteristics of any wood-supported floor.

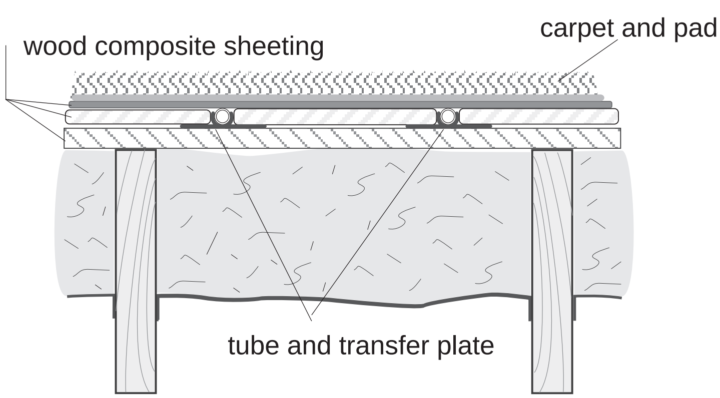
Radiant floor options for wood floors



A gypsum or concrete thin slab with a tile-floor finish offers the best heat transfer of any type of wood-supported floor.



Next best for heat transfer is a thin slab containing sleepers to facilitate fastening of the wood floor finish.



A variety of means exist for using a metal heat-transfer plate and layers of wood sheeting to produce an acceptably conductive radiant floor. The addition of carpet and pad make the floor less effective as a radiator, requiring higher floor temperatures.

how effectively they transfer heat from the pipes to the floor's surface. For example, a concrete slab may only need 85° F (29° C) water, while a wood floor with carpet may need 130° F (54° C) or more. *Striping* or concentrated heat lines directly above the tubing has been a challenging design problem for radiant wood floors. Manufacturers have developed heat-transfer plates that move heat laterally away from the tubing to make the floor temperature more uniform. The tubing is pressed into a snug circular channel in the plate, and the plate and tubing are attached either to the top or bottom of the floor.

High water temperatures, needed by some radiant floors to meet comfort requirements, can damage some finish flooring materials, especially wood. Highly insulative carpet and carpet pad usually require high radiant-floor temperatures. Most experts now agree that stapling pipe directly to the bottom of a wood floor is poor practice. The tubing often sags away from the floor in between staples, leaving contact between the floor and the tubing insufficient for good heat transfer and necessitating high water temperatures.

Whether the floor is concrete poured on gravel, a thin slab, or wood floor with aluminum heat-transfer fins, installing insulation under the floor is highly recommended by the experts. Foam insulation is typically installed beneath concrete slabs and vertically at their edges. Fiberglass insulation is commonly installed between wood floor joists to reduce downward heat flow in floors with thin slabs and aluminum heat-transfer fins.

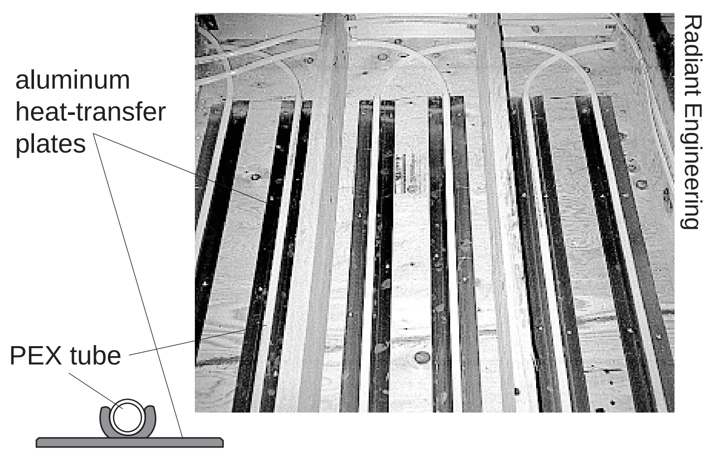
Radiant-heating designers and contractors estimate a radiant floor's heating capacity in Btuh for each square foot of floor area (watts per square meter [w/m^2]). Concrete or gypsum slabs, bare or with masonry tile, can radiate as much as 35 Btuh per square foot (110 w/m^2) and wood floors with carpet radiate as little as 8 Btuh per square foot (25 w/m^2). The lower heat capacity of the wood radiant floors reflects the slower heat transfer through the less conductive materials like wood and carpet.

A very energy-efficient home may only need 8 Btuh per square foot (25 w/m^2). Nevertheless,

Heat-transfer plates and tubing mounted on top of subfloor

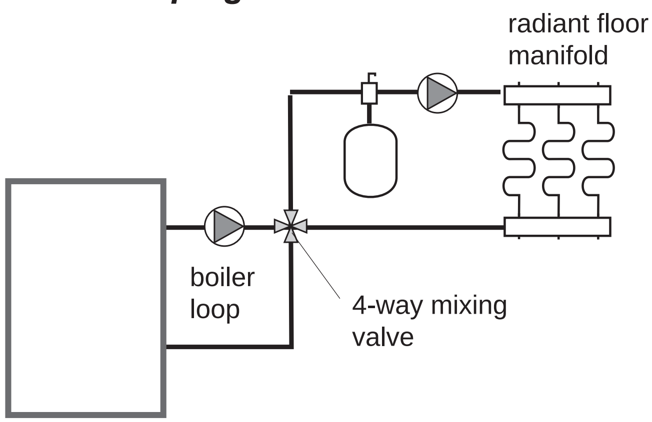
Heat-transfer plates, attached to the subfloor, spread heat from the tubing to the wood flooring materials. Plywood spacers are installed next, then wood underlayment or wood finish flooring.

Heat-transfer plates and tubing underneath subfloor

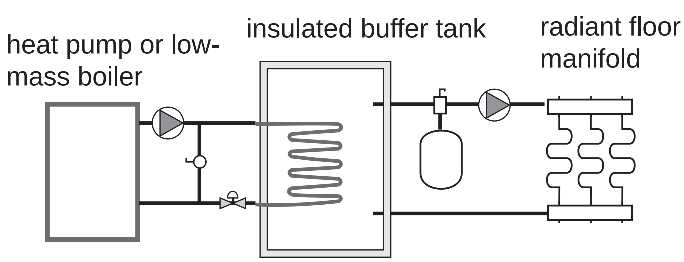


Heat-transfer plates, attached to the underside of the floor, spread heat from the tubing to the wood flooring materials. Insulation is installed underneath to reduce downward heat flow.

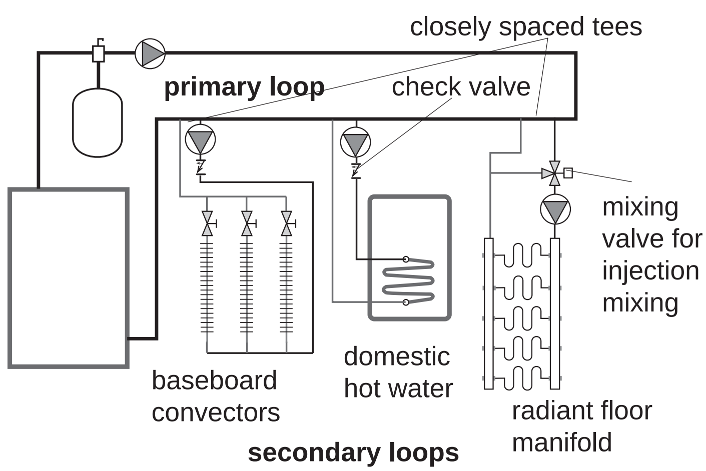
Piping radiant floors



A 4-way mixing valve blends high-temperature water from a conventional boiler with return water from the zones, giving the radiant floors the cooler water they require, while returning water to the boiler at a high enough temperature to prevent condensation.



A low-mass boiler or hydronic heat pump is connected to an insulated buffer tank, giving the heat source a steadier load. This reduces cycling and protects a low-mass boiler from thermal shock.



A hot primary loop supplies a variety of water temperatures to its secondary loops through closely spaced tees and zone circulators.

rooms with carpeted floors, large windows, and high ceilings may still need baseboard convectors or radiators, in addition to their radiant floor, to respond quickly to changing outdoor temperature.

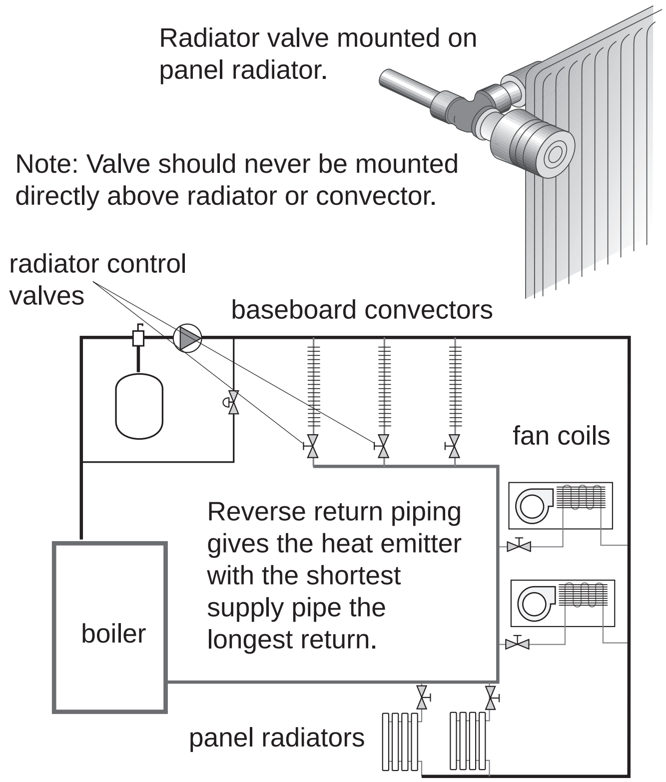
The efficiency of any hydronic system is directly related to the elevation of temperature—cooler water means higher efficiency. Condensing boilers and hydronic heat pumps are ideal heat sources for radiant floors because they process cooler water without the problems of non-condensing boilers. Non-condensing boilers must receive return water warmer than 130° F (54° C) to avoid corrosive condensation. This return-water temperature is higher than the supply-water temperature circulating in most radiant slabs. Using non-condensing boilers with radiant slabs requires mixing valves or primary-secondary piping to maintain this minimum 130° F (54° C) return-water temperature. These piping and control strategies will be discussed in **sections 4.1.3 Valves** and **4.2 Control systems**.

4.0 Designing the distribution system and control system

The distribution system's purpose is to carry water between the boiler and the heat emitters. A control system's purpose is to regulate heat flow to match heat loss by controlling water flow and temperature. The more closely the load (home) can be matched to the source (boiler or heat pump) the greater potential for optimal comfort and efficiency. Hydronic distribution and control systems have evolved dramatically in the past 10 years in their ability to deliver comfort and efficiency.

Heating systems cycle on and off during the heating season because they are sized to meet the maximum load during very cold weather. This cycling is accomplished by the thermostat in the simplest systems. An aquastat is a simple on-off water temperature control. Since the ideal water temperature changes with outdoor temperature, reset controls were developed to change water temperature in response to outdoor-temperature changes.

Automatic radiator control valves



Automatic radiator control valves meter flow to heat emitters based on temperature sensors in these valves. The above schematic shows a reverse-return piping system, which gives heat emitters piping loops of approximately equal lengths.

The system may be zoned to offer different temperature setpoints and schedules to different parts of the home. The traditional way to zone a hydronic system is with zone valves controlled by thermostats. The thermostat is located in a representative area of the zone. When the thermostat calls for heat, the zone valve opens the piping circuit between the heat source and the heat emitters in that zone. Zone valves have switches inside them that activate circulators and boilers after the valves open.

It's now common to use a separate circulator for each zone, instead of zone valves with a single circulator, because of circulator improvements and reduced prices. The most common piping arrangement for using separate circulators is primary-secondary piping. This piping system employs a primary or boiler loop, and branching off, a number of secondary loops containing the home's heating zones. The boiler loop has its own circulator, but it doesn't provide water to any heat emitters directly. Each secondary circuit has a circulator that moves warm water to and from the heat emitters.

One of the most important issues to consider in designing the distribution and control system is whether your system will use low-temperature water. Low-temperature water is used with radiant floors and fan coils. If a home can accommodate fan coils and radiant floors, then it makes sense to consider heating the water with a hydronic heat pump or a condensing boiler. If a non-condensing boiler is chosen, as it often is, then the boiler must be protected from cool return water as described in **sections 2.3.3 Cast-iron and steel boilers** and **3.4 Radiant floors**.

4.1 Hydronic distribution systems

There are three common types of distribution circuitry: series, parallel, and primary-secondary. Series (all heat emitters in the same loop) is very simple and economical, but the water temperature is lower at the inlet of every successive heat emitter, and this must be factored into design. Parallel is a very common piping method featuring the ability for zoning. Reverse-return parallel seeks to equalize head loss of parallel circuits to accommodate the one or two circulators moving the water.

The primary or boiler circuit reaches out from the boiler and provides shorter, more localized connections between the boiler and secondary circuits, instead of looping each zone to and from the boiler itself. The boiler-circuit controls ensure that the boiler water temperature is warm enough to prevent condensation in conventional boilers. However, the most important benefit of primary-secondary piping is its versatility in providing different water temperatures and flow rates to the different types of heat emitters in the zones. For example, primary-secondary pumping can provide a particular home with the following different water temperatures and flow rates:

- Bathroom radiant panel, 140° F (60° C) water at 1.5 gpm (0.09 L/s);
- Radiant slab in great room, 100° F (38° C) water at 2 gpm (0.13 L/s);
- Baseboard convectors in great room, 180° F (82° C) water at 1.5 gpm (0.09 L/s);
- Fan coil in garage, 130° F (82° C) water at 2.5 gpm (0.16 L/s); and
- Radiant masonry slab with carpet in bedrooms, 110° F (82° C) water at 2 gpm (0.13 L/s).

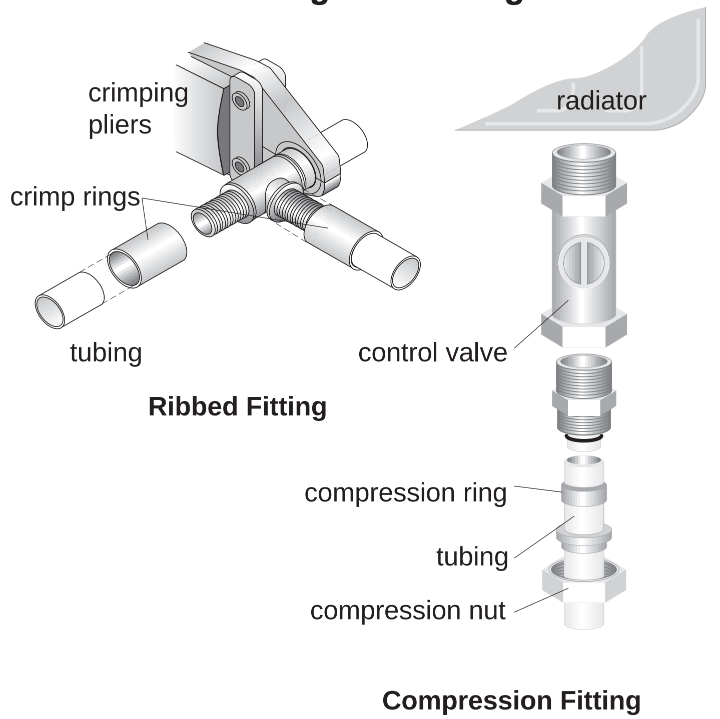
Each secondary piping circuit has a supply and return pipe connected to the boiler circuit by two tees. The tees are spaced as closely as possible to minimize pressure differences leading to inadvertent flow between the primary and the secondary circuits.

4.1.1 Piping choices

Pipe distributors offer several choices for piping hydronic heating and cooling systems. The four most common types are copper, polyethylene, polybutylene, and rubber tubing. Steel piping was commonly used until the 1960s, when copper became dominant. Now plastic piping has gained market share from copper because of its reasonable cost and easy installation.

Copper piping has been widely used for hydronic systems for many years because of its many virtues, including corrosion resistance, mechanical strength, low flow resistance, and thermal conductivity. Copper pipe and fittings are joined by the well-known technique of soft soldering. Because of its high thermal conductivity, copper is still the first choice for heat exchangers and coils. Although copper is still used for distribution piping, its conductivity can be a disadvantage because of heat loss and water-temperature reduction in uninsulated copper tubing.

Joining PEX tubing



Joints in PEX tubing are made by ribbed fittings with crimp rings, or with specially made compression fittings that join PEX to pipe threads.

Plastic tubing is less conductive than copper, making it a better choice for piping distribution systems. Plastic tubing is ideal for radiant floors and ceilings because joints aren't necessary, since plastic tubing is sold in coils 250 feet (76 meters) or longer. Plastic pipe has gained market share in recent years and may replace copper as the commodity of choice for piping hydronic distribution systems.

Plastic pipe and rubber tubing allow small amounts of oxygen to diffuse through them, creating the possibility of corrosion for iron and steel system components. Consequently, most of the plastic tubing now sold for hydronic systems has an oxygen-diffusion barrier. This barrier is most often a plastic film applied to the outer surface of the pipe or an aluminum foil tube sandwiched between two plastic-tubing layers.

The most popular and time-tested type of plastic piping is called PEX tubing. PEX is cross-linked polyethylene, composed of very large molecules arranged in a three-dimensional matrix. PEX joints, like tees, are made with grooved plastic or metal fittings and compression rings. PEX attaches to other system components, like manifolds and heat emitters, by way of fittings that adapt it to standard pipe threads. PEX is kink resistant and has the unique ability among plastic pipe to recover from kinking, after being heated to 275° F (135° C).

The sandwiched PEX-aluminum-PEX tubing known as PEX/AL/PEX is easy to install because it retains its shape when bent into loops in radiant floors. The aluminum oxygen-diffusion barrier, located within this tubing, is less likely to be damaged than barriers attached to the tubing's outer surface.

Polybutylene tubing is sometimes used in hydronic systems, although its maximum pressure and temperature ratings are less than PEX. Rubber-based tubing has been used extensively for attachment to the underside of wood floors, because of its flexibility for being threaded into spaces between floor joists. Because of its tendency to sag, rubber-based tubing must be supported every few inches. Rubber-based tubing doesn't have the long-proven reliability of PEX and some failures have occurred.

4.1.2 Circulators

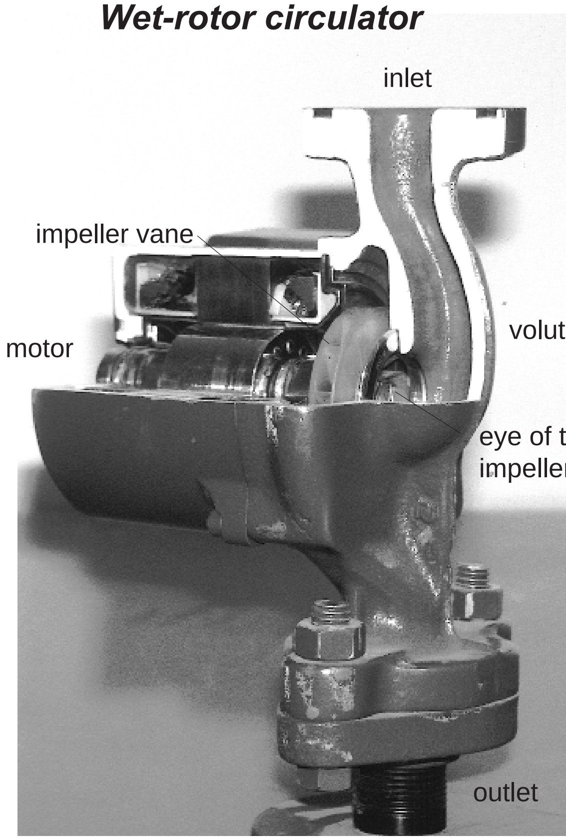
A hydronic circulator or pump consists of an electric motor coupled to an impeller by a shaft, supported by bearings. The impeller turns in a chamber, called the *volute*, where it adds mechanical energy to the water. Head is the term used to describe the mechanical energy in foot pounds per pound of water or joules per kilogram (ft-lb/lb or feet of head or J/kg). The piping system removes this head through the hydraulic resistance of its components, like valves, fittings, and heat emitters. The circulator's ability to add mechanical energy should be matched to the head-removing characteristics of the piping system.

There are two main types of circulators available for hydronic systems: the wet-rotor circulator and the mechanically coupled three-piece circulator. Both types of circulators are available with either cast-iron volutes for use in closed-loop hydronic systems, or with stainless-steel or bronze volutes for open-loop hydronic systems.

Most hydronic circulators are in-line circulators, designed to be installed in a straight piece of pipe. However, end-suction circulators that turn the water flow 90° from intake to discharge are also available. The circulator's weight generally should be supported by vibration-absorbing hangers.

Wet-rotor circulators are smaller, quieter, and work well for piping circuits with low flow and head requirements. Wet-rotor circulators are cooled and lubricated by the system's water and have no external pump seals to leak. Newer types of wet-rotor

Wet-rotor circulator



Wet-rotor circulators work well as zone circulators. Some contain speed controls and electronic chips for controlling flow rate according to demand.

circulators have variable-speed drives and offer improved pumping efficiency and room temperature control when used to inject heat from the boiler loop into a zone circuit.

Wet-rotor circulators are prone to having stuck impellers after an extended shutdown. External controls can be programmed to run the circulators for short periods during shutdown and some newer circulators have internal controls to exercise them in the off-season. Opening a wet-rotor circulator to service the motor, shaft, or impeller involves losing some water and introducing some air to the piping system.

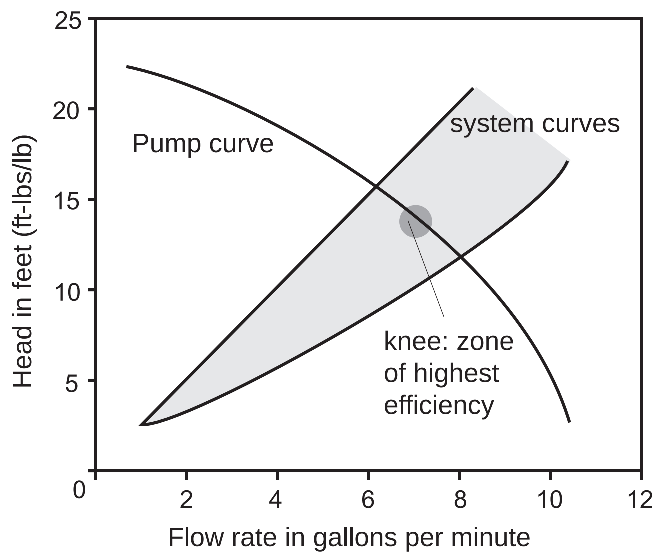
Three-piece circulators are generally more powerful than wet-rotor circulators and can overcome more pressure loss at higher flow rates. Three-piece circulators have a longer service life and their motors, bearings, and shafts may be serviced without opening the piping system to the atmosphere. However, they are noisier and heavier than wet-rotor circulators and require periodic oiling. Worn seals can leak water and allow air into the piping system.

The circulator must be designed and installed to keep the pressure in the piping above the *vapor pressure* of the water in the system. Vapor pressure is the pressure required to prevent liquid from boiling at a specific temperature. If the water begins boiling at the suction side of the circulator (the system's low-pressure point), it can wear out the circulator quickly through a process called *cavitation*.

Locating the pressure tank near the circulator's inlet and using the lowest water temperature possible are other effective ways to prevent cavitation, a notorious pump killer.

The circulator's performance is described by the same type of graph as the head loss of a piping circuit. This makes sense because the circulator adds head and the circuit subtracts head, depending on the system's flow rate in gallons per minute. Comparing the curve representing the circuit's head loss with the curve of the circulator's head gain on the same graph allows the designer to determine the actual operating head loss and flow rate. The location of the intersection of the two curves determines this operating point and also gives the designer an indication of efficiency. The peak efficiency occurs when the head-loss curve intersects the pump curve near the pump curve's "knee," or midpoint.

Pump curve and system curves



The pump curve describes the circulator's capacity to add mechanical energy or head. The system curves shown here define a region where the system curve should ideally intersect the pump curve to achieve maximum efficiency.

4.1.3 Valves

Hydronic valves range from simple plumbing devices to sophisticated servants of the control system. Simple control valves serve the hydronic system by controlling flow or by isolating parts of the system so that they can be serviced without shutting down the entire system. *Globe valves* are used whenever a throttling effect is needed in the system. *Gate valves* are used to isolate parts of the system and pose less hydraulic resistance than globe valves. *Ball valves* may be used for either isolation or throttling.

A *check valve* limits flow to one direction to prevent thermosiphoning while a circuit is off. Thermosiphoning is heated water flowing upward through the piping and cooler water flowing downward because of the density difference between the warm and cool water. Check valves are also used to prevent operating pumps from inducing flow in inactive piping circuits. This is particularly important in multi-circulator systems.

Radiator valves regulate individual heat emitters. They are available as manual valves or as *thermostatic radiator valves (TRVs)*. Some heat emitters are equipped with manual radiator valves at the factory. The thermostats on TRVs may be integral or remote for attachment to a nearby wall. It's very important to avoid locating the thermostatic element of a TRV directly above the heat emitter because this location will cause the valve to close very soon after it opens.

Zone valves

Zone valves, powered by a 24-volt control circuit, provide on-off flow control using a single circulator.

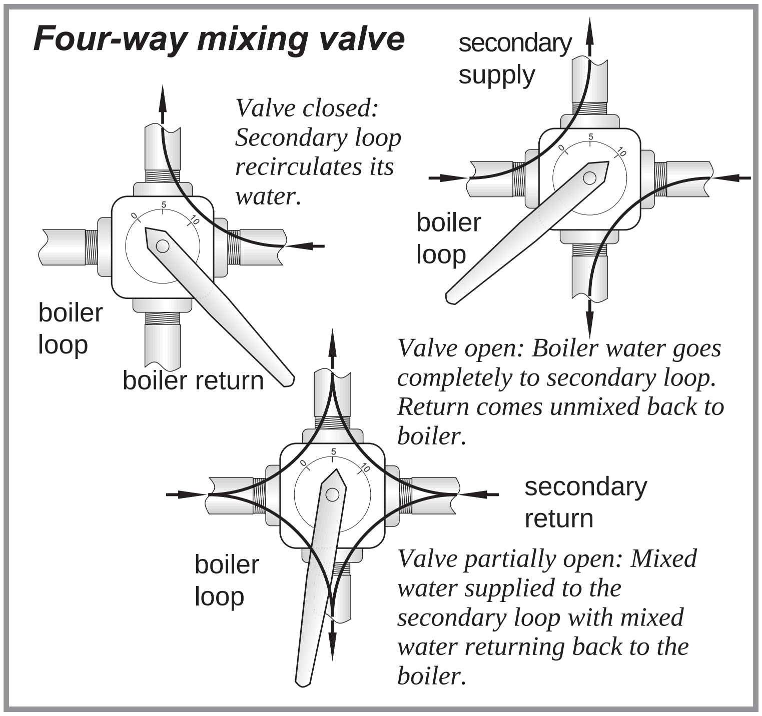
Zone valves divide the hydronic system into zones where the control system and the zone valves maintain different temperatures according to occupancy and need. Common zone valves are opened and closed by 24-volt control circuits by way of an electric motor or a slower-acting heat motor. Both types are effective and have good service records. Zone valves have switches inside them to energize a relay for controlling the circulator. When a hydronic system has three or more zone valves and a single powerful circulator, a *differential-pressure bypass valve* is used to prevent noise from high flow rates in a single active zone. The circulator, serving a single zone calling for heat, could also create high pressure against closed zone valves, causing them to fail. The differential-pressure bypass valve allows part of the flow to bypass the active zone's piping. *Manifolds*, centralized piping stations designed for three or more zones, may be equipped with zone valves, called telestats, for each zone. Zone valves may also connect a continuously circulating zone to the boiler loop hot-water injection.

Mixing valves control supply and return water temperatures in response to signals from the control system. The two types of mixing valves used with boilers to maintain an acceptable return-water temperature are *thermostatic mixing valves* and *four-way mixing valves*. These mixing valves blend hot supply water with cooler return water to supply a low-temperature radiant floor, and at the same time return blended water back to the boiler at a temperature above 130° F (54° C) to prevent condensation in the boiler. Mixing valves are also used to inject heat from the primary loop into a secondary loop in response to the control system. Mixing valves can also return cool water to a condensing boiler while supplying heating zones with a variety of water temperatures.

4.1.4 Expansion tanks

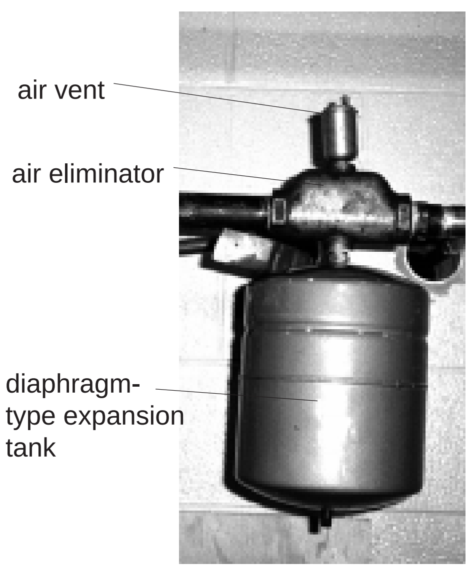
The hydronic system's water expands as it's heated and contracts as it's cooled. Since water is incompressible, the system needs a device that can absorb the water's expansion and contraction. A *diaphragm-type expansion tank* serves this purpose in a modern hydronic system. This tank is divided into two chambers: one charged with air at a pressure of about 5 pounds per square inch (34 kilopascals) below the relief-valve setting, and one filled with the system's water. As water is heated, it expands into the tank, compressing the air on the other side of a rubber diaphragm that divides the tank. As the system's water cools, water flows out of the expansion tank and returns to the system.

Older expansion tanks didn't have a rubber diaphragm between the air and water. This allowed the



air to mix with the water, resulting in the water eventually dissolving all the tank's air and carrying it around the system until it was ejected through air vents. This process created an expansion tank that was filled with water and no longer fulfilled its purpose. This waterlogged expansion tank forced water out the relief valve, in turn bringing many gallons of makeup water into the system. This water brought more dissolved air, which produced more rust. Many boilers died this way. Replacing an older expansion tank with a diaphragm-type expansion tank is a good way to save an existing boiler.

Expansion tank / air vent



The expansion tank, air eliminator, and air vent are often connected together and located near the circulator's inlet.

Expansion tanks need to be sized to meet the expansion needs of each individual system, which range from 3 to 10 gallons (11 to 38 liters).

4.1.5 Air eliminators

Air causes a host of problems in hydronic systems, including: reduced heat transfer in the boiler and heat emitters because of trapped air bubbles, corrosion of iron and steel, reduced flow rates, and pump cavitation. To prevent these problems hydronic systems use both manual and automatic air vents.

Manual air vents are installed at the top of heat emitters and at manifolds. Manual air vents also may be necessary where piping turns downward after an upward or horizontal run. Most manual vents open by screw or push-button. The installer's skill at piping and filling the system has a large effect on how much air remains in the system initially.

Automatic air vents are strategically located near the connection to the expansion tank to purge air from the piping system. The simplest type of automatic air vents use a float to open the vent's orifice and expel the air. The more sophisticated types are designed to catch small bubbles and combine them into larger bubbles before expelling them. The very smallest bubbles are the most difficult for the vent to catch because they are carried by the moving water and don't rise quickly like larger bubbles. Newer air vents called *microbubble resorbers* are designed to pluck these tiny bubbles out of the water stream.

4.1.6 Manifolds

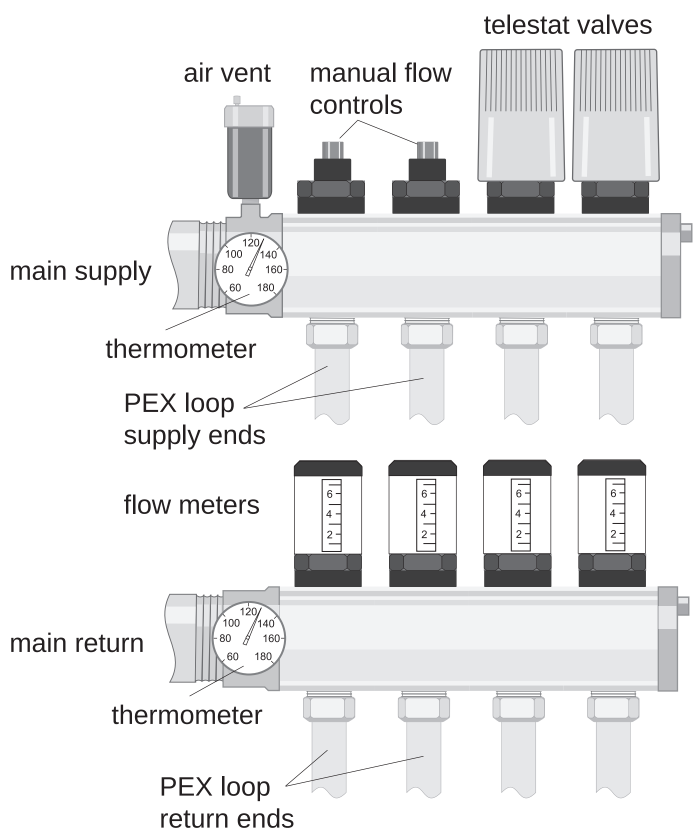
Many modern hydronic heating systems, especially radiant panel systems, use manifold stations, consisting of both a supply and a return manifold. Manifold stations are installed inside a wall or floor cavity in central locations fitted with access doors. A supply pipe from the boiler feeds the supply manifold and a return pipe conveys water from the radiant floor sections or other heat emitters back to the boiler. Each piping circuit is joined at one end to the supply manifold and at the other to the return manifold, connecting these piping circuits in parallel to each other.

Manifolds are available with a variety of optional features. Manifolds are often fitted with zone valves, called telestats, that are controlled by room thermostats. Some manifold stations are equipped with pressure gauges, flow meters, and balancing valves that can adjust the flow rate in each circuit separately. Balancing valves are handy for fine-tuning heat delivery to the home's zones.

4.2 Control systems

Hydronic control systems perform several important functions:

Hydronic supply and return manifolds



Manifolds for radiant floors: one end of a loop of PEX tubing is attached to the supply manifold while the other is attached to the return manifold. Manifolds are often located remote from the boiler.

- Minimize boiler or heat-pump short cycling,
- Optimize system water temperatures for comfort and efficiency, and
- Protect boilers from corrosion and thermal shock.

A hydronic control system should be easy to use, easy to diagnose, and reliable. The newer control systems provide automatic diagnostics, visual readouts of system functioning, and the virtual elimination of manual controls.

4.2.1 Aquastats and reset controls

An aquastat controls the temperature setpoint of the boiler water. The aquastat establishes a high limit temperature beyond which the aquastat shuts the burner off. This high limit is required for safety and to prevent overheating. Aquastats may also establish a low limit to ensure that the boiler is capable of heating domestic water on demand. A low limit is necessary for boilers that have a *tankless coil*, a pipe coil inserted into the boiler.

Many conventional aquastats sense heat through their housings, strapped directly to a supply pipe near the boiler. Other aquastats sense temperature with a remote bulb, connected to the housing. The remote bulb is filled with a fluid that responds to changing temperature, operating a bellows, which in turn operates a switch. The remote bulb is either strapped to a supply pipe near the boiler or inserted in a well inside of a tee in the pipe.

A more advanced control strategy, called reset, adjusts the aquastat's setpoint according to outdoor temperature. The reset control is an electronic aquastat equipped with an outdoor temperature sensor. The reset control adjusts the water temperature higher for cold weather and lower for warm weather. The heat emitters may need 180° F (82° C) water to heat the home when the temperature outdoors is 0° F (–18° C), but only 130° F (54° C) when the temperature outdoors is 50° F (10° C). The reset control's purpose is to control supply water to the heat emitters so that they emit heat to the home at approximately the same rate that heat is being lost. This reset strategy minimizes the tendency of boilers—necessarily overpowered for their heating load for most of the year—to pulse heat into the building, causing temperature fluctuations and energy waste.

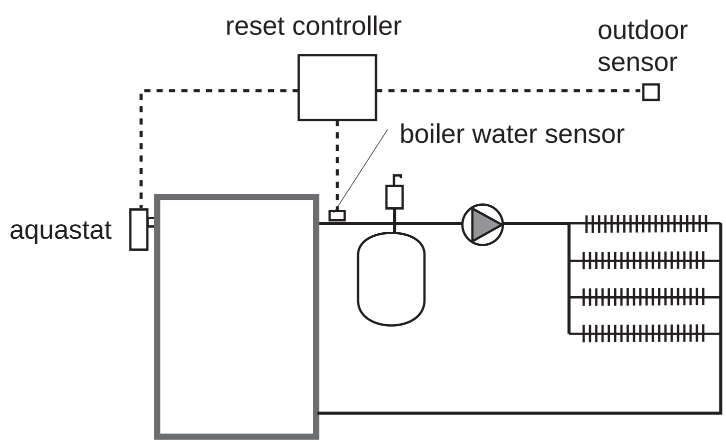
4.2.2 Electronic controls

Electronic controllers for hydronic systems have improved rapidly in their control capabilities and reliability in the past several years in response to hydronic's resurgence. Electronic controls can perform more functions and can regulate hydronic systems more precisely than simpler controls. Electronics' greater precision and capabilities help to maximize comfort and minimize energy use.

Electronic controllers combine measurement, timing, and other inputs with outputs through electronic logic and electromagnetic relays to control circulators, valves, and boiler operation. Electronic controllers give digital readouts of system status and give warnings of sensor failure and other system faults. Electronic controllers can reset boiler water temperature, prevent warm-weather boiler operation, control the position of mixing valves, activate multiple boilers in stages, control the speed of injection pumps, and activate and deactivate loads in order of priority.

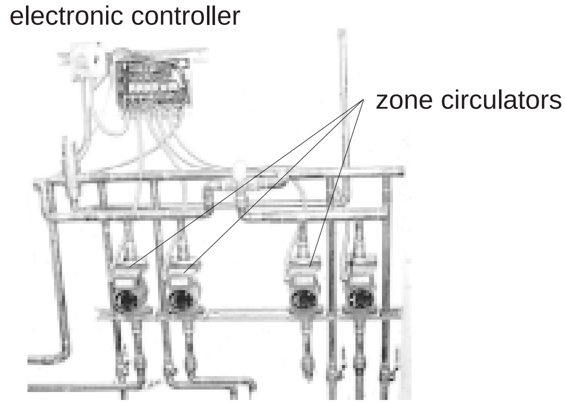
Modern electronic controllers measure temperature, process information, and switch power to the boiler, circulators, zone valves, and mixing valves. *Thermistors* are electronic sensors

Simple reset control



The circulator operates continuously, circulating water at a temperature determined by the reset controller according to outdoor temperature.

Multiple-function electronic controller



Electronic controllers combine a number of functions, including controlling zone circulators, water-temperature reset, warm-weather shutoff, and boiler-cycle control.

used to measure indoor temperature, outdoor temperature, and water temperature. Using thermistors allows the electronic controller to regulate boiler and system operation intelligently, based on a number of space and water temperatures.

Zones may be operated by zone valves and a central circulator, or each zone may have its own on-off circulator, or a zone may circulate constantly with heat injected as needed by a pump or valve. Domestic water is often just another zone, heated by the central boiler and equipped with its own circulator. A multi-zone relay center can control several zones along with domestic-hot-water circuit, giving this circuit priority whenever there's a call for hot water. The electronic controller can coordinate zone operation to allow a relatively small boiler to heat a relatively large load. Electronic controllers often provide a post-purge control that leaves a circulator on after the heat source turns off to convey the residual heat into space- or water-heating zones. And, electronic controllers can anticipate large loads and start boilers early to fill the demand.

The multi-zone relay center uses a familiar strategy of combining a number of control components into one box, where wiring connections can be easily and conveniently made. Centralizing zone controls on or near piping manifolds helps to centralize important piping and wiring components, making the system simpler, more space-efficient, and easier to troubleshoot.

4.2.3 Modular boiler systems

Large homes with hot tubs, swimming pools, and multi-headed shower spas may need up to 500,000 Btuh (146 kW) during maximum demand. Minimum demand may be only one-tenth or less of maximum. When the home's combined space- and water-heating load exceeds 150,000 Btuh (44 kW), designers often consider specifying a modular boiler system. Serving widely variable loads with a single large boiler can be both inefficient and difficult to regulate. The greater the variation in load, the more energy a modular boiler system will save.

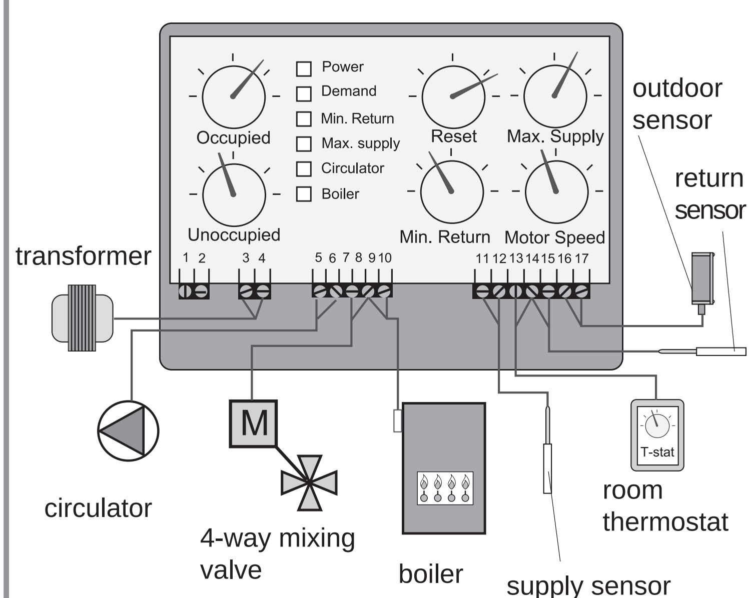
Much of the energy needed to heat up the boiler is lost after the burner turns off with each cycle. So, the less a boiler cycles, the greater its efficiency. Using two or more boilers offers a greater seasonal efficiency. The modular boiler system can also eliminate the need for separate boilers for domestic hot water, space heating, and pool heating and thereby eliminate their separate electrical service, controls, fuel supplies, and flues.

Modular boiler systems employ specially designed control systems. These controls perform the following tasks:

- Operate the correct number of boilers to match the current load,
- Change the order in which the boilers are fired to give each boiler approximately equal operating time,
- Control water temperature based on load and outdoor temperature,
- Interrupt space heating in times of high demand for domestic hot water, and
- Provide safety shutoff.

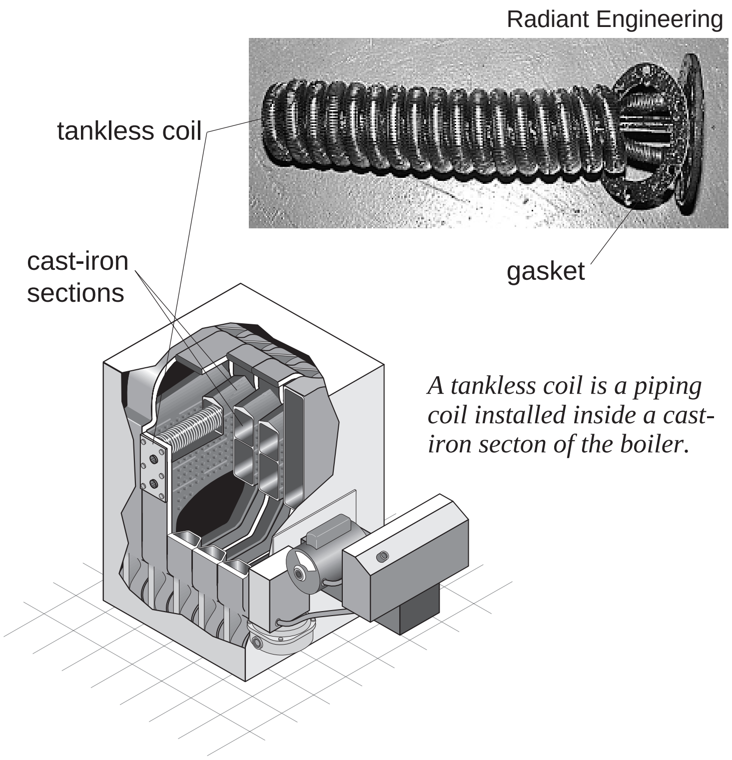
The design of the piping, circulators, and valves must prevent water heated in active boilers from circulating through inactive ones, which wastes heat. Preventing circulation through idle boilers is accomplished by installing a small circulator on each boiler, designed only to circulate water through that boiler and into the primary piping of a primary-secondary piping system.

Electronic controller for hydronic systems



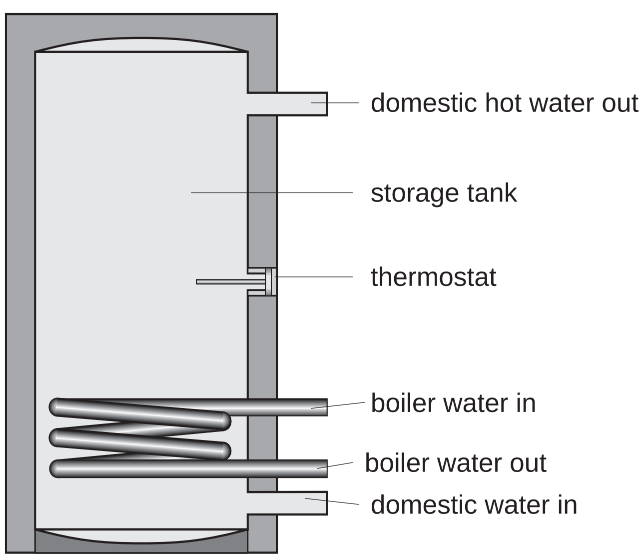
Electronic controllers for hydronic systems come in a wide variety of models for controlling mixing valves, circulators, water temperatures, space temperatures, and one or more boilers.

Tankless coil



A tankless coil is a piping coil installed inside a cast-iron secton of the boiler.

Indirectly fired storage water heater



An indirectly fired storage water heater uses a coil circulating boiler water to heat domestic hot water.

5.0 Domestic hot water, cooling, and installation issues

Water-heating tanks and coils are part of many modern hydronic systems. The most common way to couple domestic hot water and heating is with an external tank that has an internal water-heating coil. Hydronic cooling is only briefly discussed here because its use is not common in single-family and small multifamily buildings.

5.1 Domestic hot water

Water heaters can be classified as direct and indirect. Direct water heaters heat their water directly with a fuel source, like gas, oil, or electricity. Indirect water heaters use a central boiler, furnace, or heat pump to heat domestic water.

The two most common types of indirect water heaters are the tankless coil and the indirectly fired storage water heater. Tankless coils are found in single-family and multifamily buildings and often have a separate storage tank near the boiler. A tankless coil is a piping coil inserted into a reservoir in one part of the boiler. A tankless coil can waste energy when it forces the maintenance of high water temperature in a large boiler for water heating during the summer months. For this reason, the tankless-coil design is considered obsolete by many progressive designers and installers. However, well-insulated storage tanks may be combined with existing tankless coils to erase much of this efficiency disadvantage.

An indirectly fired storage water heater is a storage tank with an immersed heating coil, heated by another appliance, usually a boiler. It is the most common type of water heater for new installations. Boiler water circulates through the coil, heating the water inside the tank.

Well-engineered, indirect water heaters may have significant advantages over direct water heaters. First, they eliminate the additional chimney and chimney losses of direct units. Indirect water heaters are safer because they don’t burn fuel or need combustion air. Indirectly fired storage water heaters may be either more or less efficient than direct water heaters.

An indirectly fired storage water heater can beat a direct water heater’s efficiency, if this water heater is well-insulated and coupled to a boiler that is loaded near its capacity with space-heating and water-heating responsibilities. However, indirectly fired storage water heaters also can be less efficient because they require an additional heat exchanger, with its additional losses. This depends on the boiler’s efficiency and how closely the boiler is matched to both its space- and water-heating loads.

Domestic hot water is usually given priority by the hydronic system’s controls. Space-heating loads are temporarily interrupted during the short time periods when the water heater is supplying hot water. This control strategy can be suspended during very cold weather when heating zones need priority to maintain their setpoints. When a home has a hot tub, multiple-headed shower, or swimming pool, it is essential to plan separately for these loads, adding boiler capacity as necessary to meet maximum demand. When the total heating and water heating load exceeds 150,000 Btuh (44 kW), consider a modular boiler system.

5.2 Hydronic cooling

Hydronic heat pumps can be used for both hydronic space cooling and heating. The biggest challenge for hydronics is that warm air is best delivered near the floor, while cool air is best delivered near the ceiling. Another concern is condensation on the surfaces of convectors or fan coils. Valence cooling convectors, designed for installation near the ceiling, contain pans for draining condensate. These cooling convectors are very similar to baseboard convectors, but they don't work too well for heating. Radiant ceilings work well for cooling, too, but having customers' heads closer to a radiant heat source than their feet doesn't produce very good winter comfort. Hydronic radiators and baseboard convectors aren't usually considered appropriate for cooling.

Fan coils equipped with drip pans work well for both heating and cooling and are used in many large residential and office buildings. Radiant floors have good potential for radiant hydronic cooling, but they must be bare concrete or concrete with tile. Keeping the chilled water temperature above the air's dew point is also a key to employing any type of hydronic radiant cooling. If a radiant floor were carpeted, the cooler water temperature needed to compensate for the carpet's insulating effect would likely condense water vapor out of the air, wetting the carpet.

5.3 Putting it all together

For new installations, the house plans should include one or more sheets portraying the design of the hydronic heating system. These drawings and specifications should include:

- A schematic drawing showing the position of the system's components;
- Specifications for the boiler or other heat source;
- Specifications for the pump(s);
- Specifications for the heat emitters;
- An electric control schematic;
- Piping diagrams for radiant floors, showing manifold location, heating pipe, piping

lengths for each circuit; and
- Cross sections of the radiant floor types

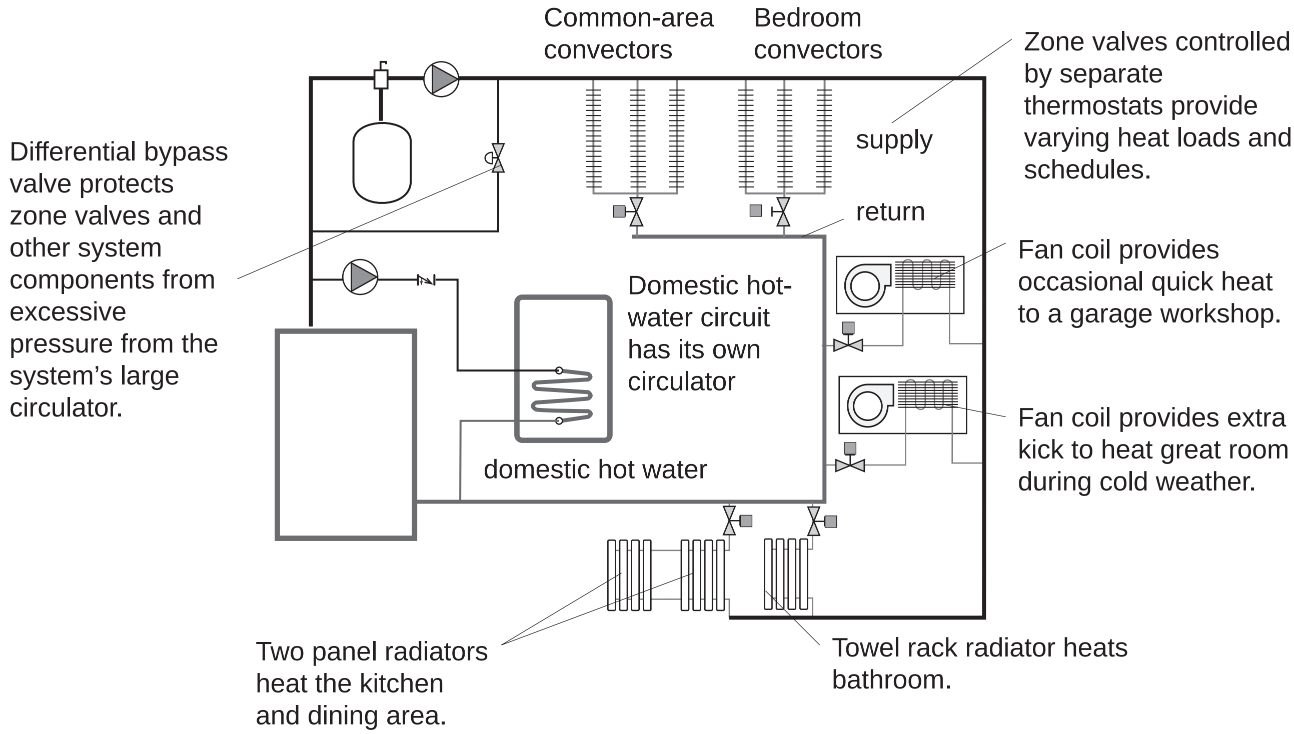
These documents should become a permanent record to be used for adjustment, repair, planning additions, and other activities that require an understanding of the hydronic heating system.

When replacing a hydronic heating system or a boiler, consider the following:

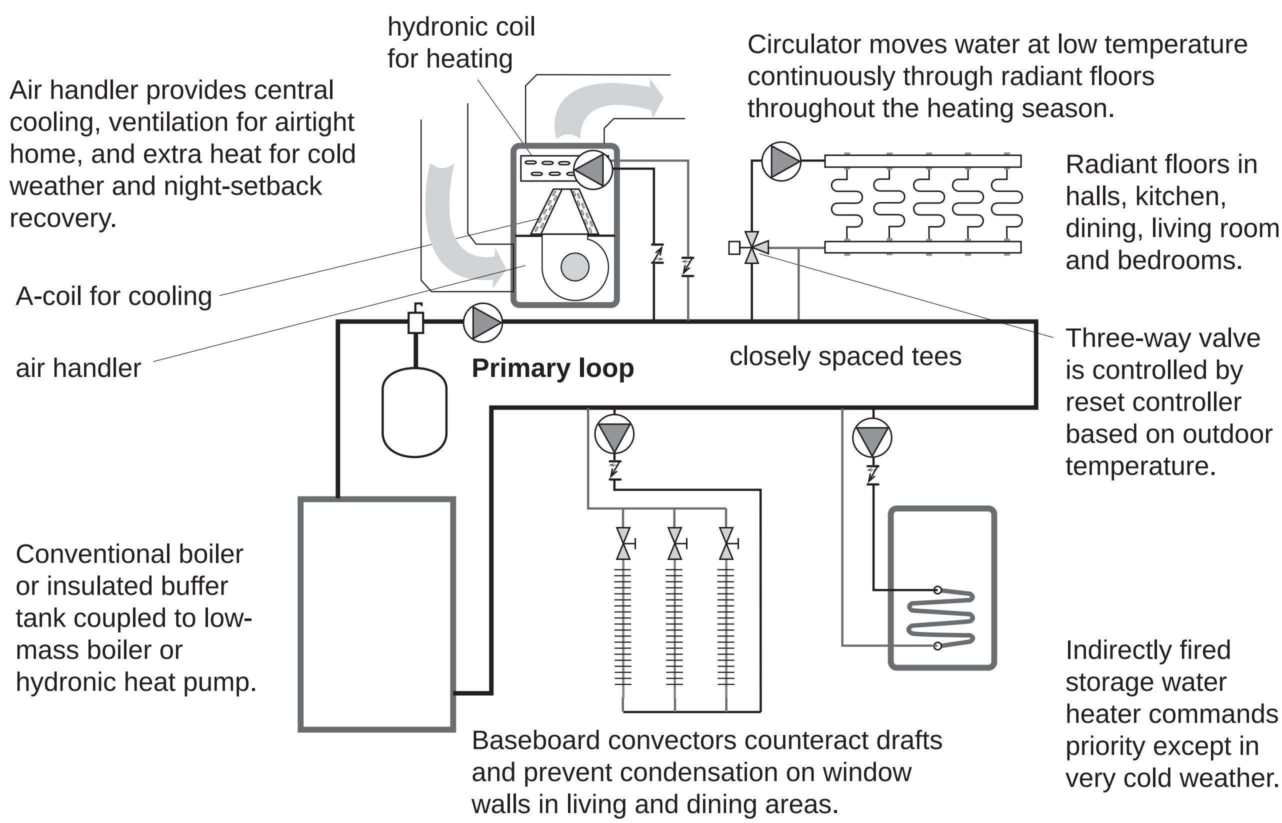
- Compare the warranties of competing heat sources,
- Ask about the heat sources' service and repair records,
- Confirm that parts and service will be available in the future,
- Insist on proper design, planning, and installation,
- Insist that deficiencies in gas service and electrical supply be corrected as part of the installation, and
- Establish a maintenance schedule for the new furnace or boiler, and stick to it.

A Tale of Two Systems

Sophisticated hydronic system for a modest home (new or retrofit)



Complex high-performance hydronic system for a new luxury home



Glossary

Air eliminator – A device that captures air bubbles from water and ejects it from the system.

Air handler - A steel cabinet containing a blower with cooling and/or heating coils connected to ducts, which transports indoor air to and from the air handler.

Air vent – A manual or automatic device that releases air from a hydronic piping system.

Annual fuel utilization efficiency (AFUE) - A laboratory-derived efficiency for heating appliances which accounts for chimney losses, jacket losses, and cycling losses, but not distribution losses or fan/pump energy.

Aquastat - A heating control that switches the burner or the circulator in a hydronic heating system.

Atmospheric – Used to describe burners that vent gases by the difference in pressure between warm gases and cooler air outside the vent.

Blower door - A device that consists of a fan, a removable panel, and gauges used to measure and locate air leaks.

British thermal unit (Btu) - The quantity of heat required to raise the temperature of one pound of water one degree Fahrenheit.

Btuh - British thermal units per hour.

Burner - A device that facilitates the burning of a fossil fuel like gas or oil.

Cavitation - Damage to a circulator from by boiling water at its inlet caused by too low pressures.

Circulator – The pump in a hydronic system.

Check valve – A valve that limits water flow to one direction.

Closed-loop system – A piping system that is completely closed to the atmosphere.

Coil - A snakelike piece of copper tubing surrounded by rows of aluminum fins which clamp tightly to the tubing to aid in heat transfer.

Combustion air - Air that chemically combines with a fuel during combustion to produce heat and flue gases, mainly carbon dioxide and water vapor.

Combustion efficiency – Efficiency of a combustion boiler, determined by measuring temperature and either oxygen or carbon dioxide.

Compressor - A motorized pump that compresses the gaseous refrigerant and sends it to the condenser where heat is released.

Condensate - Vapor condensed back to a liquid.

Condense - When a gas turns into a liquid as it cools, we say it condenses. Condensation is the opposite of evaporation. When a gas condenses into a liquid it releases heat.

Condenser – A coil where the refrigerant condenses from a vapor into a liquid, releasing heat.

Conductance - The property of a material to conduct some energy form like heat or electricity.

Conduction - Heat flow from molecule to molecule in a solid substance.

Convection - The transfer of heat caused by the movement of a fluid like water or air. When a fluid becomes warmer it becomes lighter and rises.

Demand - The peak need for electrical energy. Some utilities levy a monthly charge for demand.

Density - The weight of a material divided by its volume, usually measured in pounds per cubic foot.

Distribution system - A system of pipes or ducts used to distribute energy.

Efficiency - The ratio of output divided by input.

Electro-mechanical controls – Controls that use mechanical movement from springs, bi-metal elements, or pressure diaphragms to open and close electrical contacts.

Evaporator - The heat transfer coil of an air conditioner or heat pump that cools the surrounding air as the refrigerant inside the coil evaporates and absorbs heat.

Fan-assisted combustion – A combustion system that moves air and combustion gases through the heat exchanger and into an atmospheric chimney using a fan.

Fan coil – A forced-air convector utilizing a coil with a fan to blow room air through it.

Feet of head – Measurement of a fluid's mechanical energy similar to pressure, measured in foot pounds per pound, which simplified becomes feet of head.

Finned tube – A pipe, usually copper, with fins, usually aluminum , attached to improve heat transfer.

Flow rate – Volume of fluid flow per unit of time. For example: gallons per minute (gpm).

Flue - A channel for combustion gases.

Head – The mechanical energy of a fluid measured in foot-pounds of energy per pound of fluid or "feet of head" for short.

Head loss – The quantity of mechanical energy removed by friction as water moves through piping, fittings, and heat emitters.

Heat emitter – A hydronic device that releases heat by radiation and/or convection. Includes radiators, convectors, and fan-coils.

Heat motor – A slowly rotating motor driven by heat from an electric current. Heat motors power some hydronic zone valves.

Heat-transfer plate – An aluminum plate designed to house tubing and to conduct the tubing's heat laterally through building components.

Heating load - The maximum rate of heat conversion needed by a building during the very coldest weather.

High limit - A bimetal thermostat that turns the heating element of a furnace off if it senses a dangerously high temperature.

Hydraulic resistance – The ability of a piping system to dissipate head.

Hydronic - A heating system using hot water or steam as the heat-transfer fluid (Webster's Dictionary). A water heating system (common usage).

Infrared - Pertaining to heat rays emitted by the sun or warm objects on earth.

Injection mixing – A method of controlling water temperature in a hydronic system by injecting hot water into a circuit using a variable-speed circulator.

Load – Heating requirement to maintain a given setpoint temperature.

Make-up air - Air supplied to a space to replace exhausted air.

Manifold - A section of pipe with multiple openings.

Natural ventilation - Ventilation using only natural air movement, without fans or other mechanical devices.

Open-loop system – A piping system that is exposed to the atmosphere or one that carries fresh water.

Oxygen-diffusion barrier – A coating or film that reduces the oxygen diffusion of a plastic pipe.

Panel radiator – A wall-mounted heat emitter that emits most of its heat as infrared radiation.

Parallel piping – Branching piping paths that begin at a single point and end at another single point.

Pressure - A force encouraging movement by virtue of a difference in some condition between two areas.

Pump curve – A chart showing the pump's head energy versus the fluid flow through the pump.

R-value - A measurement of thermal resistance.

Radiant temperature - The average temperature of objects in a home like walls, ceiling, floor, furniture, and other objects.

Radiation - Heat energy, which originates on a hot body like the sun, and travels from place to place through the air.

Radiator valve – A valve that regulates hot-water flow through a heat emitter.

Relay - An electromagnet switch operated by a control circuit to energize or de-energize a motor or valve.

Reset controller - Adjusts fluid temperature or pressure in a central heating system according to outdoor air temperature.

Sealed-combustion - A venting system that draws combustion air from outdoors and has an exhaust system sealed from indoors.

Series piping – An assembly of pipes and other components that forms a single un-branching loop.

Setpoint temperature – The temperature setting of a control that represents the desired temperature in some part of a system.

Specific heat - The ratio of a material's heat storage capacity to the heat storage capacity of water.

Thermal conductance - General term applied to both K-value and U-value, meaning heat flow rate.

Thermal mass – The ability of a building component to store heat according to its mass and specific heat.

Thermal resistance - Same as R-value, expressing ability to retard heat flow.

U-value - The amount of heat that will flow through a square foot of building cross-section with multiple slabs of materials.

Vent connector - The vent pipe carrying combustion gases from the appliance to the chimney.

Venting - The removal of combustion gases by a chimney.

Wet-base boiler – A boiler with a heat exchanger that goes underneath the burner.

Zone valve – A valve that controls hot-water flow to an individual zone of a building.

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