# HEATING EQUIPMENT

**In this material the principles of combustion and data concerning various types of fuels common to HVAC systems are discussed. The information in this material has been extracted from Chapter 28 in the 2021 *ASHRAE Handbook—Fundamentals* and Chapters 28 and 31 through 37 in the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*.**

## 1 Fuels and Combustion

### 1.1 Principles of Combustion

**Combustion** is the chemical process in which an oxidant reacts rapidly with a fuel to liberate stored energy as thermal energy, generally in the form of high-temperature gases. The oxidant is usually oxygen in the air.

Conventional hydrocarbon fuels contain primarily hydrogen and carbon, in either elemental form or in various compounds. Their complete combustion produces mainly carbon dioxide and water; however, small quantities of carbon monoxide and partially reacted flue gas constituents may form. Most conventional fuels also contain small amounts of sulfur, oxidized to $SO_2$ or $SO_3$ during combustion, and noncombustible substances (mineral matter or ash, water, and inert gases). Flue gas is the product of complete or incomplete combustion, including excess air (if present) but not dilution air.

The rate of fuel combustion depends on (1) the chemical reaction rate of combustible fuel constituents with oxygen, (2) the rate at which oxygen is supplied to fuel (mixing of air and fuel), and (3) the temperature in the combustion region. The reaction rate is fixed by fuel selection. Increasing the mixing rate or temperature increases the combustion rate. In complete combustion of hydrocarbon fuels, all hydrogen and carbon in the fuel are oxidized to $H_2O$ and $CO_2$.

For complete combustion, excess oxygen or excess air must generally be supplied beyond the amount theoretically required to oxidize the fuel; this is usually expressed as a percentage of the air required to completely oxidize the fuel. Incomplete combustion occurs when a fuel element is not completely oxidized in the combustion process. For example, a hydrocarbon may not completely oxidize to carbon dioxide and water, but it may form partially oxidized compounds such as carbon monoxide, aldehydes, and ketones. Conditions that promote incomplete combustion include

- Insufficient air and fuel mixing, causing local fuel-rich and fuel-lean zones.
- Insufficient air supply to the flame, providing less than the required quantity of oxygen.
- Insufficient reactant residence time in the flame, preventing completion of combustion reactions.
- Flame impingement on a cold surface, quenching combustion reactions.
- Too-low flame temperature, slowing combustion reactions.

Incomplete combustion uses fuel inefficiently, contributes to air pollution, and can be hazardous because of carbon monoxide production.

Combustion of oxygen with the combustible elements and compounds in fuels occurs according to fixed chemical principles, including:

- Chemical reaction equations.
- Law of matter conservation. The mass of each element in the reaction products must equal the mass of that element in the reactants.
- Law of combining mass. Chemical compounds are formed by elements combining in fixed mass relationships.
- Chemical reaction rates.

**Table 1 Heating Values of Selected Fuels**
(Table 3, Chapter 28, 2021 *ASHRAE Handbook—Fundamentals*)

| Substance | Molecular Symbol | Higher Heating Values,[a] Btu/lb | Lower Heating Values,[a] Btu/lb | Specific Volume,[b] $ft^3$/lb | Higher Heating Values,[c] MJ/kg | Lower Heating Values,[c] MJ/kg | Density,[d] $kg/m^3$ |
|---|---|---|---|---|---|---|---|
| Carbon (to CO) | C | 3950 | 3950 | | 9.188 | 9.188 | |
| Carbon (to $CO_2$) | C | 14,093 | 14,093 | | 32.788 | 32.780 | 1.187 |
| Carbon monoxide | CO | 4347 | 4347 | 13.5 | 10.111 | 10.111 | 0.085 |
| Hydrogen | $H_2$ | 61,095 | 51,623 | 188.0 | 142.107 | 118.680 | 0.679 |
| Methane | $CH_4$ | 23,875 | 21,495 | 23.6 | 55.533 | 49.997 | 1.28 |
| Ethane | $C_2H_6$ | 22,323 | 20,418 | 12.5 | 51.922 | 47.492 | 1.92 |
| Propane | $C_3H_8$ | 21,669 | 19,937 | 8.36 | 50.402 | 46.373 | 2.53 |
| Butane | $C_4H_{10}$ | 21,321 | 19,678 | 6.32 | 49.593 | 45.771 | |
| Ethylene | $C_2H_4$ | 21,636 | 20,275 | | 50.325 | 47.160 | 1.78 |
| Propylene | $C_3H_6$ | 21,048 | 19,687 | 9.01 | 48.958 | 45.792 | 1.120 |
| Acetylene | $C_2H_2$ | 21,502 | 20,769 | 14.3 | 50.028 | 48.309 | |
| Sulfur (to $SO_2$) | S | 3980 | 3980 | | 9.257 | 9.257 | 1.456 |
| Sulfur (to $SO_3$) | S | 5940 | 5940 | | 13.816 | 13.816 | |
| Hydrogen sulfide | $H_2S$ | 7097 | 6537 | 11.0 | 16.508 | 15.205 | |

[a] All values corrected to 60°F, 30 in. Hg dry. For gases saturated with water vapor at 60°F, deduct 1.74% of the value to adjust for gas volume displaced by water vapor.
[b] At 32°F and 29.92 in. Hg
[c] All values corrected to 16°C, 101.4 kPa dry. For gases saturated with water vapor at 16°F, deduct 1.74% of the value to adjust for gas volume displaced by water vapor.
[d] At 32°F and 29.92 in. Hg

Oxygen for combustion is normally obtained from air, which is a physical mixture of nitrogen, oxygen, small amounts of water vapor, carbon dioxide, and inert gases. For practical combustion calculations, dry air consists of 20.95% oxygen and 79.05% inert gases, primarily nitrogen, by volume, or 23.15% oxygen and 76.85% inert gases by mass. For calculation purposes, nitrogen is assumed to pass through the combustion process unchanged (although small quantities of nitrogen oxides are known to form).

The quantity of heat generated by complete combustion of a unit of specific fuel is constant and is called the **heating value**, **heat of combustion**, or **caloric value** of that fuel. The heating value of a fuel can be determined by measuring the heat evolved during combustion of a known quantity of the fuel in a calorimeter, or it can be estimated from chemical analysis of the fuel and the heating value of the several chemical elements in the fuel.

Higher heating value, gross heating value, or total heating value is determined when water vapor in fuel combustion products is condensed and the latent heat of vaporization is included in the fuel's heating value. Conversely, lower heating value or net heating value is obtained when latent heat of vaporization is not included. When the heating value of a fuel is specified without designating higher or lower, it generally means the higher heating value in the United States. (lower heating value is mainly used for internal combustion engine fuels.)

Heating values are usually expressed in Btu/$ft^3$ ($kJ/m^3$) for gaseous fuels, Btu/gal ($kJ/m^3$) for liquid fuels, and Btu/lb (kJ/kg) for solid fuels. Heating values are always given in relation to a certain reference temperature and pressure, usually 60°F, 68°F, or 77°F and 14.696 psia (15°C, 20°C, or 25°C and 103.325 kPa), depending on the particular industry practice. Heating values of several substances and common fuels are listed in Table 1.

When combustion is incomplete, not all fuel is completely oxidized, and the heat released is less than the heating value of the fuel. Therefore, the quantity of heat produced per unit of fuel consumed decreases, implying lower combustion efficiency.

Not all heat released during combustion can be used effectively. The greatest heat loss is in the form of increased temperature (thermal energy) of hot exhaust gases above the temperature of incoming air and fuel.

Other heat losses include radiative and convective heat transfer from outer walls of combustion equipment to the environment.

## 1.2 Fuels

Generally, hydrocarbon fuels are classified according to physical state (gaseous, liquid, or solid). Different types of combustion equipment are usually needed to burn fuels in different physical states. Gaseous fuels can be burned in premix or diffusion burners that take advantage of the gaseous state. Liquid fuel burners must include a means of atomizing or vaporizing fuel into small droplets or to a vapor for burning and must provide adequate mixing of fuel and air. Solid fuel combustion equipment must (1) heat fuel to vaporize sufficient volatiles to initiate and sustain combustion, (2) provide residence time to complete combustion, and (3) provide space for ash containment.

Principal uses of fuel include space heating and cooling of residential, commercial, industrial, and institutional buildings; service water heating; steam generation; and refrigeration. Fuels for these applications are natural and liquefied petroleum gases, fuel oils, diesel and gas turbine fuels (for total energy applications), and coal.

**Gaseous Fuels**. Heating and cooling applications are presently limited to natural and liquefied petroleum gases. Natural gas is a nearly odorless and colorless gas that accumulates in the upper parts of oil and gas wells. Raw natural gas is a mixture of methane (55 to 98%), higher hydrocarbons (primarily ethane), and noncombustible gases. Some constituents, principally water vapor, hydrogen sulfide, helium, liquefied petroleum gases, and gasoline, are removed prior to distribution.

Heating values of natural gases vary from 900 to 1200 Btu/ft$^3$ (34 to 45 MJ/m$^3$); the usual range is 1000 to 1050 Btu/ft$^3$ (37 to 39 MJ/m$^3$) at sea level. Three liquefied petroleum gases—butane, propane, and a mixture of the two—are commercially available.

Commercial propane consists primarily of propane but generally contains about 5% to 10% propylene. It has a heating value of about 21,560 Btu/lb (50.15 MJ/kg) or about 2500 Btu/ft$^3$ (93 MJ/m$^3$) of gas. At atmospheric pressure, commercial propane has a boiling point of about –40°F (–40°C). The low boiling point of propane makes it usable during winter in cold climates such as the northern United States. It is available in cylinders, bottles, tank trucks, or tank cars.

Commercial butane consists primarily of butane but may contain up to 5% butylene. It has a heating value of about 21,180 Btu/lb (49.26 MJ/kg) or 3200 Btu/ft$^3$ (119 MJ/m$^3$).

Commercial propane-butane mixtures with varying ratios of propane and butane are available. Their properties generally fall between those of the unmixed fuels. Propane-air and butane-air mixtures are used in place of natural gas in small communities and by natural gas companies at peak loads. Typical heating values are listed in Table 2.

**Liquid Fuels.** Liquid fuels, with few exceptions, are mixtures of hydrocarbons refined from crude petroleum. Fuel oils for heating are broadly classified as distillate fuel oils (lighter oils) or residual fuel oils (heavier oils). ASTM has established specifications for fuel oil properties that subdivide the oils into various grades. Grades No. 1 and 2 are distillate fuel oils. Grades 4,5 (Light), 5 (Heavy), and 6 are residual fuel oils. Specifications for the grades are based on required characteristics of fuel oils for use in different types of burners. Typical gravity and heating values of standard grades of fuel oil are shown in Table 3.

**Solid Fuels**. Solid fuels include coal, coke, wood, and waste products of industrial and agricultural operations. Of these, only coal is widely used. Chemically, coal consists of carbon, hydrogen, oxygen, nitrogen, sulfur, and a mineral residue, ash. Heating values may be reported on an as-received, dry, dry and mineral-matter-free, or moist and mineral-matter-free basis. Higher heating values of coals are frequently reported with their proximate analysis. When more specific data are lacking, the higher heating value of higher quality coals can be calculated by the Dulong formula:

Higher heating value (Btu/lb)

$$= 14{,}544C + 62{,}028\,[H - (O/8)] + 4050S \tag{1}$$

or higher heating value (MJ/kg)

$$= 33.829C + 144.28\,[H - (O/8)] + 9.42S \tag{2}$$

where C, H, O, and S are the mass fractions of carbon, hydrogen, oxygen, and sulfur in the coal. Typical values for coal are listed in Table 4.

**Table 2 Heating Values of Gaseous Fuels**

| Gas | $Btu/ft^3$ | $MJ/m^3$ | Specific Gravity Air = 1.0 |
|---|---|---|---|
| Natural | 1030 | 38.4 | 0.60 |
| Propane | 2500 | 93.1 | 1.53 |
| Butane | 3175 | 118.3 | 2.00 |

**Table 3 Typical API Gravity, Density, and Heating Value of Standard Grades of Fuel Oil**

| Grade No. | API Gravity | Density, lb/gal[a] | Heating Value, Btu/gal[b] |
|---|---|---|---|
| 1 | 38 to 45 | 6.950 to 6.675 | 137,000 to 132,900 |
| 2 | 30 to 38 | 7.296 to 6.960 | 141,800 to 137,000 |
| 4 | 20 to 28 | 7.787 to 7.396 | 148,100 to 143,100 |
| 5L | 17 to 22 | 7.940 to 7.686 | 150,000 to 146,800 |
| 5H | 14 to 18 | 8.080 to 7.890 | 152,000 to 149,400 |
| 6 | 8 to 15 | 8.448 to 8.053 | 155,900 to 151,300 |

[a] 1 lb/gal = 120 $kg/m^3$ [b] 1 Btu/gal = 279 $kJ/m^3$

**Table 4 Heating Value of Coal**

| | Heating Value As Received | |
|---|---|---|
| Rank | Btu/lb | MJ/kg |
| Anthracite | 12,700 | 29.5 |
| Semianthracite | 13,600 | 31.6 |
| Low-volatile bituminous | 14,350 | 33.4 |
| Medium-volatile bituminous | 14,000 | 32.6 |
| High-volatile bituminous A | 13,800 | 32.1 |
| High-volatile bituminous B | 12,500 | 29.1 |
| High-volatile bituminous C | 11,000 | 25.6 |
| Subbituminous B | 9000 | 20.9 |
| Subbituminous C | 8500 | 19.8 |
| Lignite | 6900 | 16.0 |

## 1.3 Combustion Calculations

Calculations of the quantity of air required for combustion and quantity of flue gas products generated during combustion are frequently needed for sizing system components and as input to efficiency calculations. Other calculations, such as values for excess air and theoretical $CO_2$, are useful in estimating combustion system performance. Analysis of the flue gas products is often done using an Orsat analysis. This is a measure in percent by volume of the $CO_2$, CO, and $O_2$ in the dry products. The quantity of water vapor in the products is taken to be zero for this calculation. It is then assumed that the % $N_2$ in the products is 100% minus the % $CO_2$, % CO, and % $O_2$. Details on combustion calculations are given in Chapter 28 of the 2017 *ASHRAE Handbook—Fundamentals*.

**Example 1** Carbon burns with 160% theoretical air. Combustion goes to completion. Determine: (a) the air/fuel ratio by mass and (b) the Orsat gas analysis and dew point of the products.

**Solution**

Theoretical:

$$C + O_2 + 3.76N_2 \rightarrow CO_2 + 3.76N_2$$

Actual:

$$C + 1.6O_2 + 1.6\,(3.76)\,N_2 \rightarrow CO_2 + 6.02N_2 + 0.6O_2$$

1. A/F = [1.6(32) + 1.6(3.76)28]/12 = 18.3 $lb_{air}/lb_{fuel}$
2. 

| | | | |
|---|---|---|---|
| $CO_2$ | 1.0 moles/7.62 | = | 13.1% |
| $O_2$ | 0.6 moles/7.62 | = | 7.9% ORSAT |
| $N_2$ | 6.02 moles/7.6 | = | 79.0% |
| | 7.62 moles | = | 100.0% |

No dew point because there is no water vapor in the products.

*Note*: Assuming air is 79% $N_2$, 21% $O_2$ by volume:

$$1 \text{ mol } O_2 + 3.76 \text{ mol } N_2 = 4.76 \text{ mol air}$$

**Example 2** The flue gas analysis of a hydrocarbon fuel on a percent by volume dry basis shows $CO_2$ = 12.4%, $O_2$ = 3.2%, CO = 0.1%, $H_2$ = 0.2%, and $N_2$ = 84.1%. Determine the air/fuel ratio by volume.

**Solution**

$$C_xH_y + (84.1/3.76)\, O_2 + 84.1\, N_2 \rightarrow 12.4\, CO_2 + 3.2\, O_2 + 0.1\, CO + 0.2\, H_2 + 84.1\, N_2 + z\, H_2O$$

| | |
|---|---|
| $x = 12.4 + 0.1 = 12.5$ | Carbon balance |
| $22.4 = 12.4 + 3.2 + 0.05 + z/2$ | $O_2$ balance |
| $z = 13.5$ | |
| $y = 0.4 + 27 = 27.4$ | Hydrogen balance |

$$C_{12.5}H_{27.4} + 22.4O_2 + 84.1N_2 \rightarrow 12.4CO_2 + 3.2O_2 + 0.1CO + 0.2H_2 + 84.1N_2 + 13.5H_2O$$

$$A/F = (22.4 \text{ moles } O_2 + 84.1 \text{ moles } N_2)/\text{mole fuel}$$

$$A/F = 106.5/1 \text{ by volume}$$

# 2 Burners

When heating is required within a controlled environment, it is normally done using hot water, warm air, steam, radiant heat, or electric heat. Water, air, and steam can be heated using gas, oil, coal, or electric energy. In some instances, energy for heating can be provided by heat recovery techniques or solar energy.

## 2.1 Domestic Gas Burning Equipment

A gas burner is used to convey gas or a mixture of gas and air to the combustion zone. Burners are of the atmospheric injection, luminous flame, or power burner types.

Domestic gas burners may be classified as either those types designed for central heating plants or those designed for unit application. Gas-designed units and conversion burners are available for the several kinds of central systems and for other applications where the units are installed in the heated space. Central heating appliances include warm air furnaces and steam or hot water boilers.

Warm air furnaces are of two types, gravity and forced air. Forced warm-air furnaces use a motor-driven blower to circulate air over the heat exchanger and through the ducts. A draft hood is attached to the outlet of the furnace and replaces the barometric damper.

Gas-designed boilers for hot water or steam heating are available in cast-iron, steel, and nonferrous metals. Burners are located beneath the sections; the flue gases pass upward between the sections to the flue collector. Some boilers are designed to provide domestic hot water, using tankless or instantaneous heaters.

Some gas furnaces and boilers are available with sealed combustion chambers. These units have no draft hood and are called **direct vent appliances**. Combustion air is piped, usually through a side wall from outdoors, directly to the combustion chamber.

The air intake pipe terminates in the same location as the flue gas vent, sometimes as concentric pipes, with an appropriate terminal covering or cowl. No chimney or vertical flue is needed with such units.

Floor furnaces are used in mild climates for auxiliary heating, heating of single rooms, and, in some cases, heating of several rooms. Floor furnaces are not usually considered central heating systems. However, some are furnished with a circulating fan and as many as eight takeoff ducts. This type of floor furnace is a central heating system. In such a system, piping is below the floor as in other central warm air systems.

Space heaters are generally used for heating a single room or limited area. They differ from central heating equipment in the extent of distribution systems used. Both natural convection and forced-circulation systems distribute the warm air; however, no ductwork distributes heat beyond the immediate area occupied by the heater. Domestic, gas-fired space heaters include floor furnaces (without ductwork), vented wall furnaces, vented and unvented room heaters, radiant heaters, baseboard-sealed combustion system wall furnaces, wall heaters, and unit heaters. Some small room heaters are operated without vents, but they must be used with caution. Both manual and automatic controls are used. An automatic pilot or ignition system must be a part of any control system.

Under controlled conditions, an oil burner combines fuel oil and air for combustion. Fuel oil may be either **atomized** or **vaporized** for the combustion process. Air for combustion is supplied by natural or mechanical draft. Ignition is generally accomplished by an electric spark, gas pilot flame, oil pilot flame, or combination of these. Burners of different types operate with luminous or nonluminous flame. Operation may be continuous, modulating, or intermittent with high-low flame.

Residential oil burners are ordinarily used in the range of 0.5 to 3.5 gph (0.5 to 3.7 mL/s) fuel consumption rate. However, burners up to 7.0 gph (7.2 mL/s) sometimes fall in the residential classification because of similarities in controls and standards. Burner capacity of 7.0 gph (7.35 mL/s) and above is classified as commercial-industrial. Generally, No. 2 fuel oil is used, although burners in the residential size range can also operate on No. 1 fuel oil. In addition to boilers and furnaces for space heating, burners in the 0.5 to 1.0 gph (0.5 to 1.0 mL/s) size range are also used for separate tank type residential hot water heaters, infrared heaters, space heaters, and other commercial equipment.

Most burners manufactured (over 95%) are high-pressure, atomizing gun burners. While other types of burners are still in operation, only a few of these types are currently in production.

The high-pressure, atomizing gun burner illustrated in Figure 1 supplies oil to the atomizing nozzle at 100 to 300 psi (700 to 2100 kPa). A blower supplies air for combustion, and a damper or other device regulates the air supply at the burner. Ignition is usually accomplished by a high voltage electric spark, which may be intermittent, sometimes called either **constant ignition** (“on” when the burner motor is on) or **interrupted** (on only to start combustion). Typically, these burners fire into a combustion chamber in which negative draft is maintained.

Present high-pressure atomizing gun burner design includes retention heads and residential burner motors operating at 3450 rpm instead of 1725 rpm. The retention head assists combustion by providing better air-oil mixing, turbulence, and shear. Using the higher-speed 3450 rpm motors (often combined with a retention

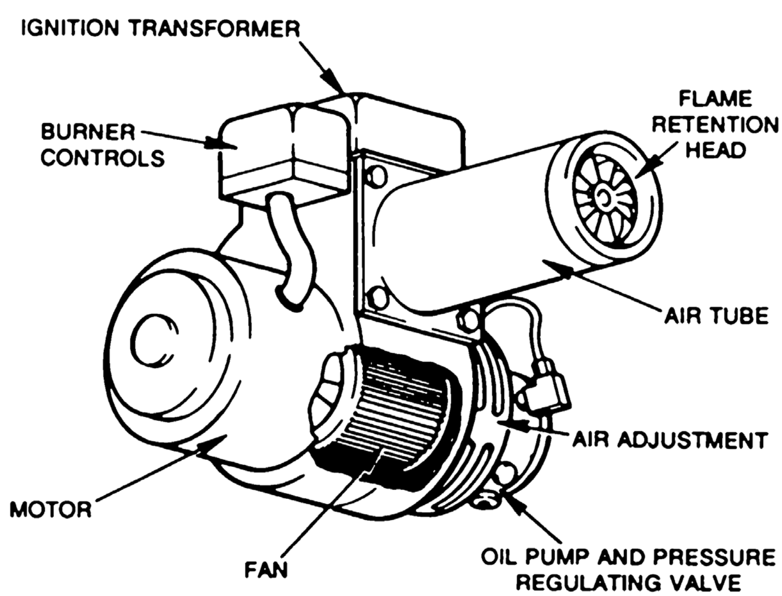


*Fig. 1 High-Pressure Atomizing Oil Burner*

head design) results in a more compact burner having equal capacity to one operating at 1725 rpm, and one that has a wide tolerance for varying combustion chamber and draft conditions.

Vaporizing burners are designed for use with No. 1 fuel oil. Fuel is ignited by manual pilot or electric spark. The combustion process usually provides enough heat for oil vaporization.

Oil-designated boiler-burner units for hydronic (hot water or steam) heating are constructed of cast iron, steel, and nonferrous metals. The oil burner is usually located at, or near, the base of the boiler; the flue gases pass upward and around the heat transfer sections and then out the chimney connector. Most oil-powered boiler burner units provide domestic hot water by incorporating a water heating coil (tankless heater) within the boiler.

Warm air furnaces with oil burner units are normally of forced-air design. A blower circulates air over the heat exchanger and through the duct. Upflow, counterflow, horizontal, or downflow furnaces are available. Most forced warm air furnaces make provisions for installing direct expansion air conditioning directly in the unit.

Additional details concerning commercial and industrial gas and/or oil burning equipment, as well as solid fuel burning equipment, can be found in Chapter 31 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment*. Details about various types of steam and hot water boilers are in Chapter 32 of the above reference.

# 3 Residential Furnaces

## 3.1 Equipment Variations

Residential furnaces provide heated air through a system of ductwork into the space being heated. They are of two basic types:

- **Fuel-Burning Furnaces.** Combustion takes place within a combustion chamber. Circulating air passes over the outside surfaces of the heat exchanger so that it does not contact the fuel or the products of combustion. The products of combustion are passed to the outside atmosphere through a vent.
- **Electric Furnaces.** A resistance-type heating element heats the circulating air either directly or through a metal sheath enclosing the resistance element.

Residential furnaces may be further categorized by:

- Fuel type
- Mounting arrangement
- Airflow direction
- Combustion system
- Installation location

A forced air furnace is a self-enclosed appliance used to heat air that is circulated through the enclosure and discharged directly into the space being heated or air that is conveyed through ducts to the space to be heated. An induced draft gas-fired unit is illustrated in Figure 2.

In fuel-burning furnaces, combustion occurs within a metal-walled heat exchanger. Air passes over the outside surfaces of the heat exchanger and the heat is transferred through the heat exchanger walls; the circulating air does not come in contact with the fuel or the products of combustion. The products of combustion are conveyed to the outside atmosphere through a flue or vent.

In an electric furnace, the heating element, heated by its electric resistance, heats the circulating air either directly or through a metal sheath enclosing the resistance element.

Residential forced air furnaces usually have a capacity under 250,000 Btu/h (74 kW) output. Residential furnaces are often used in commercial installations. The reverse is usually not true since more than one residential furnace would usually be used in an extremely large home rather than a furnace intended for commercial use.

The furnace may be designed and manufactured to combine components in a variety of ways. The relative positions of the components in the different types of furnaces are described as follows:

1. In a **horizontal furnace**, the blower is located beside the heat exchanger (Figure 3). The air enters one end and travels horizontally through the blower, over the heat exchanger, and discharges out of

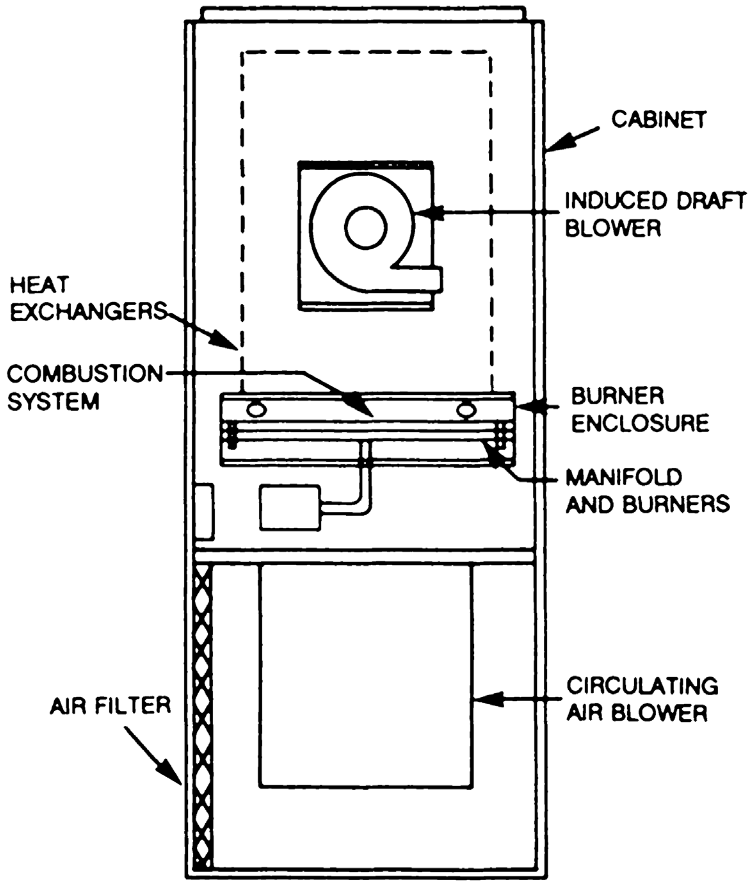


*Fig. 2 Induced Draft Gas Furnace*
(Figure 1, Chapter 33, 2016 *ASHRAE Handbook—HVAC Systems and Equipment*)

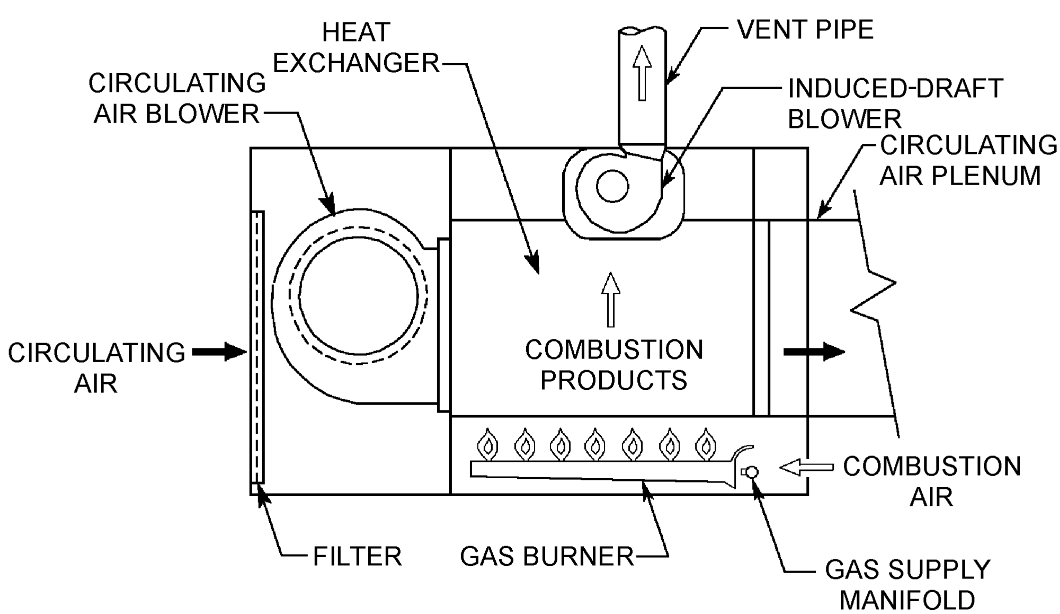


*Fig. 3 Horizontal Forced-Warm-Air Furnace*
(Figure 4, Chapter 33, 2016 *ASHRAE Handbook—HVAC Systems and Equipment*)

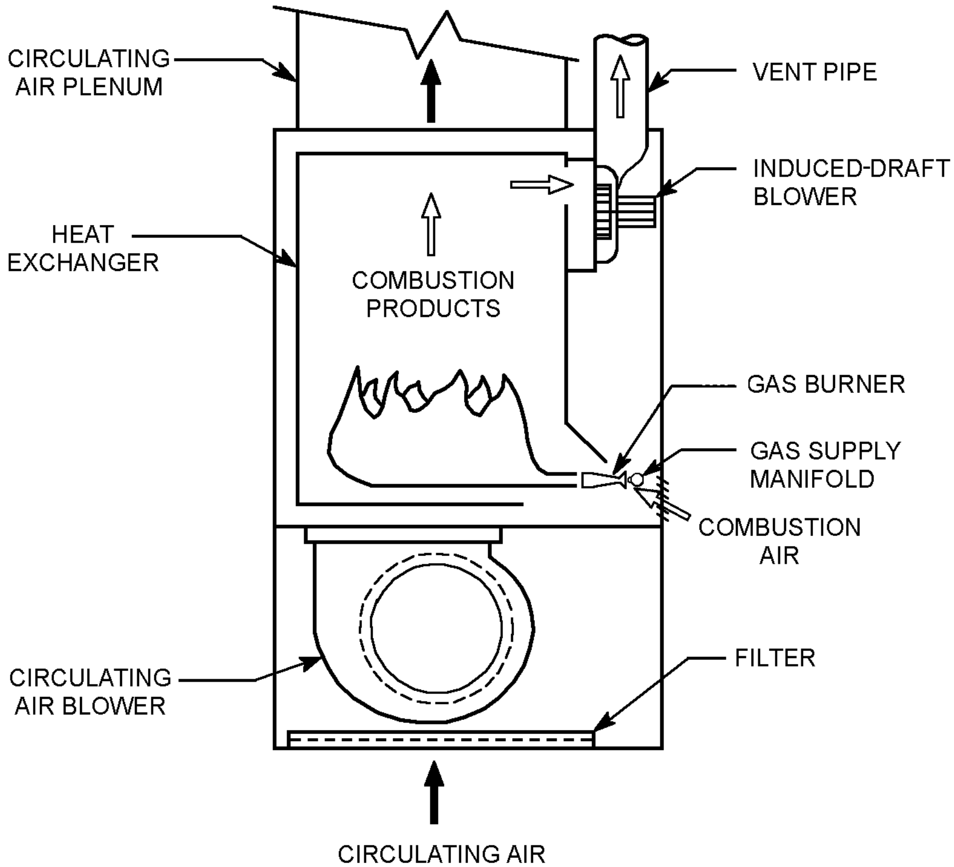


*Fig. 4 Upflow Forced-Warm-Air Furnace*
(Figure 2, Chapter 33, 2016 *ASHRAE Handbook—HVAC Systems and Equipment*)

the opposite end. Such furnaces are used for locations with limited head room (e.g., attics and crawlspaces). These units are often designed to allow for component rearrangement so that airflow may be from left to right or from right to left.

2. The blower in an **upflow furnace** is beneath the heat exchanger and discharges vertically upward (Figure 4). Air enters through the bottom or the side of the blower compartment and leaves at the top. Such furnaces may be used in utility rooms on the first floor of homes without basements or in basements with the return air ducted down to the blower compartment entrance.
3. The **basement furnace**, which is a variation of the upflow furnace, requires less head room (Figure 5). The blower is located at the bottom beside the heat exchanger. Air enters the top of the cabinet, flows down through the blower, discharges over the heat exchanger, and leaves vertically at the top.
4. The blower in the **downflow** or **counterflow furnace** is located above the heat exchanger and discharges downward (Figure 6). Air enters at the top and discharges vertically at the bottom. This style of furnace is used in a house without a basement that has a perimeter heating system.

Further discussion about furnaces and space heaters can be found in the 2016 *ASHRAE Handbook—HVAC Systems and Equipment*.

## 3.2 Capacity Selection

Heating capacity depends on several variables that may operate alone or in combination.

**Design heating requirement of building.** The heat loss of the structure can be calculated by using the procedures in Chapters 5 and 6 of *Principles of Heating, Ventilating, and Air Conditioning*, Ninth Edition.

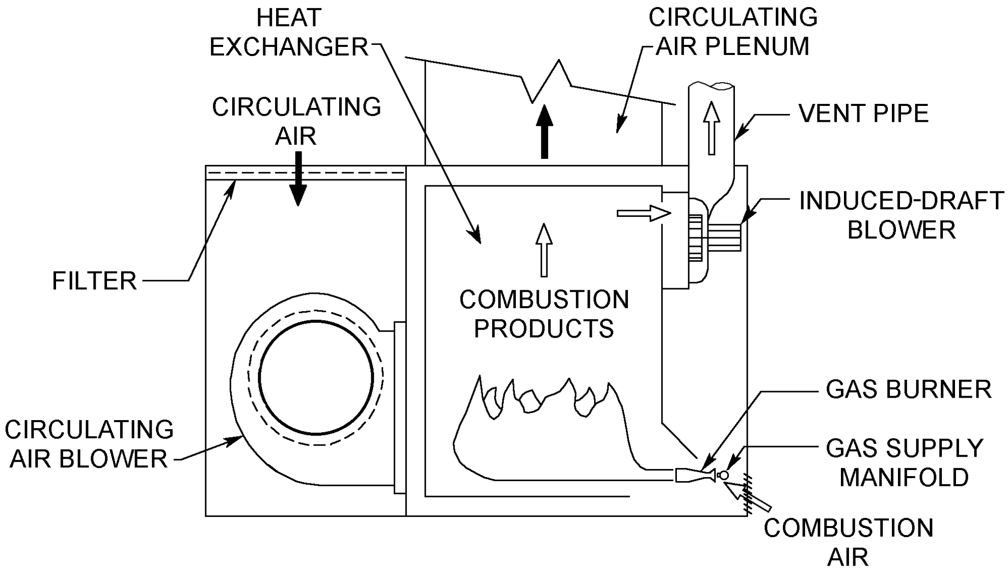


*Fig. 5 Basement Forced-Warm-Air Furnace*
(Figure 5, Chapter 33, 2016 *ASHRAE Handbook—HVAC Systems and Equipment*)

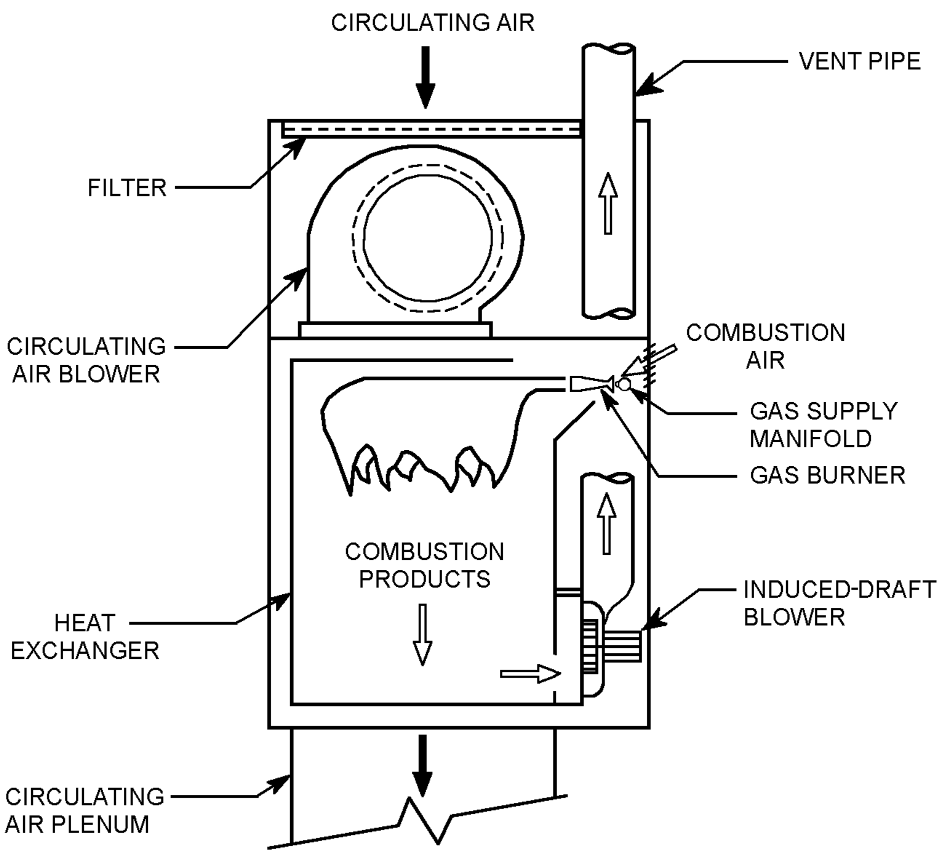


*Fig. 6 Downflow (Counterflow) Warm-Air Furnace*
(Figure 3, Chapter 33, 2016 *ASHRAE Handbook—HVAC Systems and Equipment*)

**Additional heating required if furnace is operating on night setback cycle.** During the morning recovery period, additional capacity is required to bring the conditioned space temperature up to the desired level.

**Internal loads.** Normally, the heat gain from internal loads is neglected when selecting a furnace, but if the internal loads are constant, they should be used to reduce the required capacity of the furnace. This is particularly applicable in nonresidential applications.

**Energy required for humidification.** Humidification energy depends on the desired level of relative humidity and the rate at which moisture must be supplied to maintain the specified level. Net moisture requirements must take into account internal gains as the result of people, equipment, and appliances, and losses through migration in exterior surfaces, plus air infiltration.

**Influence of off-peak storage devices.** A storage device, when used in conjunction with a furnace, decreases the required capacity of the furnace. The storage device can supply the additional capacity required during the morning recovery of a night setback cycle or reduce the daily peak loads to assist in load shedding.

**Influence of backup systems.** A furnace can exist as a backup to a solar system, a heat recovery system, or a structure requiring multiple units for uninterrupted service. Oversizing results in higher initial costs, possible increased operating costs, and decreased comfort control. Undersizing produces unacceptable comfort control near the design conditions.

**Capacity to accommodate air conditioning.** Even if air conditioning is not initially planned, the cabinet should be large enough to accept a cooling coil that satisfies the design cooling load. The blower and motor should have sufficient capacity to provide increased airflow rates typically required in air-conditioning applications.

### 3.3 Performance Criteria

Some typical efficiencies encountered in performance criteria of a furnace are (1) steady-state efficiency, (2) use efficiency, and (3) annual fuel use efficiency.

These efficiencies are generally used by the furnace industry in the following manner:

**Steady-state efficiency** is the efficiency of a furnace when it is operated under equilibrium conditions. It is calculated by measuring the energy input, subtracting the losses for exhaust gases, and then dividing by the fuel input (cabinet loss not included), i.e.,

$$\text{SS (\%)} = 100(\text{Fuel input} - \text{Flue loss} - \text{Condensate loss})/\text{Fuel input}$$

For furnaces tested under the isolated combustion system (ICS) method, cabinet heat loss must also be deducted from the energy input.

$$\text{SS (\%)(ICS)} = 100(\text{Fuel input} - \text{Flue loss} - \text{Condensate loss} - \text{Jacket loss})/\text{Fuel input}$$

**Utilization efficiency** is obtained from an empirical equation developed by Kelly et al. (1978) by starting with 100% efficiency and deducting losses for exhausted latent and sensible heat, cyclic effects, infiltration, and pilot-burner effect.

**Annual fuel utilization efficiency** (AFUE) is the same as **utilization efficiency**, except that losses from a standing pilot during nonheating season time are deducted. The equation for AFUE can also be found in Kelly et al. (1978) or ANSI/ASHRAE Standard 103.

Federal law requires manufacturers of furnaces to use AFUE to rate efficiency. Typical values of AFUE for various types of furnaces are listed in Table 5.

## 4 Commercial Furnaces

### 4.1 Equipment Variations

The basic difference between residential and commercial furnaces is the size and heating capacity of the equipment. The heating capacity of a commercial furnace may range from 150,000 Btu/h (44 kW) to over 2,000,000 Btu/h (600 kW). Generally, furnaces with output capacities less than 320,000 Btu/h (93 kW) are classified as light commercial, and those above 320,000 Btu/h (93 kW) are large commercial equipment. In addition to the difference in capacity, commercial equipment is constructed from material having increased structural strength and more sophisticated control systems.

**Table 5 Typical Values of Efficiency**
(Table 1, Chapter 33, 2016 *ASHRAE Handbook—HVAC Systems and Equipment*)

| | AFUE, % | |
|---|---|---|
| **Type of Gas Furnace** | **Indoor** | **ICS**[a] |
| 1. Natural-draft with standing pilot | 64.5 | 63.9[b] |
| 2. Natural-draft with intermittent ignition | 69.0 | 68.5[b] |
| 3. Natural-draft with intermittent ignition and auto vent damper | 78.0 | 68.5[b] |
| 4. Fan-assisted combustion with standing pilot or intermittent ignition | 80.0 | 78.0 |
| 5. Same as 4, except with improved heat transfer | 82.0 | 80.0 |
| 6. Direct vent, natural-draft with standing pilot, preheat | 66.0 | 64.5[b] |
| 7. Direct vent, fan-assisted combustion, and intermittent ignition | 80.0 | 78.0 |
| 8. Fan-assisted combustion (induced-draft) | 80.0 | 78.0 |
| 9. Condensing | 90.0 | 88.0 |
| **Type of Oil Furnace** | **Indoor** | **ICS**[a] |
| 1. Standard—pre-1992 | 71.0 | 69.0[b] |
| 2. Standard—post-1992 | 80.0 | 78.0 |
| 3. Same as 2, with improved heat transfer | 81.0 | 79.0 |
| 4. Same as 3, with automatic vent damper | 82.0 | 80.0 |
| 5. Condensing | 91.0 | 89.0 |

[a]Isolated combustion system (estimate).
[b]Pre-1992 design (see text).

Light commercial heating equipment comes in many flow arrangements and design variations. Some are identical to residential equipment, while others are unique to commercial applications. Some commercial units function as a part of a ducted system; others operate as unducted space heaters.

**Ducted Equipment.** Upflow gas-fired commercial furnaces are available up to 300,000 Btu/h (88 kW) and supply enough airflow to handle up to 10 tons (35 kW) of air conditioning. These furnaces may develop high static pressure, have belt-driven blowers, and frequently consist of two standard upflow furnaces tied together in a side-by-side arrangement.

Horizontal gas-fired duct furnaces are also available for built-in light commercial systems. This furnace is not equipped with its own blower but is designed for uniform airflow across the entire furnace.

Duct furnaces are normally certified for operation either upstream or downstream of an air-conditioner cooling coil. Electric duct furnaces are available in a great range of sizes and are suitable for operation in upflow, downflow, or horizontal positions. These units are also used to supply auxiliary heat with the indoor section of a split-heat pump.

The most common commercial furnace is the combination package unit, which is sometimes called a combination rooftop unit. They are available as air-conditioning units with liquefied petroleum gas (LPG) and natural gas furnaces, electric resistance heaters, or heat pumps. Combination oil-heat-electric-cool units are not commonly available. Combination units come in a full range of sizes covering air-conditioning ratings from 5 to 50 tons (18 to 176 kW) with matched furnaces supplying heat-to-cool ratios of approximately 1.5:1.

Combination units of 15 tons (53 kW) and under are available as single-zone units. The entire unit must be in either the heating or cooling mode. All air delivered by the unit is at the same temperature. Large combination units in the 15 to 50 ton (50 to 180 kW) range are available as single-zoned units, as are small units; however, they are also available as multizone units. A multizone unit supplies conditioned air at several different zones of a building in response to individual thermostats controlling those zones. These units are capable of supplying heating to one or more zones at the same time cooling is being supplied to other zones.

Large combination units are normally available only in a curbed configuration; i.e., the units are mounted on a roof-top over a curbed opening in the roof. The supply and return air enter through the bottom of the unit.

Smaller units may be available for either curbed or uncurbed mounting. In either case, the unit is always connected to ductwork within the building to distribute the conditioned air.

**Unducted Heaters.** Three types of commercial heating equipment used as unducted space heaters are unit heaters, infrared heaters, and floor furnaces.

**Unit heaters** are available from about 25,000 to 320,000 Btu/h (7 to 94 kW). Normally they are mounted from ceiling hangers and blow air across the heat exchanger into the heated space. Natural gas, LPG, and electric heat units are available.

**Infrared heaters** are mounted from ceiling hangers and transmit heat downward by radiation. Low- and medium-intensity infrared heaters are compact, self-contained, direct-heating devices. They are used in hangars, factories, warehouses, foundries, greenhouses, and gymnasiums and for areas such as loading docks, racetrack stands, under marquees, outdoor restaurants, and around swimming pools. Low-temperature radiant heaters are used in office buildings and other commercial buildings.

These heaters can be used with variable-air-volume systems. Infrared heating units may be electric, gas fired, or oil fired. They consist of an infrared source or generator operating in a temperature range of 350°F to 5000°F (180°C to 2800°C), with the specific temperature determined by the energy source, size, and application. Reflectors can be used to distribute radiation in specific patterns. Common configurations for gas-fired and electric infrared heaters are shown in Figures 7 and 8, respectively.

Radiant heaters transfer energy directly to solid objects. As floor and objects are warmed by the infrared energy, they, in turn, reradiate heat to solid objects, as well as transfer heat to the air by convection. Dry-bulb temperatures can be maintained slightly less than the mean radiant temperature. With convective heat, the converse is true. Since human comfort is determined by the average of mean radiant and dry-bulb temperatures, dry-bulb temperature may be lowered when heating with radiation. Heat loss to ventilating air and by transmission is correspondingly lower, as is energy consumption. Because buildings heated by infrared require less heating fuel for a given application, equipment that handles only 80% to 85% of the design heat loss calculated by ASHRAE methodology is typically installed.

**Floor furnaces** are used as large area unducted heaters. They are available in capacities ranging from 200,000 to 2,000,000 Btu/h (60 to 590 kW). Floor furnaces direct heated air through nozzles for task heating or use air circulators to heat large industrial spaces.

### 4.2 System Design and Equipment Selection

The procedure for design and selection of a commercial furnace is similar to that for a residential furnace. First, the design capacity of the heating system must be determined, considering structure heat loss, recovery load, internal load, humidification, off-peak storage, waste heat recovery, and backup capacity. Since most commercial buildings use setback periods during weekends, evenings, or other long periods of inactivity, the recovery load is important, as are internal loads and waste heat recovery.

Commercial sizing criteria are essentially the same as for residential furnaces. The furnace should be oversized 30% above the total load if setback is anticipated. Since combination units must be sized accurately for the cooling load, it is possible that the smallest gas-fired capacity available is larger than the 30% oversize value. This is especially true for the warmer climates of the United States.

Commercial units have about the same efficiency as residential units. Two-stage gas valves are frequently used with commercial furnaces, but the efficiency of a two-stage system may be lower than that of a single-stage system. At a reduced firing rate, the excess combustion airflow through the burners increases, which decreases the steady-state operating efficiency of the furnace. Multistage furnaces with multistage thermostats and controls provide more uniform distribution of heat within the building.

The useful life of commercial heating and cooling equipment is about 20 years.

## 5 Boilers

A boiler is a pressure vessel designed to transfer heat produced by combustion to a fluid. Heat is normally produced by combustion, but electrical resistance elements or electrodes acting directly on the fluid are also used. In boilers of interest to ASHRAE, the fluid is usually water, in the form of liquid or steam. If the fluid being heated is air, the heat-exchange device is called a furnace. The firebox, or combustion space, of some boilers is also called the furnace.

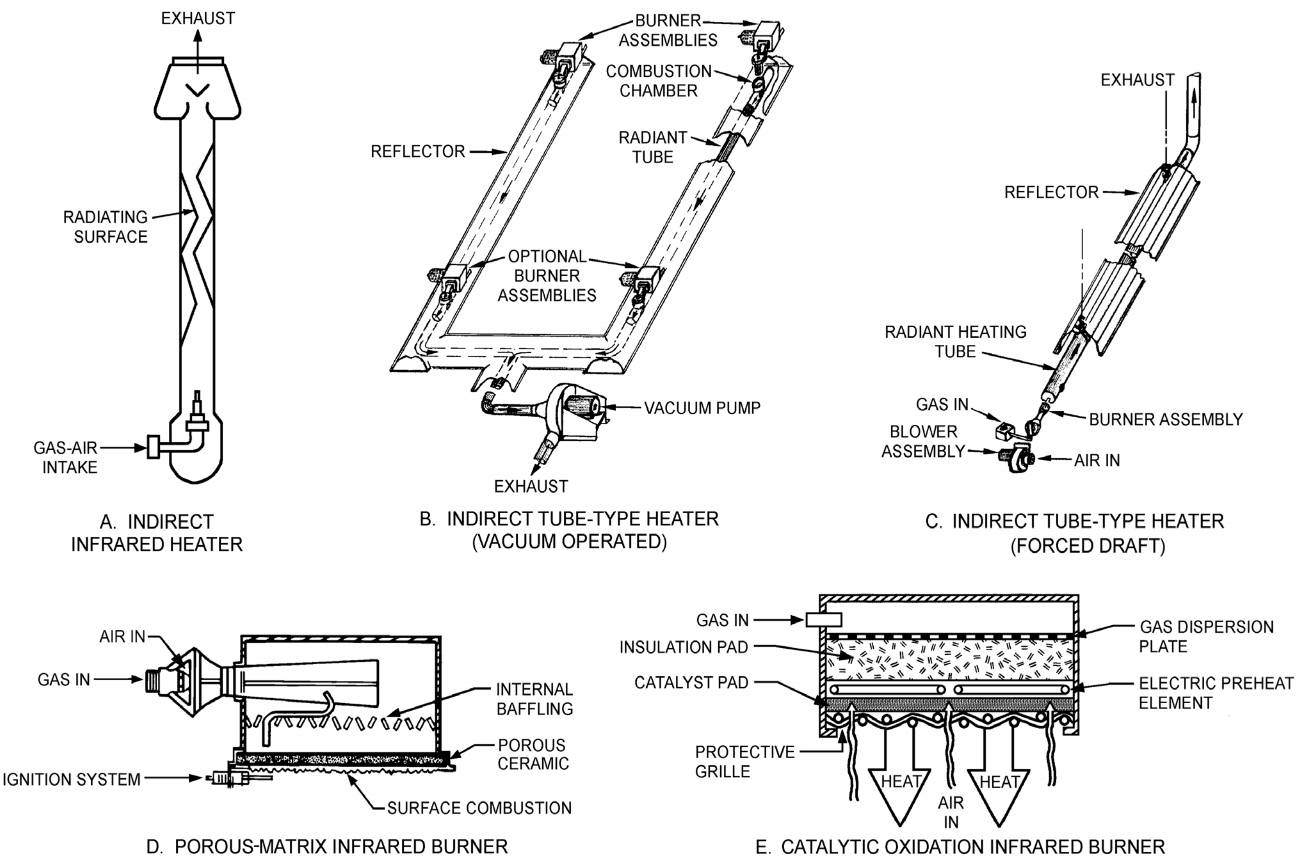


*Fig. 7 Gas-Fired Infrared Heaters*
(Figure 1, Chapter 16, 2016 *ASHRAE Handbook—HVAC Systems and Equipment*)

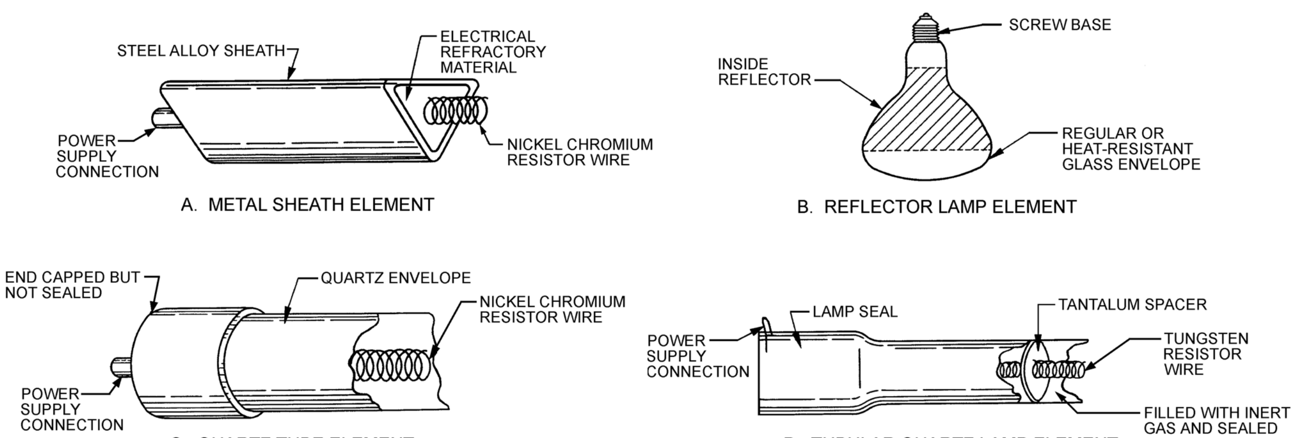


*Fig. 8 Electric Infrared Heaters*
(Figure 2, Chapter 16, 2016 *ASHRAE Handbook—HVAC Systems and Equipment*)

Excluding special and unusual fluids, materials, and methods, a boiler is a cast-iron, steel, or copper pressure vessel heat exchanger, designed with and for fuel-burning devices and other equipment (1) to burn fossil fuels (or use electric current) and (2) to transfer the released heat to water (in water boilers) or to water and steam (in steam boilers). Boiler heating surface is the area of fluid-backed surface exposed to the products of combustion, or the fire-side surface. Various codes and standards define allowable heat transfer rates in terms of heating surface. Boiler design provides for connections to a piping system, which delivers heated fluid to the point of use and returns the cooled fluid to the boiler.

## 5.1 Boiler Classifications

Boilers may be grouped into classes based on such criteria as working pressure and temperature, fuel used, shape and size, use (such as heating or process), and steam or water.

**Working Pressure/Temperature.** With few exceptions, all boilers are constructed to meet the ASME *Boiler and Pressure Vessel Code*.

**Low-pressure boilers** are constructed for maximum working pressures of 15 psi (103 kPa) steam and up to 160 psi (1100 kPa) hot water. Hot water boilers are limited to 250°F (120°C) operating temperature.

**Medium- and high-pressure boilers** are designed to operate above 15 psi (103 kPa) steam or above 160 psi (1100 kPa) water or 250°F (120°C) water boilers.

Steam boilers are available in standard sizes of up to 100,000 lb steam/h (60,000 to 100,000,000 Btu/h or 17 to 30,000 kW), many of which are used for space heating in both new and existing systems. On larger installations, they may also provide steam for auxiliary uses, such as hot-water heat exchangers, absorption cooling, laundry, and sterilizers. In addition, many steam boilers provide steam at various temperatures and pressures for a wide variety of industrial processes.

Water boilers are available in standard sizes of up to 100,000,000 Btu/h (30 MW) from 50,000 Btu/h (15 kW), many of which are in the low-pressure class and are used for space heating in both new and existing systems. Some water boilers may be equipped with either internal or external heat exchangers to supply domestic (service) hot water.

Every steam or water boiler is rated at the maximum working pressure determined by the ASME *Boiler and Pressure Vessel Code* (or other code) under which it is constructed and tested. When installed, it must also be equipped with safety controls and pressure relief devices mandated by such code provisions.

**Fuel Used**. Boilers may be designed to burn coal, wood, various grades of fuel oil, various types of fuel gas, or to operate as electric boilers. A boiler designed for one specific fuel type may not be convertible to another type of fuel. Some boiler designs can be adapted to burn coal, oil, or gas. Several designs allow firing with oil or gas by burner conversion or by using a dual-fuel burner.

**Construction Materials**. Most boilers, other than special or unusual models, are made of cast iron or steel. Some small boilers are made of copper or copper-clad steel.

Cast iron boilers are constructed of individually cast sections, assembled into blocks (assemblies) or sections. Push or screw nipples, gaskets, or an external header join the sections pressure-tight and provide passages for the water, steam, and products of combustion. The number of sections assembled determines boiler size and energy rating. Sections may be vertical or horizontal, the vertical design being the most common. The boiler may be dry-base (the firebox is beneath the fluid-backed sections), wet-leg (the firebox top and sides are enclosed by fluid-backed sections), or wet-base (the firebox is surrounded by fluid-backed sections, except for necessary openings).

Steel boilers are fabricated into one assembly of a given size and rating, usually by welding. The heat-exchange surface past the firebox usually is an assembly of vertical, horizontal, or slanted tubes. The tubes may be firetube (flue gas inside, heated fluid outside) or watertube (fluid inside, hot gas outside). The tubes may be in one or more passes. Drybase, wet-leg, or wet-base design may be used. Most small steel heating boilers are of dry-base, vertical firetube design. Larger boilers usually have horizontal or slanted tubes; both firetube and watertube designs are used. A popular design for medium and large steel boilers is the Scotch, or Scotch Marine, which is characterized by a central fluid-backed cylindrical firebox, surrounded by firetubes in one or more passes, all within the outer shell.

Cast iron boilers range in size from 35,000 to 13,000,000 Btu/h (10 to 3770 kW) gross output. Steel boilers range in size from 50,000 Btu/h (15 kW) to the largest boilers made.

**Condensing or Noncondensing Boilers.** Because higher boiler efficiencies can be achieved with lower water temperatures, condensing boilers purposely allow the flue gas water vapor in the boiler to condense and drain. Illustrated in Figure 9 is a typical relationship of overall boiler efficiency to return water temperature. The dew point of 130°F (55°C) shown varies with the percent of hydrogen in the fuel and the $CO_2$ (or excess air) in the flue gas.

Low return water temperatures and condensing boilers are particularly important because they are so efficient at part-load operation when high water temperatures are not required. For example, a hot water heating system that operates under light load conditions at 80°F (27°C) return water temperature has a potential overall boiler efficiency of 97% when operated with natural gas of the specifications applicable for Figure 9.

## 5.2 Selection Parameters

Boiler selection should be based on a competent review of the following parameters:

**All Boilers**

- ASME Code Section, under which the boiler is constructed and tested
- Net boiler output capacity, Btu/h (kW)
- Total heat transfer surface, $ft^2$ ($m^2$)
- Water content, lb (kg)
- Auxiliary power requirements, kWh
- Internal water-flow patterns
- Cleaning provisions for all heat transfer surfaces
- Operational efficiency
- Space requirements and piping arrangement
- Water treatment requirements
- Operating personnel requirements
- Maintenance requirements
- Regulatory emission limitations

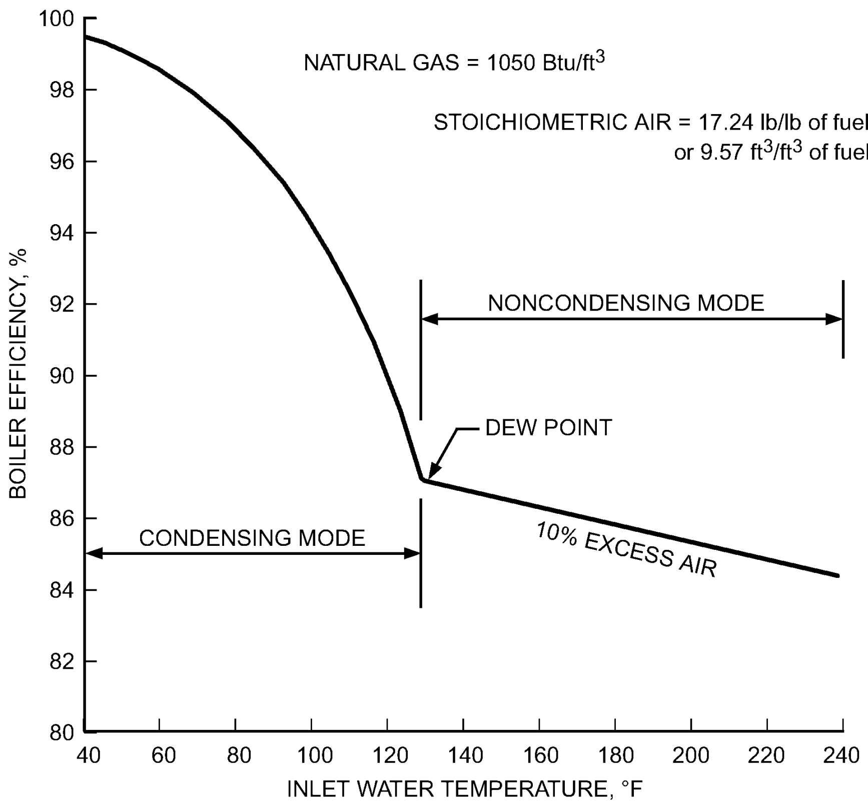


*Fig. 9 Boiler Efficiency*
(Figure 6, Chapter 32, 2016 *ASHRAE Handbook—HVAC Systems and Equipment*)

**Fuel-Fired Boilers**

- Combustion space (furnace volume), $ft^2$ ($m^2$)
- Internal flow patterns of combustion products
- Combustion air and venting requirements
- Fuel availability

**Steam Boilers**

- Steam space, $ft^3$ ($m^3$)
- Steam quality

**Electric Boilers**

- Electric boilers are in a separate class. Since no combustion occurs, no boiler heating surface and no flue openings are necessary. Heating surface is the surface of the electric elements or electrodes immersed in the boiler water. The design of electric boilers is largely determined by the shape and heat release of the electric heating elements used.

## 5.3 Efficiency: Input and Output Ratings

Efficiency of fuel-burning boilers is defined by combustion efficiency and overall efficiency. Overall efficiency of electric boilers is in the 92% to 96% range.

**Combustion efficiency** is input minus stack (chimney) loss, divided by input, and ranges from 75% to 86% for most noncondensing, mechanically fired boilers. Condensing boilers operate in the range of 88% to over 95% efficiency.

**Overall efficienc***y* is gross output divided by input. Gross output is measured in the steam or water leaving the boiler and depends on individual installation characteristics. Overall efficiency is lower than combustion efficiency by the percentage of heat lost from the outside surface of the boiler (this loss is usually termed **radiation loss**). Overall efficiency can be determined only by testing under fixed conditions. Approximate combustion efficiency can be determined under any operating condition by measuring operating flue-gas temperature and percentage $CO_2$ or $O_2$ and by consulting a chart or table for the fuel being used.

Heating boilers are usually rated according to standards developed by (1) The Hydronics Institute [formerly the Institute of Boiler and Radiator Manufacturers (IBR) and The Steel Boiler Institute (SBI)], (2) The American Gas Association (AGA), and (3) The American Boiler Manufacturers Association (ABMA).

## 5.4 Boiler Sizing

Boiler sizing is the selection of boiler output capacity to meet connected load. The boiler gross output is the rate of heat delivered by the boiler to the system under continuous firing at rated input. Net rating (IBR rating) is gross output minus a fixed percentage to allow for an estimated average piping heat loss plus an added load for initially heating the water in a system (sometimes called pickup).

Piping loss is variable. If all piping is run within the space defined as load, loss is zero. If piping runs through unheated spaces, heat loss from the piping may be higher than accounted for by the fixed net rating factor. Pickup is also variable. Pickup factor may be unnecessary when actual connected load is less than design load. On the design's coldest day, extra system output (boiler and radiation) is needed to pick up the load from a shutdown or low night setback. If night setback is not used, or if no extended shutdown occurs, no pickup load exists. Standby system capacity for pickup, if needed, can be in the form of excess capacity in base-load boilers or in a standby boiler.

## 5.5 Control of Boiler Input and Output

Boiler controls regulate the rate of fuel input (on-off, step-firing, or modulating) in response to a control signal representing load change, so that average boiler output equals load within some accepted control tolerance. Boiler controls include safety controls that shut off fuel flow when unsafe conditions develop.

Steam boilers are operated by boiler-mounted, pressure-actuated controls, which vary the input of fuel to the boiler. Common examples of controls are on-off, high-low-off, and modulating. Modulating controls continuously vary the fuel input from 100% down to a selected minimum point. The ratio of maximum to minimum is called the **turndown ratio**. The minimum input is usually between 5% and 25%, i.e., 20:1 to 4:1, and depends on the size and type of fuel-burning apparatus.

## 5.6 Hydronic Systems

Hot water heating systems are frequently called **hydronic systems**. Water systems can be classified by (1) temperature, (2) flow generation, (3) pressurization, (4) piping arrangement, and (5) pumping arrangement. Water systems are either once-through or recirculating systems.

The two types of hot water heating systems classified by flow generation are (1) the **gravity system**, which uses the difference in density between the supply and return water columns of a circuit or system to circulate water, and (2) the **forced system**, in which a pump, usually driven by an electric motor, maintains the flow.

**Low-temperature hot water systems (LTHW)** are the most widely used heating systems for residential, commercial, and institutional systems where loads consist primarily of space heating and domestic water heating and do not exceed 5,000,000 Btu/h (1.5 MW) total. The maximum allowable working pressure for low-pressure heating boilers is 160 psia (1100 kPa), with a maximum temperature limitation of 250°F (120°C). The usual maximum working pressure for boilers for LTHW systems is 30 psia (200 kPa), although boilers specifically designed, tested, and stamped for higher pressures may frequently be used with working pressures to 160 psia (1100 kPa). Steam-to-water or water-to-water heat exchangers are also often used.

**Medium-temperature hot water systems (MTHW)** (350°F [175°C] or less) are most commonly used for space heating in large commercial and institutional buildings or in industrial applications with process loads, and where total loads range from $5 \times 10^6$ to $20 \times 10^9$ Btu/h (1.5 to 6 MW). In a medium-temperature system, the usual design supply temperature is above 250°F (120°C) and below 350°F (175°C) with a usual pressure rating for boilers and equipment of 150 psia (1030 kPa).

**High-temperature hot water systems (HTHW)** are generally limited to campus-type district heating installations and to applications requiring process heating temperatures of 350°F (175°C) or higher.

The design of water systems is affected by complex relationships between the various system components. The design water temperature, flow rate, piping layout, pump selection, terminal unit selection, and control method are all interrelated. The size and complexity of the system determines the importance of these relationships in affecting the total operating success. Present hot water heating system design practice originated in residential heating applications where a 20°F (11°C) temperature drop (TD) was used to determine flow rate. Besides producing satisfactory operation and economy in small systems, this TD enabled simple calculations because 1 gpm conveys 10,000 Btu/h (1 L/s conveys 41 kW with a 10°C TD).

Elements of a high-temperature water system are illustrated in Figure 10. Requirements for such a system include a high limit control, a safety relief valve, and other safety controls and devices on the boiler, and a boiler efficiency with an accepted test rating.

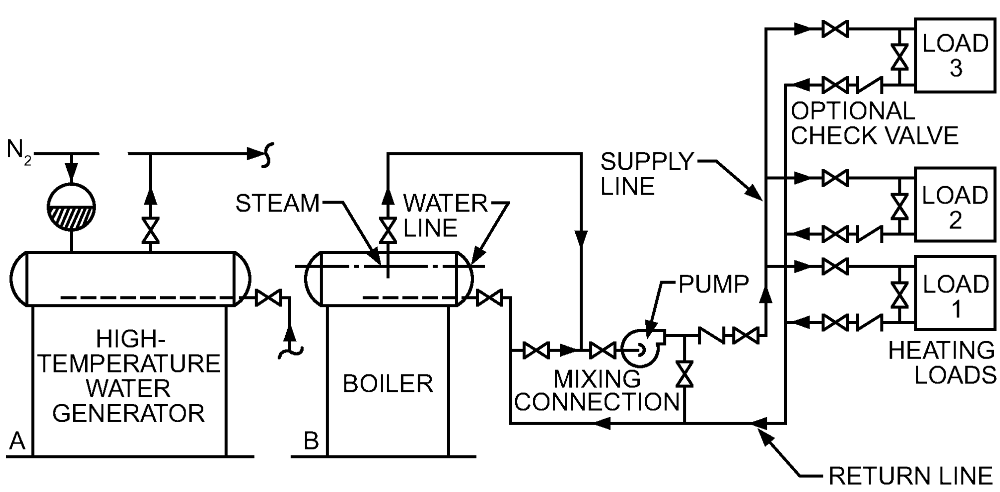


*Fig. 10 Elements of High-Temperature Water System*
(Figure 2, Chapter 15, 2016 *ASHRAE Handbook—HVAC Systems and Equipment*)

# 6 Terminal Units

Radiators, convectors, baseboard, and finned tube units are commonly used to distribute heat to the space provided by the steam or LTHW systems. They supply heat through a combination of radiation and convection. In general, these units are placed at the points of greatest heat loss of the space such as under windows, along exposed walls, and at door openings.

A **radiator** is generally considered a sectional cast-iron unit of column, large tube, or small tube type (Figure 11).

A **convector** is a heat-distributing unit that operates with gravity-circulated air. The heating element contains two or more tubes with headers at both ends. The heating element is surrounded by an enclosure with an air inlet below and an air outlet above (Figure 11).

**Baseboard** and **baseboard radiation heat distributing units** are installed at the base of walls in place of the conventional baseboard. They may be made of cast iron, with a substantial portion of the front face directly exposed to the room, or with a finned-tube element in a sheet metal enclosure (Figure 11).

**Finned tube** or **fin-tube** refers to heat-distributing units fabricated from metallic tubing with metallic fins bonded to the tube. They operate with gravity-circulated room air and may be installed bare, with an expanded metal grille, a cover, or an enclosure having top, front, or inclined outlets.

## 6.1 Radiators

The small-tube type radiators, with a length of only 1 3/4 in. (44 mm) per section, occupy less space than the older column and large-tube units and are particularly suited to installation in recesses. Shown in Figure 12 are the types of units now being manufactured.

## 6.2 Convectors

Convectors are made in a wide variety of depths, sizes, and lengths in both cabinet and enclosure style. The heating elements are fabricated in ferrous and nonferrous metals. The air enters the enclosure below the heating element, is heated as it passes through the element, and leaves the enclosure through the outlet grille located above the heating element. Factory-assembled units composed of a heating element and enclosure are widely used. These may be free standing, wall hung, or recessed and may have outlet grilles and arched inlets or inlet grilles (Figure 11).

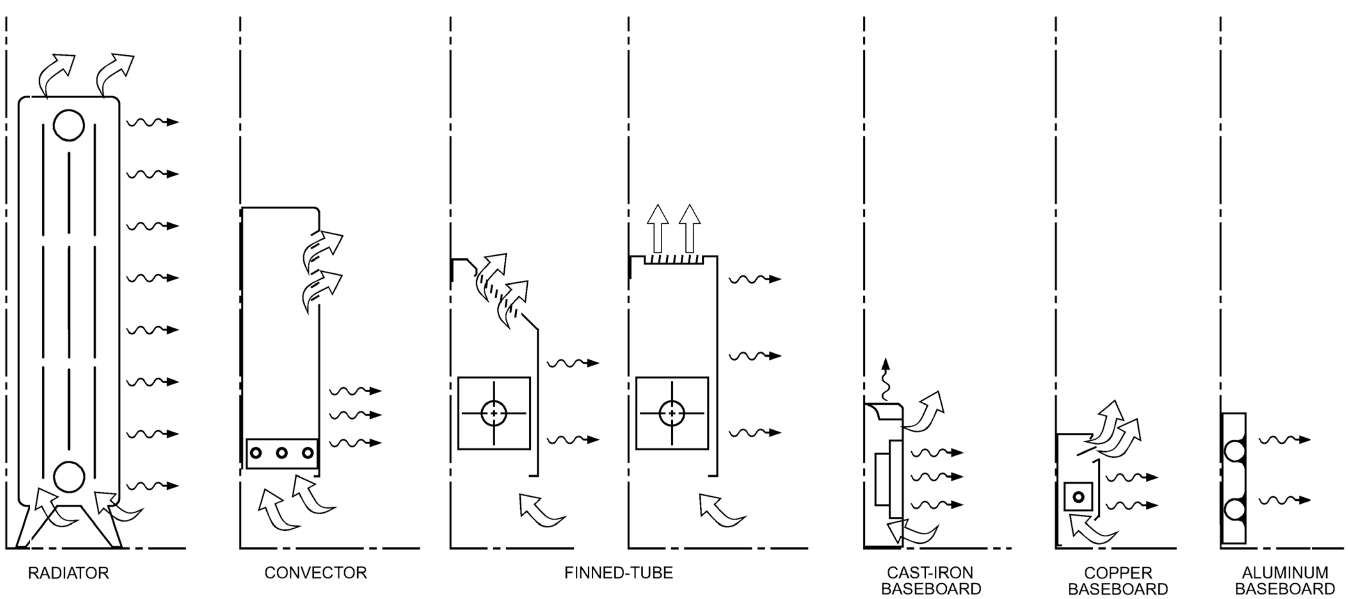


*Fig. 11 Terminal Units*
(Figure 1, Chapter 36, 2016 *ASHRAE Handbook—HVAC Systems and Equipment*)

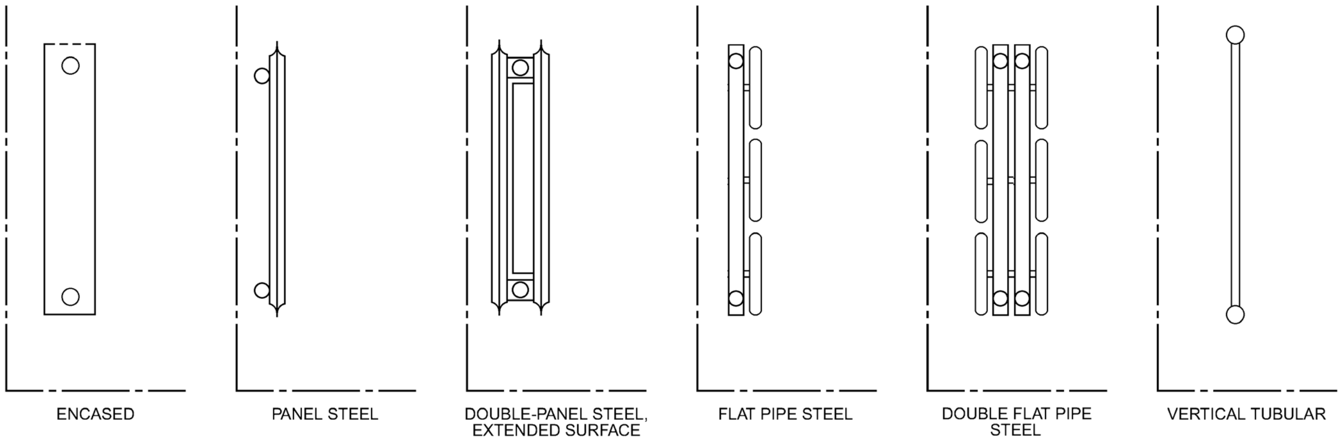


*Fig. 12 Typical Radiators*
(Figure 2, Chapter 36, 2016 *ASHRAE Handbook—HVAC Systems and Equipment*)

### 6.3 Baseboard Units

Baseboard heat-distributing units are divided into two types: (1) radiant-convector and (2) finned tube.

A **radiant-convector baseboard heating unit** is made of cast iron or steel. The units have air openings at the top and bottom to permit circulation of room air over the wall side of the unit. The wall side of the unit has an extended surface to provide increased heat output. A large portion of the heat is transferred by convection (Figure 11).

A **finned tube baseboard heating unit** has a finned-tube heating element that is concealed by a long, low, sheet-metal enclosure or cover. Most of the heat is transferred to the room by convection. Optimum comfort for room occupants is obtained when units are installed along as much of the exposed wall as possible.

The baseboard unit has the following advantages: (1) it is normally placed along the cold walls and under areas where the greatest heat loss occurs, (2) it is inconspicuous, (3) it offers minimum interference with furniture placement, and (4) it distributes heat near the floor. This last characteristic reduces the floor-to-ceiling temperature gradient to about 2°F to 4°F (1°C to 2°C) and helps produce uniform temperatures throughout the room. It also makes baseboard heat-distributing units adaptable to homes without basements, where cold floors are prevalent.

## 7 Electric Heating

For many applications, the compactness, simplicity, responsiveness, accuracy of control, safety, and cleanliness of electric heating may outweigh its disadvantages. Electric space heating is often used where minimum initial cost is the dominating factor.

### 7.1 Electric Heating Elements

Electric heating elements usually are composed of metal-alloy wire or ribbons, nonmetallic carbon compounds in rod or other shapes, or printed circuits. Heating elements may have exposed resistor coils mounted on insulators, metallic resistors embedded within refractory insulation encased in a protective metal sheath, or a printed circuit on glass sheets or vitrified panels. Fins or extended surfaces may be used to increase heat dissipation. Elements are made in many forms. Metal or oxide conductive films on glass and ceramics have been used, usually in panel form. Tubular elements may be immersed in liquids, used bare, formed into coils, or cast into metal.

Cloth fabrics, incorporating flexible resistor wires, are used for low-temperature purposes such as heating pads, sheets, blankets, aviators' clothing, window draperies, and some radiant panel heating installations. Paper or fabric incorporating a surface resistor on the back is applied for ceiling panel heating installations.

**Table 6 Types of Electric Space-Heating Equipment**

| DECENTRALIZED SYSTEMS | CENTRALIZED SYSTEMS |
|---|---|
| **Natural Convection Units** | **Heated Water Systems** |
| Floor drop-in units | Electric boiler |
| Wall insert and surface-mounted heaters | Electric boiler with hydronic off-peak storage |
| Baseboard convectors | Heat pumps |
| Hydronic baseboard convectors with immersion elements | Integrated heat recovery systems |
| **Forced Air units** | **Steam Systems** |
| Unit ventilators | Electric boiler with immersion element or electrode |
| Unit heaters | **Heated-Air Systems** |
| Wall insert heaters | Duct heaters |
| Baseboard heaters | Electric furnaces |
| Floor drop-in heaters | Heat pumps |
| **Radiant Units (High Intensity)** | Integrated heat recovery systems |
| Radiant wall, insert, or surface-mounted (open ribbon or wire element) | Unit ventilators |
| Metal-sheathed element with focusing reflector | Self-contained heating and cooling units |
| Quartz tube element with focusing reflector | Storage units (ceramic, water) |
| Quartz lamp with focusing reflector | |
| Heat lamps | |
| Valance (cove) heaters | |
| **Radiant Panel Systems (Low Intensity)** | |
| Radiant ceiling with embedded conductors | |
| Prefabricated panels | |
| Radiant floor with embedded conductors | |
| Radiant-convector panel heaters | |

## 7.2 Electric Space Heating Systems

Types of electric heating equipment and complete heating systems in use are listed in Table 6. The sequence shown is for convenient reference only and does not indicate the relative performance or extent of use. Installations of all types listed are in successful operation, but operating characteristics depend largely on proper application.

## 7.3 Calculating Capacities

The procedure outlined in Chapters 17 and 18 of the 2017 *ASHRAE Handbook—Fundamentals* for calculating heating load of residential and nonresidential buildings may be used for electric systems. The *NEMA Manual for Electric Comfort Conditioning*, published by the National Electrical Manufacturers Association, gives heat loss factors and describes methods for calculating load directly in kilowatts.

The most economical electric heating systems from an operating standpoint are decentralized, with the thermostat provided on each unit or for each room. This permits each room to compensate for heat contributed by auxiliary sources such as sunshine, lighting, and appliances. Such an arrangement also gives a better diversity of the power demand because the electric loads from all units of an installation do not coincide. Manual switches allow the heat to be turned off or allow for reduced temperatures in rooms that are not in use. When manual switches are used, adequate capacity for warm-up should be provided.

Residences and other buildings designed for electric heat should be well insulated. Depending on the climate, storm or multiple-glazed windows and storm doors are generally recommended to reduce heat loss and further increase comfort. Weather stripping doors and windows effectively reduces air infiltration.

# 8 References

Amende, K.L., J.A. Keen, L.E. Catlin, M. Tosh, A.M. Sneed, and R.H. Howell. 2021. *Principles of Heating, Ventilating, and Air Conditioning*, Ninth Edition.

ASHRAE. 2016. *ASHRAE Handbook—HVAC Systems and Equipment*.

ASHRAE. 2017a. ANSI/ASHRAE Standard 103-2017, *Method of testing for annual fuel utilization efficiency of residential central furnaces and boilers*.

ASHRAE. 2017b. *ASHRAE Handbook—Fundamentals*.

ASHRAE. 2020. *ASHRAE Handbook—HVAC Systems and Equipment*.

ASHRAE. 2021. *ASHRAE Handbook—Fundamentals*.

Kelly, G.E., J.G. Chi, and M. Kuklewicz. 1978. *Recommended testing and calculation procedures for determining the seasonal performance of residential central furnaces and boilers*. Springfield, VA: National Technical Information Service.

# 9 Problems

***Note:*** *In all problems, assume air is 79%* $N_2$ *and 21%* $O_2$.

**Problem 1** Set up the necessary combustion equations and determine the mass of air required to burn 0.45 kg (1 lb) of pure carbon to equal masses of CO and $CO_2$.

**Problem 2** The gravimetric analysis of a gaseous mixture is: $CO_2$ = 32%, $O_2$ = 54.5%, and $N_2$ = 11.5%. The mixture is at a pressure of 20.7 kPa (3 psia). Determine the following:

1. The volumetric analysis
2. The partial pressure of each component

**Problem 3** A liquid petroleum fuel, $C_2H_6OH$, is burned in a space heater at atmospheric pressure.

1. For combustion with 20% excess air, determine the air/fuel ratio by mass, the mass of water formed by combustion per pound of fuel, and the dew point of the combustion products.
2. For combustion with 80% theoretical air, determine the dry analysis of the exhaust gases in percentage by volume.

**Problem 4** Find the air/fuel ratio by mass when benzene ($C_6H_6$) burns with theoretical air and determine the dew point at atmospheric pressure of the combustion products if an air/fuel ratio of 20:1 by mass is used.

**Problem 5** A diesel engine uses 30 $lb_m$ of fuel per hour (3.8 g/s) when the brake output is 75 hp. If the heating value of the fuel is 19,600 Btu/lb (45,600 kJ/kg), what is the brake thermal efficiency of the engine?

**Problem 6** Methane ($CH_4$) is burned with air at atmospheric pressure. The Orsat analysis of the flue gas gives: $CO_2$ = 10.00%, $O_2$ = 2.41%, CO = 0.52%, and $N_2$ = 87.07%. Balance the combustion equation and determine the air-fuel ratio, the percent theoretical air, and the percent excess air.

**Problem 7** Fuel oil composed of $C_{16}H_{32}$ is burned with the chemically correct air-fuel ratio. Find the following:

1. Moisture formed per kg of fuel; moisture formed per lb of fuel
2. Partial pressure of the water vapor, kPa; water vapor, psia
3. Percentage of $CO_2$ in the stack gases on an Orsat basis
4. Volume of exhaust gases per unit mass of oil, if the gas is at 260°C (500°F) and 102 kPa (14.8 psia)

**Problem 8** Determine the composition of a hydrocarbon fuel if the Orsat analysis gives: $CO_2$ = 8.0%, CO = 1.0%, $O_2$ = 8.7%, and $N_2$ = 82.3%.

**Problem 9** Determine the air/fuel ratio by mass when a liquid fuel of 16% hydrogen and 84% carbon by mass is burned with 15% excess air.

**Problem 10** Compute the compositions of the flue gases on a percent by volume on dry basis (same as Orsat) resulting from the combustion of $C_8H_{18}$ with 85% theoretical air.

**Problem 11** A liquid petroleum fuel having a hydrogen to carbon ratio of 0.169 by mass is burned in a heater with an air/fuel ratio of 17 by mass. Determine the following:

1. The volumetric analysis on both wet and dry bases of the exhaust gases
2. The dew point of the exhaust gas

**Problem 12** Compare the heating value for semianthracite coal as given in Table 12 of Chapter 28 of the 2021 *ASHRAE Handbook—Fundamentals* with the value predicted using the Dulong formula.

**Problem 13** Natural gas with a volumetric composition of 93.32% methane, 4.17% ethane, 0.69% propane, 0.19% butane, 0.05% pentane, 0.98% carbon dioxide, and 0.61% nitrogen burns with 30% excess air. Calculate the volume of dry air at 60°F, 30 in. Hg (15.6°C, 101.5 kPa) used to burn 1000 $ft^3$ (28.3 mL) of gas at 68°F and 29.92 in. Hg (20°C and 101.4 kPa) and find the dew point of the combustion products.

**Problem 14** The proximate analysis of a coal is: moisture = 4.33%, volatile matter = 40.21%, fixed carbon = 45.07%, and ash = 10.39%. The heating value was determined as 29 000 kJ/kg (12,490 Btu/lb). Find the ASTM rank of the coal.

**Problem 15** A fuel oil shows an API gravity of 36. Calculate the specific gravity at 60°F and the pounds per gallon of fuel. Estimate the ASTM grade.

**Problem 16** A representative No. 4 fuel oil has a gravity of 25 degrees API and the following composition: carbon = 87.4%, hydrogen = 10.7%, sulfur = 1.2%, nitrogen = 0.2, moisture = 0, and solids = 0.5%.

1. Estimate its higher heating value.
2. Compute the mass of air required to burn, theoretically, 1 gallon of the fuel.

**Problem 17** The following data were taken from a test on an oil-fired furnace:

Fuel rate = 20 gal oil/h
Specific gravity of fuel oil = 0.89% by mass
Hydrogen in fuel = 14.7%
Temperature of fuel for combustion = 80°F
Temperature of entering combustion air = 80°F
Relative humidity of entering air = 45%
Temperature of flue gases leaving furnace = 550°F

1. Calculate the heat loss in water vapor in products formed by combustion.
2. Calculate the heat loss in water vapor in the combustion air.

**Problem 18** An office building requires 2901 MJ ($2.75 \times 10^9$ Btu) of heat for the winter season. Compute the seasonal heating costs, if the following fuel is used:

1. Bituminous coal: 31,380 kJ/kg (13,500 Btu/lb), $70.00 per ton
2. No. 2 fuel oil: 38,500 kJ/L (38,000 Btu/gal), $2.75 per gallon.

Assume that the conversion efficiency is 75% for the oil and 61% for the coal.

**Problem 19** Saturated air at 41°F DB (5°C) enters a furnace; it leaves the furnace at 110°F DB (43.3°C) and 0.00543 $lb_v/lb_a$ (0.00543 kg/kg) and circulates through a factory. Air leaves the factory at 65°F DB (18.3°C) and 63°F WB (17.2°C).

1. What is the sensible and latent heat change for the air passing through the factory?
2. State whether the air gains or loses sensible and latent heat during each process.

**Problem 20** A plant is maintained at 70°F DB, 60% rh, and has a low-pressure steam heating system. A makeup air system is being added to the plant and it has been decided that the input air should be 10,127 cfm. Outside design conditions are –1°F DB, 50% rh. The plant is 250 by 560 ft and normally has 325 people working per shift.

1. What are the total steam requirements for the heating coil and the humidifier?
2. What capacity should the humidifier have in pounds of water per hour?

**Problem 21** A residence with a design heating load of 26 kW (89,000 Btu/h) is to use an oil-fired warm air system with forced circulation. Return air to the furnace is at 22.2°C (72°F). Specify the following:

*This problem requires catalog data.*

1. Supply air temperature
2. Airflow rate
3. Make and catalog number of suitable furnace

**Problem 22** A residence with a design heating load of 16 kW (55,000 Btu/h) is to use a forced circulation hot-water baseboard radiator system. The baseboard units house copper tubing with aluminum fins and operate with the inlet air temperature at 18.3°C (65°F). Specify the following:

*This problem requires catalog data.*

1. Hot water inlet temperature and outlet temperature
2. Total water flow rate
3. Total length of radiator panel for house
4. Location of panels
5. Make and catalog number of suitable hot water heater

**Problem 23** For the residence of Problem 22, electric baseboard units replace the hot water system. Specify the following:

*This problem requires catalog data.*

1. Total rating of electric system, kW
2. Total length of baseboard units

**Problem 24** A large classroom has a winter design heat loss of 19.9 kW (68,000 Btu/h) with installed forced circulation hot-water baseboard radiators. The baseboard units house copper tubing with aluminum fins and operate with the inlet air temperature at 18.3°C (65°F). Specify the following:

*This problem requires catalog data.*

1. Hot water inlet temperature and outlet temperature
2. Water flow rate
3. Length of radiator panel

**Problem 25** A large classroom has a winter design load of 26 kW (89,000 Btu/h). A forced circulation warm air system is to be used with return air at 23.3°C (74°F). Specify the following:

1. Supply air temperature
2. Airflow rate

**Problem 26** For a heat loss from the space to be conditioned of $Q$, write the expression for determining the following:

1. Amount of air L/s (cfm) that must be supplied if a hot air system is used
2. Amount of hot water L/s (gpm) that must be supplied if a hydronic system is used
3. Amount of steam kg/h (lb/h) that must be supplied if a steam heating system is used
4. Size, in watts, of electric heaters required if electric heat is used

**Problem 27** List the steps taken when designing a forced-circulation hot water heating system.

**Problem 28** Compute the increase in length of 28.3 m (93 ft) of steel steam pipe when the average steam temperature is 113°C (235°F) and the air is 21°C (70°F). The pipe was installed during a period when the temperature was 15.6°C (60°F).

**Problem 29** The total mass of steel in the boiler and piping of a school's heating system is 9080 kg (20,000 lb). The piping and boiler also contain 6810 kg (15,000 lb) of water. After a weekend shutdown, the temperature of the system is 10°C (50°F). The operating temperature is 93°C (200°F).

1. Assuming the system should be warmed up in one hour, determine the required furnace size.
2. For a furnace size of 146 kW (500,000 Btu/h) output, when should the furnace be started to be up to the operating temperature of 93°C (200°F) by 7:30 AM Monday morning?