

From Makeup Air to Space Heating

Direct-Fired Technology

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Beginning with a simple open flame, direct-fired heating is the earliest means of warming structures and occupants.¹ Wood, dung, peat, coal, and oil all made for effective and accessible fuels. However, poor control of combustion and fuel purity produced emissions that could be deadly. So, early civilizations developed indirect heating, separating combustion emissions from the space to be heated. Indirect combustion provides clean, safe heating, but only a fraction of the fuel's heating value is used for useful heating. The remainder is lost through the flue. To increase energy efficiency and to conserve natural energy sources, we need to look at the modern-day applications of direct-fired heating systems.

Modern direct-fired heating technology has evolved into two main applications: makeup air and space heating. Modern direct-fired units are usually self-contained, and include both a fan and a burner. The fan draws air into the unit, across the burner and pushes the heated air into the building or duct run. Typical configurations are shown in *Photos 1* and *2*.

Makeup air applications are associated with heating large quantities of outdoor air, such as in commercial kitchens and paint booths. In these applications, an exhaust flow is balanced with large quantities of fresh makeup air. On the other hand, space heating

applications are found where a space requires conditioning to provide worker comfort or product protection. While warehouses and manufacturing facilities may be the most common examples, the only application where direct-fired heating is not permitted is for sleeping quarters (IFGC 610.2).

One of the main benefits of direct-fired heating is the elimination of the heat exchanger found in typical furnaces. This allows more compact designs, reduces initial cost and weight, eliminates the thermal energy lost in typical flue gases, and reduces fan size requirements, as there is less pressure drop across the unit. These energy

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PHOTOS 1 AND 2 Examples of horizontal rooftop and vertical ground-mounted direct-fired units.

savings translate to reduced greenhouse gas emissions and lower operating costs over the lifetime of the equipment. These advantages create a compelling argument in favor of using direct-fired equipment. This article summarizes the basic operating principles, safety, energy performance, psychrometric behavior, and recommendations for the use of direct-fired heating units.

Direct-Fired Safety

Direct-fired heating emissions using modern fuels consist primarily of water vapor and carbon dioxide. The air-fuel ratio of direct-fired heating systems is typically 50 times the stoichiometric requirement, ensuring complete combustion and minimizing production of carbon monoxide. This excess air also has the effect of limiting flame temperature, thereby reducing the formation of NO_x. To ensure minimal introduction of hazardous gases, regulating bodies such as OSHA (Z-1)² and ANSI (Z83.4,³ Z83.18⁴) have developed contaminant limits that equipment manufacturers must comply with. A sample of these limits can be seen in *Table 1*. Product testing has repeatedly shown that the levels of CO and other workplace pollutants are well below any hazardous levels.⁵

Furthermore, modern safety devices such as airflow monitoring switches are interlocked with the heating equipment to maintain design air-fuel ratios. These switches prevent unsafe levels of combustion from occurring, in addition to ensuring efficient use of fuel. With proper engineering, manufacturing and operation, direct-fired heating equipment produces less emission than operating an engine-powered forklift.

TABLE 1 Upper limits for combustion gas emissions from direct-fired units and resulting space concentrations.^{2,3,4}

CONTAMINANTS	OSHA LIMITS	ANSI LIMITS (ADDED TO AIRSTREAM)	ANSI LIMITS (ROOM LIMITS)
Carbon Monoxide	50 ppm	5 ppm	25 ppm
Carbon Dioxide	5,000 ppm	4,000 ppm	5,000 ppm
Nitrogen Dioxide	5 ppm	0.50 ppm	3 ppm

As an example, consider the indoor concentration of CO₂ when operating a direct-fired heating system. When burning natural gas (methane) with an air-fuel ratio 50 times the stoichiometric value (which corresponds to a 100°F [56°C] rise) and an ambient concentration of 400 ppm CO₂, the indoor CO₂ concentration increases to 2,470 ppm. This is well below the OSHA and ANSI maximum value of 5,000 ppm. When using propane, the indoor value is very similar at 2,410 ppm.

Direct-Fired Makeup Air—100% Outdoor Air

Makeup air applications, as noted before, are commonly found where a facility experiences a large ventilation or exhaust load. To satisfy indoor air quality requirements, fresh air is introduced into the facility to offset the exhausted air. The outdoor air, particularly in winter, requires tempering to provide worker comfort or to prevent introducing excessive thermal load on the building. Tempering in this manner is often achieved via 100% outdoor air direct-fired heating units.

Energy Analysis

A direct-fired heating system is typically a device that uses the lower heating value of the fuel to heat the air

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supplied to the space.⁶ A conceptual diagram of a 100% outdoor air unit is given in *Figure 1*.

To illustrate lower heating value, consider the following situation: fuel and air enter a burner at 77°F (25°C) (T_0), burn and convert the fuel's available energy into heat, thereby yielding combustion products at 302°F (150°C), with all the water remaining in the vapor phase. The amount of thermal energy removed from this process is termed the "lower heating value" (LHV) of the fuel. In the case of natural gas, the LHV is approximately 92% of the higher heating value (HHV).⁷

Condensing heating units are able to use the HHV of a fuel, due to their capability of accessing the energy associated with the vapor phase water. Because direct-fired units are non-condensing and have no other significant thermal losses, they are often claimed to have an efficiency of 92%.

In a properly designed and operated direct-fired system, the incoming reactants are at a lower temperature (T_0), and the products of combustion leave at a lower temperature than indicated previously, so the delivered

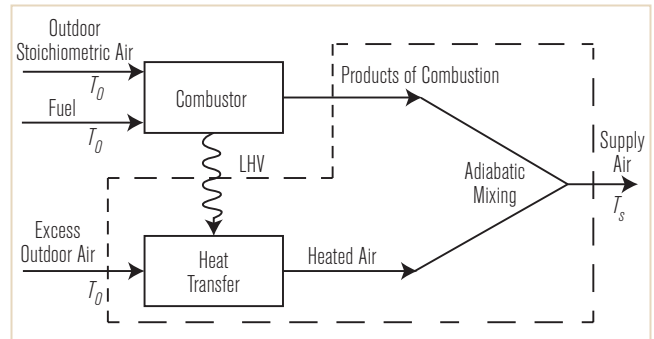


FIGURE 1 Conceptual schematic diagram that shows how the definition of lower heating value can be enhanced by the processes within the dashed lines to form a 100% outdoor air direct-fired heating system.

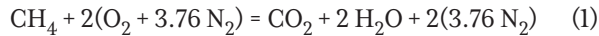
heat deviates only slightly from the published LHV of the fuel. This is achieved by controlling the pressure drop across the burner. The controller adjusts the temperature rise across the unit to about 100°F (56°C) under full fire. In practice, the extra air may pass through the burner, bypass it, or a combination of these two. Eventually, all the air is mixed downstream of the burner before being supplied to the conditioned space.

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Moisture

In addition to providing a comfortable temperature, direct-fired heating also provides comfortable humidity levels. A common misconception associated with this process is that the water vapor produced during combustion increases the volumetric flow rate downstream of a burner. Consider the stoichiometric combustion of methane (natural gas),



where the total number of moles of reactants and products is equal.

Assuming ideal gasses and using the ideal gas equation of state:

$$PV=nRuT \quad (2)$$

where

P = absolute pressure

V = volume

n = number of moles

Ru = universal gas constant

T = absolute temperature

If the absolute pressure and temperature of the reactants and products are the same and the total number of moles of each is equal as shown in *Equation 1*, the volume remains the same. However, in practice, the temperature of the products is higher than the reactants so the volume downstream of the burner is higher due to thermal expansion (Charles' law), but not because of the formation of water.

While water vapor may not increase the downstream volume, indoor moisture levels can be a design concern, so it is important to understand the impact of direct-fired systems on indoor humidity. Consider the complete combustion of natural gas (methane). For every unit of heat produced, a corresponding amount of water is generated. This ratio is fixed by the fuel chemistry, resulting in a linear relationship between quantity of water introduced and thermal load.

HVAC engineers often refer to sensible heat ratio or enthalpy-moisture ratio when considering the ratio of

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sensible heating and moisture addition. In the case of methane combustion, the sensible heat ratio becomes 0.89. For propane (C₃H₈), the value is 0.95 because a larger fraction of the sensible heat is provided by combustion of carbon and less from hydrogen.

Consider as an example a makeup air application maintained at 70°F (21°C) when the ambient air is at -20°F (-29°C) with 100% relative humidity, and natural gas is the fuel in a 100% outdoor air direct-fired heating system. The air-fuel ratio is controlled so that the temperature rise across the unit is 90°F (50°C), so the supply air temperature becomes 70°F (21°C). Using a sensible heat ratio of 0.89, the supply air has a dew-point temperature of 25°F (-4°C), and the indoor relative humidity is maintained at 17%. If propane is used, the dew point of the supply air becomes 7°F (-14°C) and the indoor relative humidity is 7%. This example shows that the moisture gains using a direct-fired heating system result in indoor humidity levels consistent with good engineering practice for winter operating conditions.

This example also shows that when using propane, one may need to add moisture to reduce static electricity buildup or to bring the space into winter comfort conditions as recommended by ASHRAE Standard 55-2013. In most applications featuring 100% outdoor air systems, there is a significant exhaust flow that mitigates the system's addition of moisture to the space. Regardless of the heating system used, the building envelope should have sufficient thermal insulation, minimal thermal breaks, and vapor retarders to minimize internal condensation.

One hundred percent outdoor air systems have many advantages for use in concert with a separate building-wide heating system. The unit's temperature rise allows for quick offset of building heat loss caused by exhaust flows. High volumes of outdoor air also effectively dilute internal emissions and offset exhausted air.

Unfortunately, these advantages do not translate well into space heating applications. While the temperature rise and exhaust-linked operation allow the units to efficiently offset exhaust flows, these operating characteristics create inefficiencies when used as the principal heat source for a building. These inefficiencies include temperature stratification within a space, intermittent cycling operation (leading to drafts), over/under pressurization, poor control of infiltration, as well as the continued reliance on a secondary system to provide continuous ventilation. If not used in conjunction with

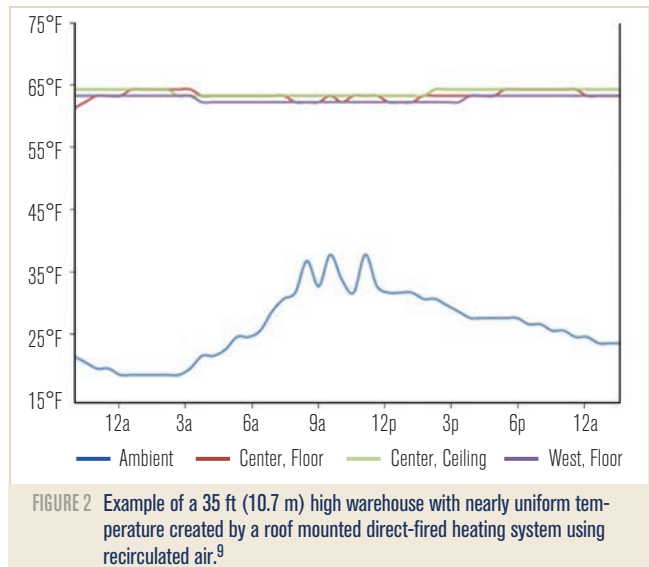


FIGURE 2 Example of a 35 ft (10.7 m) high warehouse with nearly uniform temperature created by a roof mounted direct-fired heating system using recirculated air.⁹

a secondary ventilation system, the building will fail to continuously meet the ventilation requirements stipulated by ASHRAE Standard 62.1-2013 (0.06 cfm/ft² [0.31 L/s·m²] for warehouses).⁸

Direct-Fired Space Heating With Recirculated Air

To solve the shortcomings associated with cycling 100% outdoor air, space heating is most often accomplished through direct-fired systems that recirculate some portion of the conditioned air. In most applications the units are installed outdoors to conserve floor space and to allow easy access to both indoor and outdoor air. Thus, ventilation and space heating can be provided in a single unit without the need for separate makeup air units.

Recirculation of conditioned air and subsequent mixing with varying amounts of outdoor air result in a reduced supply air temperature. By using a lower temperature, the supply air is less buoyant and is less likely to remain near the ceiling, minimizing thermal stratification as shown in *Figure 2*.

In many facilities, such as loading docks, warehouses, and sports facilities, interior pressure control is desirable to reduce infiltration, or to control exfiltration. Applying a small, constant, positive pressure to a building reduces infiltration (cold drafts), reduces the corresponding thermal loading, and increases worker comfort. Recirculating systems are advantageous in this regard as they introduce a continuous and variable amount of outdoor air. Simultaneously, direct-fired

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units with recirculated air are capable of controlling the amount of fuel supplied to the burner through the use of modulating gas valves. These two capabilities are controlled independently and allow a single unit to meet both indoor pressure and temperature requirements, efficiently modulating supply to meet demand.

The continuous influx of outdoor air, assuming appropriate unit sizing, also continuously satisfies ventilation requirements (ASHRAE Standard 62.1). Additional benefits include improved indoor air quality through pollutant dilution, the ability to handle constant exhaust flows, and increased seasonal energy efficiency.

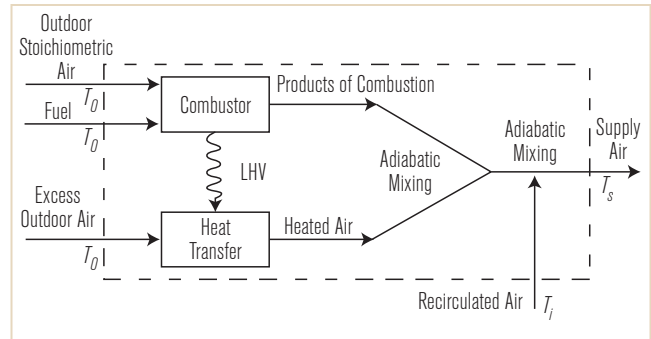


FIGURE 3 Conceptual schematic diagram of a direct-fired heating system with recirculated air.

Energy Analysis

A conceptual diagram of a recirculating air unit is given in Figure 3. The diagram can also be used to represent a 100% outdoor air unit as shown in Figure 2, but with the recirculated airflow rate set to zero. Many of the comments provided for 100% outdoor air units apply to recirculated air units. As with 100% outdoor air units, the excess outdoor air and the recirculated air can be provided through the burner or through a bypass. Again, the efficiency of 92% is derived from the LHV of the fuel.

The annual fuel utilization efficiency (AFUE) for recirculation units can be improved over 100% outdoor air cycling units by using continuous operation with burner turndown modulating to match the thermal load. Volumetric flow rates must be converted to mass flow rates to take into account the differing density of (warm) indoor and (cold) outdoor air when performing energy calculations.

For example, when the outdoor air is at -10°F (-23°C) with 100% relative humidity and the supply air is at 88°F (31°C), a volume ratio of 60% recirculated to 40% outdoor air (ratio of 1.5) becomes a dry air mass flow ratio of 57% recirculated to 43% outdoor air (ratio of 1.3).

Moisture

A sample calculation is provided here for a warehouse with -20°F (-29°C) outdoor air temperature at 100%

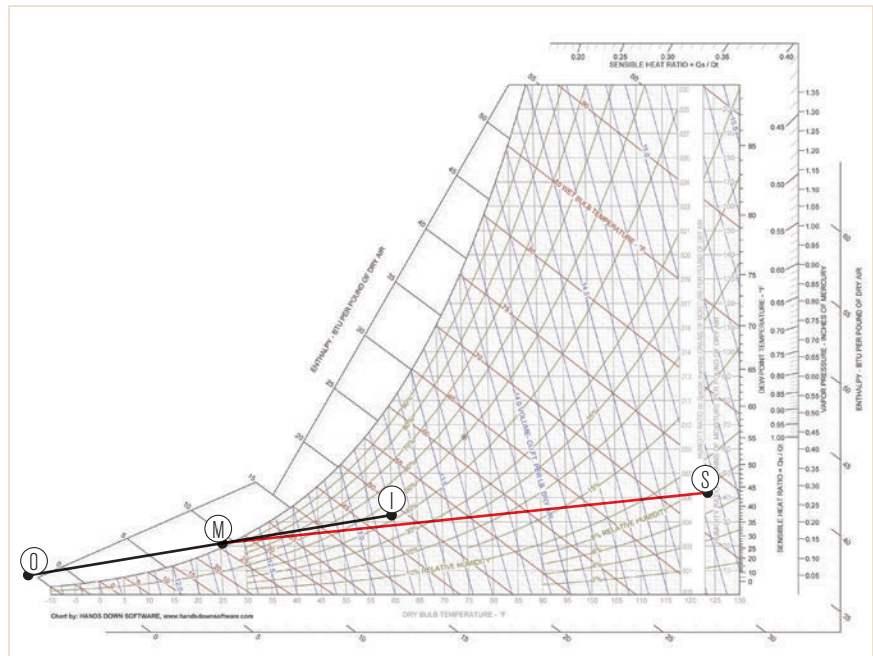


FIGURE 4 Psychrometric representation of direct-fired re-circulating system.¹⁰

relative humidity and 60°F (16°C) indoor air temperature. The heating system for this building, represented in Figure 4, consists of a unit with recirculated air and a 98°F (54°C)¹⁰ temperature rise above the mixed air temperature (mixed air temperature of 25°F (-4°C)) and supply air temperature at 123°F (51°C). The ratio of recirculated to outdoor air is 60% recirculated and 40% outdoor air by volume. This ratio offers an optimal balance between heating capacity and ventilation for many applications. Because of the density difference, this 1.5 volume ratio becomes a mass flow ratio of only 1.3.

Using natural gas as the fuel, the supply air dew point is 43°F (6°C), and the average space relative humidity becomes 41% when the envelope and

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ventilation sensible heat losses are equal. With propane the values become 17°F (−8°C) and 17%, respectively. These values are well within the recommended range of indoor relative humidity per ASHRAE winter design standards.

Conclusion

Direct-fired technology is a safe, energy-efficient, and cost-effective means to provide heating for a wide range of applications. The two main uses, makeup air and space heating, require different approaches to deliver the most efficient design.

Makeup air applications, with a focus on efficiently offsetting exhaust or ventilation flows, are well served by 100% outdoor air direct-fired heaters. These units typically contribute 17% relative humidity to a closed space. In practice, however, these systems have negligible impacts on space humidity due to the presence of significant exhaust flow. When paired with a secondary system to provide space heating, 100% outdoor air units are an economical and efficient means to offset intermittent exhaust and ventilation flows.

Space heating applications, rather than offsetting transient thermal loads, are primarily concerned with maintaining indoor air quality and worker thermal comfort. Due to this difference in design intent, 100% outdoor air cycling units often do not deliver optimum performance when used as the primary heat source for a building. As a result of intermittent operation, cycling units do not offer the capability to continually meet ventilation standards. Recirculating units, on the other hand, are able to meet ventilation requirements at all times with the constant influx of fresh air. With continuous burner modulation, direct-fired recirculating units maintain comfortable conditions with humidity levels typically around 35%. When properly applied, direct-fired products offer low initial and operating costs, as well as versatile design options.

Future Trends

As new heating techniques develop and gain popularity, technologies such as high volume, low speed (HVLS) fans, direct digital control (DDC), data collection, and sensing equipment have become more common. These technologies promise building owners a greater degree of control and enhanced energy-use

monitoring capabilities. With the adoption of these new technologies comes the challenge of integration into a building's complete HVAC system. To meet this goal, manufacturers are beginning to package direct-fired systems as fully integrated solutions, offering a variety of technologies from a single source. This development is leading toward decreased system effect between products, increasing building efficiency and inter-product compatibility.

In conjunction with advances in HVAC technology, improved building construction has also contributed to increased efficiency. As construction materials, methods, and techniques continue to advance, building envelopes are becoming better insulated, reducing heating load per unit floor area. This leads to lower heating demands, increased interior surface temperatures, and diminished moisture condensation concerns. In emergent applications such as completely automated warehouses, data centers, and manufacturing facilities, the heating, moisture, and indoor air quality requirements will shift from those developed for human occupancy to those needed for product storage and equipment operation. Direct-fired heating system technology is well positioned to address these needs.

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