
13 Thermal Radiation Burners

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CONTENTS

- 13.1 Introduction
- 13.2 Applications
 - 13.2.1 Predryers
 - 13.2.2 Dryers
- 13.3 Industries
 - 13.3.1 Paper Industry
 - 13.3.2 Printing and Publishing
 - 13.3.3 Textile Manufacturing
- 13.4 Burner Types
 - 13.4.1 Porous Ceramic Burners
 - 13.4.2 Ported Ceramic Burners
 - 13.4.3 Ported Metal Burners
 - 13.4.4 Fiber Metal Burners
 - 13.4.5 Flame Impingement Radiant Burners
 - 13.4.6 Catalytic Burners
 - 13.4.7 Advanced Ceramic Radiant Burners
- 13.5 Testing and Characterization
 - 13.5.1 Radiation Efficiency
 - 13.5.2 Heat Transfer Coefficient
- 13.6 Conclusion
- References

13.1 INTRODUCTION

Thermal radiation burners refers here to a class of burners designed specifically to transfer heat by thermal radiation, primarily infrared (IR), to the load. This does not include radiant tube burners ([Chapter 14](#)) or radiant wall burners ([Chapter 15](#)), which are discussed elsewhere and designed for some specific applications. The burners discussed here are generally designed for loads at lower temperatures, often for drying applications.

These burners generally have a rectangular plenum with four sidewalls and a back wall with an inlet for the introduction of a gaseous fuel and a porous plate enclosing the open mouth of the plenum. The porous plate may contain a series of small (<3 mm diameter) fuel injection holes or may contain a fibrous material having microscopic passages for the fuel. In the case of surface combustion and sub-surface combustion thermal radiation burners, the porous plate is also the primary IR emitter as the fuel combusts on, or within, the porous plate surface to heat it. Impingement burners have a secondary plate(s) constructed of metal or ceramic onto which the combusting fuel ejected from the porous plate holes impinges to heat the secondary plate.

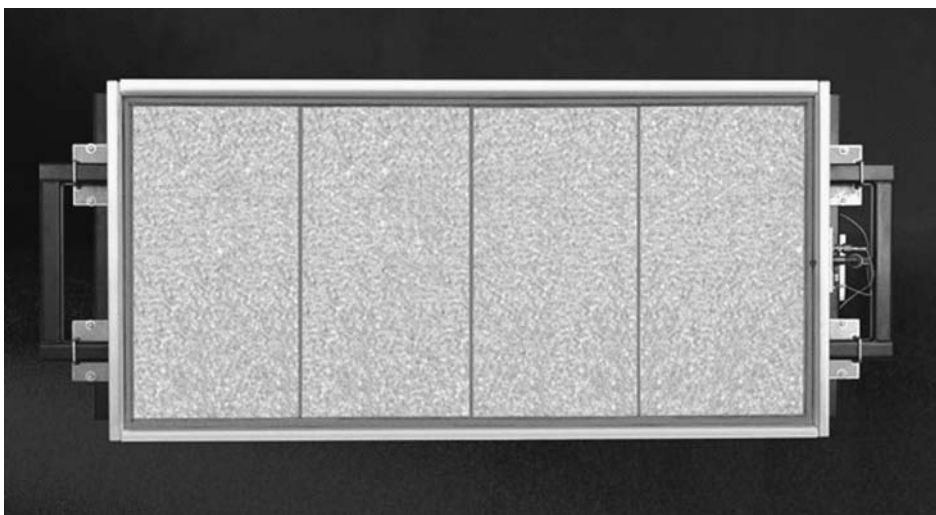


FIGURE 13.1 Uniform surface temperature of thermal radiation burner. (Courtesy of Marsden, Inc.)

Thermal radiation burners are designed to produce a uniform surface temperature (see [Figure 13.1](#)) heat source for heating and melting a variety of materials. The uniform surface temperature produces more homogeneous heating of the materials, which normally improves the product quality compared to conventional burners that may produce hot spots. Other advantages of these burners can include:

- High thermal efficiencies
- Low pollutant emissions
- Directional heating
- Very fast response time to load changes
- Very fast heating compared to convective heating
- Burner shape can be tailored to the shape of the heat load to optimize heat transfer
- Ability to segment a burner to produce a nonuniform heat output profile that might be useful in certain types of heating and drying applications
- Certain types of radiant burners have very rapid heat-up and cool-down times
- More control over the heating process because of the known and measurable surface temperature of the radiant surfaces compared to open flames where the flame temperature is very difficult to measure
- Burners are very modular and can be configured in a wide variety of geometries to accommodate the process heating requirements

The primary parameters of interest for radiant burners are the power density (firing rate per unit area), radiant efficiency (fraction of fuel heating value converted to thermal radiation), heat-up and cool-down time, and pollutant emissions. Other factors of importance include cost, durability, and longevity.

There are also some potential limitations of porous refractory burners, compared to more conventional open-flame burners, which may include:

- There can be a relatively low temperature limit for the radiant surface due to the limits of the refractory material.
- The fuel and oxidizer must be clean to avoid plugging the porous radiant surface, which essentially precludes the use of fuels such as coal or heavy fuel oil.

- Some radiant surfaces can be damaged by water or by contact with solid materials that may be prevalent in certain applications.
- Holes in the radiant surface can cause flashback because these burners use premix.
- Some designs may have high pressure drops, which means that more energy is needed for the blower to flow the combustion air through the ceramic burner material.
- Due to the limits in radiant surface temperatures, the firing rate density is usually limited.
- Some types of radiant burners using hard ceramic surfaces may have high heat capacities that could ignite certain flammable load materials upon a sudden line stoppage.

In these burners, fuel and air are premixed and combusted either just inside a radiating surface or just above the surface, depending on the operating conditions and specific radiant burner design. If the mixture velocity is too low, flashback or flame extinguishment can occur, depending on the design of the burner. In addition to the operational considerations, flashback is an obvious safety concern. If the mixture velocity is too high, the flame may blow off or the radiant performance may be severely reduced because the burner surface is not being directly heated by the hot exhaust products. Depending on the specific design of the burner, optimum performance is achieved when the flame is stabilized just inside or just above the outer burner outlet.

Howell et al. (1995) refer to the burner material as “porous inert media” and present a review of these types of burners, which have been made from a wide variety of ceramics that often include alumina, zirconia, or silicon carbide.¹

13.2 APPLICATIONS

Thermal radiation burners are used for a wide variety of applications. These are generally some type of heating, drying, or curing process, including, for example:

- Drying paper and cardboard in a paper mill
- Paper finishing
- Drying wood
- Porcelain frit drying
- Curing ceiling tiles
- Heating flooring products
- Curing coatings on carpet backs
- Teflon curing
- Paint drying
- Drying and curing coatings on paper and metals
- Curing ink on paper and powder coat paints
- Baking in mass food preparation
- Setting dyes in textile and carpet production, sometimes referred to as predrying
- Curing lens assemblies in automotive headlamp assembly manufacturing
- Plastics curing

Thermal radiation burners are often used to heat webs moving at high speeds (see [Figure 13.2](#)).

An important consideration for the choice of oven or dryer type for the specific application depends on whether direct or indirect heating is needed.² Direct heating means that the product is exposed directly to the flame (see [Figure 13.3](#)), while indirect heating means that the products of combustion do not come in contact with the material being heated (see [Figure 13.4](#)). In indirect heating, an intermediate carrier or type of heat exchanger is used to transfer the heat. Normally, an intermediate medium between the flame and the load reduces the thermal efficiency compared to direct heating. The most common reason for keeping the exhaust products separate from the heat load is for product quality reasons where the product could be contaminated by the exhaust gases.

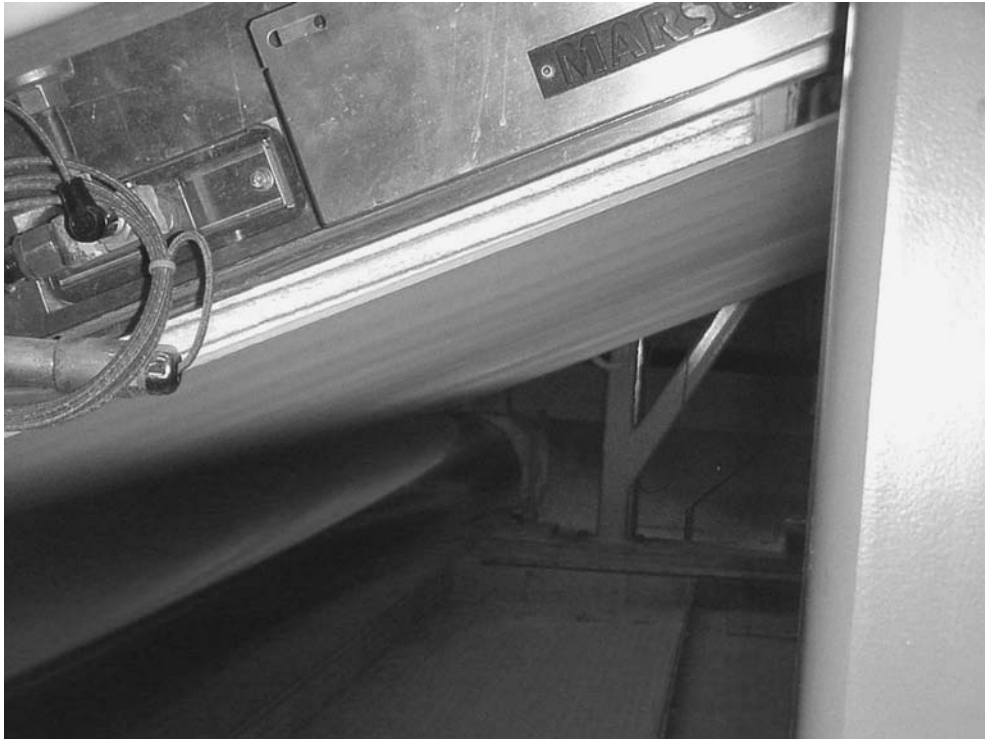


FIGURE 13.2 Example of a thermal radiation burner heating a moving web. (Courtesy of Marsden, Inc.)

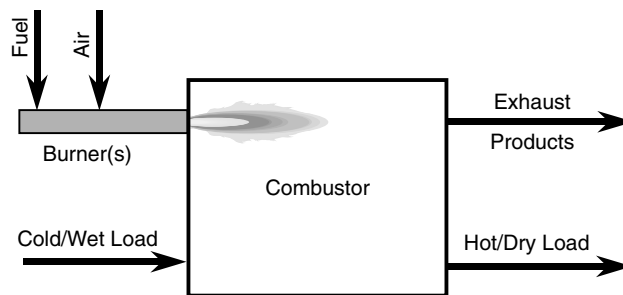


FIGURE 13.3 Schematic of direct heating system.

Another reason is that the product may be emitting combustible volatile vapors that could be ignited if they came into contact with open flames. Still another reason might be that exhaust gases could carry fine particles from the load out of the combustor. These particles would then have to be scrubbed out of the exhaust before the exhaust enters the atmosphere. That means that not only are the raw material costs higher, but there is also the added cost of removing the unused raw materials in the exhaust. As expected, the heat transfer mechanisms will be different, depending on the type of heating used in a given process.

There are some lower-temperature drying applications employing industrial combustion that are briefly considered here. These include the paper, printing and publishing, textile manufacturing, and food processing industries. Drying is defined as “a process in which a wet solid is heated or contacted with a hot gas stream, causing some or all of the liquid wetting the solid to evaporate.”³ Kudra and Mujumdar (2002) have written a book⁴ on advanced drying technologies that covers a

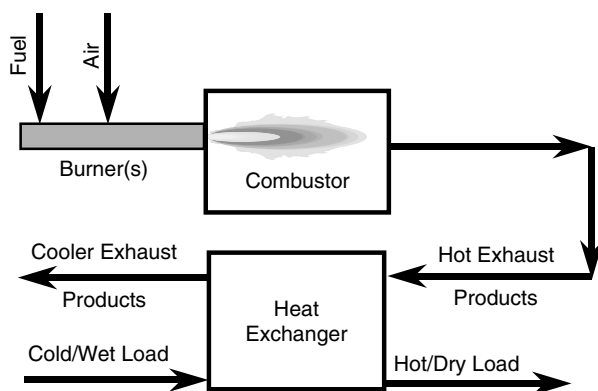


FIGURE 13.4 Schematic of indirect heating system.

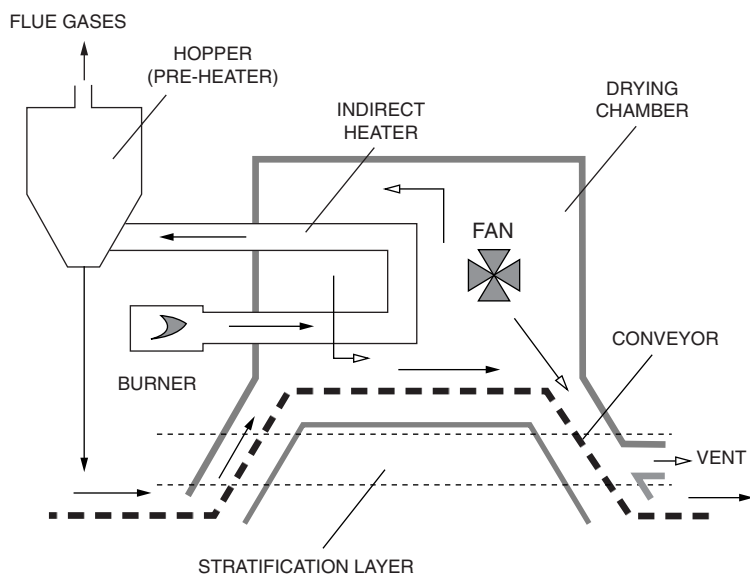


FIGURE 13.5 Continuous airless dryer. (Courtesy of Marcel Dekker.⁴)

wide range of industries, including those discussed in this chapter. Some of the more advanced drying techniques include impinging steam dryers, pulsed fluid beds, airless dryers (see Figure 13.5), sonic dryers, plasma torch dryers, slush drying, and a variety of hybrid methods. The authors call for more R&D and innovation to advance the state-of-the-art in dryers, which have received much less attention than other types of heating equipment, and has been mostly evolutionary up until fairly recently. Table 13.1 shows a classification of typical dryers.

13.2.1 PREDRYERS

Predryers are used in some applications prior to final drying of the product. An example of this type of application is the use of infrared (IR) burners to set the dyes in the dyeing of fabrics in textile manufacturing.⁵ After the dyes are applied to the fabric, they must be set prior to contact with the dryer; otherwise, the dyes will migrate to drier areas of the fabric, which reduces the quality of the textile. The IR burners in the predryer are used to rapidly set the dyes without the need to contact the material, as would be the case with, for example, a steam-heated drum dryer.

TABLE 13.1
Classification of Dryers

Criterion	Types
Mode of operation	Batch Continuous ^a
Heat input-type	Convection, ^a conduction, radiation, electro-magnetic fields, combination of heat transfer modes Intermittent or continuous ^a Adiabatic or nonadiabatic
State of material in dryer	Stationary Moving, agitated, dispersed
Operating pressure	Vacuum ^a Atmospheric
Drying medium (convection)	Air ^a Superheated steam Flue gases
Drying temperature	Below boiling temperature ^a Above boiling temperature Below freezing point
Relative motion between drying medium and drying solids	Concurrent Countercurrent Mixed flow
Number of stages	Single ^a Multistage
Residence time	Short (<1 min) Medium (1–60 min) Long (>60 min)

^aMost common in practice.

Source: Courtesy of Marcel Dekker.⁴

IR predrying in the paper industry occurs in several areas. After the last wet press and before the first steam cylinder contact dryer, IR is used to evaporate the surface water to minimize “picking.” Picking is caused by the explosive evaporation of the surface water and dislodging of surface fibers when the paper meets the hot cylinder surface. The dislodged fibers start to coat the drying cylinder, reducing its heat transfer ability. Another area is where IR burners are installed after the coating machine and are used to set the coatings on the paper prior to the paper contacting a steam-heated cylinder drum dryer or the hot air “floater” dryer, used to complete the drying (see next section).⁶ The IR predryer is primarily used to increase productivity and improve the paper coating quality. The productivity is increased because of the additional drying. The quality is improved because the rapid drying minimizes binder migration from the coating into the paper, which minimizes or eliminates mottle. Also, the IR energy does not physically disturb the coating as convection or conduction heat transfer methods might. [Figure 13.6](#) shows the typical spectral radiant transmissivity for uncoated paper. The paper is more absorbent (less transmissive) at longer wavelengths and less absorbent (more transmissive) at shorter wavelengths. Because IR burners typically have their peak radiant output at wavelengths less than 3 μm , this leads to good thermal efficiencies because the paper is highly absorbent at those wavelengths. Mottle is a measure of the quality of the finished paper product and refers to the finish. Higher mottle means the paper has more blemishes on the surface than lower mottle. [Figure 13.7](#) shows how mottle, measured by a surface image analyzer, was affected by the evaporation rate (related to the firing rate of the burners) and the type of heat source. This shows that gas-fired IR burners produced less mottle and, therefore, higher quality paper, than electric IR burners.

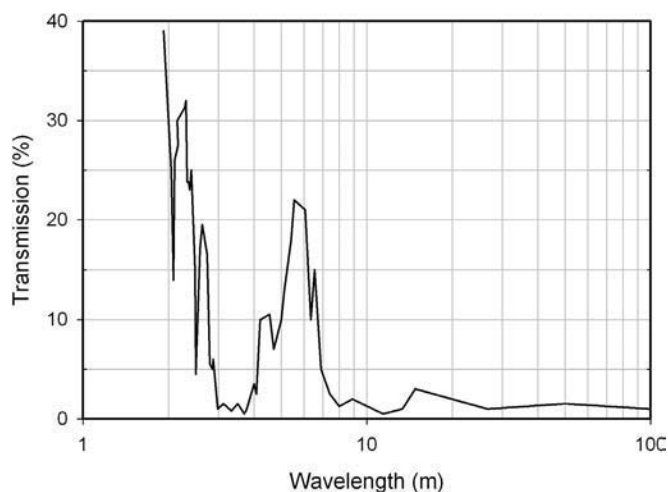


FIGURE 13.6 Spectral transmissivity for typical uncoated paper. (Adapted from Reference 6.)

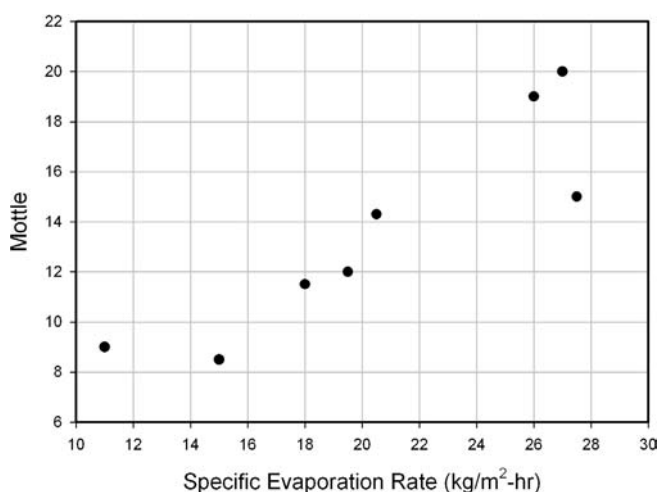


FIGURE 13.7 Mottle as a function of evaporation rate and heat source type. (Adapted from Reference 6.)

Pettersson and Stenström (1998) compared the use of gas-fired and electric infrared burners used to set the coating before the paper reached the next cylinder in a paper line.⁷ Figure 13.8 shows the IR heaters between the coating station and the next steel cylinder in the paper machine. IR burners are preferred in this application, instead of convective or conductive dryers, because they are noncontact and have high power densities (10 to 40 kW/m² or 3000 to 13,000 Btu/hr-ft²). The thermal efficiencies were calculated as 30 and 40%, respectively, for the gas-fired (propane) and electric IR burners. However, the burners were tested on two different machines and there was some uncertainty in the measurements. That being said, the gas-fired IR burners may still be more economical than the electric IR burners, because electricity is often much more expensive than natural gas on an equal energy basis. It is noted that some thermal radiation burners are capable of power densities up to 120 kW/m² and total efficiencies of 50%.⁸

Riikonen et al. (1987) developed a computer model to simulate both the convection and radiation heat transfer in IR heating systems used in paper drying.⁹ Experiments were conducted to test the model. The model significantly underpredicted the time for the sample to dry. The error in the calculations was identified as the moisture isotherm predictions. The explanation was that IR heating

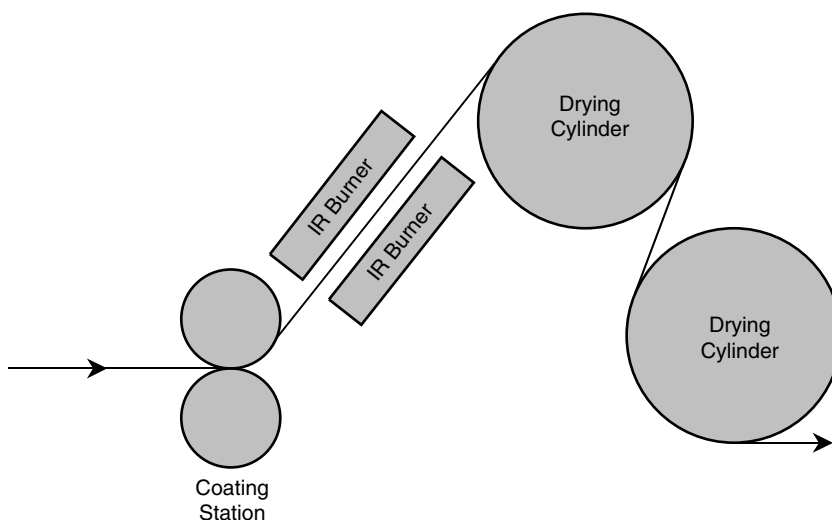


FIGURE 13.8 Schematic of IR heaters used to set coating in a paper machine where the paper is traveling from left to right.

quickly removes the bound water between fibers but more slowly removes water inside the fibers. A suggested correction was to use an apparent diffusivity to correct for the difference in moisture evaporation rates in and around the pulp fibers.

The difference in heat transfer requirement at low moisture contents is the higher temperature required to free the bound water from the fiber, which requires that the paper mass as well as the water mass must be heated to the higher temperature. In the constant rate period, the paper/water temperature remains fairly constant at 60 to 89°C (140 to 190°F). At moisture contents below about 15%, the paper temperature rises. Because the percent water decreases and the percent fiber increases at lower moisture contents, the additional energy required for drying per unit mass of water increases as well.

13.2.2 DRYERS

Dryers are commonly used to remove moisture from products during the manufacturing process. Common industries using dryers include the color, pigment, and dyestuff industries; the pharmaceutical and fine chemicals industry; natural ores, minerals, and heavy chemicals; paper and allied products; foodstuffs and agricultural products; and the ceramics and textile industries.¹⁰ If the heat source is some type of burner, dryers can be directly fired or indirectly fired, depending on the application. Dryers can also be batch or continuous.¹¹ Figure 13.9 shows some examples of continuous dryers. Sloan (1967) reviewed the following classes of dryers: air-suspended systems that rely primarily on using air for mass transfer, direct-heat continuous systems, direct-heat batch systems, indirect-heat continuous systems, and indirect-heat batch systems.¹² IR burners can be used to boost the performance of conventional hot-air convective dryers.¹³ Direct flame impingement is even used in limited cases, such as drying refractory-lined vessels and moulds used in metals and minerals production.¹⁴

There are commonly three periods in the drying process, as shown in Figure 13.10. The period from A to B is the warming-up period where the material is heated up to the evaporation temperature. The period from B to C is referred to as the constant rate period, where the drying rate is constant. The rate of drying is essentially that for the liquid and behaves as if there were no solid present. The liquid wicks rapidly during this period. The period from C to D is referred to as the falling rate period, where the free liquid has been essentially removed and the remaining liquid must move to the surface by diffusion and capillarity. During that period, the solid is an impediment to the liquid removal.

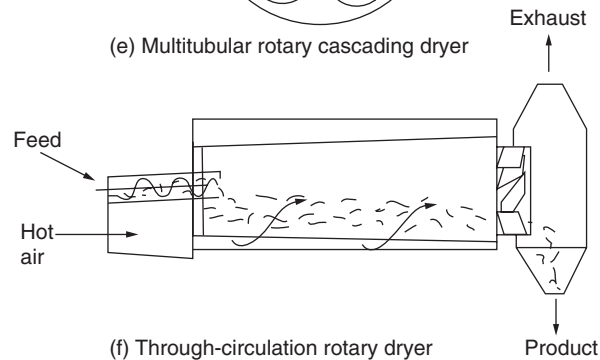
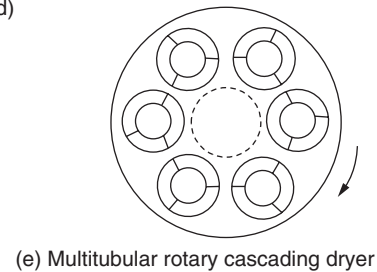
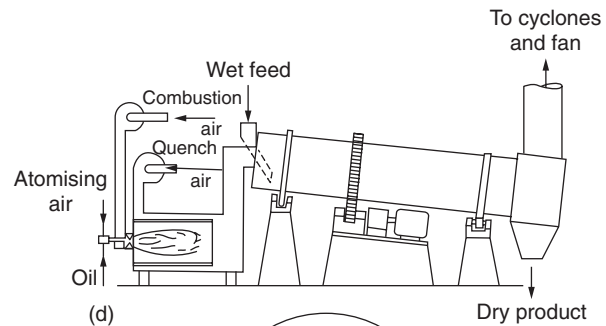
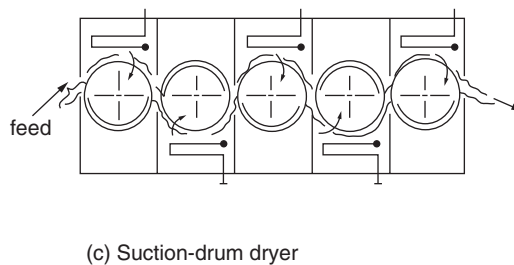
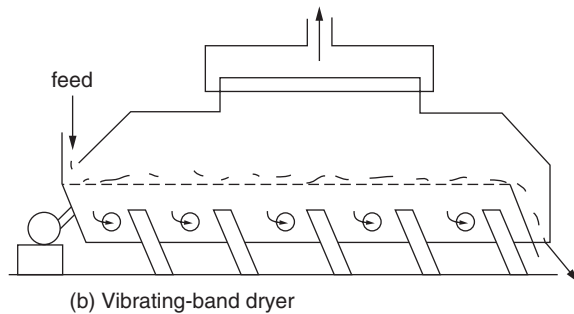
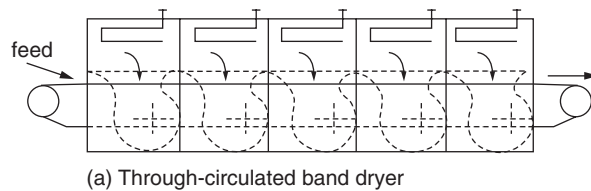


FIGURE 13.9 Examples of continuous dryers.¹¹

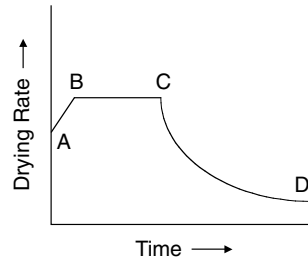


FIGURE 13.10 Periods of drying.¹⁹

Dryers are sometimes classified by the predominant heat transfer mechanism: convection, conduction, or radiation. They are then sub-classified into batch and continuous dryers. An example of a batch convection dryer is a tray dryer. Continuous convection dryers include truck-and-tray tunnels, continuous through-circulation, rotary dryers, fluid bed dryers, spray dryers, and pneumatic or flash dryers. Batch conduction dryers include vacuum tray dryers, vacuum double cone dryers, trough dryers, pan dryers, and rotary dryers. Continuous conduction dryers include film drum or roller dryers, cylinder or can dryers, rotary dryers, and trough dryers. There are both batch and continuous radiation dryers that use IR heating. While not all of these dryers use combustion, many of the convection dryers preheat the air with burners and the radiation dryers often use gas-fired IR burners.

Dryers are usually low-temperature applications as the material is usually no more than about 300°F (400°K). One example is in the drying of paper and board in a paper mill. The paper products are made from pulp in a slurry that has a very high moisture content. The paper is then dried in one of several ways. First, as much water as possible is removed mechanically, typically with some type of press. The remaining moisture is removed by heating, using some type of dryer.

Another type of dryer uses very-high-velocity hot air impingement on both sides of a moving web. The web “floats” through the nozzles, which is where this type of dryer gets its name — *floaters dryer*. The primary mode of heat transfer for this dryer is convection. This technique combines heat and mass transfer in the same apparatus, as the hot air both heats the web and carries away the moisture that evolves from it. This type of dryer has several potential advantages over other types of dryers. No additional systems are needed to remove the volatiles vaporizing from the material being dried. There is no direct contact with the product that could reduce the quality. It is possible to segment this type of dryer to vary the moisture removal rate across the width, although the reaction time is slow compared to IR dryers. There are also potential disadvantages. The air nozzles can become plugged because they are typically fairly small to achieve the high gas velocities. In drying materials such as papers and textiles, this method also ultimately relies on conduction for the energy to get to the core of the product whose thermal conductivity decreases as the moisture content decreases. Another version of an air dryer is where heated air is blown only onto one side of a paper web traveling through a dryer where a coating is to be dried, as shown in Figure 13.11.¹⁵ In hot air dryers, burners are used to heat the air blown onto the material being dried.

13.3 INDUSTRIES

Some of the common industries that use thermal radiation burners are briefly considered here. These include the paper, printing and publishing, and textile manufacturing industries.

13.3.1 PAPER INDUSTRY

The paper industry is composed of two primary sectors:¹⁶

- Pulp and paper mills, which produce mechanical, thermomechanical, and chemical pulps and process these pulps to form paper, paperboard, or building papers
- Converting operations, which manufacture boxes, tablets, and other finished paper products

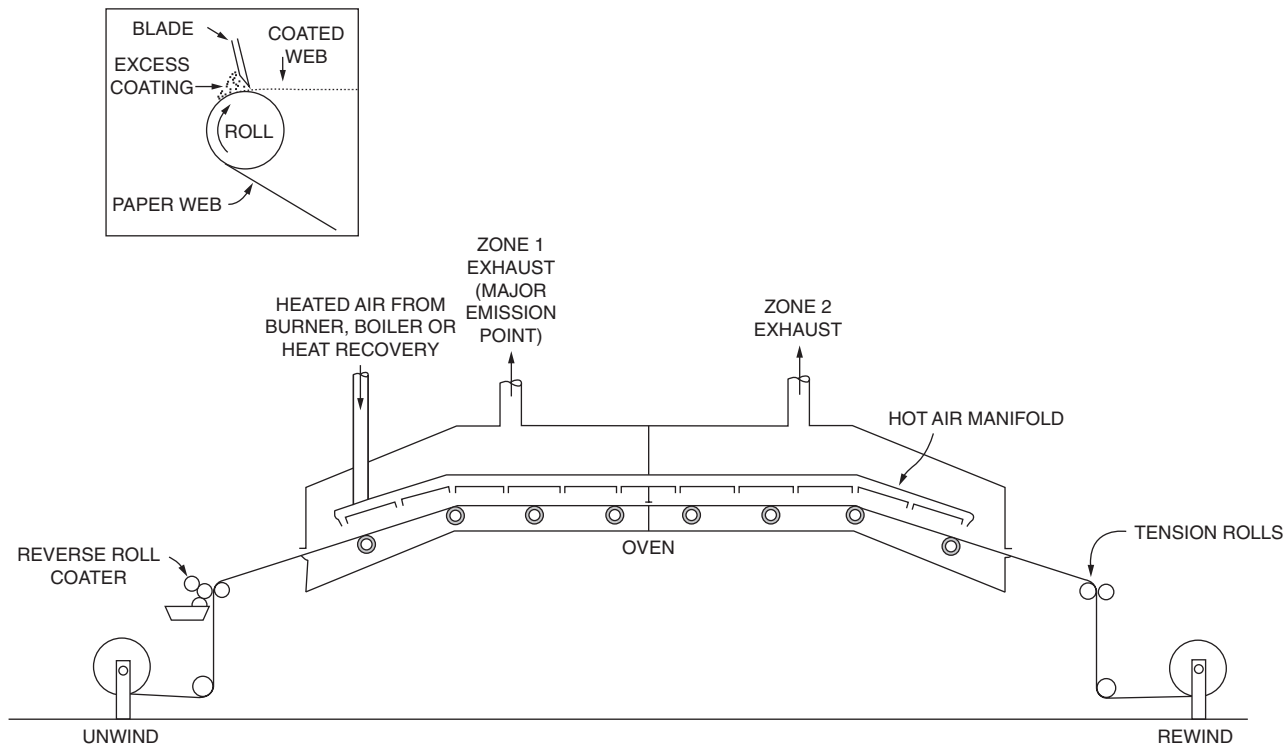


FIGURE 13.11 Schematic of a paper coating dryer. (Source: U.S. EPA.)

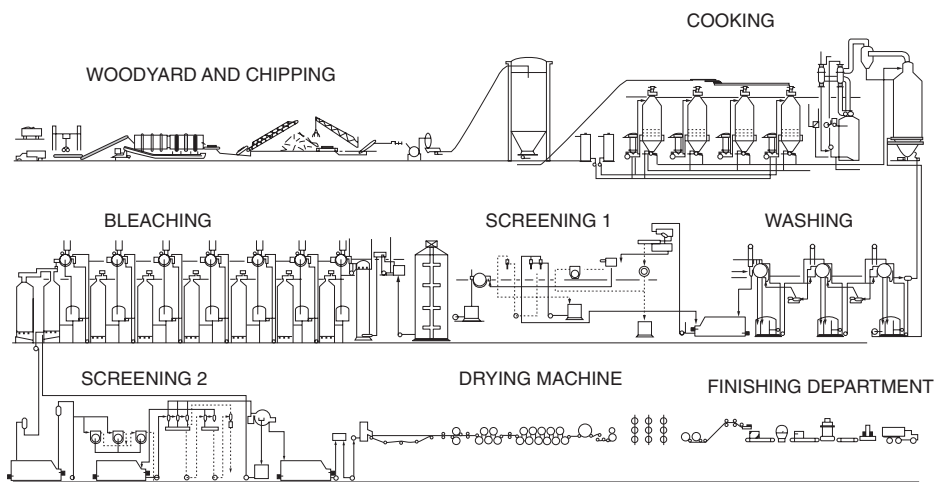


FIGURE 13.12 Integrated paper mill. (Source: U.S. EPA.¹⁷)

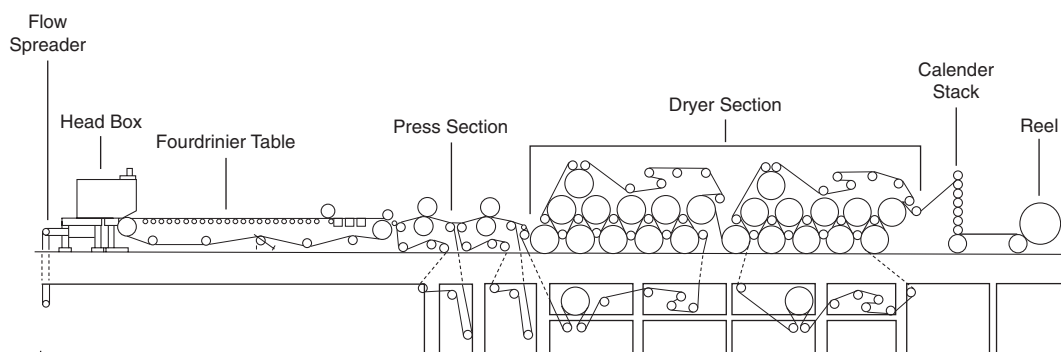


FIGURE 13.13 Fourdrinier paper machine. (Source: U.S. EPA.¹⁷)

The first sector involves production of paper products from raw wood while the second sector involves converting those initial products into more specialized end products. The pulp and paper industry produces commodity grades of wood pulp, primary paper products, and paper board products such as: printing and writing papers, sanitary tissue, industrial-type papers, container board and boxboard.¹⁷ Figure 13.12 shows a schematic of an integrated paper mill. The only part of the mill that uses industrial combustion is the drying machine. Even there, it is only supplemental to the steam-heated cylinders, which do the bulk of the drying. Figure 13.13 shows an elevation view of a Fourdrinier paper machine commonly used to make paper. A steam-heated cylinder in the drying section can be seen in more detail in Figure 13.17. Figure 13.14 shows a schematic of the Kraft process for handling the pulp and bark used to make the paper, including the treatment of the chemicals in the various reactors that are considered in more detail below.

Paper is commonly dried using the three primary modes of heat transfer: convection, conduction, or radiation (see Chapter 2). Convection dryers use heated air. Conduction drying is done with steam-heated cylinders. Radiation drying is done with thermal radiation burners. These three methods are sometimes used in combination. The most common way to dry paper traveling at high velocities is by contact with steam-heated cylinders. The paper wraps around the drums in a serpentine fashion to maximize the contact area with the drum. In this type of dryer, the primary method of drying is by thermal conduction.¹⁸ One problem with this technique is that as the paper

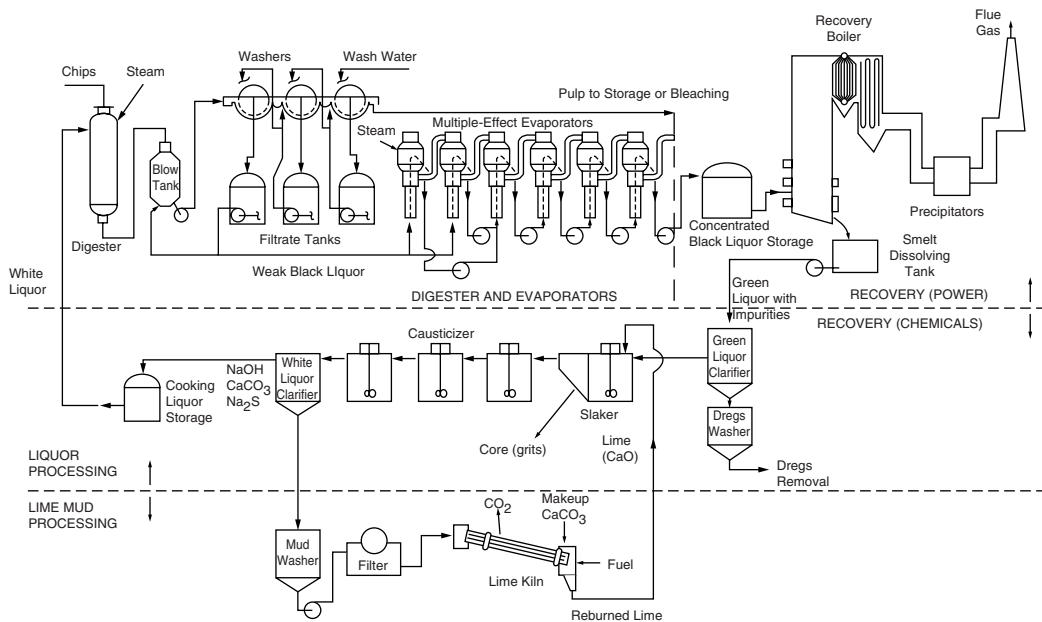


FIGURE 13.14 Kraft process flow diagram. (Source: U.S. EPA.¹⁷)



FIGURE 13.15 Infrared burner heating a continuously moving paper web. (Courtesy of Marsden, Inc.¹⁹)

dries, the thermal conductivity goes down, which makes it more difficult to conduct the heat into the paper. As previously discussed, this is known as the “falling rate period,” where the downstream steam cylinders are much less effective at removing moisture than the upstream cylinders.

In many drying processes, moisture is removed from paper webs often traveling at high speeds. Radiant heating (see Figure 13.15) is often used to supplement steam-heated cylinder drying or

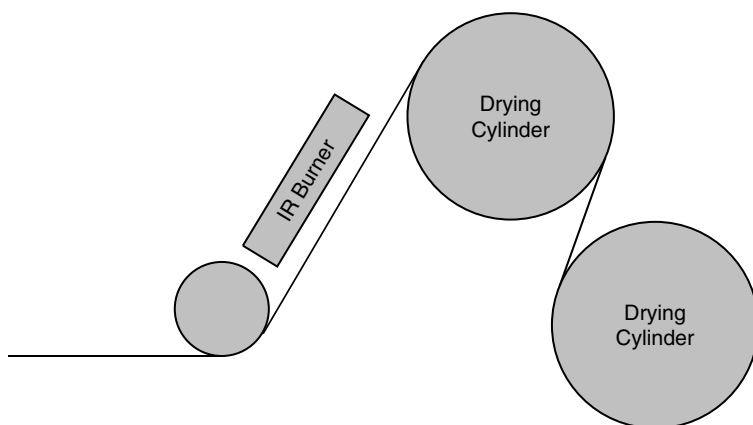


FIGURE 13.16 Schematic of an IR burner located before a steam cylinder in a paper drying process.



FIGURE 13.17 Supplemental IR burners for paper drying located over steam cylinders. (Courtesy of Marsden, Inc.)

high-velocity hot air dryers.¹⁹ The radiant heaters are either electric or fired with a fuel such as natural gas. These supplemental heaters may be located before the steam-heated cylinders (see [Figure 13.16](#)), in between cylinders, over cylinders (see [Figure 13.17](#)), and/or after the cylinders.

The heaters can also be partitioned across the machine to vary the drying capacity. The moisture content of the paper web often varies across the machine direction. Some streaks may be significantly wetter than others and therefore require more drying energy. A fictitious example is shown in [Figure 13.18](#) where the peak moisture content is near 15% while the minimum is at 10%. The paper is normally specified to have a maximum moisture content. Assume for the sake of argument

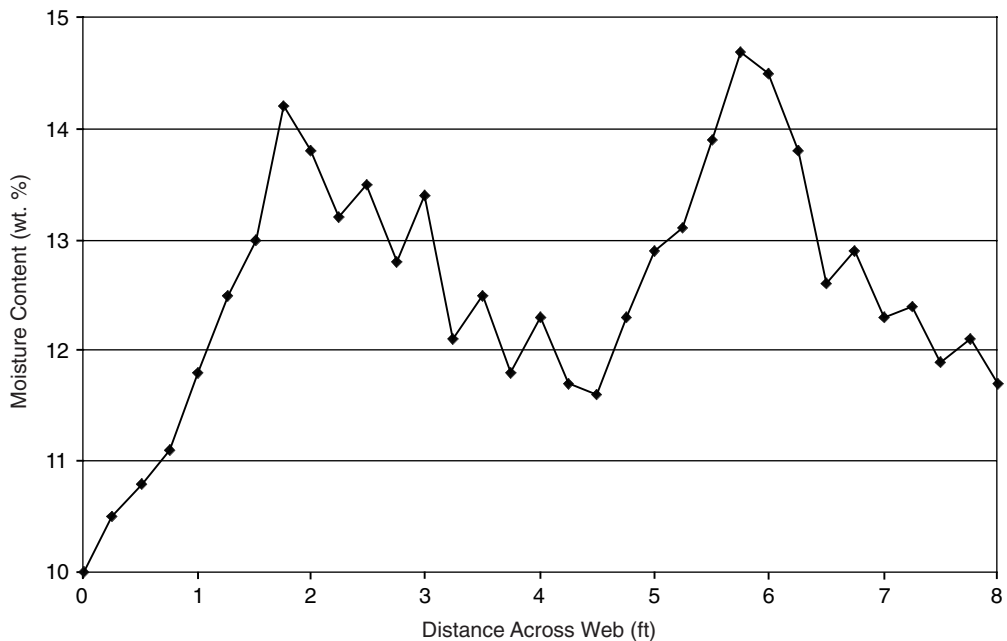


FIGURE 13.18 Moisture profile across a paper web prior to drying.

that it is 4%. This means that the entire paper must be dried so that the wettest streaks are at or below the maximum allowable moisture content. If the heating is uniform across the web, then enough energy must be supplied to reduce the moisture streak of nearly 15% water content down to 4%. This means that the section of the web at 10% will be dried well below 4%. However, this is detrimental for several reasons. Because paper is sold by weight, removing more moisture than necessary in drier sections of the paper reduces profitability. More fuel than necessary is used to dry some sections well below the maximum allowable moisture limit. The paper quality also suffers when some sections of the paper are overdried, which causes handling problems for machines such as printers and copiers. Some paper manufacturers actually spray water back onto the drier streaks to make the profile more uniform. This is energy inefficient as energy was spent removing the moisture, which is then re-added. So-called moisture profiling is where the radiant output of the burners varies across the machine direction (see [Figure 13.19](#)) to match the moisture levels. This fixes the problems of overdrying some sections that occurs with a uniform radiant heating level. This is much more fuel efficient and economic because more moisture can be sold and the product quality is also improved.

Infrared dryers can have significantly higher evaporation rates for removing moisture from paper webs, compared to steam cylinders and air dryers. Longacre (1997) has shown that typical evaporation rates using steam cylinders, air dryers, and infrared dryers are 5, 8, and 20+ lb/ft²/hr, respectively.²⁰

Another example of predrying is in the paper industry where IR burners are installed after the coating machine and are used to set the coatings on the paper prior to the paper contacting a steam cylinder drum dryer which is used to complete the drying.²¹ The IR predryer is primarily used to increase productivity and improve the paper coating quality. The productivity is increased because of the added heat. The quality is improved because the IR energy does not disturb the coating as convection or conduction heat transfer methods could, which lets the coating set on the paper prior to contact with the steam cylinder which relies on thermal conduction heat transfer.

IR burners (see [Figure 13.20](#)) are often used to supplement these dryers because the IR radiation sees 100% of the surface area and thus is better able to penetrate into the paper. Steam cylinder

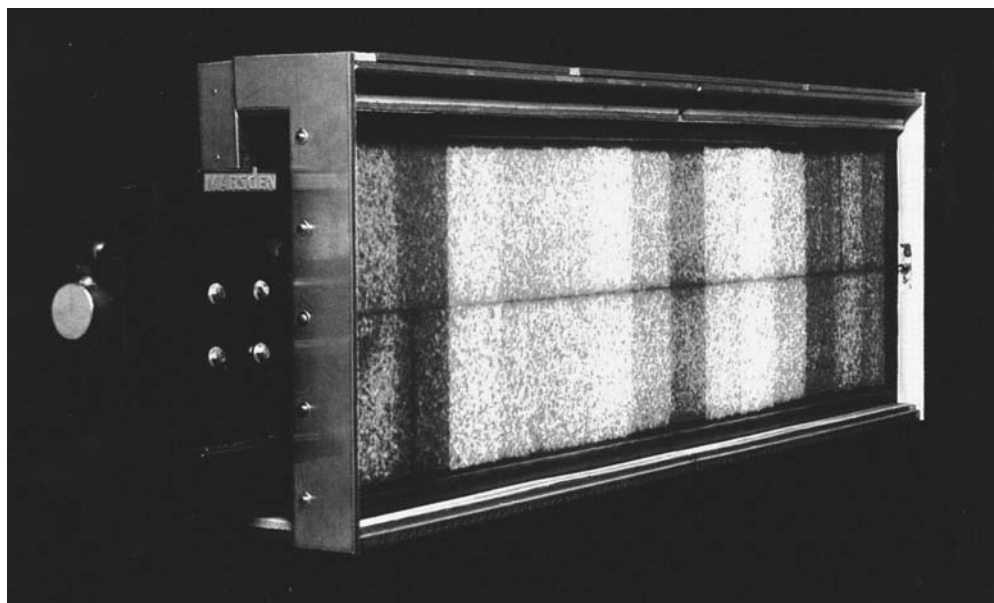


FIGURE 13.19 IR burners designed for moisture profiling. (Courtesy of Marsden, Inc.)

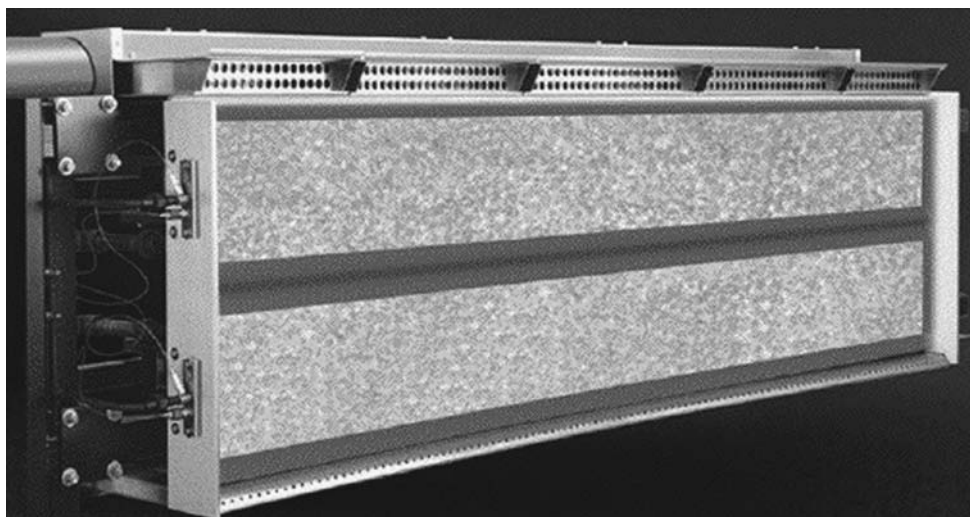


FIGURE 13.20 Example of a flat-panel gas-fired infrared burner. (Courtesy of Marsden, Inc.¹⁹)

dryers only contact the fibers on the top of the fiber matrix, which is a comparatively small area. Compounding the conductive heat transfer problem is that the fibers on the surface have been dried by previous contact and now are good heat insulators. In a survey of paper makers by the Gas Research Institute (Chicago, IL), respondents believed the best place to install infrared burners on a paper drying line is in the pre-heat zone.²² This is undoubtedly because early gas IR dryers cooled very slowly and often set the paper on fire, but there is much less danger of fire in the beginning of the paper machine where the paper is wet. In actual fact, using IR on the dry end of the paper machine makes for better utilization of the whole drying system. As previously discussed, contact

dryers are most effective in the constant rate period of the dryer where there is sufficient water movement to keep the paper surface moist. IR, with its better heat transfer ability, is best utilized where the contact dryers are least effective. If the IR is added to increase speed, putting it in the dry end of the paper machine provides for a bonus effect because the end of the constant rate period moves toward the end of the machine and some cylinders move from the falling rate to the constant rate drying period. If IR is added somewhere in the middle of the machine, trailing cylinders move from the constant to the falling rate period of drying. Other locations identified in the survey included in the forming section, above and below the steam cylinders in the constant rate zones, and above and below the steam cylinders in the falling rate zone.

One reason for the popularity of steam cylinder dryers is that there is usually plenty of steam available in paper mills because much of the waste bark and liquor from the trees used to make the paper is burned in hog fuel boilers. Another reason is that the cylinders help guide and transport the paper. Contact dryers generally help smooth the paper surface and minimize shrinking. One disadvantage includes the large thermal inertia of the metal (typically cast iron) cylinders, which causes longer start-up times and a reduced ability to quickly change the drying rate. An important disadvantage is the reduced drying effectiveness as the moisture content of the paper decreases because of the reduction in the thermal conductivity. These dryers do not typically have the capability to vary the drying capacity across the width of the paper. Also, for thicker materials, the drying rate is reduced because the evolving water vapor is trapped between the cylinder and the paper as it is unable to come out the side of the paper in contact with the cylinder.

Hannum et al. (2000) discuss the development of a high-intensity lean premix combustion system with low NO_x emissions for use in drying applications such as tissue and plasterboard drying.²³ The burner was used to heat air for use in drying in a loop drying system. Measured NO_x emissions were below 10 ppmvd (3% O₂).

In most paper drying applications, the only pollutant of significant concern is NO_x. Carbon monoxide emissions are relatively easy to minimize due to the high degree of control of the combustion process. The gaseous fuels used, such as natural gas, contain little or no sulfur to produce SO_x. These clean fuels and moist webs generate little if any particulates. There are no VOCs in the process. There is very little noise produced. While there are significant levels of thermal radiation, this is directed at the paper and is not usually a problem for personnel operating the equipment. Even NO_x emissions are typically low because of the relatively low operating temperatures.

13.3.2 PRINTING AND PUBLISHING

Web offset lithography is used to produce about 75% of books and pamphlets as well as an increasing number of newspapers.²⁴ Dryers and ovens are sometimes used to dry ink in the printing and publishing industry.²⁵ One of the major environmental concerns related to the printing and publishing industry is VOC emissions. VOCs are used in ink to promote fast drying. This ink is commonly referred to as “heatset” ink. In many applications, no ovens or dryers are required to dry the ink during the production process because of the rapid vaporization of the VOC solvents in the ink compared to the slower speed of the production process. However, high-speed paper webs are used in some printing applications where dryers are required to set the ink before it contacts downstream rollers that would cause the ink to smear if it were not set. [Figure 13.21](#) shows a schematic of a webfed high-speed rotary flexographic press with a printing and drying section used to dry the ink on the paper.²⁶

These printing presses are often of multiple colors, which means that each color must be individually set before the next color can be applied; otherwise, the colors will smear. The heater to set the ink may be as simple as an electric infrared or ultraviolet lamp. [Figure 13.21](#) shows a heater between each color application of the roller ink system. In some cases, natural-gas-fired burners may be used because of their lower operating costs compared to using electricity. Whichever technology

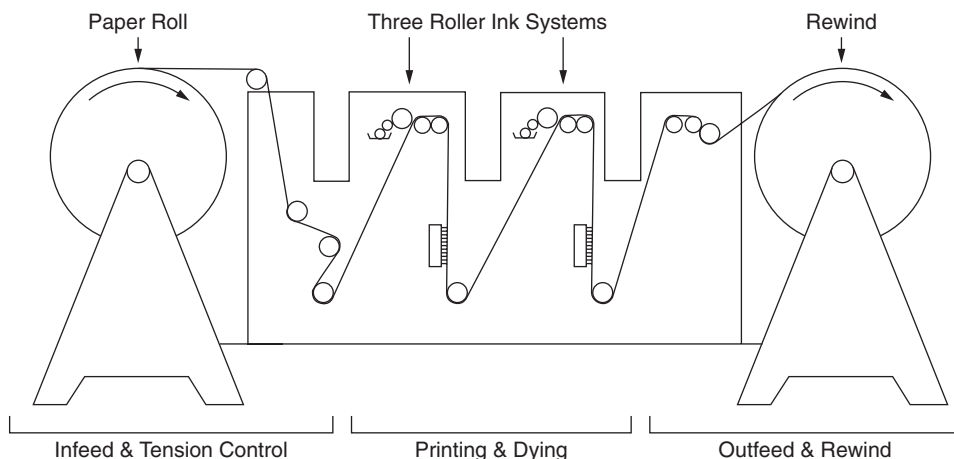


FIGURE 13.21 Schematic of a webfed rotary flexographic press. (Source: U.S. EPA.²⁶)

is used, the heater must either be capable of very rapid cool-down or some type of shielding from the web in the event of a sudden line stoppage, in order to prevent the paper from catching fire.

However, because of the increased concern about VOC emissions, inks are being made with less VOCs and with more aqueous-based solvents that require heat to set. The heaters can be gas-fired infrared burners. For larger and higher-speed presses, gas-fired ovens can be used where air is heated and blown at high velocity onto the paper to both dry the paper and remove the vaporized solvents. These ovens are often designed to float the paper by having air nozzles on both sides of the paper. The floater dryer temperature is in the range of 400 to 500°F (200 to 290°C). One or more burners are fired in the dryer to maintain a given air temperature. An afterburner may also be included in the drying system if there are significant VOC emissions in the recycled air containing ink solvents.

Other than VOCs, there are no other significant pollutants produced by the dryer. The fuel is typically natural gas, which contains little or no sulfur to produce SO_x. There are no significant sources for particulate emissions. Noise may be an issue for hot air dryers because of the fans and high gas velocities. Thermal radiation exposure to personnel could be a consideration if radiant burners are used to set the ink.

13.3.3 TEXTILE MANUFACTURING

The textile manufacturing industry consists of the following segments:²⁷

- Broad woven fabric mills and wool mills, including dyeing and finishing
- Knitting mills and knit goods finishing
- Other dyeing and finishing textile mills
- Floor covering mills, including dyeing and finishing

Predryers are used in some applications prior to the final drying of the product. An example of this type of application is the use of IR burners to set the dyes in the dyeing of fabrics in textile manufacturing.²⁸ After the dyes are applied to the fabric, they must be set or dried uniformly (typically to 30% wet pick-up) prior to contact with the dryer (tenter); otherwise, the dyes will migrate to drier areas of the fabric, which causes shading that reduces the quality of the textile. The IR burners in the predryer are used to rapidly set the dyes without the need to contact the material, as would be the case with, for example, a drum dryer.²⁹ Dryers and ovens are also used to cure inks used in textile printing, as shown in [Figure 13.22](#).³⁰

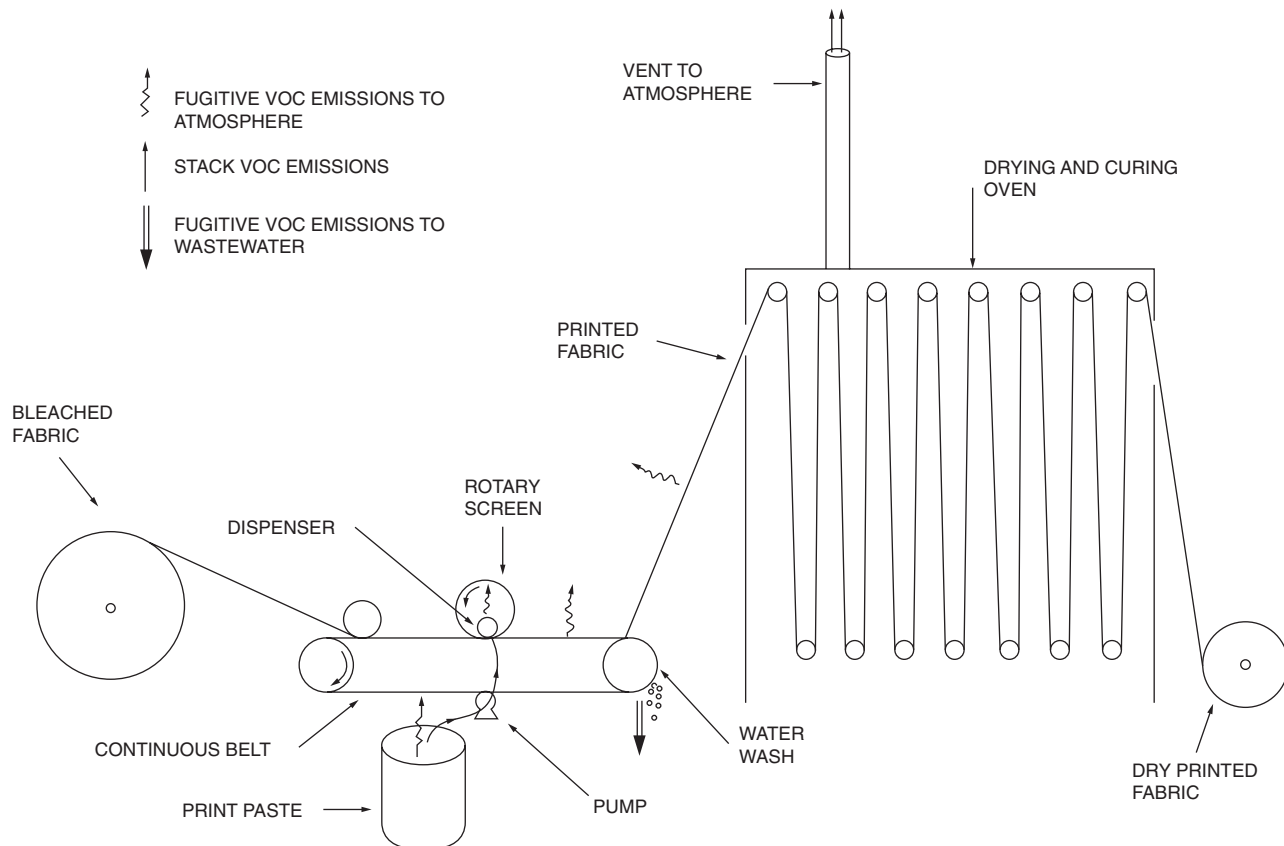


FIGURE 13.22 Schematic of a textile printing process. (Source: U.S. EPA.³⁰)

TABLE 13.2
Comparison of Thermal Efficiencies for Radiant Burners³⁵

Radiant Burner Type	Combustion Intensity (kW/m ²)	Thermal Efficiency Range (%)
Metal fiber		
No perforations	150–540	18–26
With perforations	150–540	16–27
With perforations and front metal screen	100–440	22–38
Reticulated ceramic	150–630	27–39
Ported ceramic	140–520	37–54
Flame impingement	150–430	46–52

13.4 BURNER TYPES

Speyer et al. (1997) studied the performance of four different types of commercial gas-fired radiant burners: a metal (Fe-Cr-Al) fiber (~40 µm diameter) burner, a reticulated ceramic burner made of a porous cordierite (Mg₂Al₄Si₅O₁₈), a porous single-unit mullite (Al₆Si₂O₁₃) tile burner, and a flame impingement burner where the products of combustion are forced around a metal screen that radiates to the load.³¹ The study was sponsored by the Gas Research Institute (Chicago, IL). The thermal efficiencies as a function of the combustion intensity are shown in Table 13.2. The efficiency was determined by measuring the radiant output or radiosity from the burner surface and was calculated using:

$$e = \frac{R_T}{\dot{V}_g \Delta H_c / A} \quad (13.1)$$

where e is the calculated efficiency, R_T is the measured radiosity, $\dot{V}_g$ is the volume flow rate of the fuel, H_c is the heating value of the fuel, and A is the surface area of the burner. The experimental results showed that the peak radiosity measurements as a function of the air-to-fuel mixture ratio occurred for percent excess fuels ranging from 6 to 7.5%, depending on the specific burner design. Similar results were calculated for the radiant efficiencies. Preheating the air/fuel mixture increased both the radiosity and thermal efficiencies, essentially in a linear manner for mixture temperatures ranging from 40 to 155°C (100 to 311°F). In most cases, the efficiency declined with combustion intensity, except for the reticulated ceramic and metal fiber with perforations and a front metal screen, both of which had peak efficiencies at intermediate combustion intensities. The flame impingement and ported ceramic burners were the most efficient, while the metal fiber with and without perforations was the least efficient. The study also showed that the thermal efficiency generally increased as the fraction of closed area increased on the burner surface. Porous ceramic fiber emitters were not included in this report.

13.4.1 POROUS CERAMIC BURNERS

There are two main types: reticulated ceramic and ceramic fiber burners. Reticulated ceramic burners have lightweight, foam-like rectangular blocks attached to a metal plenum. The length and width dimensions are normally less than 250 mm (9.8 in.) to minimize problems due to thermal expansion and contraction. They are designed as a surface combustion burner. They may also have a silicon carbide (SiC) coated ceramic lace-like topcoating or metal screen to increase heat transfer to the emitter surface. The heat-up and cool-down time is in the 15- to 30-s range.

Ceramic fiber burners are generally molded into flat rectangular blocks from a mixture of refractory fibers and binders. They are then machined to smooth the surfaces and meet thickness requirements. Some types have the firing surface coated with a high-emissivity material while another type has a molded-in opacifier. Ceramic fiber burners can be molded into cylindrical, conical, or compound shapes to suit special applications. Most ceramic fiber burners are surface combustion burners. One type, manufactured by Marsden, Inc. (Pennsauken, NJ), has an integral opacifier that permits the combustion process to occur about 3 mm (0.12 in.) below the outer surface. This greatly enhances the conversion to radiation efficiency by increasing the surface area and the time for the hot gas molecules to exchange energy to the emitter material. This, in turn, lowers the flame temperature and eliminates the formation of NO_x. An advantage of ceramic fiber burners is the low mass at radiant temperature that permits rapid heat-up (5 s) and instantaneous cool-down (1 s).

In this type of burner, the surface is made of a porous ceramic fiber that is often made in a vacuum-forming process. A relatively new type is now available and is made from a woven ceramic fiber mesh, similar to the wire mesh radiant burners except that ceramic fiber is used instead of metal. The predominant shape used in porous refractory burners is a flat panel. An example is shown in Figure 13.20.

In addition to flat panels, other shapes are also available. Alzeta Corp. (Santa Clara, CA) makes many cylindrically shaped porous refractory burners.^{32,33} For their Duratherm™ burners, sizes range from as small as 2 in. (5 cm) in diameter by 4.5 in. (11 cm) long, to as large as 30 in. (76 cm) in diameter by 180 in. (460 cm) long. Firing rates range from 23,000 Btu/hr (6.7 kW) to 16.5×10^6 Btu/hr (4.83 MW). Bartz et al. (1992) describe the use of an Alzeta porous refractory radiant burner to incinerate volatile organic compounds (VOCs).³⁴ The unique aspect of the combustion system was that the burner was formed into a cylinder and fired inwardly while the VOCs flowed into that inner core with the combustion products where the VOCs were then destroyed as shown in Figure 13.23. Very high VOC destruction efficiencies were measured.

In the early 1960s, the American Gas Association made an extensive study of radiant burners, both gas-fired and electric.³⁵ For the gas-fired burners, they determined what was termed a Gas Infrared Radiation factor (GIR), which was determined as follows:

$$\text{GIR} = \frac{W}{\sigma T_b^4} \quad (13.2)$$

where $W = Q/A$ is the total normal infrared radiation from the burner measured by a spectrophotometer, σ is the Stefan-Boltzmann constant, and T_b is the absolute brightness temperature of the

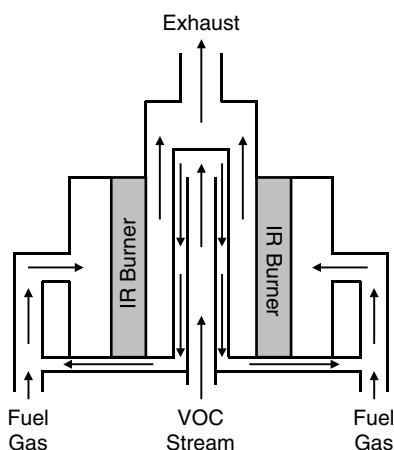


FIGURE 13.23 Inwardly fired porous refractory radiant burner, with heat recovery, for VOC destruction. (Adapted from Reference 34.)

TABLE 13.3
Results of Gas-Fired Infrared Burner Studies

Infrared Burner Type	Emitting Surface	Operating Red Brightness Temperature (°F)	Total Normal Radiation (Btu/hr-ft ²)	GIR Factor
Atmospheric	Ceramic tile or inconel	1400–1650	17,800–32,600	0.51–1.06
Powered	Cordurite, low-density refractory, refractory brick, or inconel	1500–2300	18,000–62,800	0.63–1.17
Catalytic	Glass wool	600–800	800–3300	0.36–0.65

Adapted from Reference 35.

burner surface measured with an optical pyrometer. The GIR factor was similar to a burner emissivity. However, for some of the burners, the GIR factor exceeded 1.0. The GIR factor was approximately 15% higher than the true burner surface emissivity. This is due to the gaseous non-luminous radiation in addition to the surface radiation from the burner. For the burners tested, the GIR factor ranged from 0.36 to 1.17, depending on the burner type. Table 13.3 shows the GIR factors for several types of gas-fired infrared burners, in addition to some other useful operating data. The red brightness temperature was determined using a spectrophotometer in comparison with a blackbody. The study concluded that the flue gas layer contributes up to 18% of the energy input to the useful radiant output and that the layer radiates more than it absorbs. Gas-fired IR burners emit primarily in the 2- to 6-micron region of the IR spectrum. Proper selection of a surface coating for a burner can improve the radiant output. The study also investigated electric IR burners and the spectral absorption characteristics of various loads (e.g., paints, food types, inks, and building materials) heated with IR burners.

Sathe et al. (1990) made experimental measurements and numerical predictions on a porous radiant burner.³⁶ They used the following correlation for flow over circular cylinders for the convection heat transfer coefficient from the flame to the porous refractory:

$$\text{Nu} = 0.989 \text{ Re}^{0.33} \quad (13.3)$$

where the characteristic length d is the equivalent particle diameter. Figure 13.24 shows a comparison of the measured and predicted result as a function of the axial location of the flame (x_p) normalized by the porous layer length (L). The figure shows that both the radiant output and the flame speed are fairly independent of the flame location, but are dependent on the equivalence ratio. Zabielski et al. (1991) used an optical technique to measure the radiant characteristics of a porous ceramic fiber radiant burner.³⁷ The macroscopic emittance of the burner was estimated to be 0.70. Xiong and Viskanta (1992) measured the heat flux and calculated the thermal efficiency of a porous matrix ceramic combustor.³⁸ The thermal efficiency declined with firing rate. The heat transfer rate increased with firing rate up to about 45 kW and then slightly declined at a higher firing rate.

Jugjai and Sanitjai (1996) presented a concept for a new type of porous radiant burner incorporating internal heat recirculation to increase thermal efficiency.³⁹ They studied the effects of the optical thickness of the porous medium on the radiant output of porous radiant burners. The optical thickness was increased by added layers of stainless steel wire mesh that formed the porous medium for the burners tested. The added layers improved the heat transfer from the hot gases to the porous medium.

Mital et al. (1996) claimed to have made the first measurements of temperature and species distributions inside submerged flames stabilized inside porous ceramic burners.⁴⁰ They noted the wide discrepancy in the performance of these burners in the literature and in manufacturers' literature.

Rumminger et al. (1996) developed a one-dimensional model of a bilayered reticulated ceramics radiant burner.⁴¹ The model results showed that for a "submerged flame" where the flame is anchored

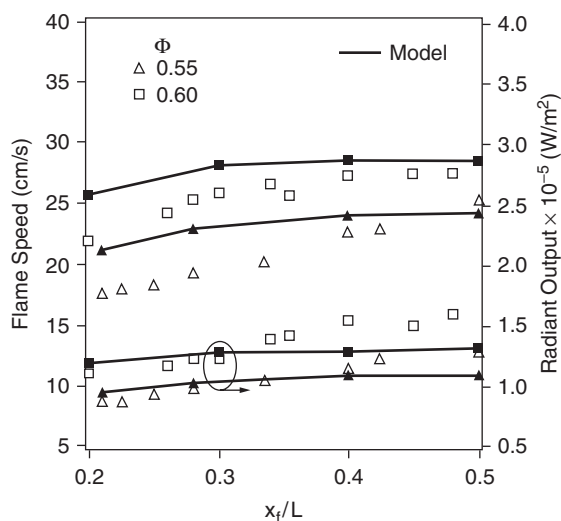


FIGURE 13.24 Measured and predicted flame speed and radiant output for a porous radiant burner. (Courtesy of The Combustion Institute.³⁶)

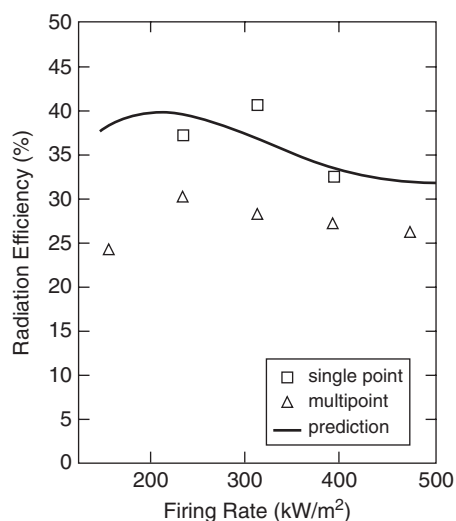


FIGURE 13.25 Predicted and measured radiation efficiency for a porous radiant burner at an equivalence ratio of 0.9. (Courtesy of The Combustion Institute.⁴³)

inside the porous refractory, nearly all of the important reactions occur inside the porous medium. This complicates the study for this type of burner because of the difficulty in making measurements inside the porous medium. They speculated that it is possible that the large internal surface area of the porous medium could affect the chemistry, but there is no data at this time to confirm that possibility.

Van der Drift et al. (1997) studied various coatings on porous foam ceramic IR burners to determine the effects of heat transfer to wet paper and to three colors (white, blue, and black).⁴² They showed that there can be up to a 10% improvement using coated burners compared to a base case metal fiber burner.

Mital et al. (1998) made experimental measurements on a bilayered reticulated ceramic foam made of cordierite.⁴³ Measurements included radiation efficiency using a heat flux gage and burner surface measurements with a type-R thermocouple. Radiation efficiency results are shown in Figure 13.25, which include both single and multi-point measurements and model predictions.

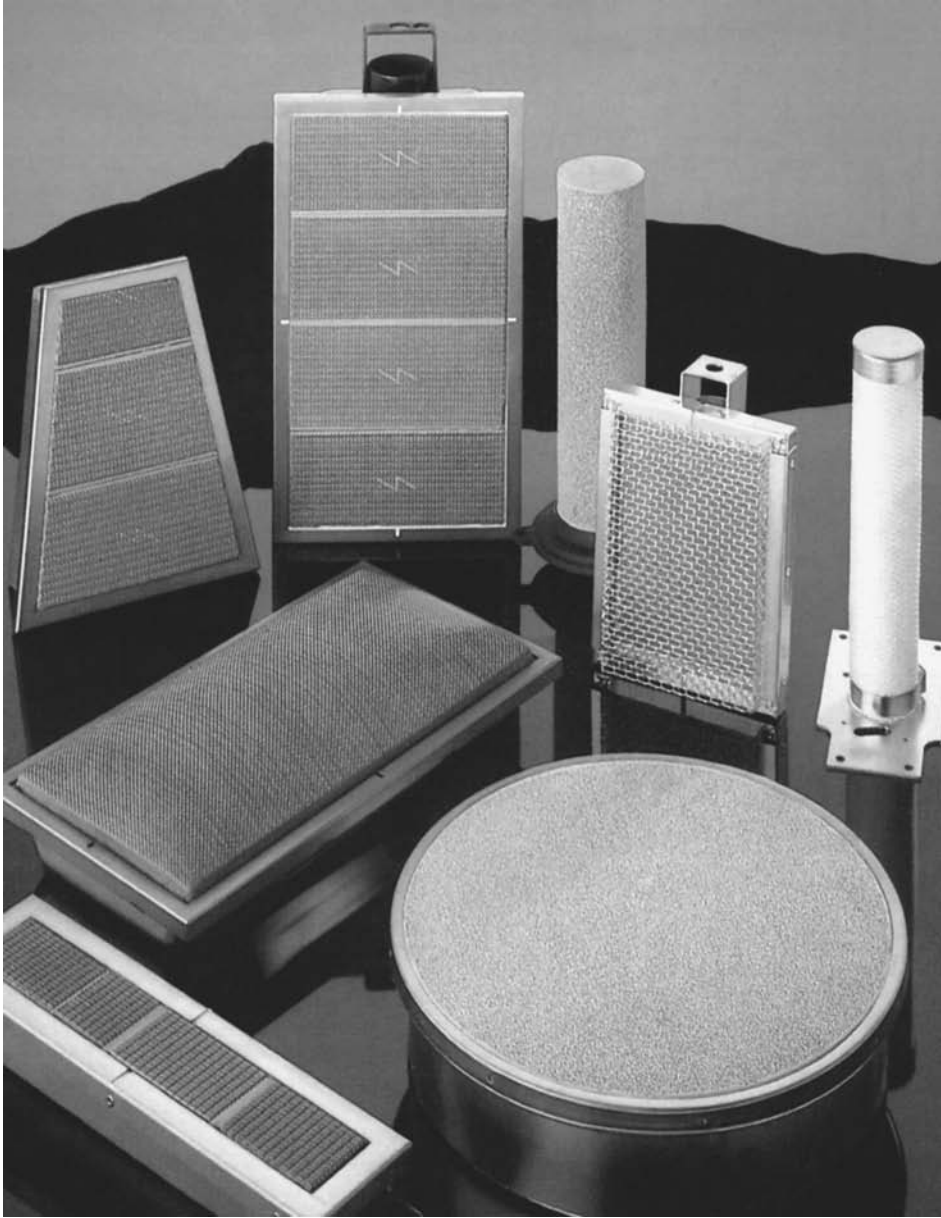


FIGURE 13.26 Examples of porous ceramic and wire mesh radiant burners. (Courtesy of Solaronics.⁴⁴)

13.4.2 PORTED CERAMIC BURNERS

Ported or perforated ceramic burners have a plenum across the open mouth that is mounted to a cast ceramic plate (approximately 12 mm or 0.5 in. thick) with a multitude of very small holes (about 2 mm or 0.08 in.) (12 to 16 holes/cm²). Ported ceramic burners are surface combustion types. They are often fitted with a metal screen to improve their conversion to radiation efficiency, in which case they become a combination surface combustion and impingement type. The relatively high mass produces slow heating and cooling times that are further exacerbated by the metal screen.

Examples of these types of burners are shown in Figure 13.26. Perforated or ported ceramic burners may consist of a pressed ceramic plate, which may include prepunched holes, where the

flames heat the surface directly.⁴⁴ The surface can be textured to further enhance the radiant efficiency of the burner. New developments in ceramic foams are being applied to this type of burner. These foams are often less expensive to make than perforated ceramics. They provide a higher surface area for radiation and a more uniform heating surface, compared to perforated ceramics. Many shapes are possible with the ceramic foams and the pore size is adjustable. Flanagan et al. (1992) described the use of a ported ceramic burner to achieve low NO_x emissions.⁴⁵ However, the burner was actually fired at up to 15 times its normal maximum design firing rate so that the flames were highly lifted and therefore did not radiate from the surface as in normal operation. Mital and Gore (1994) discussed the use of a reticulated ceramic insert to enhance radiation heat transfer in direct-fired furnaces.⁴⁶ The insert was placed downstream of the outlet of a laminar diffusion flame. Experimental results showed up to a 60% improvement in radiative heat flux compared to the case with no insert. The radiative heat flux as a function of radius increased with the insert. Kataoka (1998) described a new type of high-temperature, porous ceramic burner made of aluminum titanate (Al₂TiO₅) capable of surface temperatures up to 1100°C (2000°F).⁴⁷

Wire mesh burners are made from high-temperature-resistant metals, such as stainless steels or inconel. The open area in the mesh serves as the port area for the burner. However, due to the high thermal conductivity of metals, several layers of mesh are often required to prevent flashback. The thermal conductivity between the layers is much less than through the mesh itself because of the contact resistance between the layers. An important problem with wire mesh radiant burners are the lower temperature limits compared to ceramic burners, due to the temperature limits of the metals.

13.4.3 PORTED METAL BURNERS

Ported metal burners are similar to the ported ceramic burners discussed above. Ported metal burners can be classified as surface combustion, impingement, or a combination of the two, depending on design and manufacturer. Due to the high metal mass, the heat-up and cool-down times are measured in minutes. The maximum operating temperature is limited by metal oxidation at the higher temperatures.

13.4.4 FIBER METAL BURNERS

Fiber metal burners use a thin (<2 mm or 0.08 in.) knitted or sintered metal fiber pad as the emitter. They were originally developed as a low NO_x nonradiant burner. These are surface combustion burners and have the lowest conversion to radiation efficiency of all the types above (<20%) at maximum radiant temperatures of about 935°C (1715°F).

13.4.5 FLAME IMPINGEMENT RADIANT BURNERS

This burner is sometimes referred to as a direct-fired refractory burner. An example of this type of burner is shown schematically in [Figure 13.27](#). An actual burner is shown in [Figure 13.28](#). In this type of radiant burner, the flame impinges on a hard ceramic surface, which then radiates to the load. The heat transfer from the flame to the tile is mostly by convection due to the direct flame impingement. The heat transfer from the burner tile to the load is typically purely by radiation. The hot exhaust gases from the burner heat up the surrounding wall by convection, but at a much lower rate than to the burner tile. One advantage of this type of burner is that there is no metal matrix with lower temperature limits compared to ceramic, which has high temperature limits. Therefore, this type of burner can often be used in higher-temperature applications. There also is no matrix of porous ceramic fiber refractory that could get plugged up as in the next type of burner. This type of burner can also fire a liquid fuel, as opposed to many other radiant burners that use only gaseous fuels. A disadvantage is that the heat flux is not as uniform as other types of radiant burners. Another problem is that the burner tile has the typical problem of thermal cycling, which can cause the tile to disintegrate over time and become a maintenance issue.

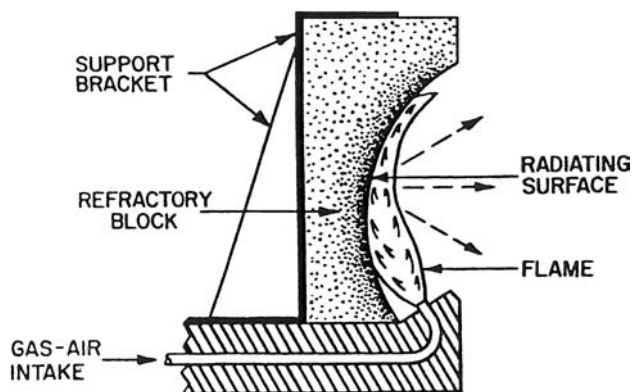


FIGURE 13.27 Schematic of a flame impingement radiant burner. (Courtesy of American Gas Association.³⁵)

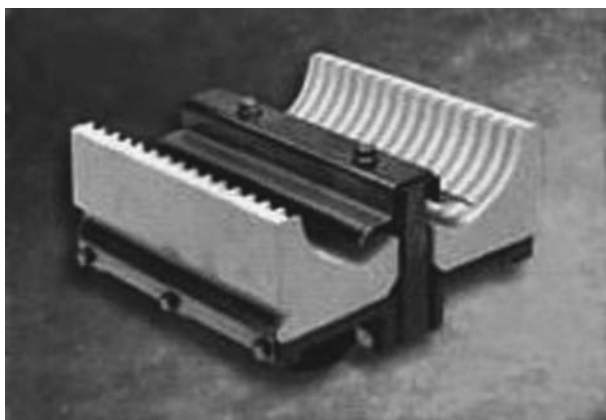


FIGURE 13.28 InfraRad ceramic radiant infrared burner. (Courtesy of Eclipse, Rockford, IL.)

13.4.6 CATALYTIC BURNERS

Catalytic heaters operate at comparatively low temperature ($<475^{\circ}\text{C}$ or $<887^{\circ}\text{F}$). Nonaerated fuel gas is introduced into a plenum behind a catalytically doped fiber pad. An electric heating coil is layered within the fiber pad to preheat it so the catalytic reaction can proceed between the introduced fuel gas, the catalyst, and oxygen in air, which diffuses into the pad from its outer surface. Very low radiant power is generated because of the low operating temperature ($<15\text{ kW/m}^2$ or $4800\text{ Btu/ft}^2\text{-hr}$).

13.4.7 ADVANCED CERAMIC RADIANT BURNERS

Tong et al. (1989) showed through computer modeling that the performance of porous radiant burners can be improved by as much as 109% using sub-micron diameter ceramic fibers.⁴⁸ Bell et al. (1992) describe a staged porous ceramic burner that demonstrated low NO_x emissions.⁴⁹ Kendall and Sullivan (1993) studied enhancing the radiant performance of porous surface radiant burners by using improved ceramic, high-temperature, high-emissivity fibers.⁵⁰ Selective emissivity was achieved by coating a standard ceramic fiber burner with an outer layer of ytterbia. The output of the uncoated vs. the coated burner is shown in Figure 13.29. As can be seen, there is a large spike in the output of the coated burner at around $1\text{ }\mu\text{m}$. However, there was no significant improvement

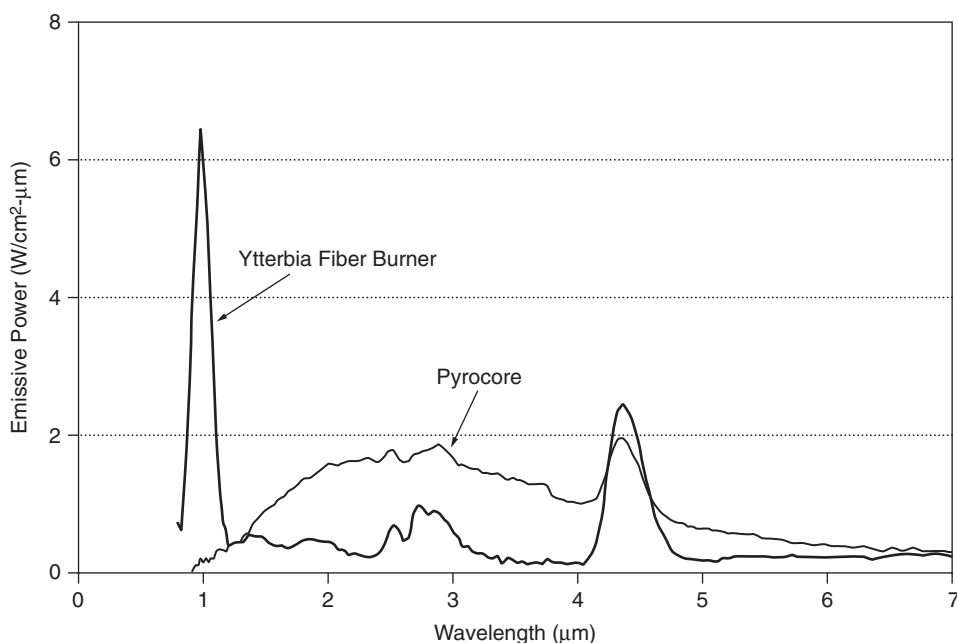


FIGURE 13.29 Emission spectra of ytterbia fiber burner compared to Alzeta (Santa Clara, CA) Pyrocore burner, both operating at 127,000 Btu/hr-ft² (400 kW/m²). (Courtesy of GRI.⁵⁰)

in performance and the durability was in question. In certain applications, there may be a need to have a burner with selective radiant emissions corresponding to selective absorption in the load. Potential applications include glass melting, glass bending and lamination, thin-film drying, and indirect heating. Xiong et al. (1993) described a porous ceramic surface combustor-heater with a built-in heat exchanger for improving the thermal efficiency, as shown in Figure 13.30.⁵¹ Ruiz and Singh (1993) described an advanced IR burner.⁵² The new burner design had considerably higher radiant outputs than the previous style design. The new burner increased a powder paint drying process by 40% and a paper drying process by 200%. Severens et al. (1995) modeled porous radiant burners.⁵³ The one-dimensional model results compared favorably with experimental data for the radiant fraction as a function of the gas velocity through the burner. Bogstra (1998) described a new type of IR radiant burner, referred to as CHERUB, with a closed surface to separate the combustion exhaust gases from the product being heated.⁵⁴ The burner had an enclosed, flat, multi-burner system that heats a ceramic radiant plate. The burner was reported to have a radiant efficiency of 80%, compared to an efficiency of 40% for conventional high-temperature radiant burners.

As previously discussed, one of the limitations of porous refractory burners is the burner surface temperature. If the firing rate density is to be increased, new refractory materials are needed that can withstand continuous operation at higher temperatures, while maintaining their integrity during thermal cycling. One example of research to develop improved radiant burner materials is by Superkinetic, Inc. (Albuquerque, NM) with funding from the U.S. Dept. of Energy.⁵⁵ Three single-crystal ceramic fibers were produced and two fiber materials were successfully made into felt for testing as radiant burner screen surfaces. The materials were alpha-alumina and alpha-silicon carbide, which were successfully bonded with a high-temperature ceramic to form the burner screens that were 95% porous. The purpose of this project was to develop materials capable of radiant burner service near 3000°F (1900°K), compared to conventional radiant burner surface temperatures of about 1800°F (1300°K). The new materials performed well in actual burner operation, but more research was recommended.

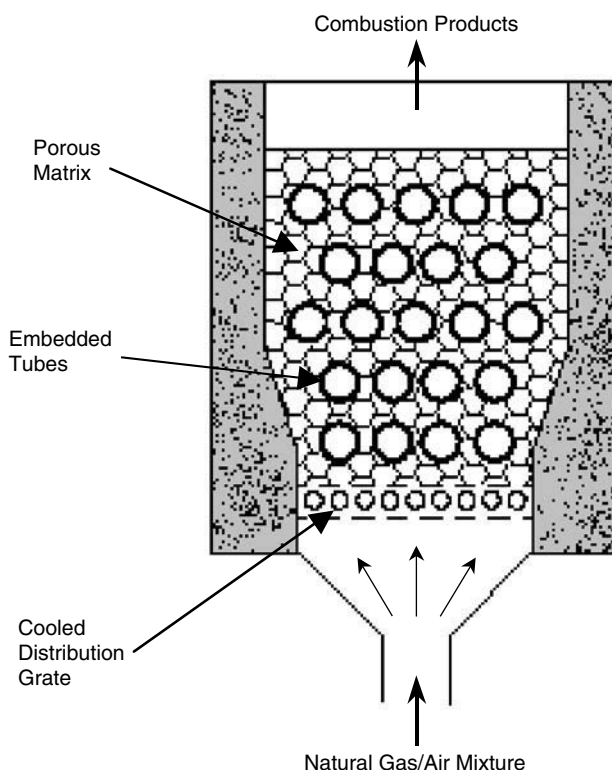


FIGURE 13.30 Surface combustor-heater concept. (Adapted from Reference 51.)

13.5 TESTING AND CHARACTERIZATION

13.5.1 RADIATION EFFICIENCY

One of the challenges of gas-fired IR burners is determining the radiant efficiencies. Mital et al. (1998) noted that there is a wide discrepancy in the reported radiant efficiencies (varying by more than 200%) for radiant burners.⁵⁶ Part of the discrepancy was attributed to a lack of a standard measurement technique to determine the efficiency. Other problems include nondiffuse radiation from the burners and nonuniform burner surfaces. They presented a technique that is not sensitive to burner surface nonuniformities. A calorimetric method was used to check the consistency of the data. It was shown that single-point radiation measurements can deviate considerably from more rigorous multi-point measurement techniques. Yetman (1993) described a simple technique for measuring the total radiant output of an IR burner using a narrow angle pyrometer.⁵⁷ Johansson (1993) presented a method for measuring the spectral output of radiant burners using an IR spectrometer.⁵⁸

Madsen et al. (1996) measured the spectral radiation from several types of radiant burners.⁵⁹ The spectra were fairly similar, with distinctive peaks around 3 and 4.5 μm . This shows the selective emittance of certain types of radiant burners and the possibility of matching the burner to the load spectral absorptivity to optimize heat transfer efficiency.

Radiation efficiency is a controversial measurement that is often overstated in manufacturers' literature. The true measure of radiation efficiency (conversion to thermal radiation efficiency) measures the global thermal radiation output according to accepted formulas and measurement means and divides it by the gross fuel input:

$$\eta_{\text{rad}} = \frac{\text{Radiant output}}{\text{Gross fuel input/Unit area}} \quad (13.4)$$

Example 13.1

Given: 20 kW/m² radiant output at 100 kW fuel input, 1 m² burner output area.

Find: Radiation efficiency.

Solution:

$$\eta_{\text{rad}} = \frac{\text{Radiant output}}{\text{Gross fuel input/Unit area}} = \frac{20 \text{ kW/m}^2}{100 \text{ kW/1m}^2} = 0.20 = 20\%$$

The performance of a gas thermal radiation burner is often optimistically given as “combustion intensity” or “energy release,” which is actually either the gross energy input or total thermal radiation plus conductive/convective output. Neither of these are the true measure of radiation efficiency.

Testing methods can be very sophisticated, utilizing expensive equipment. A reasonably accurate conversion to radiation efficiency can be obtained by measuring the emitter radiant face temperature using an infrared thermometer (see Figure 13.31) set for 1.0 emissivity, measuring the fuel gas input with a flow meter and measuring the actual radiant area of the emitter not including nonradiant perimeter frames, clamps, etc. The thermal radiation heat flux between surfaces can be calculated according to the formula:

$$q_r \text{ (kW/m}^2\text{)} = \sigma * \{T_s^4 - T_r^4\} * F_s * F_r * A \quad (13.5)$$

where q_r is the thermal radiation heat flux between the source and the receiver in kW/m²; $\sigma = 5.669 \times 10^{-8} \text{ W/m}^2\text{-K}^4$ (Stephan-Boltzmann constant); T_s and T_r are the absolute temperatures of the source



FIGURE 13.31 Example of an infrared pyrometer measuring the surface temperature of a porous refractory matrix burner.¹⁹

and receiver in degrees Kelvin, respectively; F_s and F_r are the emittances of the source and receiver, respectively; and A is the arrangement or view factor.

Example 13.2

Given: Source or emitter temperature = 836°C, the receiver (sink or load) temperature = 40°C, the source (emitter) emittance is 0.97, the receiver (sink or load) emittance is 0.90, and the arrangement factor is 0.95.

Find: Radiant flux from the source to the receiver.

$$\text{Solution: } q_r = (5.669 \cdot 10^{-8})[(836 + 273.15)^4 - (40 + 273.15)^4](0.97)(0.90)(0.95) = 70,700 \frac{\text{kW}}{\text{m}^2}$$

The radiant area in square meters (m^2) is then multiplied by the calculated thermal radiation output/ m^2 to obtain the emitter's thermal radiation output in kilowatts (kW). The emitter's thermal radiation output is then divided by the fuel gas energy input (in kW) to obtain the emitter's conversion to radiation efficiency. The actual heat flux between the emitter and a target to be heated is then a factor of the target's temperature, emissivity, and view angle.

The thermal radiation thermometer when set for an emissivity of 1.0 will give the temperature of the emitter as if the emitter's emissivity were 1.0. The actual emitter temperature will be greater and the emitter's emissivity will be lower. By setting the thermometer emissivity at 1.0, the actual thermal radiation output of the emitter is equated to the formula calculation to obtain a reasonably accurate result.

13.5.2 HEAT TRANSFER COEFFICIENT

The heat transfer coefficient between the hot exhaust products and the radiant burner material is difficult to predict and measure due to the uncertainty in the surface area of the ceramic structure. These coefficients have traditionally been presented in terms of a volumetric coefficient ($\text{Btu/hr-}^\circ\text{F-ft}^3$ or $\text{kW/}^\circ\text{C-m}^3$). Chen et al. (1987) assumed the coefficient was large enough that the temperature of the solid was essentially the same as the temperature of the hot flowing gas.⁶⁰ Sathe et al. (1990) used a value of $2 \times 10^9 \text{ W/m}^3\text{-K}$ ($1 \times 10^8 \text{ Btu/hr-}^\circ\text{F-ft}^3$) computed for cylinders in cross flow.⁶¹ Hsu et al. (1993) used $10^7 \text{ W/m}^3\text{-K}$ ($5 \times 10^5 \text{ Btu/hr-}^\circ\text{F-ft}^3$).⁶² Younis and Viskanta (1993) empirically determined the following correlation for alumina and cordierite ceramic foams with pore diameters ranging from 0.29 to 1.52 mm (0.011 to 0.0598 in.):⁶³

$$\text{Nu} = 0.819 [1 - 7.33 (d/L)] \text{Re}^{0.36[1 + 15(d/L)]} \quad (13.6)$$

where d is the actual pore diameter and L is the thickness of the specimen in the flow direction. Fu et al. (1998) noted the relationship between the volumetric heat transfer coefficient h_v and the convection coefficient h :⁶⁴

$$h_v = a_v h \quad (13.7)$$

where a_v can be computed using the following empirical equation:

$$a_v = 169.4 \text{ PPC } (\text{m}^2/\text{m}^3) \quad (13.8)$$

where PPC is the number of pores per centimeter for cellular ceramics. Four different choices for the characteristic dimension were identified: the reciprocal of the surface area,

$$d_a = 1/a_v \quad (13.9)$$

the hydraulic diameter,

$$d_h = 4\phi/a_v \quad (13.10)$$

the mean pore diameter,

$$d_m = \frac{\sqrt{4\phi/\pi}}{\text{PPC}} \text{ (cm)} \quad (13.11)$$

and the ratio of the inertial to the viscous friction coefficients,

$$d_r = \beta/\alpha \quad (13.12)$$

where ϕ is the porosity, β is the inertia coefficient in the Reynolds-Forchheimer equation, and α is the viscous coefficient in the Reynolds-Forchheimer equation. The following empirical correlations, using each of these characteristic dimensions, were developed for specimens having a PPC ranging from 4 to 26:

$$\text{Nu}_v = \left[0.0426 + \frac{1.236}{L/d_m} \right] \text{Re}_{d_m} \text{ for } 2 \leq \text{Re}_{d_m} \leq 836 \quad (13.13)$$

$$\text{Nu}_v = \left[0.0730 + \frac{1.302}{L/d_h} \right] \text{Re}_{d_h} \text{ for } 3 \leq \text{Re}_{d_h} \leq 1594 \quad (13.14)$$

$$\text{Nu}_v = \left[0.0252 + \frac{1.280}{L/d_a} \right] \text{Re}_{d_a} \text{ for } 1 \leq \text{Re}_{d_a} \leq 480 \quad (13.15)$$

$$\text{Nu}_v = \left[0.000267 + \frac{1.447}{L/d_r} \right] \text{Re}_{d_r} \text{ for } 0.02 \leq \text{Re}_{d_r} \leq 2.4 \quad (13.16)$$

where Nu_v is the volumetric Nusselt number, defined as:

$$\text{Nu}_v = \frac{h_v l_c^2}{k} \quad (13.17)$$

where l_c is the characteristic pore length and k is the thermal conductivity of the gas. The uncertainty in the correlations was largest for the smaller Reynolds numbers.

13.6 CONCLUSION

Thermal radiation burners are used in a wide range of heating and drying applications. They have a number of unique properties compared to other burners, including very uniform surface temperatures, high conversion of fuel energy to thermal radiation, flat shapes, very low pollutant emissions, and some have the ability to heat up and cool down very rapidly. These burners can be used to supplement other heating and drying techniques, or they can be the primary source of heat. They are commonly

fired on fuel gases such as natural gas. They offer the end user considerable flexibility in how they are applied and operated. They will continue to play an important role in industry.

REFERENCES

1. J.R. Howell, M.J. Hall, and J.L. Ellzey, Combustion within porous media, in *Heat Transfer in Porous Media*, Y. Bayazitoglu and U.B. Sathuvalli, Ed., ASME, HTD-Vol. 302, 1–27, 1995.
2. D. Traub, Indirect vs. direct: the heat transfer method does affect the process, *Process Heating*, 6(2), 26–29, 1999.
3. R.M. Fedler and R.W. Rousseau, *Elementary Principles of Chemical Process*, third edition, John Wiley & Sons, New York, 2000.
4. T. Kudra and A.S. Mujumdar, *Advanced Drying Technologies*, Marcel Dekker, New York, 2002.
5. Anonymous, Ceramic tile burner improves performance of infrared predryer, *Process Heating*, 4(7), 43–45, 1997.
6. P. Mattsson, J. Perkonen, and A. Riikonen, Infrared drying of coated paper, *Proc. 1989 International Gas Research Conf.*, T.L. Cramer, Ed., Government Institutes, Rockville, MD, 1989, 1308–1316.
7. M. Pettersson and S. Stenström, Evaluation of gas-fired and electrically heated industrial infrared paper dryers, *Proc. 1998 International Gas Research Conf.*, Vol. V: Industrial Utilization and Power Generation, D. Dolenc, Ed., Government Institutes, Rockville, MD, 1998, 100–112.
8. Thomas M. Smith, *Heat Transfer Dynamics*, TAPPI 1994 Non-Woven Conference.
9. J. Riikonen, E. Härkönen, and S. Palosaari, Modeling of Infrared Drying of Pulp, in *Drying '87*, A.S. Majumdar, Ed., Hemisphere, Washington, D.C., 1987, 18–23.
10. A. Williams-Gardner, *Industrial Drying*, Leonard Hill, London, 1971.
11. R.B. Keey, Dryers, in *International Encyclopedia of Heat & Mass Transfer*, G.F. Hewitt, G.L. Shires, and Y.V. Polezhaev, Eds., CRC Press, Boca Raton, FL, 1997, 337–342.
12. C.E. Sloan, Drying Systems and Equipment, *Chem. Eng.*, 74(14), 169–200, 1967.
13. B.J. Ezerski and G.P. Megan, Boosting the performance of your convection oven, *Process Heating*, 7(1), 22–26, 2000.
14. J.R. Cornforth, Ed., *Combustion Engineering and Gas Utilisation*, E&FN Spon, London, 1992.
15. U.S. EPA, *Compilation of Air Pollutant Emission Factors, Vol. I: Stationary Point and Area Sources*, Section 4.2.2.6: Paper Coating, fifth edition, U.S. Environmental Protection Agency report AP-42, Washington, D.C., 1995.
16. U.S. EPA, Paper Industry, Report EPA/530-SW-90-027o, U.S. Environmental Protection Agency, Washington, D.C., 1990.
17. U.S. EPA, Profile of the Pulp and Paper Industry, Report EPA/310-R-95-015, U. S. Environmental Protection Agency, Washington, D.C., 1995.
18. T. Berntsson, P-A Franck, and A. Åsblad, *Learning from experiences with Process Heating in the Low and Medium Temperature Ranges*, CADDET Energy Efficiency, Sittard, the Netherlands, 1997.
19. C.E. Baukal, *Heat Transfer in Industrial Combustion*, CRC Press, Boca Raton, FL, 2000.
20. S. Longacre, Using infrared to dry paper and its coatings, *Process Heating*, 4(2), 45–49, 1997.
21. P. Mattsson, J. Perkonen, and A. Riikonen, Infrared Drying of Coated Paper, *Proc. 1989 International Gas Research Conf.*, T.L. Cramer, Ed., Government Institutes, Rockville, MD, 1989, 1308–1316.
22. C.E. Bean and J.M. Cocagne, Assessment of Gas-Fired Infrared Heaters in the Paper Industry, Gas Research Institute report GRI-96/0087, Chicago, IL, 1996.
23. M. Hannum, T. Robertson, J. Winter, B. Schmotzer, and T. Neville, High Intensity Lean Premix Combustion Systems for Drying Applications, *Proc. 5th European Conf. on Industrial Furnaces and Boilers*, Portugal, Vol. 1, 455–464, 2000.
24. U.S. EPA, *Compilation of Air Pollutant Emission Factors, Vol. I: Stationary Point and Area Sources*, Section 4.9.1: General Graphic Printing, fifth edition, U.S. Environmental Protection Agency report AP-42, Washington, D.C., 1995.
25. U.S. EPA, Profile of the Printing and Publishing Industry, U.S. Environmental Protection Agency Report EPA/310-R-95-014, Washington, D.C., 1995.
26. U.S. EPA, Printing Industry and Use Cluster Profile, U.S. Environmental Protection Agency Report EPA/744-R94-003, Washington, DC, 1994.

27. U.S. EPA, Textile Manufacturing. Report EPA/530-SW-90-027e, U.S. Environmental Protection Agency, Washington, D.C., 1990.
28. Anonymous, Ceramic tile burner improves performance of infrared predryer, *Process Heating*, 4(7), 43–45, 1997.
29. T.M. Smith and C.E. Baukal, Space-age refractory fibers improve gas-fired infrared generators for heat processing textile webs, *J. Coated Fabrics*, 12, 160–173, 1983.
30. U.S. EPA, *Compilation of Air Pollutant Emission Factors, Vol. I: Stationary Point and Area Sources*, Section 4.11: Textile Fabric Printing, fifth edition, U.S. Environmental Protection Agency Report AP-42, Washington, D.C., 1995.
31. R.F. Speyer, W-Y Lin, and G. Agarwal, Radiant efficiencies and performance considerations of commercially manufactured gas radiant burners, *Exp. Heat Transfer*, 9, 213–245, 1996.
32. W.V. Krill and R. Pam, Industrial applications of the pyrocore burner, in *Industrial Combustion Technologies*, M.A. Lukasiewicz, Ed., American Society of Metals, Warren, PA, 1986, 267–271.
33. Alzeta Corp., brochure, Santa Clara, CA, 1998.
34. D.F. Bartz, F.E. Moreno, and P.A. Duggan, Ultra-low, NO_x ultra-high VOC destruction with adiabatic radiant combustors, in *Fossil Fuels Combustion — 1992*, R. Ruiz, Ed., ASME PD-Vol. 39, 7–12, New York, 1992.
35. D.W. DeWerth, A Study of Infra-Red Energy Generated by Radiant Gas Burners, American Gas Association Research Bulletin 92, Catalog No. 41/IR, Cleveland, 1962.
36. S.B. Sathe, M.R. Kulkarni, R.E. Peck, and T.W. Tong, An Experimental and Theoretical Study of Porous Radiant Burner Performance, *Twenty-Third Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, 1990, 1011–1018.
37. M.F. Zabielski, J.D. Freihaut, and C.J. Egolf, Fuel/air control of industrial fiber matrix burners using optical emission, in *Fossil Fuel Combustion 1991*, R. Ruiz, Ed., ASME PD-Vol. 33, 41–48, New York, 1991.
38. T.-Y. Xiong and R. Viskanta, A basic study of a porous-matrix combustor-heater, in *Fossil Fuels Combustion — 1992*, R. Ruiz, Ed., ASME PD-Vol. 39, 31–39, New York, 1992.
39. S. Jugjai and S. Sanitjai, Parametric studies of thermal efficiency in a proposed porous radiant recirculated burner (PRRB): a design concept for the future burner, *ENERG Inter. Energy Journal*, 18(2), 97–111, 1996.
40. R. Mital, J.P. Gore, R. Viskanta, and S. Singh, Radiation efficiency and structure of flames stabilized inside radiant porous ceramic burners, in *Combustion and Fire*, M. Q. McQuay, W. Schreiber, E. Bigzadeh, K. Annamalai, D. Choudhury, and A. Runchal, Eds., ASME Proceedings of the 31st National Heat Transfer Conf., Vol. 6, ASME HTD-Vol. 328, 131–137, New York, 1996.
41. M.D. Rumminger, R.W. Dibble, N.H. Heberle, and D.R. Crosley, Gas Temperature above a porous radiant burner: comparison of measurements and model predictions, *Twenty-Sixth Symposium (Int'l) on Combustion*, The Combustion Institute, Pittsburgh, PA, 1996, 1755–1762.
42. A. van der Drift, N.B.K. Rasmussen, and K. Jorgensen, Improved efficiency drying using selective emittance radiant burners, *Applied Therm. Eng.*, 17(8–10), 911–920, 1997.
43. R. Mital, J.P. Gore, R. Viskanta, and A.C. McIntosh, An experimental evaluation of asymptotic analysis of radiant burners, *Twenty-Seventh Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, 1998, 3163–3171, 1998.
44. F. Ahmady, Gas-Fired IR Burners Are Worth Considering, *Process Heating*, 1(2), 38–43, 1994.
45. P. Flanagan, K. Gretsinger, H.A. Abbasi, and D. Cygan, Factors influencing low emissions combustion, in *Fossil Fuels Combustion — 1992*, R. Ruiz, Ed., ASME PD-Vol. 39, 13–22, New York, 1992.
46. R. Mital and J.P. Gore, An experimental study of laminar diffusion flames with enhanced heat transfer by reticulated ceramic inserts, in *Heat Transfer in Fire and Combustion Systems*, W. W. Yuen and K. S. Ball, Eds., ASME HTD-Vol. 272, 7–12, New York, 1994.
47. A. Kataoka, New Type of high temperature surface combustion burner, *Proc. 1998 International Gas Research Conf.*, Vol. V: Industrial Utilization, D.A. Dolenc, Ed., Gas Research Institute, Chicago, 1998, 115–124.
48. T.W. Tong, S.B. Sathe, and R.E. Peck, Improving the performance of porous radiant burners through use of sub-micron size fibers, in *Heat Transfer Phenomena in Radiation, Combustion, and Fires*, R.K. Shah, Ed., ASME HTD-Vol. 106, 257–264, New York, 1989.
49. R.D. Bell, C. Chaffin, and M. Koeroghlian, Experimental Investigation of a Staged Porous Ceramic Burner, in *Fossil Fuels Combustion — 1992*, R. Ruiz, Ed., ASME PD-Vol. 39, 41–46, New York, 1992.

50. R.M. Kendall and J.D. Sullivan, Selective and Enhanced Radiation from Porous Surface Radiant Burners, Gas Research Institute Report GRI-93/0160, Chicago, 1993.
51. T.-Y. Xiong, M.J. Khinkis, B.M. Kramnik, R. Viskanta, and F. F. Fish, An experimental and theoretical study of a porous-matrix combustor-heater, *Proc. 1992 International Gas Research Conf.*, H. A. Thompson, Ed., Government Institutes, Rockville, MD, 2013–2024, 1993.
52. R. Ruiz and S.N. Singh, Enhanced infrared burner system, *Proc. 1992 International Gas Research Conf.*, H.A. Thompson, Ed., Government Institutes, Rockville, MD, 1993, 2410–2419.
53. P.F.J. Severens, P.H. Bouma, C.J.H. van de Ven, L.P.H. de Goey, and A. van der Drift, Modeling of twofold flame behavior of ceramic foam surface burners, *J Energy Resources Tech.*, 117(1), 29–36, 1995.
54. A.N. Bogstra, Development of a new prototype of a flat closed high efficient infrared radiant burner, *Proc. 1998 International Gas Research Conf.*, Vol. V: Industrial Utilization, D. A. Dolenc, Ed., Gas Research Institute, Chicago, 1998, 24–33.
55. Milewski, J.V., Shoultz, R.A., McConnell, M.M.B., and Milewski, E. B., Improved Radiant Burner Material, Superkinetic, Inc., Albuquerque, NM, Final Report, U.S. Dept. of Energy report DOE/EE/15643-T2, 1998.
56. R. Mital, J. P. Gore, and R. Viskanta, A radiation measurement procedure for gas-fired radiant burners, *Proc. 1998 International Gas Research Conf.*, Vol. V: Industrial Utilization, D. A. Dolenc, Gas Research Institute, Chicago, 1998, 197–209.
57. M. E. Yetman, Evaluation of Infrared Generators, *Proc. 1992 International Gas Research Conf.*, H. A. Thompson, Ed., Government Institutes, Rockville, MD, 1993, 2401–2409.
58. M. Johansson, Spectral characteristics and efficiency of gasfired infrared heaters, *Proc. 1992 International Gas Research Conf.*, edited by H. A. Thompson, Govt. Institutes, Rockville, MD, pp. 2420–2426, 1993.
59. O.H. Madsen, K. Jørgensen, N.B.K. Rasmussen, and A. van der Drift, Improved efficiency heat transfer using selective emittance radiant burners, *Proc. 1995 International Gas Research Conf.*, D.A. Dolenc, Ed., Government Institutes, Rockville, MD, 1996, 2208–2217.
60. Y.-K. Chen, R.D. Matthews, and J.R. Howell, The effect of radiation on the structure of a premixed flame within a highly porous inert medium, in radiation, *Phase Change Heat Transfer and Thermal Systems*, Y. Jaluria, V. P. Carey, W. A. Fiveland, and W. Yuen, Eds., ASME, HTD-Vol. 81, 35–42, 1987.
61. S.B. Sathé, R. E. Peck, and T.W. Tong, Flame stabilization and multimode heat transfer in inert porous media: a numerical study, *Comb. Sci. Tech.*, 70, 93–109, 1990.
62. P.F. Hsu, J.R. Howell, and R.D. Matthews, A numerical investigation of pre-mixed combustion within porous media, *J. Heat Transfer*, 115(3), 744–750, 1993.
63. L.B. Younis and R. Viskanta, Experimental determination of the volumetric heat transfer coefficient between stream of air and ceramic foam, *Int. J. Heat Mass Transfer*, 36(6), 1425–1434, 1993.
64. X. Fu, R. Viskanta, and J.P. Gore, Measurement and correlation of volumetric heat transfer coefficients of cellular ceramics, *Exper. Thermal Fluid Sci.*, 17, 285–293, 1998.