
12 Regenerative Burners

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12.1 INTRODUCTION

In 1858, William Siemens built the first experimental furnace using the regenerative principle to achieve high temperatures¹. Two years later, he built and patented the first practical furnace using regenerators for the melting of glass. The significant advantages of the principle of regeneration were quickly understood, and it was quickly adopted in furnaces for zinc distillation, the puddling of iron, the reheating of iron and steel, and for the melting of steel. From these applications evolved the Siemens Martin Basic Open Hearth Furnace, used in the making of steel until displaced by the electric arc furnace, and the Glass Melting Tanks used today for all large-scale glass production.

The regenerators of today's glass melter are large refractory structures containing a refractory checkerwork heat storage mass — usually substantially larger than the actual glass-melting furnace section itself. Reversal times of 40 to 50 minutes between the heating and cooling functions are common, with 2-minute firing interruptions for valve cycling to take place.

In the early 1980s, attention was turned from the use of the compact self-recuperative burner that was then the leading high-efficiency, small-to-medium capacity, direct-firing burner technology to the development of compact regenerative burners to bring the inherently high regenerator efficiency to furnace plant and processes previously considered unsuitable for the application of regenerators. It is the combination of a high air preheat temperature burner and a compact high-efficiency heat recovery device to which this chapter is devoted.

12.2 EFFICIENCY IN THE CONTEXT OF HIGH-PERFORMANCE HEAT RECOVERY FROM COMBUSTION PRODUCTS

Industrial combustion produces hot gases to be utilized in the transfer of heat to another body. The primary attributes of the hot gases in achieving this transfer are temperature and heat content, with the secondary properties of heat emissivity and chemical characteristics such as oxidizing or reducing potential.

This chapter is primarily devoted to the production and use of those gases where they are directly in contact with the material to be heated, but the principles of this section apply also in the case where the fuel is combusted in an enclosure separated from the work by a partition, such as muffle furnaces or those fired with radiant tubes.

The process of utilization of the heat of the combustion gases involves some waste. Only part of the heat is used in heating the work; part is used in heating the work enclosure, part will be lost from that enclosure, and part will exit at the full process temperature in the exhaust gases from the work enclosure. The regenerative burner is devoted to the combination functions of producing the hot combustion gases and recovering a significant portion of that heat leaving the process at full process temperature.

The basic Sankey diagram in [Figure 12.1](#) illustrates the relationship of the gross heat input of the fuel to the useful heat output.

The process efficiency can be calculated as:

$$\% \text{Process Efficiency} = \left[\frac{\text{Usable Heat To Load}}{\text{Gross Heat Input}} \right] \times 100 \quad (12.1)$$

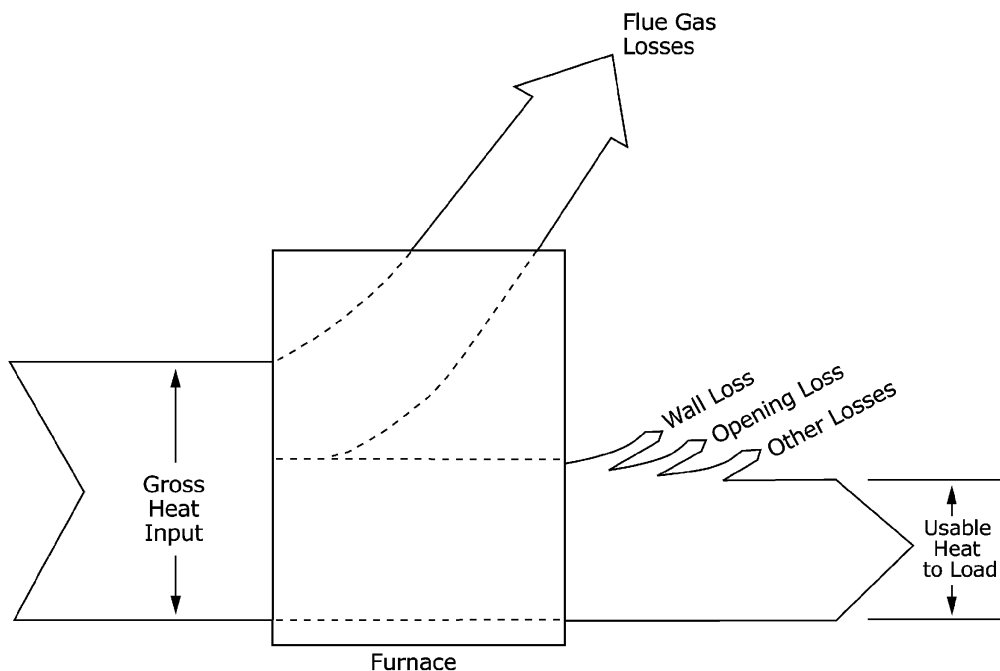


FIGURE 12.1 Basic Sankey diagram.

Because the Usable Heat to Load, Wall Loss, Opening Loss, and Other Losses are all functions of the particular furnace and load in process and not related to the combustion process, the efficiency related to combustion can be calculated as:

$$\% \text{Combustion Efficiency} = \left[\frac{(\text{Gross Heat Input} - \text{Flue Gas Losses})}{\text{Gross Heat Input}} \right] \times 100 \quad (12.2)$$

The amount of heat derived from (Gross Heat Input – Flue Gas Losses) is commonly referred to as the “Available Heat to the process,” and the % Combustion Efficiency from Equation 12.2 as the “% Available Heat.”

12.2.1 AVAILABLE HEAT

Most fuel-fired industrial heating applications can increase their overall heating efficiency and reduce fuel consumption by preheating of the combustion air. Preheating combustion air requires less of the chemical energy derived from the fuel to be used to raise the air to furnace temperature.

$$\text{Available Heat} = [\text{Gross Heat Input} - (\text{Moist Loss} + \text{Dry Loss})] \quad (12.3)$$

The moist flue loss is the heat given up by the water vapor in the combustion products as it cools to the base temperature at which the calorific value of the fuel was determined. It is mainly the latent heat of condensation of the water vapor formed by combustion of the hydrogen in the fuel. The dry flue loss is the amount of heat given up by the dry combustion products as they cool to the base temperature at which the calorific value of the fuel was determined.

The available heat can be calculated for each specific fuel and oxidant, cold or preheated combustion air, oxygen enriched air, and oxy-fuel, for specific air/fuel ratios at, above (excess air), or below (excess fuel) the ideal stoichiometric ratio, at any flue gas temperature.

The Sankey diagram in Figure 12.2 expands on the basic diagram of Figure 12.1 to include the additional components previously described. The Sankey diagram of Figure 12.3 expands on Figure 12.2 by including the illustration for recovered heat from the flue gases to the combustion air.

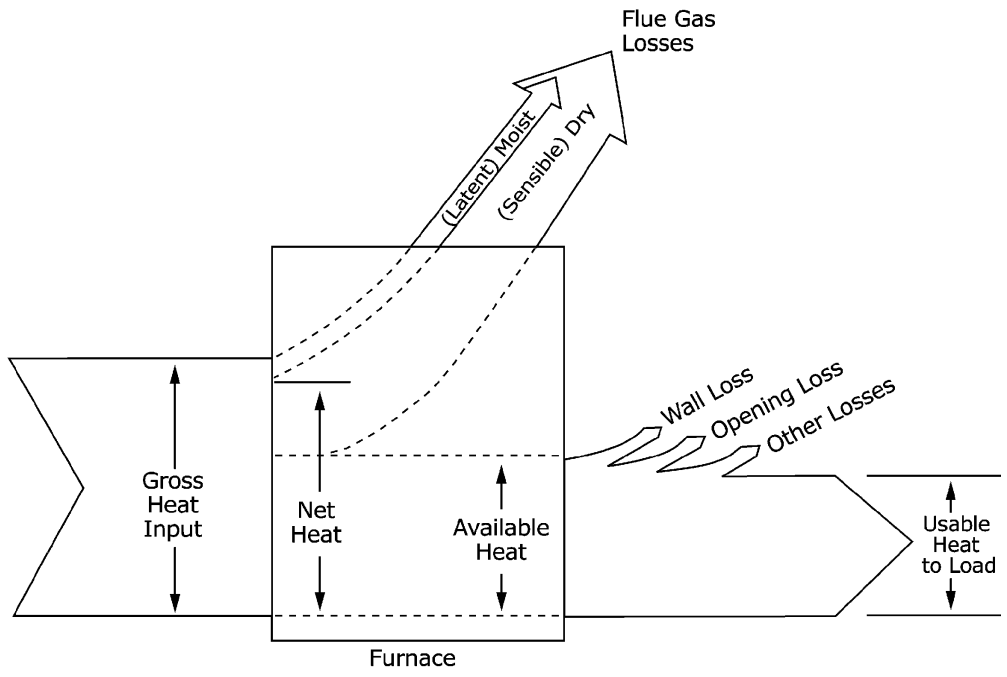


FIGURE 12.2 Expanded Sankey diagram to include the moist flue gas loss.

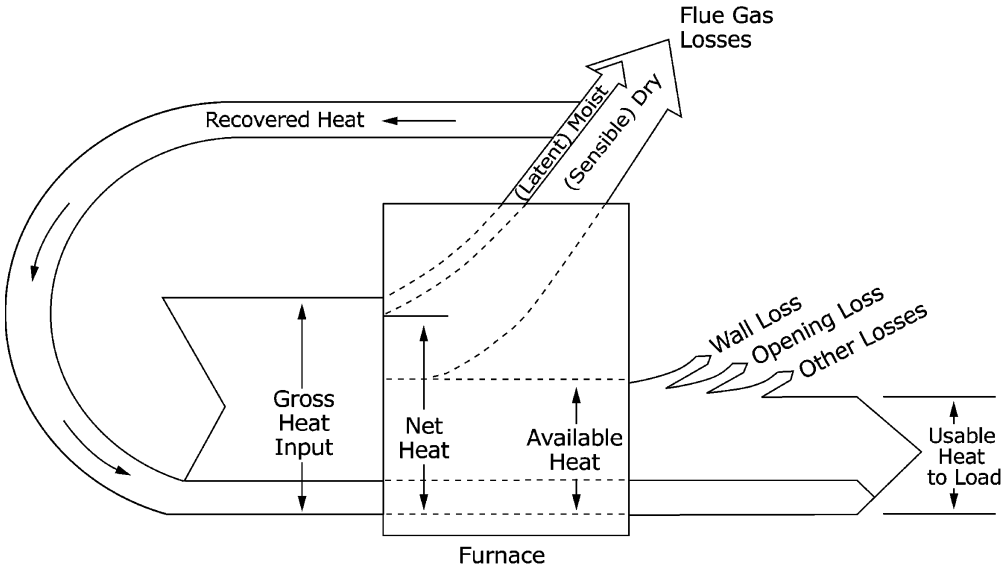


FIGURE 12.3 Sankey diagram, including recovered exhaust heat.

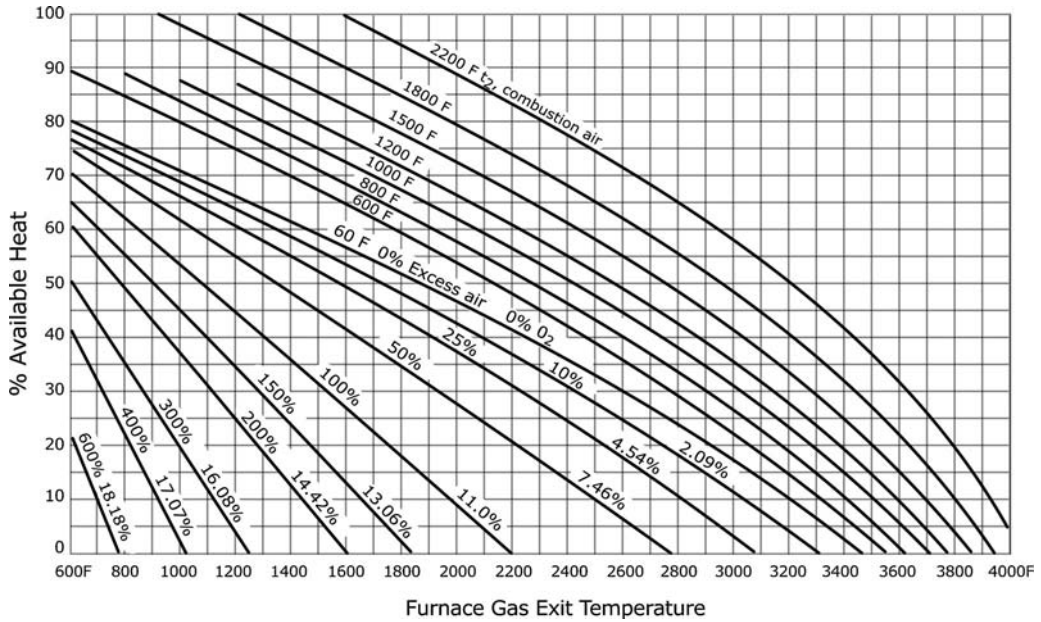


FIGURE 12.4 Available heat for 1000 BTU/ft³ natural gas at various furnace temperatures and air preheat levels.

Figure 12.4 is a typical chart-plotting % Available Heat against flue gas temperature for both cold and preheated air for a typical natural gas.

The following example demonstrates the use of Figure 12.4. The intersection of a 2000°F furnace temperature with cold (unheated) combustion air at 10% excess air shows an available heat of 42%. The intersection of combustion air preheated to approximately 1660°F with a furnace temperature of 2000°F shows 75% available heat. It can be seen that preheating the combustion air results in higher combustion efficiency as only 25% (100% minus 75%) of the gross heat input is lost to the flue gases compared to 58% (100% minus 42%) when using cold combustion air.

12.2.2 EVALUATING FUEL SAVINGS POTENTIAL FROM AIR PREHEATING

The available heat concept can be used to evaluate the fuel saving resulting from preheating the combustion air (or changing the amount of excess air in use):

$$\% \text{Fuel Saved} = \left[1 - \left(\frac{\text{Original \% Available Heat}}{\text{New \% Available Heat}} \right) \right] \times 100 \quad (12.4)$$

Applying Equation 12.4 to the previously referenced values for a 2000°F furnace yields:

$$\% \text{Fuel Saved} = \left[1 - \left(\frac{42}{75} \right) \right] \times 100 = 44\% \quad (12.5)$$

The higher the furnace operating temperature, the greater the potential fuel savings can be with preheated combustion air. The 75% available heat value is indicative of that typically realized by regenerative burners.

12.3 THE REGENERATOR PRINCIPLE

The principle of the regenerator, the alternate heating of a heat storage mass by flowing exhaust gas and subsequent cooling of it by the combustion air on its way to the burner, with the units applied in pairs to allow a virtually continuous firing process interrupted only by reversal of the functions of the two regenerators, is a highly efficient means of heat recovery from exhausting combustion products. Because the heating/cooling process is in counter flow, and the hot end of the heat storage mass reaches the full temperature of the gases exhausted from the furnace, the combustion air can be heated to a temperature very close to that of the furnace. The inherent heat recovery effectiveness of a regenerator can approach 90%, compared with ~40% for a typical recuperator.

12.3.1 THE REGENERATOR

The regenerative principle was first developed by the prolific inventor William Siemens and employed in the construction of steam engines, although later abandoned for this use as a result of the severe wear to the cylinders from the high temperatures attained. In 1858 Siemens built his first experimental furnace with regenerators to elevate the combustion air temperature in order to achieve higher flame temperatures. Two years later, he built and patented the first practical gas-fired regenerative furnace, used in melting glass. It was soon established that the use of regenerators would provide significant fuel savings in high-temperature furnaces, leading to their adoption in zinc distillation furnaces, for the puddling of iron, the reheating of iron and steel, and in the well-known Siemens Martin Basic Open Hearth Furnace for the making of steel and the Glass Melting Tank still used today for all large-scale glass production.

An example of a traditional regenerator is shown in Figure 12.5.² It can be seen that the regenerators are of significant size relative to the furnace.

Refractory checkerwork is used as the heat transfer mass, and a series of valves and dampers are used to control the direction of combustion air and waste gas flows. In the example of Figure 12.5,

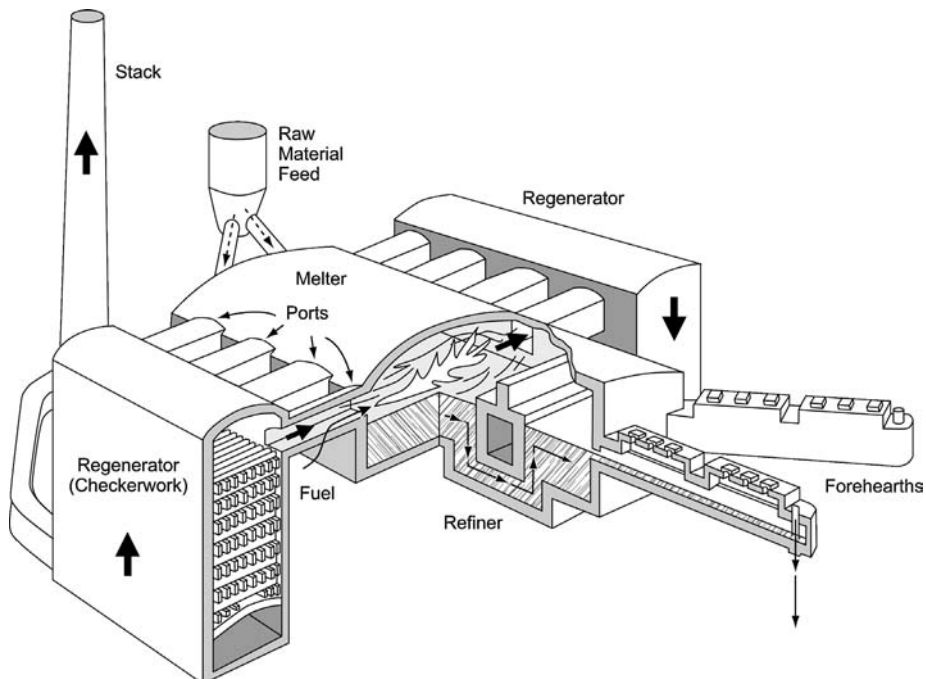


FIGURE 12.5 A regenerative side-port glass melting furnace.

there are four air/exhaust ports on each side of the furnace. Only the ports on one side fire at any one time, fuel being injected into the air stream adjacent to the furnace end of the air port. During the first cycle, products of combustion (POC) from the firing side are carried through the opposite brick checkerwork after they exit the furnace. As the POC travel through the cool checkerwork, they lose heat to the refractory and drop in temperature. After a period as long as 40 to 50 minutes, the valves and dampers are reversed to change the direction of flow. Cold combustion air is now directed through the previously heated checkerwork, absorbing the heat from the refractory and rising in temperature before reaching the ports now to be fired.

The choice of individual shapes, their refractory composition, and the arrangement of the shapes in a conventional regenerator checkerwork packing are strongly influenced by the temperature and constituents of the flue gas from the fired process, as well as the desire for high-performance heat recovery. Depending on the furnace charge and the heat processing, the hot exhaust products exiting the furnace may not only contain the normal products of combustion, but also may contain volatilized compounds and particulates emanating from the charge and the furnace structure. The fuel fired in the furnace may also be a source of elements such as sulfur and vanadium.

As the exhaust gases cool, these various “passengers” will have the potential to combine, condense, and deposit on the packing, depending on their nature. The chemistry of the packing must be chosen taking into consideration the potential for any corrosion attack by the deposits. The shape and size of the gas passages in the packing must be selected with an eye toward the heat transfer and the resistance to flow (affecting the power required to move the gases through the regenerator), and also with the aspects of the potential degradation to performance caused by any fouling, and the possible removal of the fouling to maintain heat transfer performance or keep air and exhaust gas pressure drops within the bounds of the capability of their flow-producing devices.

Using the glass melting furnace as an example, the typical soda-lime glass container tank exhaust gases will be carrying at least volatile sodium sulfate and some fine, but sticky, batch material particles. The accumulation of these will cause fouling and give rise to the potential of slagging of the refractory materials of the packing. Although the regenerator packings are designed to minimize the effect of accumulation and corrosion on regenerator efficiency and availability, it is common practice in the industry to utilize special portable burner equipment and trained crews to “melt out” glass tank regenerator accumulations *in situ* in cases where resistance to flow has become extreme.

Traditional regenerators use large refractory shapes in the packing that are placed according to a pattern to create gas flow passages of the desired hydraulic and thermal properties. Different materials can be used at different levels in the packing according to the design conditions of temperature, corrosion potential, and mechanical loading at the particular location.

12.3.2 THE MODERN COMPACT REGENERATIVE BURNER

In the early 1980s, work began on the development of compact regenerative burners. Although difficult to track exactly, it seems that it may have begun almost simultaneously in the U.K. at what was then British Gas,³ in conjunction with the British combustion company Hotwork Development, and in the U.S. at the authors’ company, The North American Manufacturing Company.⁴ Certainly, the first commercial installation, in February 1983, was a 1 MMBtu/hr, 1400°C, open pot glass melting furnace.^{3,5} From that small beginning in Wakefield, England, have come hundreds of installations spanning the steel, aluminum, glass, and ceramic industries, with standard burners from 100,000 Btu/hr to close to 50 MMBtu/hr in individual heat input capacity, across the globe. In Japan where high fuel prices and a government-sponsored energy/emissions initiative spurred adoption,^{6,7} in Europe with high energy prices and emissions concerns, and in the U.S. where a high initial adoption rate was influenced by the rise and decline of energy prices, the regenerative burner constitutes the leading technology for the firing of high-temperature, high-efficiency, low emissions, industrial furnaces.

12.3.3 THE PRINCIPLE OF THE COMPACT REGENERATIVE BURNER

The compact regenerative burner, a high-temperature preheated air burner close-coupled to a compact, fast-cycle ceramic regenerator, can provide air preheat in excess of 85% of the process temperature in fuel-fired applications up to 3000°F.

The average 90% effectiveness of the compact regenerator gives close-to-ultimate performance for any combustion air preheater recovering heat from exhaust gas. The high preheat level and insensitivity to the operating environment combine to provide good economics with trouble-free, low-maintenance operation.

The burner serves double duty, acting also as the exhaust port and flueway from the fired chamber. One complete compact regenerative burner set comprises two burners, two regenerators, reversing valves, and the reversing logic.

Each burner has a compact heat storage regenerator containing a bed of ceramic balls. Operating in pairs, one burner fires with cold air fed to the base of its regenerator, and the other burner acts as the exhaust from the fired chamber. Combustion air is preheated as it passes through the bed of the firing burner by removing heat stored in the ceramic balls. At the same time, hot furnace gases give up heat to the ceramic balls in the regenerator of the exhausting burner. Burner duties are reversed within an application-specific time period on the basis of time, or a combination of exhaust temperature and time. The burners continuously cycle between firing and exhausting when the fired process demands heat. A simple representation of this can be seen in Figure 12.6 and Figure 12.7.

12.3.4 TYPES AND STYLES OF REGENERATIVE BURNERS

There are two major components of a regenerative burner: (1) a high-temperature preheated air burner that can do double duty as an exhaust port, and (2) its companion heat-storage-medium-containing regenerator.

Mostly influenced by the heat input capacity of the unit, there are two basic styles – the generally smaller-capacity unit where the burner and the regenerator share the same housing and the regenerator has a horizontal flow path, and the generally larger-capacity unit where the burner has an appearance not unlike a conventional hot air burner, but is connected by high-temperature ductwork to a regenerator having vertical gas flow through the regenerative medium. For the sake of ease of distinction between the two types, the authors will use the convenient terminology one of them first heard in Japan to describe them: “one-box” and “two-box,” respectively.

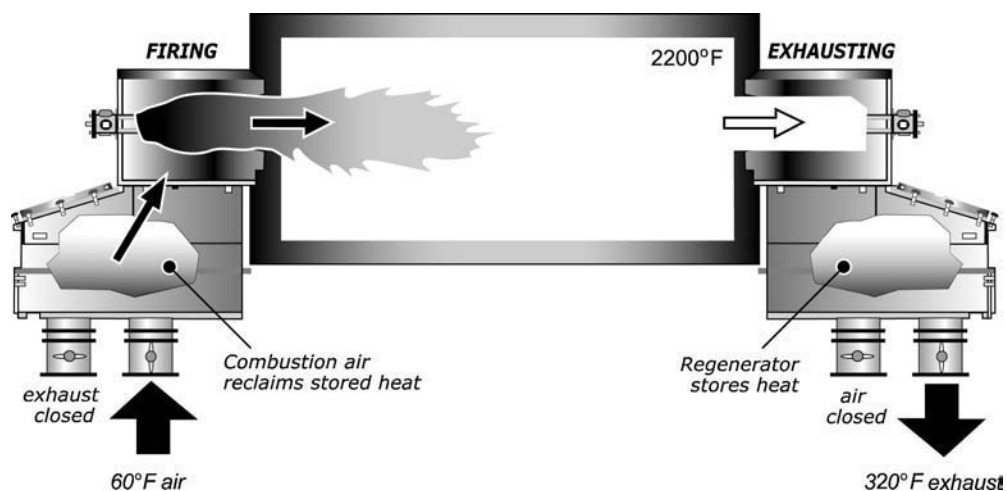


FIGURE 12.6 Regenerative burner operation: first half of cycle.

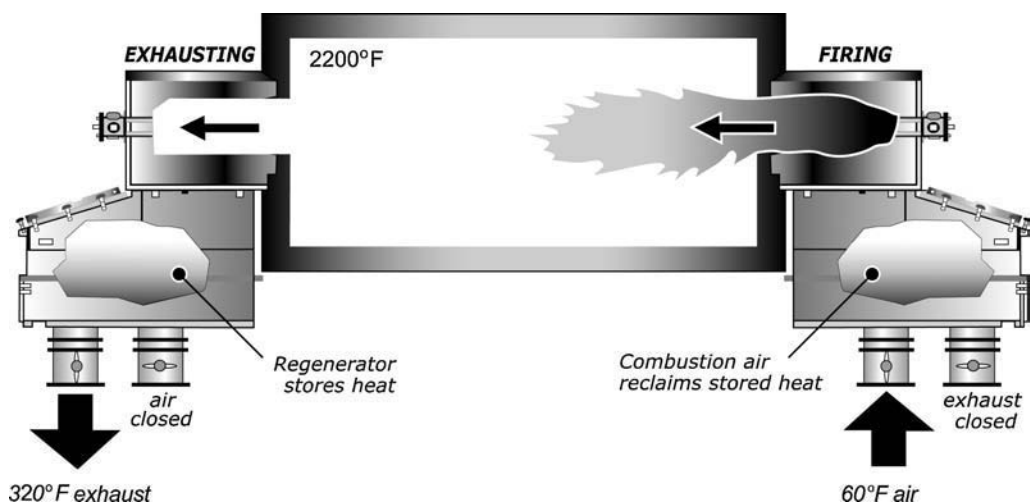


FIGURE 12.7 Regenerative burner operation: second half of cycle.

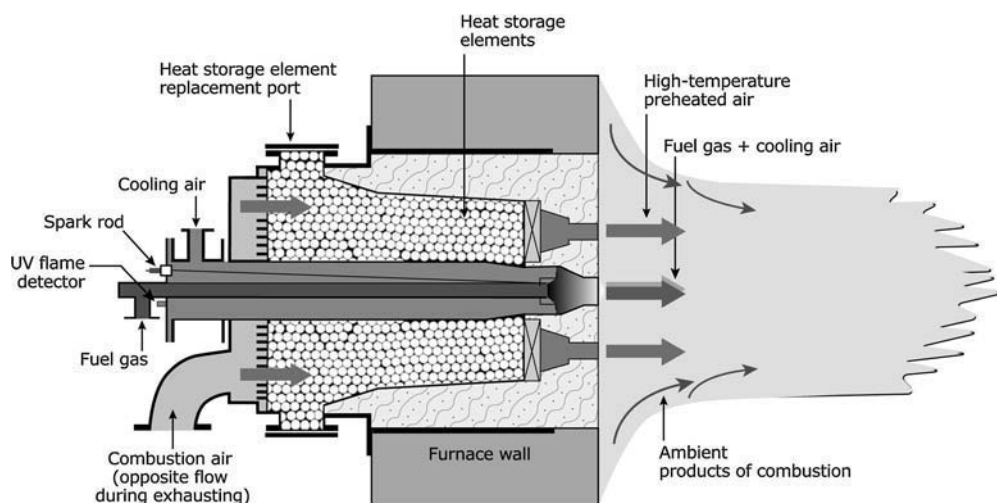


FIGURE 12.8 Cross section of Tokyo Gas FFR burner. (Courtesy of Tokyo Gas Co. Ltd.⁹ With permission.)

Both types exist as direct-fired units, wherein the products of combustion come directly into contact with the work being heated in the fired chamber. The one-box type is also used as a regenerative radiant tube burner, where the products of combustion are separated from the work by a tube that contains the combustion and radiates heat to the furnace workload. This regenerative burner application is covered in another chapter in this book.

The one-box burner design of Tokyo Gas Company⁸ is shown in Figure 12.8. With a range of capacities from 0.5 to 2.5 MMBtu/hr, it can be seen that this unit has the horizontal flow regenerator directly behind the burner tile ports that alternately carry the preheated air to the furnace and the exhaust gas into the regenerator. The ceramic ball regenerator packing is contained and supported at the hot end by a series of perforated SiC discs, and a perforated metal plate at the cold end. The burner's fuel tube passes down the center of the regenerator to the fuel port in the burner tile.

The standard two-box burner design of the author's company is shown in Figure 12.9. With standard capacities ranging from 3.0 to 30 MMBtu/hr, this unit has a high-temperature preheated

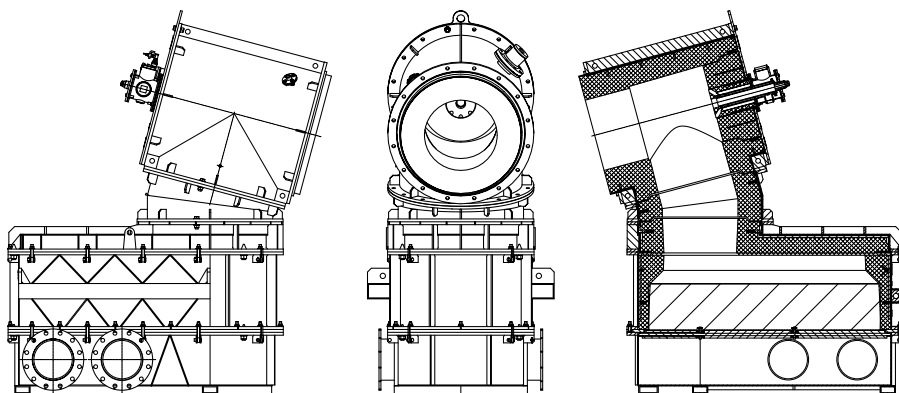


FIGURE 12.9 TwinBed® II (The North American Manufacturing Company, Ltd.) regenerative burner.

air burner connected to a separate refractory-lined regenerator housing containing the ceramic ball regenerator media. It will be appreciated that the vertical flow regenerator needs no containment for the hot end of the packing, merely a support structure for the cold end that will allow even gas flow through the cold face.

The burner head on the example two-box burner is a simple high-temperature insulating refractory-lined unit with no internal obstructions to air or exhaust flow through it, unlike most conventional burners which contain air and gas porting and mixing promotion elements. The necessity of passage of high-temperature exhaust gases through the compact regenerative burner dictates the simplest burner head structure possible. In this case, the fuel tube is mounted on the burner backplate and discharges into the void of the burner body, with mixing and stabilization being achieved by the aerodynamic design of air and gas flows within the burner head.

Both the one-box and two-box burner designs depicted here are provisioned on the burner head for ignition and flame detection devices, as with conventional burners.

At the time of writing, the marketplace for the compact regenerative burner has driven the majority of the development work to be centered on gas firing, for which both the one- and two-box versions are commonly available. With some limitations on their operation over the gas-fired versions, oil-fired systems using the two-box version have been successfully applied.

12.3.5 HEAT TRANSFER MEDIA

The most common type of heat transfer medium used in compact regenerative burners today is alumina balls. With a melting temperature of over 3700°F, alumina provides excellent durability for the high-temperature service it must endure. It is also highly corrosion resistant to the more common contaminants found in industrial furnace exhaust streams. While not normally noted for good thermal shock resistance, it can be appreciated that alumina is suitable for use in compact regenerators when one considers that, despite the fact that typical cycle times from exhausting to air heating are between 20 sec and 3 min, each individual element of the packing only changes its temperature by a small amount during each cycle. Alumina balls used in typical compact regenerators range in size from 3/8 up to 1 in. Although the most common shape today is spherical, alumina can also be used in other shapes, such as nuggets and saddles. For glass applications where alumina will be subject to hot corrosion from contaminants in the exhaust gas, nuggets of zirconia–mullite are successfully used.

The previously described packing materials are purchased in bulk and may be “poured” into a regenerator housing (Figure 12.10) to achieve statistically consistent packing density, thus with statistically consistent thermal and hydraulic characteristics. This placement ability is significant in certain types of applications and is discussed later in this chapter.

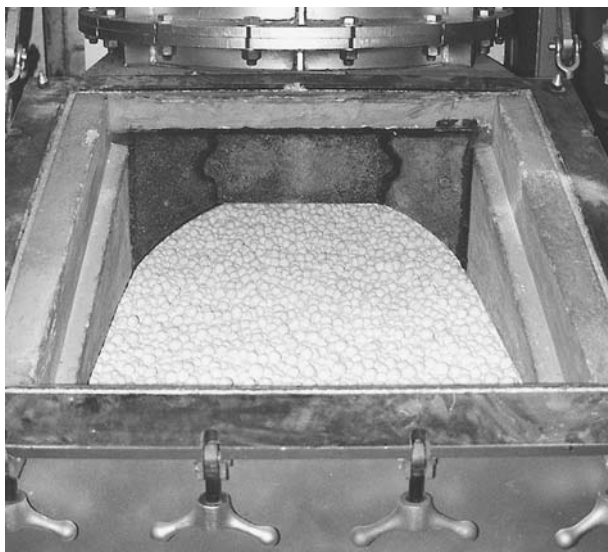


FIGURE 12.10 Open regenerator showing alumina balls.

An alternative approach that has been successfully applied to small input burners in nonfouling exhaust gas streams is to use an engineered packing of high surface-to-mass ratio ceramic components. Examples of such packings are cordierite or SiC honeycomb blocks having very small gas passages separated by very thin ceramic walls. These blocks may be monoliths shaped to fit a particular regenerator box cross section, or a packing may be made up of a series of small blocks placed to ensure that their gas passages are all aligned in the desired direction of flow. For suitable applications, this type of packing has proved itself amenable to the production of very compact, high-performance regenerators, although lacking the flexibility of the “pour to place” packing earlier described.

12.3.6 HEAT TRANSFER CHARACTERISTICS FOR COMPACT REGENERATOR MEDIA

In the convective heat transfer process, the amount of heat transferred from the hot products of combustion to the media, and likewise the heat transferred from the media to the cold combustion air, is directly proportional to the surface area of the media. For this reason, it is desirable to maximize the amount of surface area available for a given volume. When spheres are theoretically nested, regardless of their diameter, they will take up the same volume within the box. (Although the void between smaller diameter balls is smaller, there are more of them, such that the sum of the volume of the voids adds up to the same total volume for all ball diameters.) The void fraction (percent of open volume in the media bed) for balls is 37 to 39%. When comparing the commercially available 3/8-in. diameter balls to 3/4-in. diameter balls, the surface-area-to-volume ratio for the 3/8-in. balls is twice that of the 3/4-in. balls, resulting in more surface area and therefore a potential gain in heat recovery performance. However there are downsides to using smaller balls, the main two being increased pressure drop and a greater potential for plugging. The smaller voids create greater frictional losses, increasing the pressure loss through the media bed. Smaller voids also create more of a filtering effect, increasing the likelihood of trapping particles in applications where the products of combustion contain contaminants. The two common compact regenerative burner applications most likely to have a greater potential for plugging are aluminum melting where fluxing salts are used and glass melting where there are volatiles and particulates in the furnace atmosphere. In these cases, it may be more practical to select a larger-sized medium to reduce the opportunity for plugging.

Similar considerations on the thermal and hydraulic performance, and the potential for fouling, apply to the use of monolithic material structures as regenerator medium. These have very high surface-area-to-mass ratios and thus high heat recovery potential, but typically very small passages for air and waste gas.

12.3.7 THE PERFORMANCE OF COMPACT REGENERATIVE BURNERS

A common method for analyzing and comparing the thermal performance of various heat exchangers is their heat transfer effectiveness e , expressed as:

$$e = \frac{\text{heat_transferred}}{\text{maximum_heat_available_to_be_transferred}}$$

$$= \frac{C_h(t_{h,\text{in}} - t_{h,\text{out}})}{C_{\min}(t_{h,\text{in}} - t_{c,\text{in}})} = \frac{C_c(t_{c,\text{out}} - t_{c,\text{in}})}{C_{\min}(t_{h,\text{in}} - t_{c,\text{in}})} \quad (12.6)$$

where:

$t_{h,\text{in}}$ and $t_{h,\text{out}}$ are the hot fluid entrance and exit temperatures
 $t_{c,\text{in}}$ and $t_{c,\text{out}}$ are the cold fluid entrance and exit temperatures
 $C_h = (MC_p)_h$ is the hot fluid capacity rate
 $C_c = (MC_p)_c$ is the cold fluid capacity rate

For natural gas combustion products with air, the cold fluid capacity rate has a value of about 79% of the hot fluid capacity rate (mass of air is less, specific heat of air is less, maximum possible air temperature is that of the incoming exhaust gas). Accordingly, there is no benefit to extracting more than approximately 80% of the products of combustion through the regenerators because the air cannot carry more heat away. Extracting more than 80% will only elevate the exhaust gas temperature leaving the regenerator and necessitate higher service duty for downstream components, including increasing the size and power consumption of the exhaust fan. The benefits of limiting the extracted rate to 80% thus include lower exhaust temperatures out of the regenerator, a smaller exhaust fan, and providing smoother furnace pressure control through the use of a dampered direct flue from the fired chamber.

Figure 12.11 shows the effectiveness of regenerative and recuperative systems for heating 60°F combustion air. It can be seen in the figure that a regenerative system is nearly twice as effective as even the best typical recuperative system.

Table 12.1 and Figure 12.12 are taken from a record of a laboratory trial of a pair of regenerative burners operating in a test furnace.

12.4 TYPES OF REGENERATOR FOR COMPACT REGENERATIVE BURNERS

The typical regenerator's entire packing is cycled back and forth between hot and cold gases. Unlike the rotational regenerators addressed in Chapter 12.4.4, these regenerators are operated in physical or logical pairs if the process firing is to be substantially continuous. At any given moment, one regenerator will be heating combustion air and the other will be storing heat being recovered from the waste gas. A combination of valves is used to direct gases in the appropriate manner.

TABLE 12.1
Actual Performance Data from Laboratory Trial

Furnace Temp. (°F)	Available Heat (cold air) (%)	Air Preheat Temp. (average) (°F)	Exhaust Gas Temp. at 90% Bed Extraction (°F)	TwinBed Available Heat (average) (%)	Fuel Saving over Cold Air Operation (%)
1470	57	1220	270	82	30
1830	47	1560	330	79	42
2190	37	1900	370	77	52
2640	23	2280	460	74	69

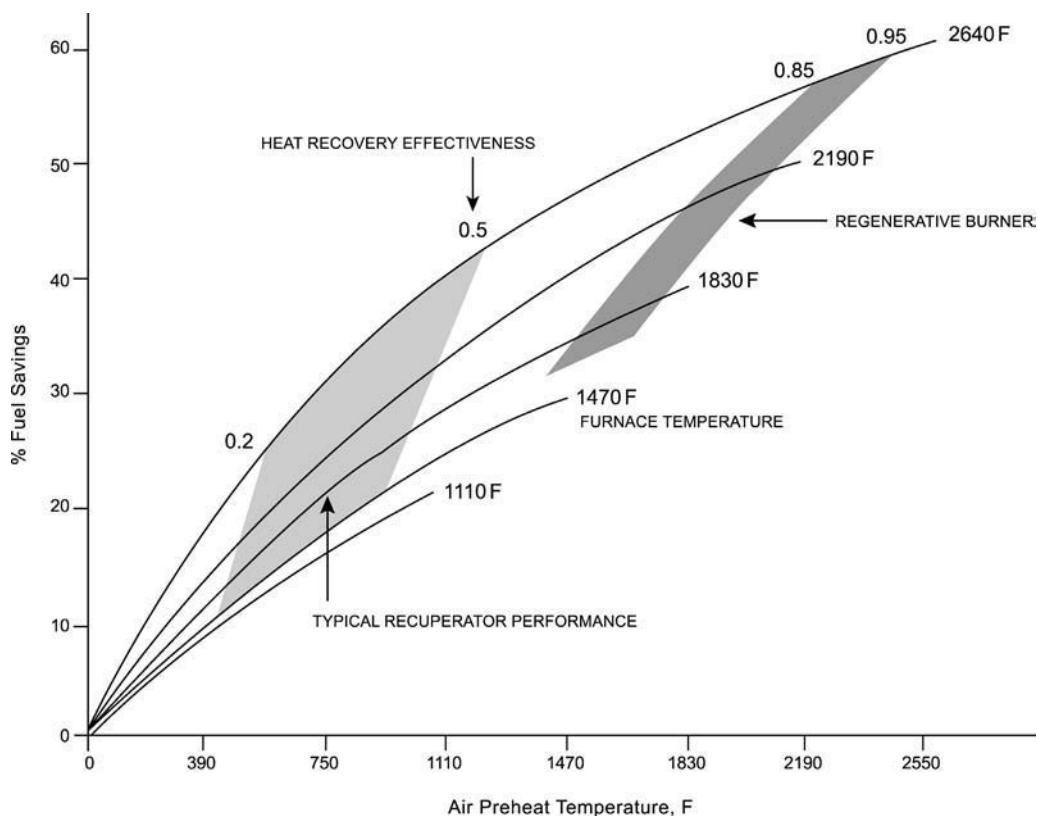


FIGURE 12.11 Comparative performance of regenerative burners and recuperators.

12.4.1 BASIC SHAPES

The most common regenerator shapes adopted for compact regenerative burners are rectangular and cylindrical. Both shapes have their advantages and disadvantages. The simplest to manufacture is the cylindrical regenerator. The necessary refractory lining of the cylindrical regenerator will suffer less natural thermal stresses and, depending on its diameter and lining thickness, less chance of lining collapse because of the natural “keying” of the wall. The cylindrical design will have lower wall heat losses than a rectangular version of the same area, because it has a lower wall-surface-to-regenerator-area ratio and does not have “corner losses.” The reduced perimeter also provides for less “bypass loss” from the edge effect of the increased voidage where packing rests

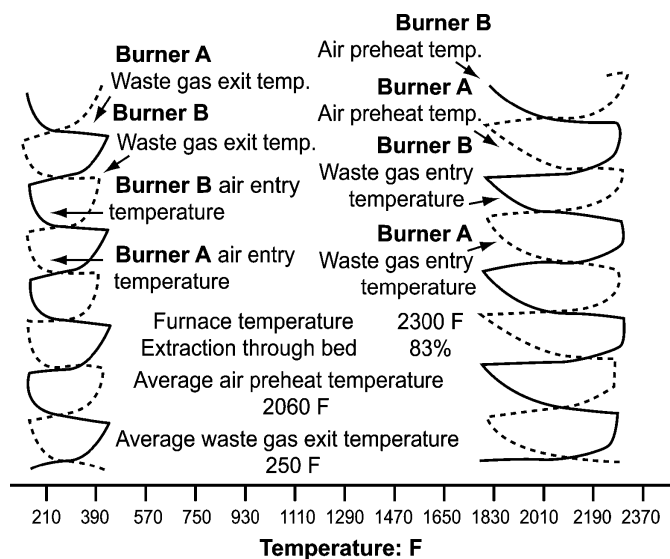


FIGURE 12.12 Combustion air and exhaust gas temperatures measured during laboratory trial.



FIGURE 12.13 An aluminum melter's cassette regenerator being removed by forklift truck.

against a plane wall. The primary advantage of a square or rectangular regenerator is that of efficient use of real estate. The aspect ratio can be easily changed to accommodate available space.

12.4.2 REGENERATORS WITH REMOVABLE PACKING

In applications such as aluminum and glass melting, fouling of the regenerator packing is common. In the aluminum application, for example, fluxing salts will enter the regenerator in the form of a vapor, condense/sublime as they pass through the cold media bed, and deposit on the media surface. Because the rate of accumulation is strongly temperature dependent, the deposition is typically over a particular stratum in the height of the packing, forming a hardened layer that is sometimes difficult to break.

In such cases where frequent cleaning of the media is required, the regenerator can be designed for fast removal and replacement of the packing, or in "cassette" form such that the media section of the regenerator can be quickly removed and replaced, as is shown in Figure 12.13. Spare cassettes can be preloaded with clean media, allowing for a quick exchange as shown in Figure 12.14. As with

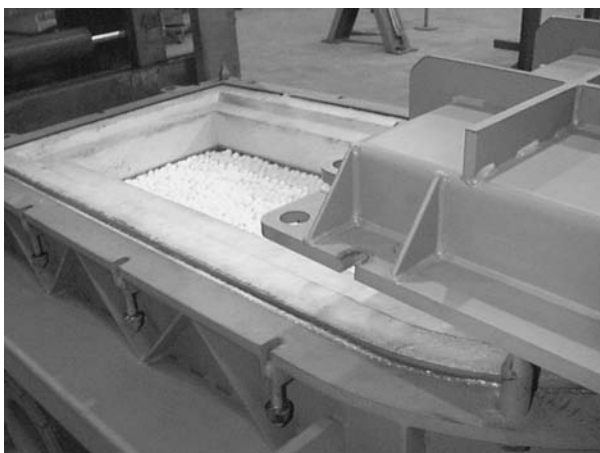


FIGURE 12.14 Putting a fresh media cassette in place.

all regenerative burners, media changes should be performed at the same time for both burners of a pair in order to maintain balanced performance.

Appropriate choice of media form for dirty applications will allow the fouled media to be cleaned and reused. Alumina balls, for example, can be cleaned by methods such as tumbling or high-pressure washing.

12.4.3 REMOTE REGENERATORS

Although the typical compact regenerative burner uses a close-coupled regenerator, if space is restricted, the regenerator can be remotely mounted from its associated burner. Considerations in these instances include allowance for the thermal expansion of the hot duct carrying the exhaust and air back and forth between the regenerator and burner. Appropriate timings of the reversal control system to ensure purging on switching from exhausting to firing modes are also required to compensate for the increased swept volume. [Figure 12.15](#) shows remote regenerators mounted on the roof of a steel rehear furnace. Five other such burner and regenerator combinations are located on the opposite side of the furnace.

12.4.4 ROTARY REGENERATORS

First conceived in the 1930s, the rotary regenerator (often called a “heat wheel;” [Figure 12.16](#)) consists of a cylindrical drum packed with heat storage media in such a way that gases can flow parallel to the axis, but divided (commonly into segments) such that they cannot flow circumferentially. The drum is rotated on its axis between two stationary sections. Each stationary section has two chambers, sealed from each other by sealing surfaces close to the surface of the drum. Exhaust gases enter and leave from the corresponding chambers at each end of the drum, and combustion air through the other pair of corresponding chambers. The rotation of the drum between the stationary sections continuously presents “cold” and “hot” segments of the media in the drum to the air and waste gas streams. The exhaust gas flows through a cold section and preheats the media. That hot section then proceeds into the air path where it preheats the air as the media is cooled. This process occurs without the need for interruption of the air and gas flows, as occurs with the fixed regenerator system, and thus, the burner system can fire continuously.

Heat wheels of metallic construction are in common use in boilers and the process industries with low-temperature waste gas streams.¹⁰ In the late 1970s and early 1980s, newly developed ceramic materials and fabrication techniques allowed monolithic wheels to be made of cordierite and silicon

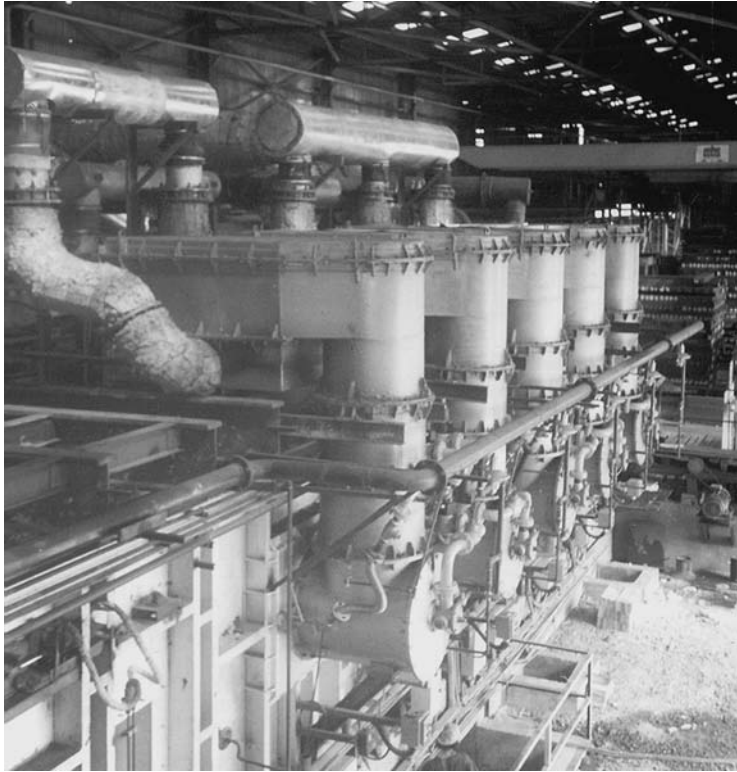


FIGURE 12.15 Remote regenerators on the roof of a steel reheat furnace.

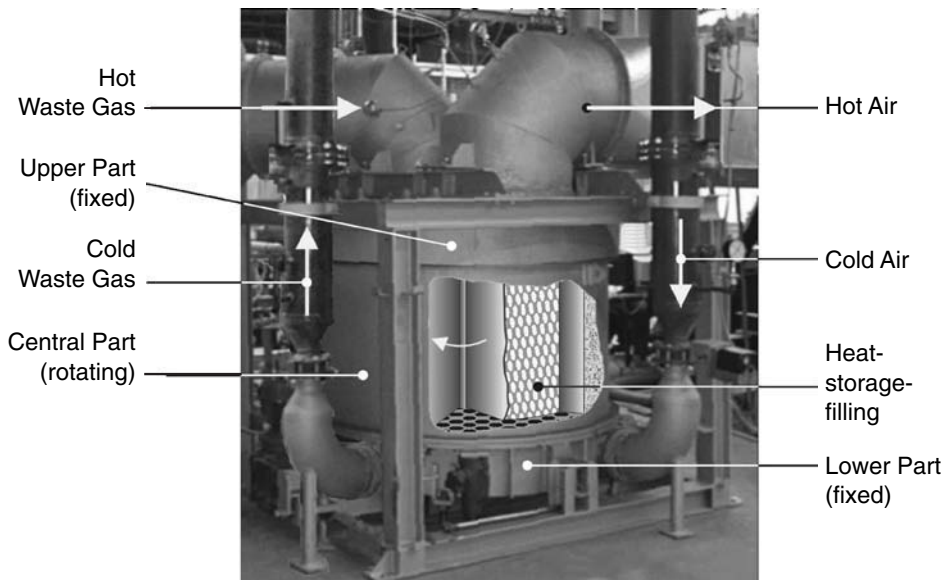


FIGURE 12.16 The EcoReg® (Jasper GmbH) rotary regenerator. (Courtesy of Jasper GmbH.¹¹ With permission.)

carbide and tested in higher temperature industrial applications. However, in addition to material shortcomings leading to short life of the wheel structure, they developed a reputation for excessive seal leakage between the air and waste gas chambers, and their use was substantially abandoned.

In the late 1980s and through the 1990s, development of these devices continued in Europe and Japan. In Europe, there are systems operating with exhaust gas temperatures as high as 2800°F, preheating air up to some 90% of the temperature of the inlet waste gas.¹¹ These latest practical manifestations of the high-temperature heat wheel use packings similar to those previously described for the conventional compact regenerators. They have sealing technologies capable of sustainable practical performance at pressure differences between combustion air and exhaust gas suitable for industrial combustion applications, although with lower hot combustion air pressures that require the use of larger insulated burner structures than the fixed regenerator technology. They have been successfully applied to such applications as clean aluminum melting and steel billet reheating furnaces.

12.5 CONTROLS FOR REGENERATIVE BURNERS

Of all industrial burner controls, in these authors' experience none is more challenging than the control required for regenerative burners. In addition to the safety and fuel/air ratio requirements of conventional industrial burners, the control system must deal with burners switching from being a "burner" to being a "flue" as often as twice a minute.

In the firing periods between switching events, both the firing and exhausting regenerators' temperature profiles change. As the temperatures are changing, the regenerators' flow resistances (flow with respect to pressure drop) are changing. The control system needs to be able to correct the fuel/air ratio and maintain a balance between the firing rate and the exhaust extracted (control the furnace pressure) throughout the reversing regenerative cycle.

Most compact regenerative burner systems fire into a chamber having a conventional flue. That flue can be sized for that part of the exhaust gases from which heat cannot be recovered (see Chapter 12.5.7), or it can be sized to accept the exhaust gases of one or more of the burners firing in a "direct" (nonreversing) mode. This flue will have a damper of some type that needs to be controlled as part of the furnace pressure control loop.

Maintaining control of all of these variables to simultaneously optimize efficiency, in-furnace conditions, and emissions is a complex control problem. The following sections identify control system requirements peculiar to regenerative burner systems when compared with conventional burner systems in industrial practice.

12.5.1 SAFETY SYSTEMS

Regenerative burner systems must meet the same insurance and regulatory standards for safety and flame monitoring as a conventional burner applied to the same process. In general, the furnace temperature, combustion air, and main fuel limits are handled in the same way as with any non-regenerative system. The system's main safety shutoff valving is also the same as that for conventional burners. Most regulatory standards do not allow the function of individual burner fuel safety shutoff valves to be combined with that of the regenerative system's fuel reversal valving, requiring additional valves for this purpose.

The requirements for fuel reversal valving and flame monitoring are discussed later in this chapter. Figure 12.17 shows a typical schematic of a single pair regenerative control system.

12.5.2 EXHAUST FAN PROVING

Most regenerative systems require an exhaust fan to pull the products of combustion through the regenerators. The operation of that fan requires proving. This can be accomplished with a pressure (suction) switch connected to the exhaust header between the exhaust fan inlet and any exhaust

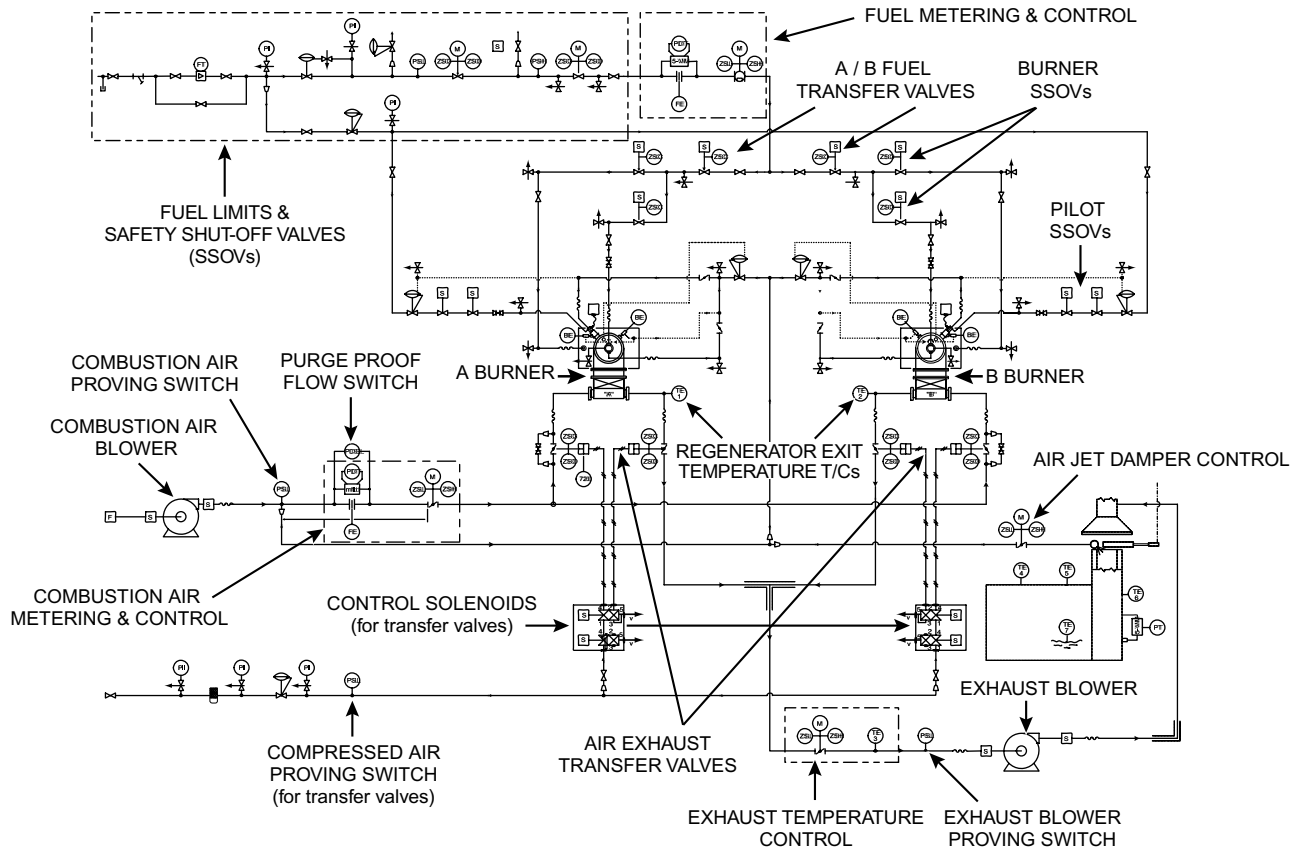


FIGURE 12.17 Typical single pair control schematic.

flow control or regenerator switching valve. As with other critical fans, most regulatory agencies also require that there be a contact from the fan motor starter in the checked limit string.

Some regenerative burner applications provide the ability to fire the burners “direct” as conventional cold air burners, either for process reasons or to maintain operation if there is a failure of the exhaust system. In such cases, the implications of the direct vs. conventional cycling regenerative modes need to be considered in the design of the limits and purge circuitry.

12.5.3 PRE-PURGE

When considering the issue of purging, it is important to remember that you are purging two different flow paths: one through the regenerators and their associated exhaust system and fan, and one through a conventional flue from the furnace chamber. For safety, both paths must be adequately purged of potentially combustible gases. In most applications, purging can be accomplished in the cycling regenerative mode as long as continuous airflow is proven. The purge air will exit via both the regenerative burner exhaust system and the conventional flue from the furnace chamber. If the direct mode is chosen for process reasons, special consideration will be needed to ensure purging of the regenerative burner exhaust system. If the exhaust fan is on during a direct-mode purge, the typical leakage past the air and exhaust cycle valves will pull some air through the exhaust system, requiring only a purge of sufficient duration to ensure no combustible gases remain in the exhaust system.

12.5.4 AIR/FUEL RATIO

From an efficiency standpoint, running a regenerative system with excess air is not as detrimental to efficiency as it is with a cold-air combustion system — the excess air is preheated close to the process temperature. Excess air (O_2) is, however, detrimental to achieving low NO_x generation and to product quality in many processes, so it is generally minimized.

The fuel/air ratio system must use airflow, rather than pressure, as its reference base because the regenerators’ resistance to flow changes with temperature and/or fouling. Ratio control is typically performed on a physical or logical “per pair,” rather than zone (multiple pair) basis to better compensate for the changing resistance of the regenerators. Ratio control on a per-burner basis can be advantageous in some situations — to eliminate long piping runs on large furnaces, for example.

Because most systems meter the combustion air flow at ambient temperature, thus requiring no temperature compensation, regulator-based mass flow ratio systems may be adequate for some applications using small-capacity burners. However, given the limited capacity of suitable regulators and the greater flexibility and accuracy of fully metered air and fuel flow systems, the latter are the control systems of choice for the high heat input capability of most applications using regenerative burners.

12.5.5 FLOW MEASUREMENT AND CONTROL

During the transition of a burner from firing to fluing, there are step changes in flows of air, exhaust, and fuel. The resistance of the regenerators of a physical or logical burner pairing will be different, depending on their respective temperatures and fouling levels. It is important that the flow measuring system be able to quickly determine the flows, and that the flow control system’s components be able to quickly position themselves to control the newly determined required flow after the step change.

12.5.6 RATIO CONTROL SPECIAL FUNCTIONS

Logic to limit air or exhaust flow may be required to prevent overfiring the burners or overloading the blowers when the regenerators are cold and thus at their highest-flow-for-lowest-pressure-drop condition.

Electronic ratio systems can incorporate a function to hold the flow control valve actuators during reversal, and for a short duration after reversal, until the flows stabilize. The duration of such holds will depend on the specific system's response to step changes in flow.

12.5.7 FURNACE PRESSURE AND REGENERATOR EXHAUST

No control function associated with regenerative burners has more influence on the ultimate efficiency of the system than that which determines the balance of the exhaust flow between the regenerators and the hot flue. Typically, a combination of one exhaust control loop per pair of burners and one furnace pressure control loop is used.

Systems with a direct-firing capability require a high turndown or multi-stage damper system. The hot flue of a regenerative furnace needs to be able to controllably handle as little as less than 20% of the POC from one burner in a pair firing at turndown, to as high as 100% of the POC of the full-design firing rate of all the burners in the system allowed to fire simultaneously. A form of split range output function should be used in the furnace pressure control loop. Figure 12.19 shows a flue that utilizes both a "hard" damper and an auxiliary air jet damper. Increased flow from the air jet acts to form a curtain across the opening, adding resistance to fluing gases. The air jet has two advantages: (1) it has the ability to "fine-tune" the flue dampening and (2) it is more forgiving of sudden pressure spikes. The jet and damper combination should be designed such that the curtain of air covers all open areas created when the damper opens. A jet damper will work best when used in conjunction with a sliding damper as shown in the Figure 12.18.

The first action to increase furnace pressure (decrease flue area) should be to close the auxiliary (hot) flue damper and increase the air jet flow (if one is used). Once it is at or near its minimum open (fluing) position, the control action should be to decrease the regenerator exhaust flow (also decreasing the total effective flue area). If the regenerative burner exhaust system can be allowed to satisfy its needs without regard to the furnace pressure, the exhaust fan is likely to pull the furnace chamber negative. This will draw cold air through any crack or opening, possibly even reversing the flow in the hot flue, with corresponding influence on the fuel/air ratio and the system efficiency. Figure 12.19 expresses the logic used to maintain furnace pressure control.

During regenerator reversals, the furnace pressure transmitter will experience a rapid decrease in pressure as a firing burner stops firing, followed by a pressure spike as the new burner starts to fire. The magnitude of these spikes will be influenced by that proportion of the total input represented by the firing rate of the reversing burners. The exhaust system will not be able to respond to this pressure spike, nor should it be allowed to try to do so. The furnace pressure controller should have an input averaging feature to minimize the effects of such spikes on its control output.

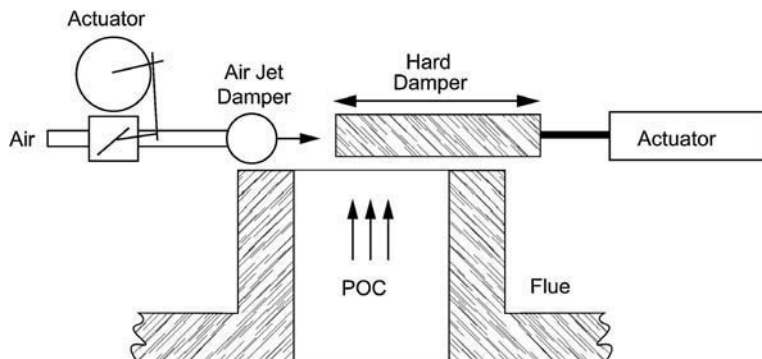


FIGURE 12.18 Two-stage flue damper for a regenerative burner system.

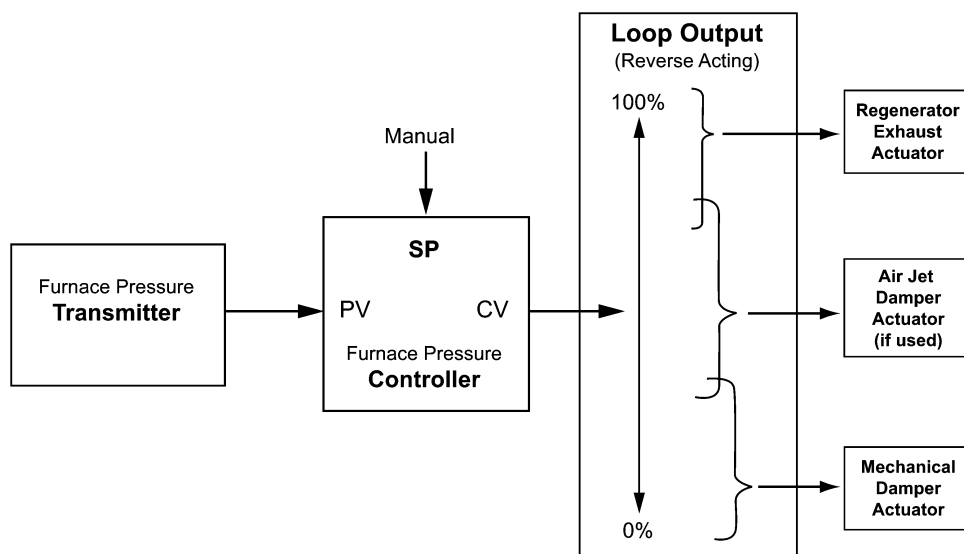


FIGURE 12.19 Regenerative burner furnace pressure control logic.

12.5.8 REGENERATOR SYSTEM REVERSALS

Regenerator reversals can be based on time, on exhaust temperature, or on a combination of both time and temperature.

Time-based systems work well for processes that are relatively steady-state — each burner in a pair fires and exhausts on a constant predetermined time base with each burner firing and exhausting for the same amount of time.

In temperature-based systems, the time one burner of a pair fires while the other burner is exhausting is determined by the temperature of the exhaust of the exhausting regenerator.

Time-and temperature-based systems switch at a predetermined exhaust temperature within a minimum and maximum exhaust time window, as shown in [Figure 12.20](#).

The optimal times and temperatures are determined are based on regenerator efficiency, process temperature, and flow through the regenerator. Additionally, the optimal temperature setting varies with sensor location and response time.

To minimize the furnace pressure spike during reversals, multi-pair systems can incorporate anti-coincidence logic to prevent more than one pair from reversing simultaneously.

12.5.9 REVERSING VALVE TYPES AND OPERATION

Listed and approved high-duty cycle safety shutoff valves are used to interrupt the flow path of the fuel to the burners. Each burner will have one or more of these valves based on local codes, insurance underwriter requirements, and regulatory standards. In general, the valves used for fuel reversal control cannot do double-duty as the burners' safety shutoff valves even if they are listed as safety shutoff valves.

Many of the early compact regenerative burner systems used a single actuator and a multi-port five-port spool valve to switch the air and exhaust flow paths for a pair of burners. In one position, it closed the exhaust flow and opened combustion airflow to the first burner in the pair as it opened the exhaust and closed the air to the second burner. The combustion air and exhaust flow paths could not get out of synchronization. It had the disadvantage that it would neither permit the burners to fire in the nonregenerative mode required by some processes, nor would it simultaneously shut off the air and exhaust flows of all the burners.

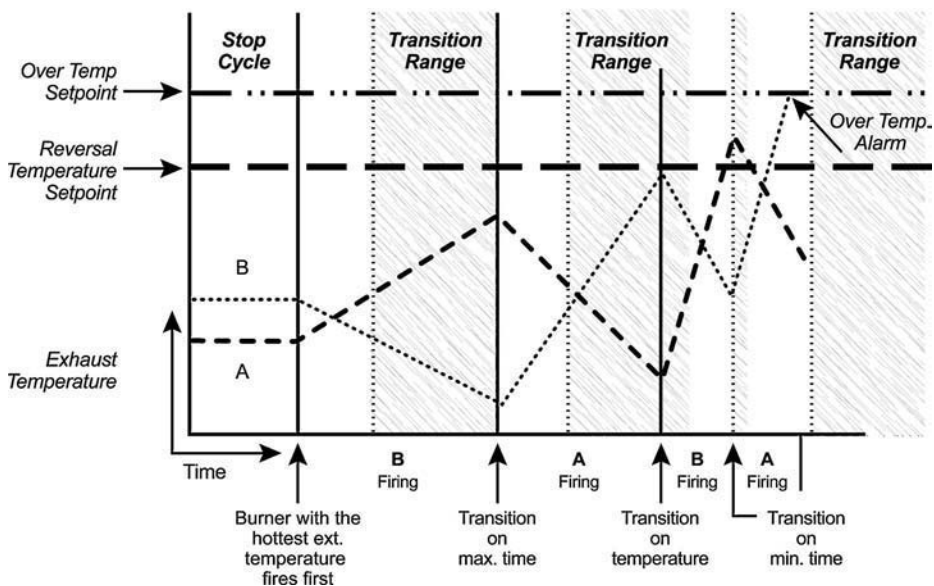


FIGURE 12.20 Combination time and temperature reversing sequence.

Most direct-fired (nonradiant tube) regenerative burner systems today use four valves per pair for the air and exhaust switching function. Each regenerator has a valve and actuator combination for each of the air and for the exhaust. This arrangement allows each burner in a pair to operate independently if required. A pair can be operated with one burner on, both on, or both off, in addition to running in the conventional reversing regenerative mode.

A burner firing as a cold air burner (i.e., firing in “direct mode”) can be used to continue heating the process in the event the other burner in the pair is inoperable or the exhaust system is down. Direct mode is commonly used, by design, at certain points in the normal operation of some heating processes; for example, in aluminum melters at times when they are producing particularly “dirty” flue products that could very rapidly plug the regenerators.

If a regenerator becomes plugged, a system with direct-mode capability will allow it to be cleaned or changed with the other burner in the pair still firing on cold air to maintain production.

Direct-mode firing of both burners in a pair can be used to “boost” the fuel input of a system during the early, cool stages of some batch processes to allow for faster building of a required heat head in the fired chamber.

Both burners off, all reversing valves closed, is used as a standard control mode to extend system input turndown, particularly for batch processes. Some systems that can benefit from the effect of high rates of POC recirculation in the fired chamber are operated in this essentially on/off mode, with pulse-width modulated input control superimposed upon the reversing controls.

12.5.10 REVERSAL VALVES SEQUENCING

When in the regenerative mode, most control systems sequence the simultaneous actuation of the air and exhaust reversing valves for each pair. Air is opened to one burner as it is closed to the other. At the same time, exhaust is closed to one as it is opened to the other. The fuel reversing valves are generally closed prior to the air and exhaust valve movement to provide a short, “post purge” of the firing burner. The fuel reversing valves are generally opened after the air and exhaust valves’ new positions are confirmed, providing safe operation and sufficient time for the airflow to pre-purge the regenerator on the burner about to be fired.

12.5.11 CONFIRMATION OF REVERSAL VALVE OPERATION

The control system should check the operation of all air, exhaust, and fuel valves used for reversing control to ensure they are in the proper position for the firing mode of the burner that they supply. This requires the air and exhaust valves to have position switches to indicate both the open and closed positions. The fuel valves require a switch to prove the closed position.

When a burner is to be firing, its air valve should be proven open and its exhaust valve proven closed. If the exhaust valve is not closed, some or all of the combustion air that is being metered by the fuel/air ratio control will bypass the regenerator directly to the exhaust system, causing the burner to be fuel-rich.

When a burner is to be exhausting, its exhaust valve should be proven open and its air and fuel valves closed. If the air valve is not closed, a portion of the combustion air that is being metered by the fuel/air ratio control will bypass the firing burner, causing the firing burner to be fuel-rich.

12.5.12 FLAME SUPERVISION AND REVERSALS

Note: This section is not intended to act as a specific guide to the use of flame supervision systems for regenerative or any other burners. The reader is referred to the applicable international, national, local, and insurance industry codes, standards, requirements, etc. for appropriate information on this subject.

Flame monitoring and the reversal sequence are handled in a variety of ways, depending on the design of the specific burner and the local code requirements. In the authors' company case, each burner of a pair has two UV flame detectors. One detector monitors the pilot and a separate detector monitors the main flame. The detector mounting locations are such that the main flame detector cannot sight the pilot flame under any conditions. The pilot is burning in all modes when its burner has permission to be fired. When a burner is actually to be firing, the flame detector for the main flame is active and the pilot detector is switched out of the monitoring circuit. Loss of the main flame will shut down the burner. When a burner is acting as the exhaust, the flame detector for the pilot is switched back into the monitoring circuit. Loss of the pilot flame while exhausting shuts down the burner. Loss of either flame as described requires resetting the flame monitoring system and restarting the burner in the same manner as with nonregenerative burners.

12.6 EMISSIONS

The primary products of combustion are carbon dioxide (CO_2), water vapor (H_2O), oxygen (O_2), and nitrogen (N_2). CO_2 reduction is being pursued in many countries because, although not harmful to human health, CO_2 is considered the most significant "greenhouse gas" due its abundance in the lower atmosphere. Trace species that are harmful pollutants include nitric oxide (NO), nitrogen dioxide (NO_2), carbon monoxide (CO), sulfur dioxide (SO_2), and particulates.¹² This discussion includes NO and NO_2 — collectively referred to as NO_x — and CO_2 as those most directly involved with use of regenerative burners. SO_2 is not discussed here, because it is most directly related to the use of heavy fuel oil, a fuel used by only a very small number of the world's regenerative burner installations.

12.6.1 CO_2 EMISSIONS

To deal with the easiest pollutant emission subject first, as stated above — CO_2 is considered the most significant "greenhouse gas" although it is not harmful to human health. The use of regenerative burners is extremely helpful in reducing CO_2 emissions. The amount of CO_2 produced is directly related to the amount of fuel burned in a process. The energy saved by the application of a regenerative burner system will produce a commensurate reduction in the amount of CO_2 emitted into the atmosphere. Given the significant energy reductions available from the use of regenerative burners in high-temperature processes, they may be regarded as a significant "green" product in the reduction of CO_2 .

12.6.2 NO_x EMISSIONS

When fossil fuels are burned using air as the oxidant source, virtually all the nitrogen contained in the air (approximately 79% by volume) goes through the process as an inert. However, under the extremely high temperatures experienced during combustion, a relatively small portion of nitrogen reacts with oxygen to form NO and NO₂. The very highly preheated air of a regenerative burner results in high peak flame temperatures and leads to potentially high NO_x emissions.¹²

12.6.3 NO_x REDUCTION METHODS FOR REGENERATIVE BURNERS

To reduce the primary cause of NO_x emissions with regenerative burners — the high peak flame temperatures — NO_x reduction methods employ various techniques to reduce the reaction rate between the fuel and the highly preheated air, and/or reduce its temperature.

Flue gas recirculation (FGR) is a common and fairly simple method of NO_x reduction. FGR is the process of returning a portion of the POC to the combustion zone, most commonly done by mixing with the combustion air supply to the burner. Other means of introducing POC are to mix with the fuel, add directly to the burner through a separate connection, or to use self-recirculated FGR where the energy in the flame front itself induces POC into the combustion zone. All methods using FGR, except the last one mentioned, have potential costs, such as additional piping, increased burner size, larger blowers to handle the extra volume or possibly an additional blower to transport the FGR, increased maintenance, and reduced efficiency. The quality of the FGR is also important; it should be of the lowest feasible oxygen content and, for systems using external piping and components, as clean as possible to prevent problems such as fouling and corrosion. Condensation of water is also possible if the FGR becomes cold.

Regenerative burners might be considered ideal candidates for the application of FGR for NO_x reduction. The exhaust gas at the outlet of the regenerators is cool FGR. The cool FGR available at the outlet of the exhaust fan can be led back to the burner, possibly via an additional FGR blower, and mixed with the combustion air. It can be mixed with the air at the inlet to the regenerator, likely requiring an increase in regenerator size to handle the increased volume without an excessive pressure requirement. In this case, however, all the FGR is heated as it passes through the regenerator with the combustion air and will thus place only a minimal system efficiency penalty on the use of FGR. Alternatively, the cool FGR can be fed directly to the hot air stream entering the burner. In this case, there will be no effect on the performance or the required size of the regenerator, but the cool FGR will have to be heated to furnace temperature, resulting in a larger loss in efficiency. A further means of introducing FGR is to mix it with the fuel entering the burner. This is an effective means of using FGR, requiring less FGR per unit NO_x reduction than addition to the air.

Air staging and fuel staging are other common methods of reducing NO_x emissions. Staging is performed by splitting one of the reactants — either the air or the fuel — into two or more separate streams. Part of one of the reactants is mixed and combusted with all of the other reactants in a primary zone. The remainder of the split reactant is then introduced downstream of the primary zone. The use of these methods requires complex burner structures to keep the various flows separated. Such structures may not be favored in the construction of regenerative burners that operate with very highly preheated air and must also be capable of handling the full-temperature exhaust gases from the furnace.

The NO_x reduction technique used with the regenerative burners of the authors' company is a dilute gas combustion scheme called "fuel direct injection" (FDI).^{13–15} It was developed by Tokyo Gas Co. in the late 1980s.

As the exclusive licensee, the authors' company has developed and widely applied low-NO_x regenerative burners based on this technology. Known as the Low-NO_x Injection (LNI) technique, it has been used in the aluminum, steel, and glass industries and has demonstrated outstanding low-NO_x performance.¹⁶ An LNI-equipped regenerative burner operates as a conventional nozzle-mixing regenerative burner when the furnace temperature is below 1450°F. Above 1450°F, fuel is switched

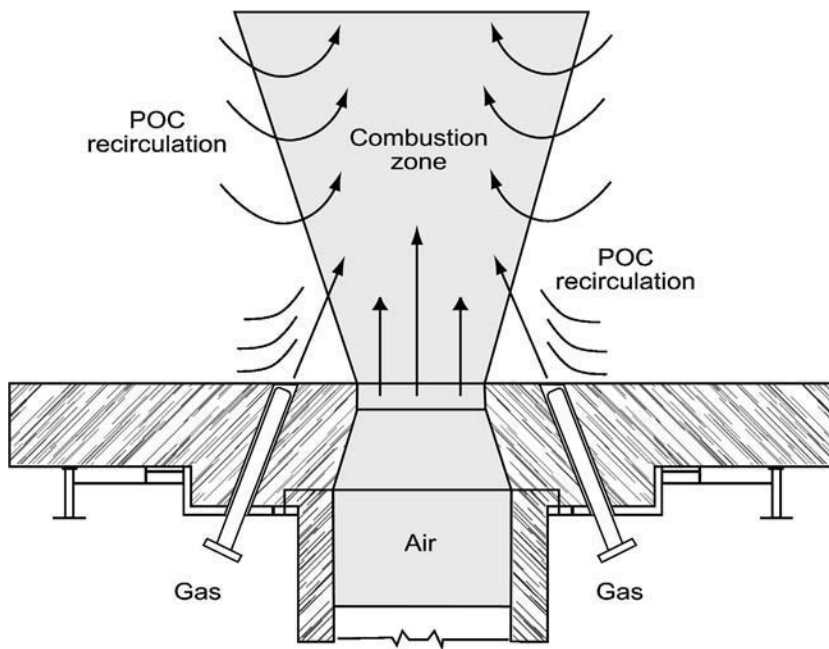


FIGURE 12.21 LNI burner arrangement.

to one or more strategically positioned nozzles adjacent to the burner tile port. These injectors are displaced from the burner tile exit inside the furnace (Figure 12.21). Fuel and preheated air streams mix thoroughly with furnace gases, becoming extremely dilute before combining in front of the burner tile. The dilute gas streams auto-ignite and achieve complete combustion within the furnace environment. In the flame envelope, entrained gases limit maximum in-flame combustion temperatures that generate high NO_x emissions.

The low NO_x emissions realized using the LNI technique are displayed in Figure 12.22, where NO_x emissions are presented for a conventionally fired nozzle-mix regenerative burner vs. LNI firing, for natural gas and fuel oil.

12.7 SOME REGENERATIVE BURNER APPLICATIONS

12.7.1 WELL-CHARGED ALUMINUM MELTER

This furnace was converted from conventional cold-air burners to regenerative burners using LNI technology with the aim of reducing the specific fuel consumption and at the same time providing the low emissions mandated for the Los Angeles area.

Originally fired with 41 MMBtu/hr through three high-velocity burners, the new installation comprised one pair of regenerative burners with an input capacity of 25 MMBtu/hr. A plan view of the furnace is shown in Figure 12.23.

With an operating roof temperature setpoint of 2075°F and a bath setpoint temperature of 1350°F, the target melt rate was 12500 lb/hr with a charge of 70% continuously fed used beverage cans, 30% sow and coil. The target-specific fuel consumption was 1050 Btu/lb of aluminum, and NO_x emissions of 58 ppm, corrected to 3% oxygen. The required average air preheat level for the regenerative burners in this installation would be above 1590°F in order to attain the desired melt rate and commensurate fuel input rate.

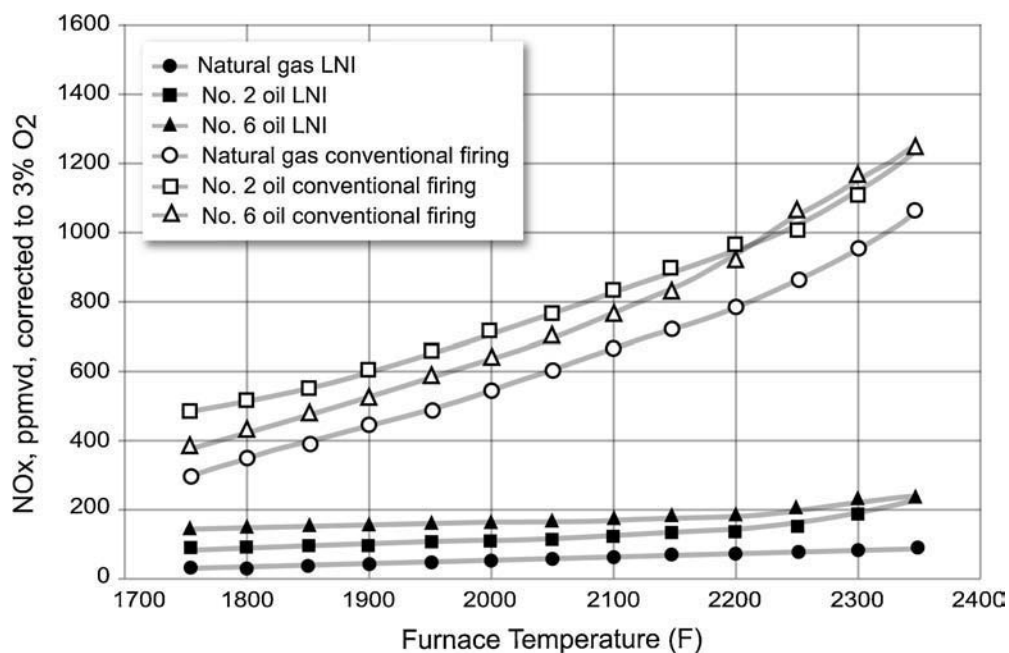


FIGURE 12.22 LNI regenerative burner NOx performance.

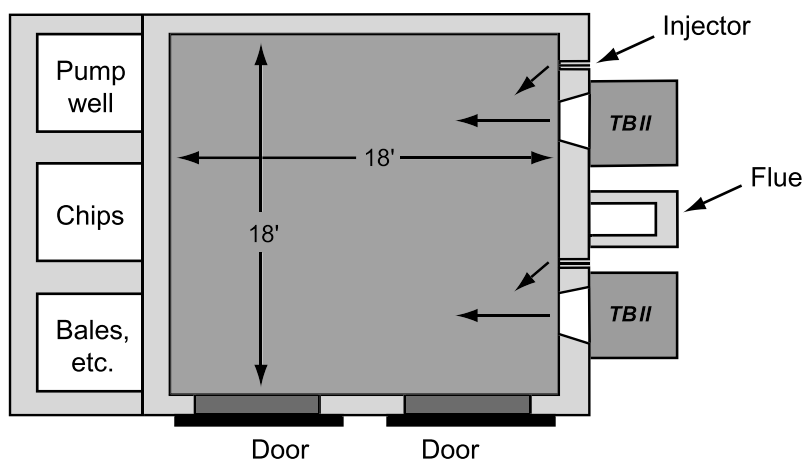


FIGURE 12.23 Plan view of well-charged aluminum melting furnace.

NO_x and specific fuel consumption targets were both met with this arrangement, and a successful compliance test completed. Table 12.2 shows a side-by-side comparison of before and after the conversion to the regenerative system.

12.7.2 DIRECT-CHARGED ALUMINUM MELTER

The furnace shown in Figure 12.24 is a direct-charged rectangular tilting aluminum melter with a capacity of 66,150 lb and a melt rate of 22,050 lb/hr. The unit is charged with 70% extrusion scrap and 30% ingot. The basic internal furnace dimensions are 24.7 ft wide $\times$ 16.9 ft deep $\times$ 5.4 ft from top of bath to roof.

TABLE 12.2
Before and After Comparison of Regenerative Conversion

Parameter	Cold Air System	Regenerative System
Combustion air temperature	Ambient	1620°F average
Available heat	41%	71%
Specific fuel consumption	1960 Btu/lb	1050 Btu/lb
NOx emissions	60 ppmvd @ 3% O ₂	58 ppmvd @ 3% O ₂
NOx emissions per ton aluminum	0.28 lb	0.15 lb
CO ₂ emissions per ton aluminum	494 lb	265 lb

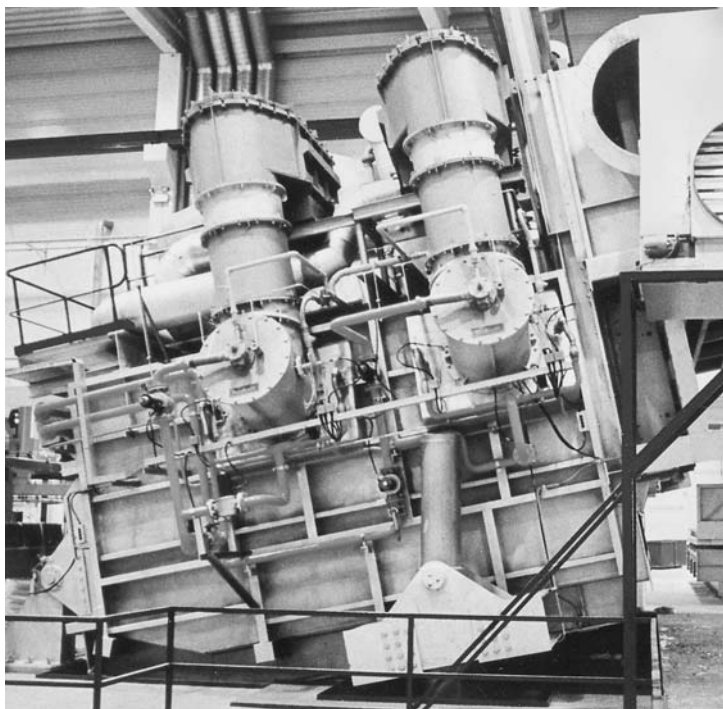


FIGURE 12.24 Tilting aluminum melter.

The furnace is fired with two pairs of regenerative burners, one pair mounted on each 17-ft wall, with burners angled downward to the bath surface at 15°. Each burner pair is rated at a capacity of 13 MMBtu/hr.

The nominal furnace operating temperature is 1700°F and the specified NOx target was a generous 225 ppm, corrected to 3% oxygen. The actual emissions performance was measured at 55 ppm NOx, with 51 ppm CO (both corrected to 3% oxygen).

Table 12.3 shows comparative data from three similar furnaces by the same manufacturer:¹⁷ one cold air, one low-NOx recuperative with 750°F preheated combustion air, and the subject regenerative furnace (average, 1395°F preheated combustion air). It can be seen from Table 12.3 that furnaces equipped with low-NOx regenerative burners can produce NOx levels similar to ambient air burners.

TABLE 12.3
Comparative Emissions Data for Three Similar Aluminum Melters

Burner Type	Flue Gas Temp. (°F)	NOx (ppmv @ 3% O ₂)	CO (ppmv @ 3% O ₂)
Cold Air	1670	66	401
Recuperative	1650	143	401
Regenerative	1680	55	51

TABLE 12.4
Efficiency and Emissions Data Summary for Three Similar Aluminum Melters

Burner Type	Energy Consumption (Btu/lb of aluminum)	NOx (lb NOx/ton of aluminum melted)
Cold Air	1305	0.2
Recuperative	1045	0.36
Regenerative	835	0.11

However, the energy efficiency of the ambient air burner system is low compared with the regenerative system. To compensate for this, more fuel is consumed but still producing the same volumetric value of NOx. When the amount of NOx generated per pound of aluminum melted is computed, it can be seen that the regenerative system, even with its high-temperature combustion air, produces less NOx for the operation of the furnace. The results are tabulated in [Table 12.4](#).

12.7.3 STEEL REHEAT FURNACE APPLICATIONS

Steel reheat furnaces can be an excellent platform for regenerative burners as they operate at high temperatures and allow the opportunity to achieve substantial fuel savings.

The highly effective heat exchange capability (low final exhaust temperatures) of regenerative burners allows them to be located right up to the charge door of a pre-heat zone, eliminating the traditional unfired section and thus saving construction cost in a new furnace designed for their use. An existing furnace can have regenerative burners added in its unfired front section to increase production capability without suffering any significant decrease in efficiency, and sometimes even allowing a slight gain.

12.7.3.1 New Reheat Furnace Designed for Regenerative Firing

The four-zone steel reheat furnace shown in [Figure 12.25](#) and Figure 12.26 was specifically designed to be fired using regenerative burners. Furnace heating curves were developed to calculate the overall length of 52.5 ft and width of 28 ft, and to determine the zone lengths and heat inputs. The Top and Bottom Preheat zones are each fired with a design input of 57.6 MMBtu/hr. The Top fired Heat zone has a design input of 18 MMBtu/hr and the soak zone 16 MMBtu/hr. The furnace that it replaced had a specific fuel consumption of 2.11 MMBtu/ton. The regenerative furnace operates at an average of 1.15 MMBtu/ton. A fuel efficiency of 78% was been achieved heating 121 tons/hr to a temperature of 2150°F with a uniformity of $\pm 25^\circ\text{F}$.

12.7.3.2 Addition of Booster Zone to Existing Furnace

As previously mentioned, regenerative burners can be added to existing furnaces to increase production. The walking beam furnace shown in [Figure 12.27](#) was purchased for a production rate of 73 tons/hr of 4.5 in. $\times$ 4.5 in. $\times$ 24 ft long billets using hot-air flat-flame burners. The objective of

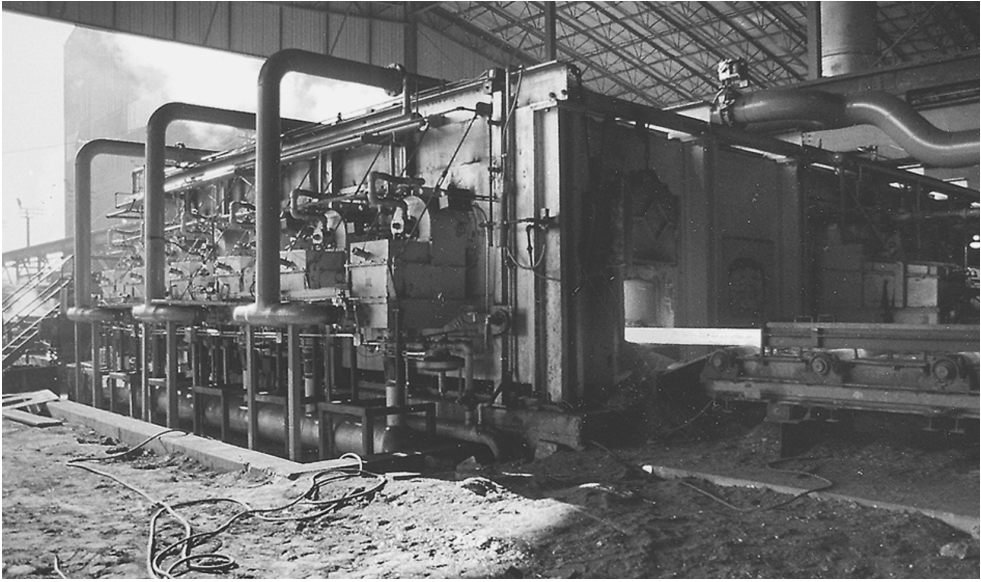


FIGURE 12.25 A 52.5-ft steel reheat furnace.

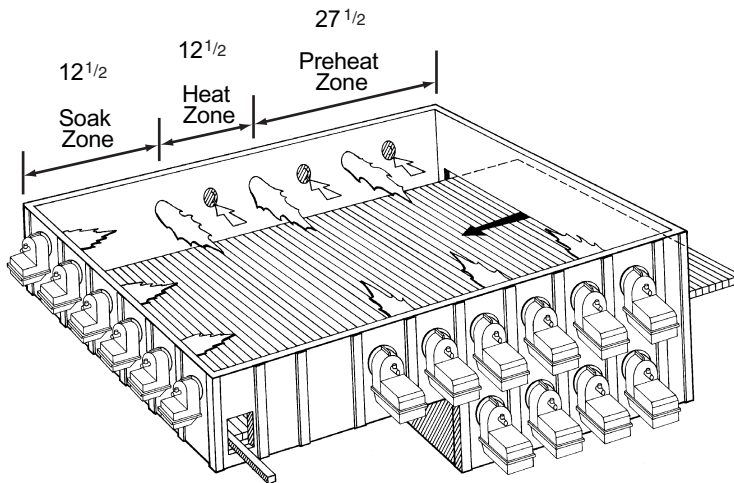


FIGURE 12.26 Model of 52.5-ft steel reheat furnace.

adding four pairs of regenerative burners to the furnace was to increase the production rate to at least 80 tons/hr.

The pre-conversion specific fuel consumption of the furnace was 1.3 MMBtu/ton. With the regenerative burners, production capacity was increased to 92 tons/hr and the specific fuel consumption reduced to 1.1 MMBtu/ton.

12.7.3.3 Addition of Booster Zone to Existing Furnace

A further example of adding regenerative burners to an unfired section is the addition of a pair of heavy fuel oil-fired compact regenerative burners to the front end of the first heating zone of a 30-year-old, three-zone walking hearth reheating furnace in order to increase the production rate

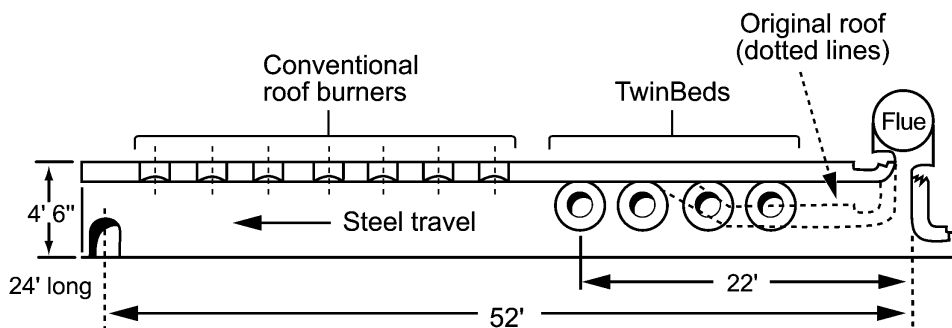


FIGURE 12.27 Addition of booster zone to walking beam furnace.

reported by Nordell and Fredriksson.¹⁸ The addition of regenerative burners was chosen as the existing recuperator was already operating at its maximum capability and could not accept additional hot flue gases from conventional burners. From this, the desired production capacity of 72 ton/hr, from 66 ton/hr, was achieved.

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