FURNACES, FUEL-FIRED

1. Introduction

A furnace is a device (enclosure) for generating controlled heat with the objective of performing work. In fossil-fuel furnaces, the work application may be direct (eg, rotary kilns) or indirect (eg, plants for electric power generation). The furnace chamber is either cooled (waterwall enclosure) or not cooled (refractory lining). In this article, furnaces related to metallurgy such as blast furnaces are excluded because they are covered under associated topics (see IRON; COMBUSTION TECHNOLOGY; COAL; FURNACES, ELECTRIC).

Among the technologies in existence by ~4000 BC, which included the manufacture of synthetic lapis lazuli, the development of the first true pottery kilns must rate as a significant achievement (1). For polychrome pottery to be successfully manufactured, it was essential to separate the fire (fuel) from the work (clay pottery). The excavations performed in the near east (Mesopotamia in antiquity) indicate that these early kilns were probably of beehive construction. Subsequent Egyptian pottery kilns of the period ~3000 BC were the familiar chimney shape. With the smelting of copper in pit hearths predating by perhaps a millenium the start of the Bronze Age at ~3000 BC, another important advance was the invention of the bellows at ~2000 BC. Bellows supply combustion air where it is needed and are used as a means of raising furnace temperature.

Waterwall furnaces were employed by the ancient Greeks and Romans for household services. A water boiler, found in Pompeii, was constructed of cast bronze and incorporated the water-tube principle (2). The earliest recorded instance of boilers performing mechanical work (130 BC) was Hero's engine, (3), which is the earliest known reaction turbine. Furnaces, in general, and waterwall furnaces, in particular, were neglected for about the next 1600 years. In part, this may be ascribed to the fact that steam as a working fluid had no application until the invention of the first commercially successful steam engine at the end of the seventeenth century, followed by Newcomen's engine in 1705 with self-regulating steam valves. These machines were generally used for pumping water from coal mines (2). Their sequence furnace-boiler-work foreshadowed the eventual emergence of the utility power plant which, in essence, is the same concept.

In fire-tube furnaces developed in the nineteenth century, such as typified by the Scotch-Marine boiler (Fig. 1), thin currents of water contact a multiplicity of tubes; thus, the hot gases transmit heat simultaneously to all regions of the bulk of the water. Therefore, this boiler–furnace combination steams readily

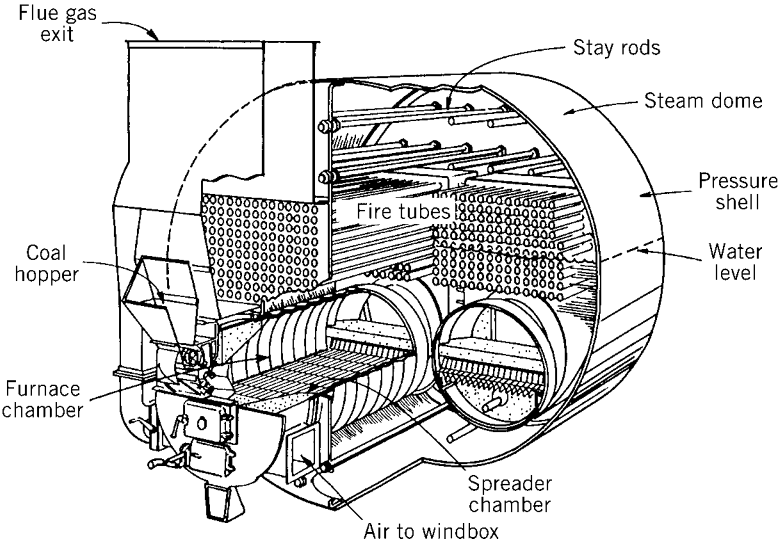

Fig. 1. Scotch-Marine boiler, ~1930.

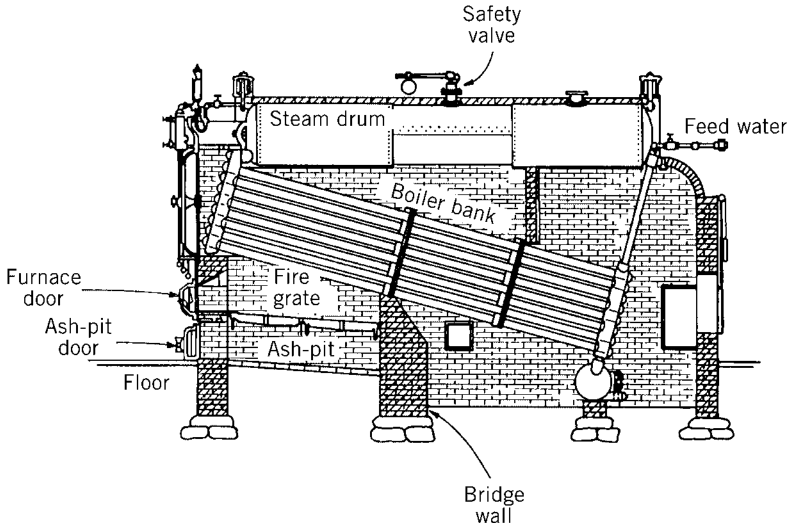

Fig. 2. Early Babcock and Wilcox boiler, 1877.

and responds promptly to load changes, and is, for a given amount of heating surface, the least expensive of all furnace–boiler installations (4). Furnaces of this type, such as the steam locomotive furnace–boiler design, had the obvious disadvantage that pressure was limited to ~1 MPa (150 psi). The development of seamless, thick-wall tubing for stationary power plants (ie, water-tube furnaces) and other engines for motive power, such as diesel–electric, has in many cases eclipsed the fire-tube boiler. For applications calling for moderate amounts of lower pressure steam, however, the modern fire-tube boiler continues to be the indicated choice (5).

A key development in water-tube furnace design was the Babcock and Wilcox boiler of 1877 (Fig. 2) (3). This can be considered the direct evolutionary ancestor of the 1000 MW steam power plants a century later (see STEAM).

2. Classification

Furnaces are either cooled (water- or air-cooled chamber) or not cooled (refractory-lined chamber). In general, the basic structure roughly resembles either a rectangular box or a cylinder with variations for generally good reasons (6). For example, if the material being processed is a liquid, the furnace bottom must provide a bath. Hence, the open-hearth furnace is used for steel melting and refining, the reverbatory furnace for copper, and glass tanks for various materials. If the material tends to be lumpy, as in smelting, cupola melting, or lime burning, the furnace is constructed vertically to make gravity feeding possible.

The roof of the typical furnace collapses unless it is built as a sprung or self-supporting arch, or is flat but suspended, along with the rest of the furnace, from an enclosing structural framework. All modern power-plant waterwall furnaces of any significant megawatt rating are of suspended construction.

If a refractory-wall furnace is very large, the walls must be relatively thick to provide the necessary structural strength required to withstand the weight of the roof and thermal stresses as well as to retain heat. Large furnaces are built with two or even three different types of brick, with the outer brick generally the more highly insulating and the inside brick able to withstand the highest temperatures. The middle bricks are, therefore, often of lower quality and carefully selected since their softening temperature must not be exceeded.

Wall losses through most refractory walls are ~10% of the heat supplied by the fuel. Losses increase with rising operating temperature. In special cases, eg, in glass tanks, losses can be as high as 30–35%. In these instances, very high values are required to maintain the refractory at a temperature below which it does not melt or collapse.

A furnace may be direct-fired or indirect-fired. The indirect-fired is known as a muffle furnace, and in such furnaces the combustion gases are separated from the stock being heated to prevent contamination.

3. Fuels

Fuel-fired furnaces primarily utilize carbonaceous or hydrocarbon fuels. Since the purpose of a furnace is to generate heat for some useful application, flame temperature and heat transfer are important aspects of furnace design. Heat transfer is impacted by the flame emissivity. A high emissivity means strong radiation to the walls.

The carbon/hydrogen ratio of fuels is a variable used widely in fuel technology to estimate emissivity as shown in Figure 3. However, its effect on flame

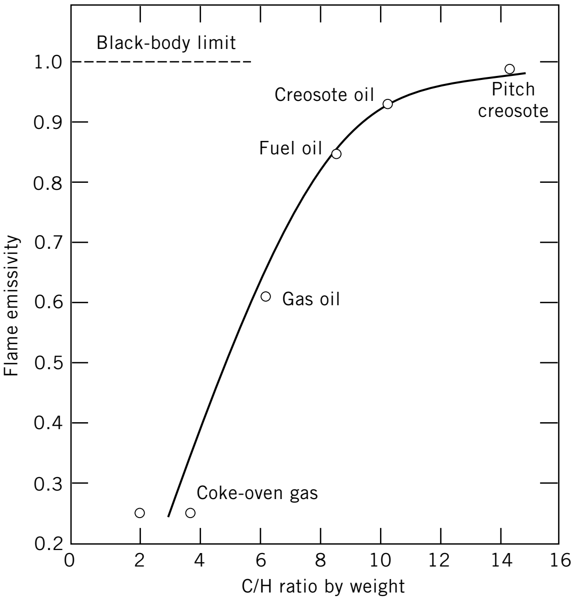

Fig. 3. Influence of C/H ratio on flame emissivity.

Table 1. **Theoretical Air Requirement for Stoichiometric Combustion**

Fuel	Air (dry), wt/wt fuel
gas	
blast furnace	1.54
average natural	15.86
coke oven	11.36
oil, bunker C	13.83
coal	
coke by-product	10.03
anthracite	10.64
bituminous, Eastern low vol	10.80
bituminous, Eastern high vol	10.38
bituminous, Midwest	8.54
subbituminous, Wyo.	7.03
lignite, N. Dak.	5.33
wood	
30% moisture	4.06
50% moisture	2.90
bagasse, 50% moisture	2.61

temperature is usually misrepresented (7). The adiabatic flame temperature, T_{ad}, is the theoretical maximum flame temperature. It is commonly believed that flame temperature is a significant function of heat of combustion. This is only true at very low values of heat of combustion, below ~13.9 MJ/kg (6000 Btu/lb), because the largest weight of material moving through most furnaces is atmospheric nitrogen (7). This usually outweighs the contribution from the fuel by 10 to 1 or more (Table 1). Coupled with a statistical requirement of roughly 0.0283 m^3 (1 ft^3) of cold air for every 105 kJ (100 Btu) released, fossil-fuel combustion is roughly equivalent to a release of 3.7 MJ/m^3 (100 Btu/ft^3) of combustion mixture at STP [or 5.4 MJ/m^3 (145 Btu/ft^3) for the combustion of CO and H_2]. Consequently, most adiabatic flame temperatures are $\sim 2000 \pm 100°C$ (6). This temperature holds for the heat of combustion range of ~14–140 MJ/kg (6000–60,000 Btu/lb). The range includes CO and H_2 although they are not strictly fossil fuels.

Figure 4 illustrates the trend in adiabatic flame temperatures with heat of combustion as described. Also indicated is the consequence of another statistical result, ie, flames extinguish at a roughly common low limit (1200°C). This corresponds to heat-release density of ~1.9 MJ/m^3 (50 Btu/ft^3) of fuel–air mixtures, or one-half that for the stoichiometric ratio. It also corresponds to flame temperature, as indicated, of ~1220°C. Because these are statistical quantities, the same numerical values of flame temperature, low limit excess air, etc, can be expected to apply to coal–air mixtures and to fuels derived from coal (see FUELS, SYNTHETIC).

The insensitivity of adiabatic flame temperature to heat of combustion does not necessarily apply to the operational flame temperature, T_o, which is the flame temperature found in an actual furnace (remembering that this refers to some average temperature). The higher excess air requirements at higher C/H

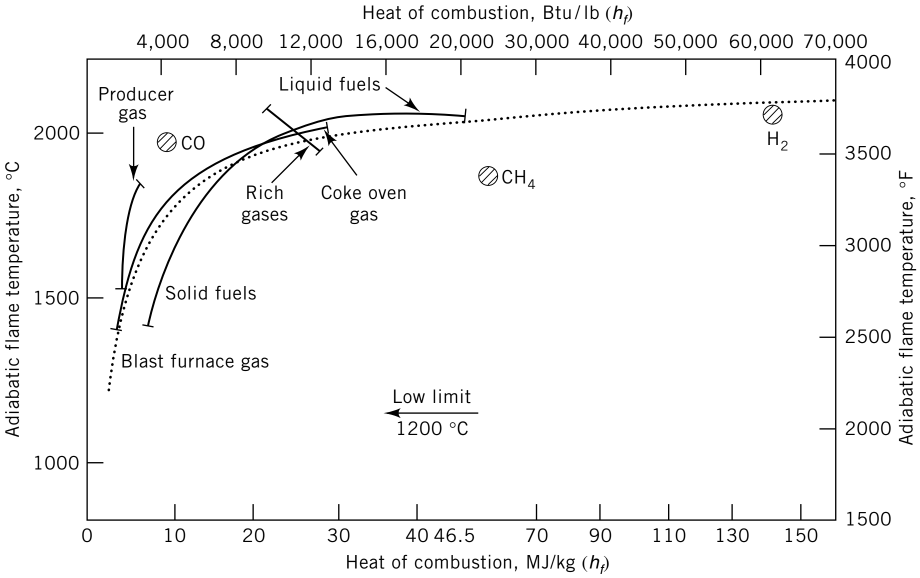

Fig. 4. Variation of adiabatic flame temperature with heat of combustion where $T_{\mathrm{ad}} = T_{\mathrm{o}} + 2083/1 + 1.7/h_f$ (°C). Note change of scale at 46.5 MJ/kg (20,000 Btu/lb).

ratios coupled with greater thermal loads on longer flames generally results in markedly lower operational temperatures as the C/H ratio increases.

The fuels listed in Table 2 are generally representative of fuels to be encountered over the range of industrial furnaces and, depending on the type (cooled or refractory wall), exhibit operating temperatures considerably different from adiabatic values. The choice of fuel is dependent on a number of factors including cost, availability, cleanliness, emissions, reliability, and operations. Small furnaces tend to burn cleaner, easier to use fuels. Large furnaces can more effectively use coal, or other solid fuels.

The transition from a choice of multiple fossil fuels to various ranks of coal, with the subbituminous varieties a common choice, does in effect entail a fuel-dependent size aspect in furnace design. A controlling factor of furnace design is the ash content and composition of the coal. If wall deposition thereof (slagging) is not properly allowed for or controlled, the furnace may not perform as predicted. Furnace size varies with the ash content and composition of the coals used. The ash composition for various coals of industrial importance is shown in Table 3.

4. Power-Plant Furnaces

In 2000, 71% of the electric power consumed in the United States was generated by fossil fuel combustion. This situation is expected to continue for some time, in spite of the efforts directed at renewable energy. The bulk of electric power

Table 2. **Fuel Analyses, Wt%**^{a}

Fuel	Carbon	Hydrogen	Sulfur	Nitrogen	Oxygen	Ash	Moisture	HHV,^{a} MJ/kg^b
gas								
blast furnace	15.86	0.20		53.97	28.91		1.06	2.62
natural	69.20	23.09	0.35	5.81	1.55			51.02
coke oven	48.62	20.03		4.91	26.44			39.95
oil (fuel)	85.5	11.5	1.6	0.7	0.7			43.03
coal								
coke by-product	85.0	0.7	1.0	1.3	0.5	10.7	0.8	29.51
anthracite	83.9	2.9	0.7	1.3	0.7	8.0	2.5	31.91
bituminous, low vol	80.7	4.5	1.8	1.1	2.4	6.2	3.3	33.28
bituminous, high vol A	76.6	4.9	1.3	1.6	3.9	9.1	2.6	31.65
bituminous, high vol B	67.6	4.3	1.8	1.4	5.4	13.5	6.0	28.37
bituminous, Midwest	63.4	4.3	2.3	1.3	7.6	8.7	12.4	26.56
bituminous, West	66.7	5.2	0.5	1.2	9.7	8.7	8.0	27.91
subbituminous A	60.6	4.6	0.5	1.3	13.3	7.3	12.4	24.65
subbituminous B	54.6	3.8	0.4	1.0	13.2	3.8	23.2	21.91
subbituminous C	47.3	3.3	0.7	0.6	12.1	9.5	26.5	19.12
lignite, N. Dak.	42.4	2.8	0.7	0.7	12.4	6.2	34.8	16.77
lignite, Tex.	41.0	3.1	0.7	0.7	12.3	9.9	32.2	16.86
wood								
30% moisture	34.3	4.2			30.8	0.7	30.0	15.39
50% moisture	24.5	3.0			22.0	0.5	50.0	11.00
bagasse	22.5	3.0			23.5	1.0	50.0	9.76

[a] High heating value (HHV).
[b] To convert MJ/kg to Btu/lb, multiply by 430.

Table 3. **Ash Properties of Typical Coals**

Property	Eastern bituminous	Midwest bituminous	Western subbituminous	N. Dak lignite
	Ash composition, wt%			
acid SiO_2	44.8	44.7	33.5	13.8
acid Al_2O_3	28.0	18.4	18.0	10.7
base Fe_2O_3	17.8	18.3	7.3	8.4
base CaO	2.0	5.3	18.4	24.2
base MgO	0.6	1.1	4.7	7.6
base Na_2O	0.3	1.8	0.2	9.0
base K_2O	1.7	2.1	0.2	0.4
acid TiO_2	1.4	0.8	0.7	0.4
acid P_2O_5	0.3	0.2	0.2	0.6
acid SO_3	0.8	5.8	15.3	20.3
other	2.3	1.5	1.5	4.6
base/acid ratio	0.30	0.45	0.59	2.0
Fe_2O_3/CaO ratio	8.9	3.5	0.4	0.35
	Ash fusibility temperatures, °C			
initial deformation	1210	1120	1130	1130
softening	1350	1150	1200	1200
fluid	1420	1240	1270	1350

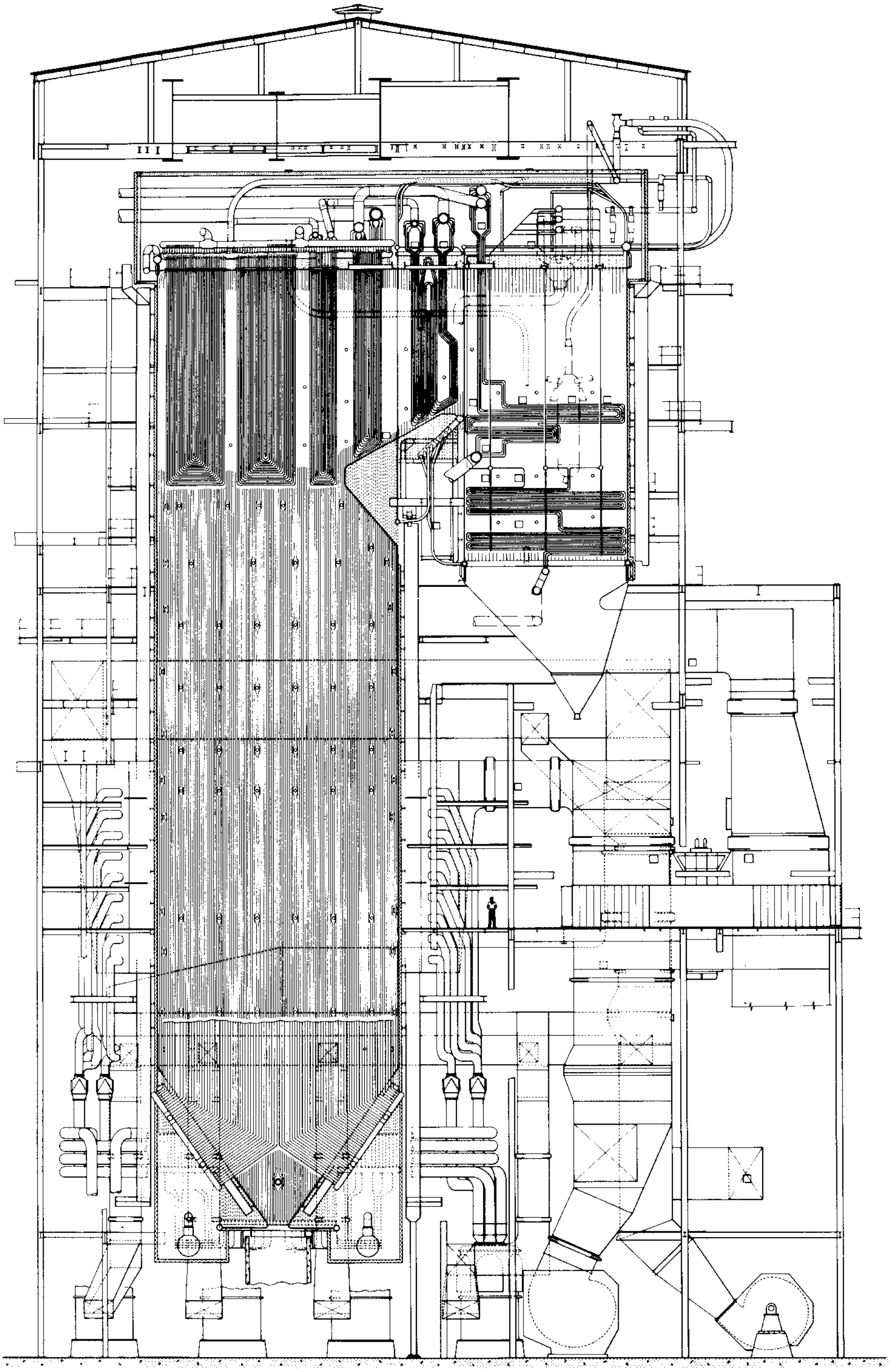

Fig. 5. Martin Lake unit of Texas Utilities Services, Inc., 750 MW; a representative of modern supercritical design. Courtesy of Combustion Engineering, Inc.

generation will probably be supplied by coal-fired power-plant furnaces supplying steam to turbogenerators. In terms of megawatts supplied, the coal-fired power plant is, therefore, the foremost component of importance in the energy supply system. Power-plant furnaces are of waterwall type and are generally designed for steam pressures in the range of 12.4–24.1 MPa (1800–3500 psi); the latter value is referred to as supercritical, ie, >22.1 MPa abs (3208 psia).

An example of a modern, tangentially fired, supercritical, lignite-fuel furnace is shown in Figure 5. This unit, at maximum continuous ratings, supplies 2450 metric tons per hour superheat steam at 26.6 MPa (3850 psi) and 544°C, and 2160 t/h reheat steam at 5.32 MPa (772 psi) and 541°C. These are the values at the superheater and reheater outlet, respectively. Supercritical fluid-pressure installations are, however, only rarely needed. Most power plants operate at subcritical pressures in the range of 12.4–19.3 MPa (1800–2800 psi).

Although furnace sizes (dimensions for a given MW production) do not vary too widely between principal manufacturers, the type of firing employed by each is generally quite distinctive. This finding indicates that the furnace size is not strongly controlled by the type of firing system, particularly for pulverized-coal firing (8) [70% through 74-μm (200 mesh) screen for a mean size of ∼40–50 μm]. The furnace needs to be sufficiently large to permit the oxygen enough time to penetrate (diffuse through) the blanketing CO_2 layer evolving from the burning coal particle. The residual ash particles are, of course, considerably smaller than the parent coal particle, on the order of a mean size of ∼10 μm before postcombustion agglomeration. Although flame temperatures should be high for combustion efficiency in order to minimize CO formation and combustible carbon loss, it is further required that the combustion products (gases) are sufficiently cooled to

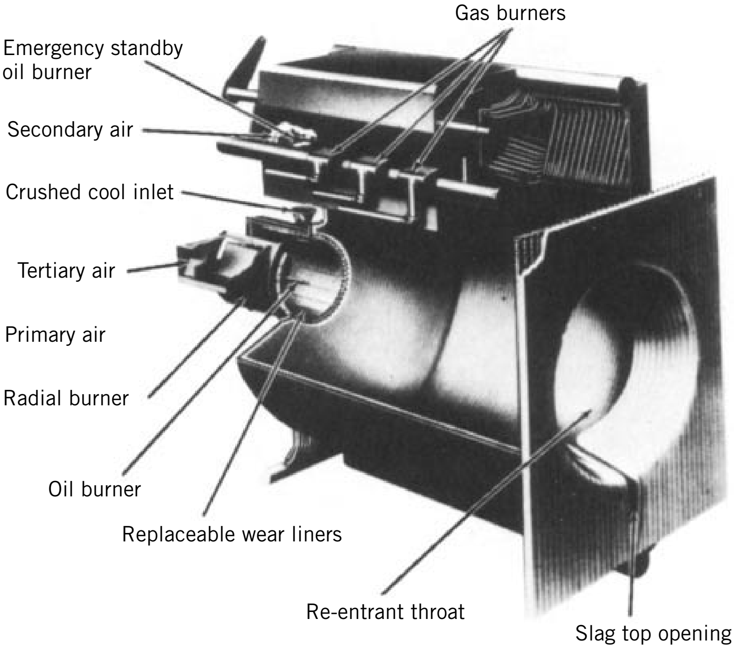

Fig. 6. Cyclone furnace: In effect a high temperature, slag removal combustion chamber auxiliary to the gas-cooling boiler furnace. Courtesy of Babcock & Wilcox, Inc.

enter the convection banks below the temperature at which slagging occurs. These contradictory conditions (aside from pollution control requirements) influence the furnace size and have led to solutions such as tangential firing. Other solutions include front wall, opposed wall, cyclone, and down fired units (Fig. 6).

5. Industrial Furnaces

Generally speaking, industrial furnaces are an order of magnitude smaller than power-plant furnaces since the applications are usually on an individual basis (hospital complex, chemical plant, paper mill, etc) rather than feeding power to a regional electric grid (4). Like the power-plant furnace, the function of the industrial furnace usually is to generate steam, generally for a chemical process, mechanical power, or heating application, rather than electric power generation. There are also many fired heaters that utilize the hot exhaust gases directly for heating, drying, roasting, calcining, etc.

These boilers are also known as shop-assembled boilers. Low capacity units are shipped complete with fuel-burning equipment, safety and combustion controls, and boiler trim. Large capacity units, because of tunnel and overpass shipping clearances and railroad flatcar limitations, are designed as multiple integrated-component packages such as the complete furnace–burner assembly, forced-draft fan assembly, and the like. In this category of steam generators, the fire-tube furnace competes with waterwall furnaces, particularly for duty in the capacity range of 205 kPa–1.8 MPa (15–250 psig) and 1800–9100 kg steam/h. Figure 7 shows a modern fire-tube furnace of four-pass design. Like the

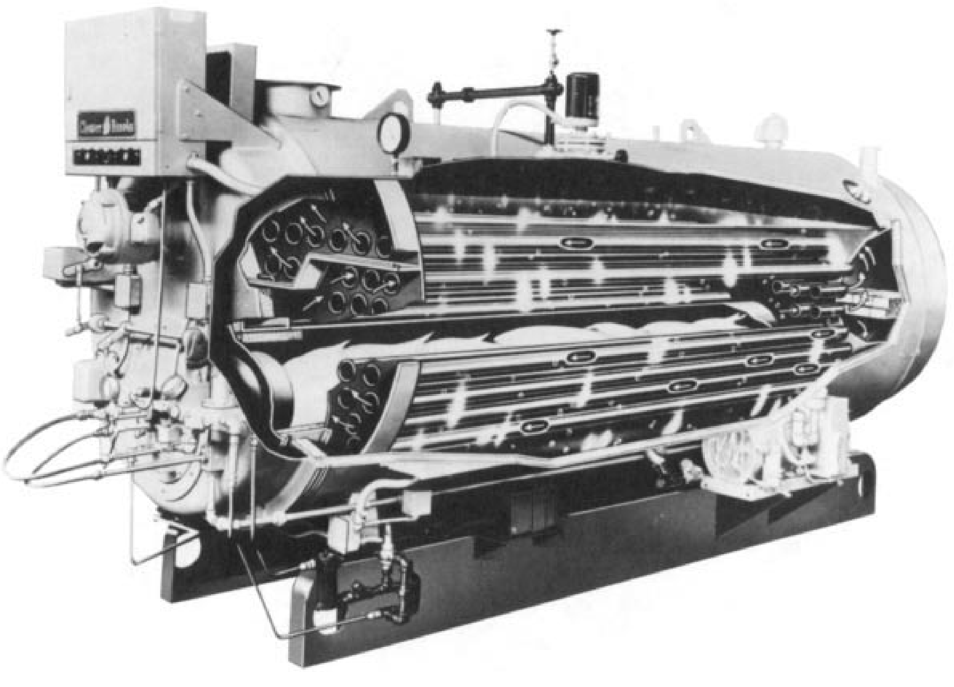

Fig. 7. Four-pass fire-tube boiler. Courtesy of Cleaver Brooks.

fire-tube furnace, the waterwall package furnace, because of the temperature quenching effect of the immediate proximity of the cold sink (steam and water), requires a long flame path (ie, residence time) to permit the combustion reaction to go to completion.

The conversion of wood chips into cellulose and lignins by chemical pulping requires considerable amounts of steam. Paper is made from the cellulose fibers, which amount to ~50% of the decomposition products, with the remainder (including bark) being burned to generate the process steam (see PULP). In terms of power generated, the paper industry ranks second (after electric utilities), all of the generated power being consumed in-plant. The pulp is produced by either the kraft or the soda process. The main chemical constituent is sodium sulfate (kraft process, on the order of 80% of the production) with the sodium carbonate process (soda ash) roughly accounting for the remaining production. In the kraft process, wood chips are cooked under pressure (by steam heating) in an aqueous solution of NaOH and Na_2S, known as white liquor. In this operation, the lignin binder is dissolved, freeing the cellulose fibers. The spent cooking liquor (containing the lignin), called black liquor, is successively steam and stack-gas dried for concentration; sodium sulfate, Na_2SO_4, is added to make up chemical losses. The main function of the recovery furnace is to reduce the sodium sulfate content of the black liquor to sodium sulfide, Na_2S. The heat obtained from the combustion of the organic black liquor constituent as well as from the supplementary fuel produce steam and molten smelt, largely composed of Na_2CO_3 and Na_2S. It is tapped from the furnace bottom and dissolved in water to form green liquor for further processing. In the recovery furnace shown in Figure 8, liquor spray nozzles are used to inject the heavy black liquor into the furnace of the recovery unit.

The burning of the ligneous portion of the black liquor produces sufficient heat in the furnace to sustain flash drying of residual moisture, salt-cake reduction, and chemical smelting. The heat in the gas passing through the furnace, boiler, and economizer produces steam for power and process.

In contrast to the shop-assembled waterwall furnace (package boilers), the large industrial furnaces are erected on site. Steam capacities are in the range of 45–450 t of superheated steam/h and generally serve industries such as steel, oil refining, automotive, sugar, and chemical. In distinction to the power-plant utility furnace, the industrial furnace is of considerably smaller capacity and is likely to be of modular design and operationally flexible. It generally is designed to burn two or more fuels of the industrial range comprised of coal, oil, gas, refuse, wood products, bagasse, sewage sludge, and other solid, liquid, or gaseous waste products. Consequently, the furnace is often equipped with several firing methods in order to accommodate different fuels. For example, it may be arranged for tangential, horizontal, or stoker firing of single or multiple fuels.

Many types of refractory-wall furnaces are used for melting or heat treatment of metals, at temperatures ranging from less than 540°C to as high as 1760°C, such as ceramic and glass kilns and furnaces, ovens and dryers operating from 50 to 600°C, and stills and retorts (7) (see CLAYS). Heaters can be directly fired when the products of combustion do not seriously affect the process stream (see PETROLEUM). Indirect heaters use heat exchangers to transfer heat to the process medium. Incinerators are special furnaces designed to consume waste

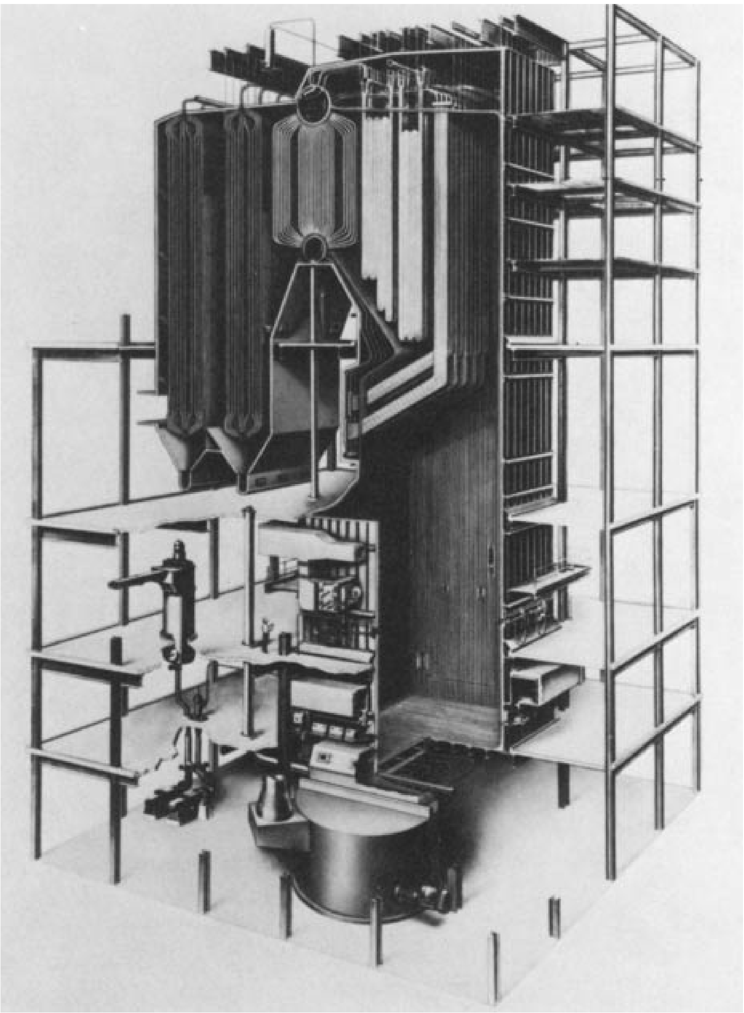

Fig. 8. Black liquor recovery furnace. Courtesy of Combustion Engineering, Inc.

products that must be disposed of without creating pollution problems. Trash or solid waste incinerators usually employ a grate or rotating kiln to accomplish mixing of the air with the waste for combustion.

These furnaces may operate batchwise or continuous. In the batch, intermittent, or periodic types, the content is heated at the desired temperature for the stipulated time and then removed. In the continuous type, the charge moves at a predetermined rate through one or more heating zones to emerge in most cases at the end opposite the point of entry. Figures 9 and 10 are representative examples of typical, industrial refractory-wall furnaces.

In glass making furnaces, energy efficiency is enhanced through the utilzation of regenerative air heating. In these furnaces, two sets of refractory chambers are set up with open brickwork, or checkers. The flame gases, preferably

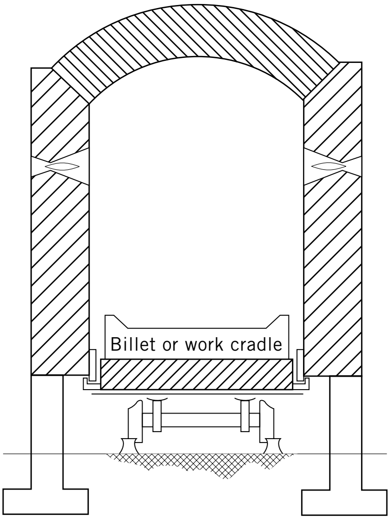

Fig. 9. Car-type annealing furnace.

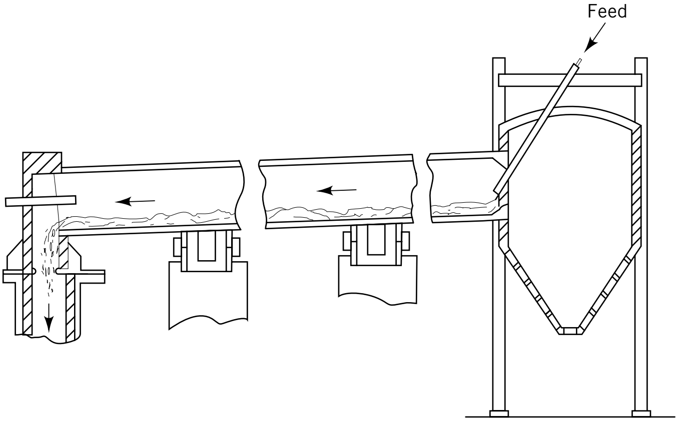

Fig. 10. Revolving-drum cement kiln.

long diffusion flames, pass over the molten glass and then pass down through one of the regenerators. This heats up the brick work to a very high temperature. At regular intervals of 20–30 min, a valve is switched such that the gas flows down the second regenerator. Air is now passed over the first regenerator and preheated to a very high temperature. Thus, at all times, air is being heated in one regenerator and flue gas is being cooled in the other (Fig. 11).

6. Fluidized-Bed Combustion

New furnace concepts in development stages include fluidized-bed furnaces (9), coal gasification furnaces (10), and MHD furnaces (11,12). Of these technologies,

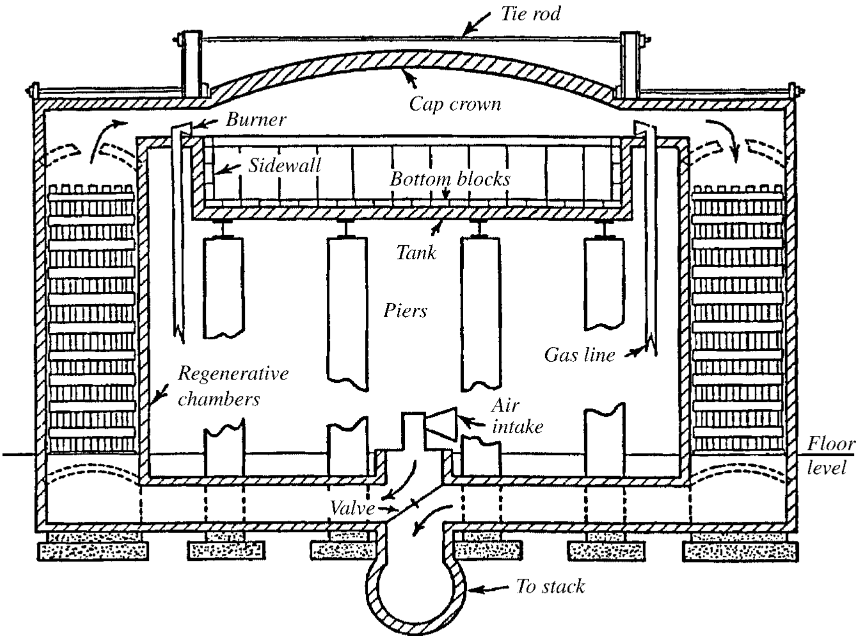

Fig. 11. Cross-section of glass tank furnace showing regenerative chambers.

fluidized-bed combustion has reached commercial-scale operations (Fig. 12), coal gasification has reached the demonstration phase.

Fluidization refers to the condition in which solid materials are given free-flowing, fluid-like behavior (13). As a gas is passed upward through a bed of solid particles, the flow of gas produces forces which tend to separate the particles from one another. At low gas flows, the particles remain in relative contact with other solids and tend to resist movement. This condition is referred to as a fixed bed. As the gas flow is increased, a point is reached at which the forces on the particles are just sufficient to cause separation. The bed then becomes fluidized. The gas cushion between the solids allows the particles to move freely, giving the bed a liquid-like characteristic. With still higher gas flows, the particles begin to be carried up toward the top of the reactor. If the gas flow is high enough, most of the solids are entrained and carried out. This entrained flow regime is typical of a pulverized coal furnace. For gas flows between the onset of fluidization and full entrainment, the solids rise at an average slip velocity compared to the gas. Solids that approach the walls of the furnace tend to cascade down the wall (the gas velocity in the boundary layer is low). In order to maintain a certain solids density in the system, a large circulating cyclone is used at the outlet of the furnace to capture the solids that are escaping and send them back to the bottom of the furnace. These systems are called ciruclating fluidized beds.

For decades, fluidized-bed reactors have been used in noncombustion reactions in which the thorough mixing and intimate contact of the reactants in a fluidized bed result in high product yield with improved economy of time and energy. Although other methods of burning solid fuels also can generate energy

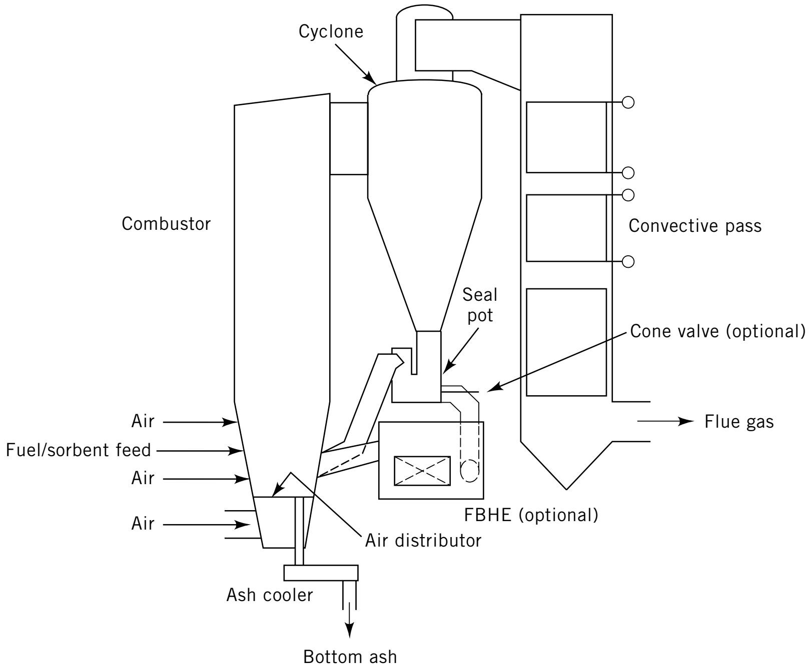

Fig. 12. Typical circulating fluidized-bed (CFB) steam generator (FBHE = fluidized-bed, high efficiency).

with very high efficiency, fluidized-bed combustion is adaptable to a wide variety of fuels can burn coal efficiently at a temperature low enough to avoid ash slagging and NO_x formation from combustion in the other modes. With the addition of limestone to these furnaces, SO_2 capture can be obtained directly in the bed. Fluid-bed systems of up to 300 MW are in commercial operation with designs available up to 600 MW including supercritical steam conditions. Fuels such as waste coals with heat contents as low as 6.5 MJ/kg up to petroleum coke with a heat content of 34.9 MJ/kg have been used commercially in the same furnace.

In coal gasification, the coal is reacted with a deficiency of air in a furnace. The product is CO, carbon monoxide, rather than CO_2, carbon dioxide. Due to the presence of some hydrogen and water in the fuel, the gas exiting the furnace is typically in equilibrium with regard to the water gas shift reaction, so that CO, CO_2, H_2, and H_2O are all present. This synthesis gas is combustible and can be burned in a conventional furnace or engine (such as a gas turbine). These processes may be air blown or oxygen blown, pressurized or atmospheric, or run in fixed, fluidized, or entrained beds. Demonstration plants of up to 250 MW are in operation for commercial evaluation.

7. Analysis

The rising demand for fuel efficiency and performance guarantees are imposing increasing requirements for analytical complexity. Furnace orientation in this area has developed only since the early 1920s. Starting with the Rosin analysis of the 1920s (14), subsequent development of furnace and combustion analysis proceeded along distinctively dissimilar lines. The Russian approach (15,16) in particular includes considerable theoretical (mathematical) emphasis, whereas the European–British–American approach concentrates on a fuel and flame chemistry orientation (17–19). Analytical emphasis has shifted toward a heat-transfer oriented view of predicting furnace performance: (*1*) wall absorption rate and gas temperature profiles, and (*2*) pollutant formation. Among the various models (20), the Hottel zoning method (21) is still popular (22). Another analytical model that lends itself to engineering analysis of furnaces is generally referred to as PSR theory (perfectly stirred reactor theory) (23) and is, in fact, applied on an industrial basis (24), where it is important to obtain a quantitative evaluation of the emissivity of the combustion products (25). Commercial computer codes that calculate complex flow fields with reacting flows are available and being validated. A detailed treatment of combustion modeling has been given (26) (see COMBUSTION SCIENCE AND TECHNOLOGY). The advent of very high speed computers has brought furnace calculations into managable proportions. Using the finite volume approach, it is now possible to set up a 1 million node furnace simulation which can be run on parallel processors and get a converged solution with a few days.

The analytical mechanisms for predicting the corresponding pollutant formation associated with fossil-fuel-fired furnaces lag the thermal performance prediction capability. This is due to the complexity of the furnace chemistry at the high temperatures. The most firmly established mechanism at this time is the prediction of thermal NO_x formation (27). The chemical kinetics of pollutant formation is, in fact, a subject of research. There are > 230 potential reactions in the gas phase. These can be analyzed to create a reduced chemistry set utilizing only several of the most important chemical reactions. These simulations are being compared with operating data on pollutant emissions, particularly NO_x. Further work is needed.

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