THE COEN & HAMWORTHY COMBUSTION HANDBOOK

Fundamentals for Power, Marine & Industrial Applications

STEPHEN B. LONDERVILLE
CHARLES E. BAUKAL, JR.
Editors

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Charles E. Baukal, Jr.

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This book would not have been possible without the feedback from the thousands of Coen and Hamworthy customers, who have been requesting this handbook for many years. In many cases, our innovative products were initiated by our customers' special needs and requirements. Therefore, we humbly dedicate this book to all our customers worldwide who we have been proud to serve for over 100 years.

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Foreword

Combustion has routinely been defined as the rapid oxidation of a fuel producing an exothermic reaction.[1,2] A first order of complexity can be added to this definition as two solutions of the Rankine–Hugoniot equations, resulting in detonation and deflagration combustions.[3] Detonation combustion results in a shock wave of supersonic velocities and can loosely be described as an explosion. Deflagration combustion is a very fast process and results in subsonic flame velocities. The editors of this book restrict the discussion to subsonic deflagration.

A primary division of combustion categories relevant to our target reader is premixed and non-premixed flames, both of which are considered in this book. A further subcategory is turbulent and laminar flames. Industrial flames are generally designed for turbulent flows, but can be laminar at turndown or near the surface of small solid or liquid droplets[4,5]; these are dealt with in this text. Another variant to the treatment of combustion covered in this book is the generation of useful heat via combustion. Efficiencies and computing the amount of useful heat absorbed are discussed as they are critical to the usefulness of combustion in industrial applications.

The rigorous treatment of combustion can at times be so complex that the kinetic variables, fluid turbulence factors, luminosity, and other factors cannot be defined well enough to find a realistic solution. It is our intention in this text to simplify the processes and not to create more complexities. This book is written for those involved in applications of full-size combustion systems. The applications are provided with state-of-the-art solutions. Several practical and solvable examples are also provided.

Several chapters contain significant discussions on emissions. The formation, reduction, and prediction of emissions from combustion systems are examined in detail. The impact of external variables is also discussed. The reader can thus make intelligent choices on fuels, burners, and combustion chambers and clearly understand the impacts of the many variables.

Stephen B. Londerville

References

1. C.E. Baukal (ed.), *The John Zink Combustion Handbook*, CRC Press, Boca Raton, FL, 2001.
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Preface

The last *Coen & Hamworthy Combustion Handbook* was written by Arthur H. Light in 1920.[1] In the late 1980s, Coen authorized the publication of a new combustion handbook at the request of its customers, but day-to-day work never allowed time for the book.

The origins of this book started during a business trip. In early 2000, one of the editors (Steve) was on a trip to visit a major Coen customer with a young Coen application engineer. During dinner, the engineer told Steve a story of a number of engineers debating the units of molecular weight for hours. It was at this moment that Steve decided a unique kind of book was needed that did not exist for combustion engineers. The book needed to be all inclusive and cover the very basics in building block form up to more complex combustion topics for everyone involved in combustion systems to use.

This book is designed for all engineers and professionals involved in the field of industrial and utility combustion systems. It is roughly divided into two parts, consisting of a total of 17 chapters, sequentially covering relevant and important combustion engineering basics and then specific computations and applications. Each chapter is roughly organized from simple to more complex, thus allowing the reader to absorb as much as they may need before moving on to the next chapter. Practical examples are also included.

The intent is to have a ready reference combined with a practical review needed for engineers in the field of combustion. The practical aspects of all combustion systems include by necessity a variety of subsystems that include, as a minimum, methods to

- Transport and introduce fuel and air to a system
- Safely monitor the combustion system
- Control all the flows and operational parameters
- Design a burner/combustion chamber to achieve performance levels such as emissions and heat transfer
- Avoid excessive noise and vibration and provide long, durable equipment life under adverse conditions

As a result, the topics in this book include units, chemistry, fluid flow, heat transfer, atomization, solid fuels including handling, liquid and gaseous fuels, pollution emissions, CFD, noise and practical discussions on controls, auxiliary support, and burner selection criteria.

This book is designed to be a review of the critical, relevant elements of combustion science required to apply simple calculations and more advanced computations. It is especially targeted at engineers and professionals in the field of combustion who need a review of fundamentals so they can make calculations and decisions on proper design features, computations, emissions, fuel choices, controls, burner selection, and burner/furnace combinations. In addition to the building block organization, users can go directly to individual chapters concerned with specific applications to get information on different applications without reading the preceding chapters.

Reference

1. A.H. Light, *Efficient Oil Burner*, Coen Company, San Francisco, CA, 1920.

Acknowledgments

The authors collectively thank the Coen, John Zink, and Hamworthy companies for their help and support during the preparation of this book. Many colleagues helped with ideas, content, and the preparation of figures and tables. We especially thank Rick Ketchum, Andrew Walter, Vincent Wong, and Jeffrey Ma for their help in preparing the materials for this book.

Chuck Baukal thanks his wife, Beth, and his daughters, Christine, Caitlyn, and Courtney, for their continued support. He also thanks the good Lord above, without whom this would not have been possible. Wes Bussman thanks his family, Brenda, Sean, and Zach, for their support. He also thanks all of his colleagues at the John Zink Company for their encouragement and for the knowledge they have shared with him throughout his career. Vladimir Lifshits acknowledges Coen Company, Inc. and his long-term boss, Steve Londerville, for a stimulating work environment and opportunity to expand combustion technology during his 23-year career with Coen and for the invitation to write chapters of this book on burners and controls. Steve Londerville acknowledges Chet Binasik for hiring him at Coen in 1977 and providing a long, fulfilling career in R&D; Temple Voorhees for his continuous guidance in the drive for new products with a passion that was unparalleled in this industry; Sherman Eaton, his mentor for many years, who paved the way for his career and accomplishments; Jim Church for driving into his mind that engineers need to understand financials and for their many discussions; his wife Pure who never complained about, "Sorry I have work this weekend"; and finally John Baxter, his lifelong friend since childhood, who always said, "Just get it done, and then we can have some fun."

Editors

Charles E. Baukal, Jr., PhD, is the director of the John Zink Institute for the John Zink Company, LLC (Tulsa, Oklahoma), where he has been since 1998. He has also been the director of R&D and the director of the R&D Test Center at Zink. He previously worked for 13 years at Air Products and Chemicals, Inc. (Allentown, Pennsylvania) in the areas of oxygen-enhanced combustion and rapid gas quenching in the ferrous and nonferrous metals, minerals, and waste incineration industries. He worked for Marsden, Inc. (a burner supplier in Pennsauken, New Jersey), for five years in the paper, printing, and textile industries and for Selas Corp. (a burner supplier in Dresher, Pennsylvania) in the metals industry, both in the area of industrial combustion equipment. He has over 30 years of experience in the fields of industrial combustion, pollution control, and heat transfer and has authored more than 100 publications in those areas. Dr. Baukal is an adjunct instructor at Oral Roberts University, the University of Oklahoma, the University of Tulsa, and the University of Utah. He is the author/editor of eight books in the field of industrial combustion, including *Oxygen-Enhanced Combustion* (1998), *Heat Transfer in Industrial Combustion* (2000), *Computational Fluid Dynamics in Industrial Combustion* (2001), *The John Zink Combustion Handbook* (2001), *Industrial Combustion Pollution and Control* (2004), *Handbook of Industrial Burners* (2004), *Heat Transfer from Flame Impingement Normal to a Plane Surface* (2009), and *Industrial Combustion Testing* (2011).

Dr. Baukal earned his PhD in mechanical engineering from the University of Pennsylvania (Philadelphia, Pennsylvania) and is a licensed professional engineer in the state of Pennsylvania, a board-certified environmental engineer (BCEE), and a qualified environmental professional (QEP). He has served as an expert witness in the field of combustion, has 11 U.S. patents, and is a member of numerous honorary societies and *Who's Who* compilations. He is also a member of the American Society of Mechanical Engineers, the American Society for Engineering Education (ASEE), and the Combustion Institute. He serves on several advisory boards, holds offices in the Combustion Institute and ASEE, and is a reviewer for combustion, heat transfer, environmental, and energy journals.

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1

Introduction

Stephen B. Londerville, Timothy Webster, and Charles E. Baukal, Jr.

CONTENTS

1.1 Introduction

While fire has been existent since the beginning of time, much remains to be learned about it. Because the science of combustion combines heat transfer, thermodynamics, chemical kinetics, and multiphase turbulent fluid flow to name a few areas of physics, the study of industrial combustion is interdisciplinary by necessity.

The field of industrial combustion is very broad and touches directly, or indirectly, nearly all aspects of life. Electronic devices are generally powered by fossil-fuel-fired power plants. Automobiles use internal combustion engines. Planes use jet-fuel-powered turbine engines. Most materials have been made through some type of heating process. While this book is concerned specifically with industrial/utility combustion, all of these combustion processes share many features in common.

The last Coen combustion handbook was written in 1920 by Arthur H. Light.[1] This current handbook was inspired from an internal Coen week-long engineering workshop that was developed as an in-depth review for engineers specializing in combustion applications. The course was required for all company engineers and included a comprehensive final exam. This workshop formed the basis for the topics and order of introduction in this handbook. This handbook is intended to be a review of basic engineering topics, followed by more detailed topics and practical examples.

1.2 History of Coen Company

The origins of Coen Company can be traced back to 1912, when Garnet Coen first fashioned an innovative device which would heavily impact the fuel burning industry. His invention—the adjustable tip mechanical oil burner, a unique device that could maintain atomization quality at low supply pressure via an adjustable tip—was what ultimately spurred the company to its present success.[2]

In 1914, Coen employed Joseph Voorheis, a mechanical engineer who at the time was working for Shell Oil Company. Voorheis sought after Coen's burner design for the retrofit of a mechanical burner onto a tugboat and soon after began working for the company. With his help, the first "Coen system" of mechanical oil burning was created consisting of an oil heater, a duplex strainer, and simple integrated pumping systems ahead of the burner.

From the beginning, it was obvious the company intended to offer more than just a product or system. It was offering engineering expertise to accommodate the combustion requirements and capabilities of any furnace, at sea or on land. This early emphasis on engineering would serve the company well in the decades ahead as new technologies created expanding markets and opportunities.

It was not long before the efficiency engineers of large oil and industrial companies recognized the adaptability of the Coen systems for operation of the boiler and refinery heater furnaces of their stationary installations. By 1921, hundreds of Coen burner systems were fueling boilers and furnaces in the oil companies' pumping stations and refinery heaters, in breweries, power plants, foundries, smelters, and institutions throughout the United States.

By the early 1950s, a new trend was being established in the boiler industry—packaged boilers. Packaged water tube boilers were shop-assembled and could be transported and installed within days after unloading. Prior to this, multi-burner boilers were erected on site and took months to construct. Packaged boilers resolved these issues and could be shipped on a flat car to the site, thus saving time, labor, and money. However, these new long furnaces did not permit the application of multiple burners, common with field-erected boilers. To overcome this problem, Coen developed new forced draft large single burners custom engineered for these new furnaces. Further, Coen provided package burners for these boilers, complete with piping and controls, so the entire boiler/burner/controls became a package unit. Coen has provided thousands of these package burner units.

In the 1970s, Coen realized that oil and gas prices would drive large fuel users, such as cement plants and larger boilers, to the use of coal. The company developed a complete line of coal-fired burners and its fuel feed system for rotary kiln firing and industrial boilers. The system provided higher output, lower fuel consumption, and better quality product than any other coal firing system available at the time. This was also a time of alternative fuels and efficiency innovations. Coen developed biomass burners and slurry burners together with complicated microprocessor control systems into packages. At the time, it was projected that natural gas would cease to be used as a boiler fuel.

In recent years, the trend toward the use of natural gas has increased dramatically, due to lower relative cost, higher availability, and lower pollution emissions. Coen responded to this need with the development of Low NO_x gas burners and Ultra Low NO_x gas burners and the associated controls required. Unknown in the 1970s, Coen was converting kilns, industrial boilers, and utility boilers to natural gas firing. Although seemingly simple, conversion to fire natural gas in many cases required a detailed heat transfer analysis due to changes in heat losses and luminosity of the flames. These conversions were uniquely engineered solutions that by then had become a common Coen supplied offering.

Coen remained under the control of Garnet Coen until 1934 when Joe Voorheis acquired principal ownership of the company. Coen continued as a privately owned company (Voorheis) when in April 2007 it was acquired by another privately owned company: Koch Chemical Technology Group, a division of Koch Industries. This acquisition merged Coen products and Todd combustion products. In 2011, Coen acquired Hamworthy Peabody Combustion, further expanding its combustion products and offerings. On August 2, 2012, Coen celebrated 100 years since its incorporation on August 2, 1912. For all those years, Coen has remained innovative and privately owned.

Although Coen began as a company providing burners for industrial boiler and process heaters, it has expanded since the inception 100 years ago to include

- Utility/industrial/process burners and associated support products
- Advanced combustion controls and burner managements systems
- Applications and systems for a wide variety of solid, liquid, and gaseous fuels
- Pump sets, fuel trains, and custom systems such as solid conveying
- Cement, lime and ore kilns, air heaters, incinerators, and duct burners systems
- Unique custom solutions to one of a kind combustion applications

1.3 History of Hamworthy Combustion

While Coen, based in San Francisco, California, was retrofitting boilers with a novel mechanical atomizer around 1912, two brothers, Percy and Sidney Hall, incorporated the Hamworthy Engineering Company on April 16, 1914, located 5350 miles away in Poole England. Hamworthy designed and built oil engines initially for marine use plus pumps and compressors.[3]

After surviving two wars and the great depression, Hamworthy realized the trend in switching from coal fuels to oil and established the British Combustion Equipment (BCE) group in 1946. By 1956 the BCE had become the driving force in the Hamworthy group. From 1960 to 1980, Hamworthy had close links with the British Central Generating Board (CEGB) in the supply of utility-grade oil-fired burners to new oil-fired utility furnaces. In the early 1990s, Hamworthy acquired Peabody Combustion, another burner-based company founded in the United States in 1920.

From the mid-1980s to the present time, Hamworthy either acquired or developed a complete line of burners for gas and oil firing, ignition systems, and package burners systems. Together, Coen and Hamworthy will be celebrating nearly 200 years of combined combustion experience at the time of this publication.

1.4 Boiler Basics

Included later is a significant discussion on boilers in this section because this is the largest application of large burners and the burner design and placement is essential for the boiler performance. Simply stated, boilers convert water to steam; however, the actual process is very complex. Water tube boilers can be simply described as an upper steam drum and a lower water drum (mud drum). These drums are connected by a multitude of tubes forming both a large open volume called a radiant section and a multitude of closely spaced tubes forming a convection section (see Figure 1.1). Some of these tubes can be "risers" and some "down comers" causing natural circulation in the boiler water/steam system. Larger boilers may have forced circulation using pumps. Flames are introduced in the radiant section, producing mostly radiant heat transfer. The post-flame gases enter the convection section where the dominant mode of heat transfer is convection (see Chapter 7).

Boilers receive treated feed water (liquid). This is added to the lower "mud" drum at 212°F–300°F (100°C–150°C). The heat from flame or post-flame gases heats the water which is converted into steam in the "rising tubes" up to the steam drum. At the steam drum, both water and steam exist. Separators are used (not shown) that separate steam from water. The result is saturated steam at the exit.

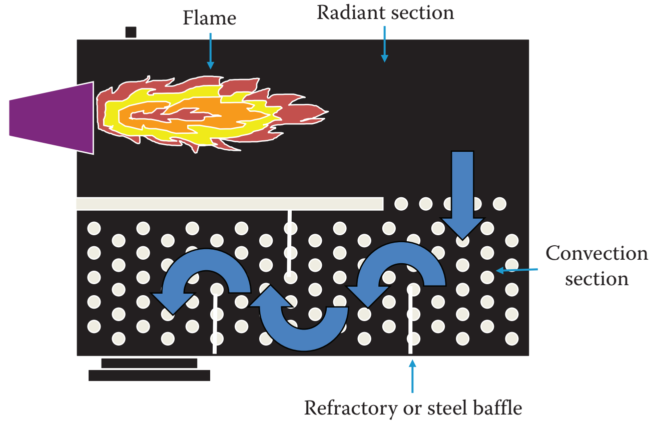

FIGURE 1.1
Flow through a boiler, highlighting radiant and convection sections.

The boiled water (steam) is usually controlled at a much higher pressure than ambient, for example, maybe 150–500 PSIG (10–35 barg). This means the temperature of the steam is higher than atmospheric boiling (212°F = 100°C). The steam generated by boilers can be saturated or superheated. Saturated steam is in equilibrium with the hot water at any given pressure, meaning both liquid and steam exist in the same volume/space. Saturated steam temperature is a direct function of pressure, that is, 212°F (100°C) at atmospheric pressures. At 350 PSIG (24 barg), the saturated temperature for boiling is at 435°F (223°C). Heating the resultant saturated steam to higher temperatures will result in superheated steam by returning saturated steam back to the boiler from the steam drum to super heater tubes for further heating.

Although the firing rate of the burner defines the boiler steam output, the burner design and placement must be engineered to achieve the boiler essential operation such as

- Prevention of flame impingement
- Emission compliance, NO_x, CO, HCs. VOC, particulate, opacity, etc.
- Efficiency, limiting excess air, turndown
- Noise from piping and combustion roar
- Control of superheat temperature

1.4.1 Industrial Boilers

Burners designed for use in industrial boilers are most commonly of the circular register design, range in size from heat inputs of 20 to 400 × 10^6 British Thermal Units (Btus)/h (6–115 MW), operate with forced draft (FD) fans supplying the combustion air, and burn gas or liquid hydrocarbon fuels. This section covers a variety of different sizes and types of industrial boilers. The most commonly encountered boilers would be single-burner industrial-packaged boilers and wall fired field-erected boilers with up to six burners per boiler. Industrial-packaged boilers consist of a furnace and boiler, which is a self-contained system that can basically be shipped as a unit, which became prevalent in the 1950s as a method to save time and labor. While some larger field-erected boilers with more burners, and designs such as the tangentially fired, turbo-fired, or cyclonic-fired boilers, can occasionally be found in these applications, they make up a very small percentage of the total number of installed units.

1.4.2 Package Boilers

The simplest form of burner arrangement is to have only one burner that provides all of the necessary heat input to the boiler. The most simple package boiler consists of an FD fan, burner and wind box, breeching, and stack. This is possible in industrial-package boilers generating up to 300,000 lb/h (136,000 kg/h) of steam, where single burners can reach heat inputs up to 400 × 10^6 Btu/h (115 MW). The burner is located on the end wall of the boiler, which can be fully refractory lined or a combination of refractory around the burner throat and tubes comprising the rest of the wall. Industrial-package boiler configurations are typically denoted by the drum configuration, with "D" style (see Figure 1.2), "O" style (see Figure 1.3), and "A" style (Figure 1.4) boilers being the most common.

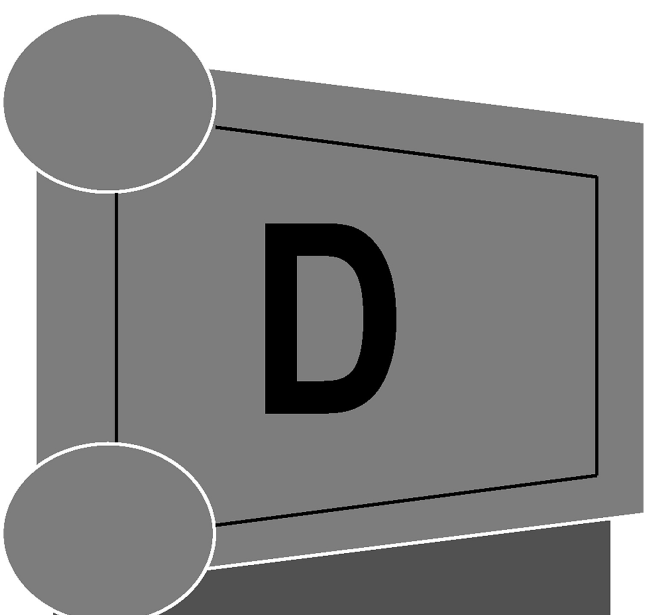

FIGURE 1.2
Front elevation of "D" type boiler—the furnace and drum locations form the letter "D," hence the name.

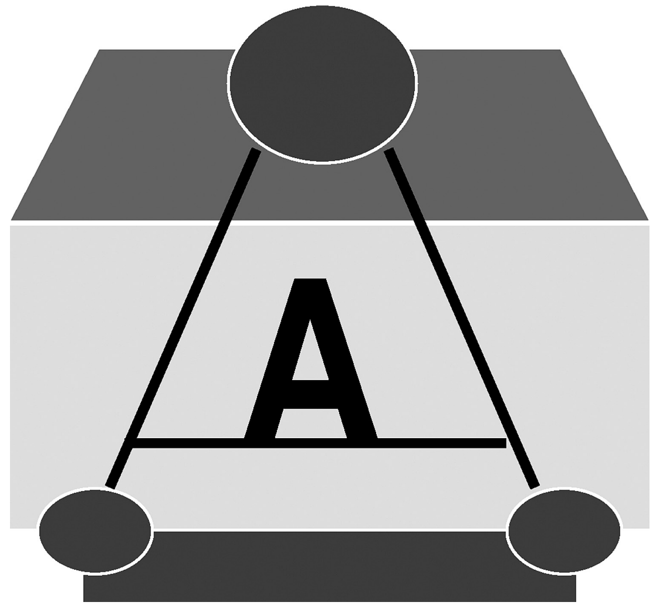

FIGURE 1.3
Front elevation of "A" type boiler—the furnace and drum locations form the letter "A," hence the name.

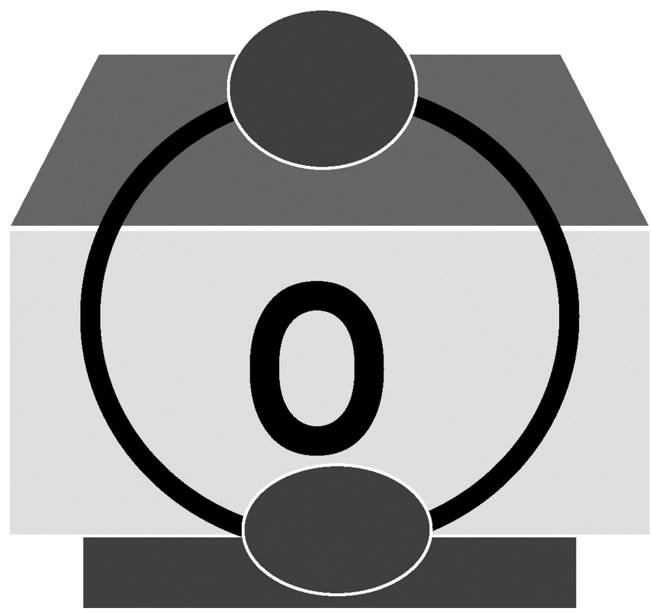

FIGURE 1.4
Front elevation of "O" type boiler—the furnace and drum locations form the letter "O," hence the name.

A "D" style boiler has two drums located directly above each other on either the right or the left side of the boiler, with the tubes extending out to form the furnace in a "D" configuration. This boiler type has only a single convection bank located on the same side as the drums (see Figure 1.5). An "O" style boiler is similar to a "D" style in that it utilizes two drums centered over each other; however, in the case of an "O" style boiler

FIGURE 1.5
"D" type package boiler. (Courtesy of Victory Energy Operations, LLC.)

the drums are located over the center of the furnace. In this configuration, a convective bank is located on each side of the furnace so the flow out of the furnace is split evenly between these two convective banks (see Figure 1.6). An "A" style boiler has three drums, a single steam drum in the top center of the furnace, and two mud drums located in each corner of the furnace. Similar to the "O" style boiler, the "A" style also has two convection banks located on each side of the furnace.

As the capacity of the boilers gets larger, the most constrained dimension is typically the width of the boiler, which is restricted to allow shipment by road or rail. Space constraints at the site may also constrain the allowable length of the boiler. In these cases, the firebox dimensions may not be sufficient to accommodate the flame geometry required from a single burner. In some of these cases, given the right firebox geometry, two burners can be supplied in a common wind box and operated as

FIGURE 1.6
"O" type package boiler. (Courtesy of Victory Energy Operations, LLC.)

a single unit, called *unison firing*. This also can be used to reach heat inputs higher than those available from one burner only. In the case of unison firing, both burners operate as a single unit with the loss of flame on either burner causing a shutdown of the entire system.

1.4.3 Field-Erected Boilers

As boiler capacities get larger than the physical size that can be shipped as an assembled unit, the boilers are shipped in pieces and erected at the site. These field-erected boilers example (shown in Figure 1.7) are usually a large furnace and boiler system with multiple ancillary systems. The system is shipped to the field in pieces and erected on site. Sometimes, portions are fabricated on site. To minimize the footprint of these "field-erected" boilers, the fireboxes get taller as the boiler capacity grows, while the width and depth of the boiler do not typically grow proportionally with capacity. Since the depth of the firebox that is available to accommodate the flame length is constrained, these boilers will utilize multiple burners, from 4 to as many as 16, arranged in rows on a single wall or on opposed firing walls. The number and arrangement of the burners is based on the required heat input and the available width and depth to accommodate the flame geometry.

Burner spacing is important to ensure that no flame-to-flame interaction occurs which can increase emissions and flame lengths, leading to impingement. This can vary based on the different designs of burners employed and the design pressure drop across the burner.

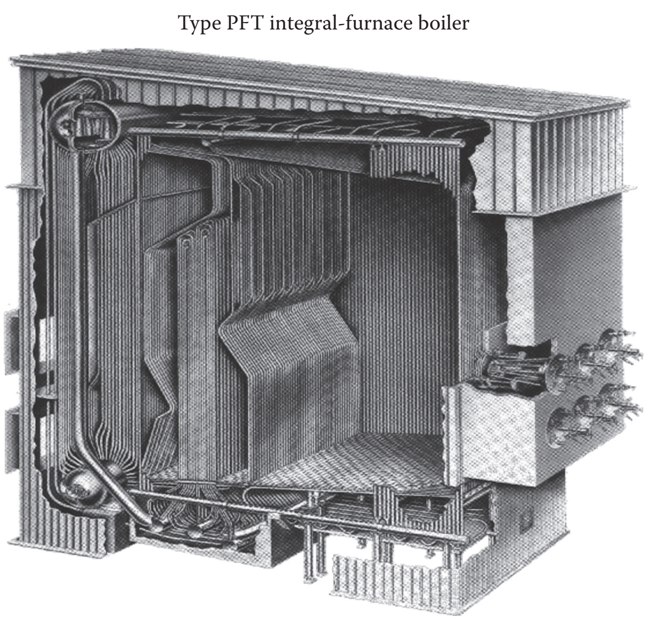

FIGURE 1.7
Typical field-erected boiler.

For multiple burner applications, each burner can be brought in and out of service independently, allowing greater flexibility in operating turndown. Typically all burners in service are controlled by a single fuel-control valve and therefore operate at the same heat input. For added flexibility on units with several rows or columns of burners, a flow-control valve can be supplied for each row or column, allowing more flexibility in controlling heat input and distribution within the firebox. Burners should be brought into service symmetrically about the boiler drum centerline to provide balanced heating to the boiler and to minimize drum level fluctuations.

1.4.4 Power Generation Industry

Boilers are used for a variety of purposes in an assortment of applications. Common uses include producing hot water or steam for heating, producing steam for use within a plant such as atomizing oil for oil-fired burners, and producing steam to generate power in large power plants. Applications range from small single-burner uses in hospitals, schools, and small businesses up to large multi-burner boilers in power plants.

Both duct burners and boiler burners are used in the power generation industries. Duct burners (see Chapter 15) are burners that are inserted into large ducts to boost the temperature of the gases flowing through the ducts. These burners are frequently used in cogeneration projects, electrical utility peaking stations, repowering programs, and in industrial mechanical driver systems employing gas turbines with site requirements for steam. They are also used in fluidized bed combustors and chemical process plants. The efficiency of a duct burner to supply additional heat approaches 100% (on a lower heating value basis), which is much higher than, for example, a backup boiler system in generating more steam. Duct burners are often easily retrofitted into existing ductwork. Several important factors in-duct burner applications include low pollutant emissions, safe operation, and uniform heat distribution from the duct burners to the gases flowing through the duct, getting uniform gas distribution through the duct burners, and having adequate turndown to meet fluctuating demands. Duct burners typically use gaseous fuels, but occasionally fire on oil.

Boiler burners (see Chapter 14) are used to combust fuels, commonly natural gas or fuel oil, in the production of steam, which is often used to produce electrical energy for power generation. These burners produce radiation and convection used to heat water flowing through the boiler. The water is vaporized into steam. Sometimes the steam is used in the plant in the case of smaller industrial boilers. Larger utility boilers produce steam to drive turbines for electrical energy production. While boiler burners have been around for many years, there have been many design changes in recent years due to the current emphasis on minimizing pollutant emissions.

1.5 Utility Boilers

Burners designed for use in utility boilers are very similar to those found in industrial boilers, with a few minor differences. Utility boilers typically employ multiple burners, from 4 to as many as 48 or more. These burners can be brought in and out of service as needed, allowing the firing rate of the boiler to be varied greatly without needing to achieve a high turndown ratio on any single burner. Therefore, each burner on a utility boiler does not need to cover as wide a size range as the burner on industrial boiler, and typically range in size with heat inputs of 50–400 × 10^6 Btu/h (15–115 MW). They operate with forced draft fans supplying the combustion air, which is typically preheated to between 400°F (200°C) and 650°F (340°C) as compared to ambient temperature air in most industrial applications. They burn gaseous, liquid, or solid fuels, and may need to be fuel-flexible to take advantage of changing fuel costs.

1.6 Utility Boiler/Burner Design

Utility boiler/burner designs, both conventional and low NO_x, employ similar design techniques as those for industrial boilers/burners. The differences that separate utility applications are generally based on their intended operational parameters, such as the fuels to be fired and level of air pre-heat they are designed to handle. Due to the importance of maintaining high electrical system reliability and minimizing generation costs, utility boiler burners must offer

- High reliability during long-term operation
- Simplicity and reliability of fuel ignition
- High flame stability across the operational turndown range
- Fuel flexibility, including the ability to co-fire multiple fuels
- High thermal efficiency by minimizing excess air levels
- Minimizing emissions through operation with flue gas recirculation (FGR) and over fire air (OFA)
- Minimum parasitic power requirements through low pressure drop of combustion air and flue gas systems, especially the burner register draft loss
- Simplicity of burner maintenance and adjustment
- Flame dimensions to match the dimensions of the furnace, with no flame impingement on any furnace wall

The burners are typically located in common wind boxes which supply air to all of the burners located on each firing wall (or corner). Proper air flow distribution to each burner must be ensured during the system design and is typically accomplished through physical or computational fluid dynamic (CFD) modeling (see Chapter 9) of the air delivery system and wind box. The goal is to provide equal combustion air flow between burners, uniform peripheral velocity distributions at the burner inlets, and the elimination of tangential velocities within each burner. If the unit has been designed with FGR, the O_2 content must be equal between the burners, and this is accomplished by balancing the FGR distribution to each burner.

As the burners are taken in and out of service, to maximize boiler efficiency, it is desirable to limit the air flow through the out-of-service burners. This is typically done by including an air damper or register on each burner which can be closed when the burner is out of service to allow only enough air flow through the burner as needed for cooling and purging. These dampers can be automated, along with the burner fuel shutoff valves, so that operators can take burners in and out of service from the control room or even automate this function as part of the boiler's combustion controls.

In multiple burner installations, NO_x reduction can be achieved by biasing the fuel to some burners. This causes some burners to operate fuel rich and others to operate fuel lean. This may include shutting off the fuel completely to one or more burners, which is called burners-out-of-service (BOOS). The optimum amount and pattern of biasing or BOOS is often very boiler-dependent, with the best NO_x reduction (see Chapter 10) results found through a series of tests during commissioning.

1.7 Utility Boiler Types

1.7.1 Wall Fired Burner Installation

The simplest form of burner arrangement is to have all of the burners located on only one wall of the furnace in a common wind box. The burners will be located in rows and columns, based on the number of burners required. The simplest configuration would be a four burner arrangement with two rows and two columns of burners. Very large boilers may have up to 24 burners, or more, which could be arranged in a pattern of 4 rows each containing 6 burners.

Spacing of the burners is important to ensure that no flame-to-flame interaction occurs which can increase emissions and flame lengths, leading to impingement. This can vary based on the different designs of burners employed and the design pressure drop across the burner.

For multiple-burner applications, each burner can be brought in and out of service independently, allowing greater flexibility in operating turndown. Typically, all burners in service are controlled by a single fuel-control valve and therefore operate at the same heat input. For added flexibility on units with several rows or columns of burners, a flow-control valve can be supplied for each row or column, allowing more flexibility in controlling heat input and distribution within the firebox. Burners should be brought into service symmetrically about the boiler drum centerline to provide balanced heating to the boiler and to minimize drum level fluctuations.

1.7.2 Opposed Fired Installation

Larger utility boilers are designed to have burners on two of the four walls and firing toward the center of the furnace, and in some cases boilers have been designed with burners located on all four walls. The burners are located on opposite walls and are therefore called "opposed fired" boilers (see Figure 1.8). In opposed fired applications, not only is the spacing between burners important, but also, the interaction between the flames of the opposed burners meeting in the center of the furnace. Depending on the boiler design, the burners may be directly opposite each other or may be staggered to help avoid interaction with the burners from the opposite wall. In some instances, the boilers may include a "division wall" along the centerline of the furnace that extends from the bottom to some height in the furnace. This wall eliminates some concerns over opposed burner flames interacting, but does present concerns for flame impingement.

1.7.3 Tangentially Fired Installations

Combustion Engineering developed a boiler design that places all of the burners at the corners of the boiler, firing tangentially toward a pitch circle in the center of the firebox. This tangentially fired or *T-fired* boiler design utilizes a vertical column of burners in each corner of the firebox (see Figure 1.9). The burner flames all converge

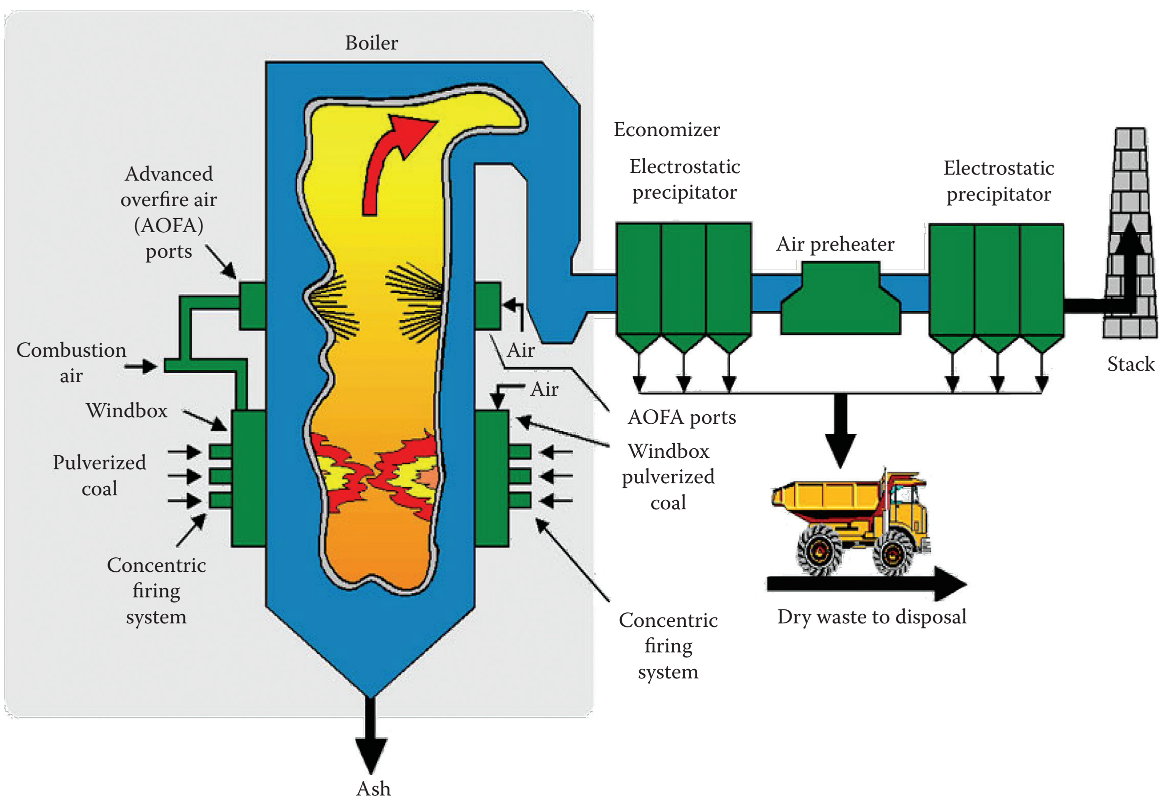

FIGURE 1.8
Opposed wall fired boiler.

FIGURE 1.9
TXU Electric Collin Station Power Plant, a tangential fired boiler.

into a swirling "fireball" in the center of the furnace. The number of burners in each column is the same and is dependent on the capacity of the boiler and number of fuels being fired.

The burners originally supplied by the boiler OEM for these boilers consisted of square burner "buckets" that were either fixed or tilting. The vertical column would contain some buckets dedicated to each particular fuel and some buckets that supplied only air. Some of the fixed (non-tilting) bucket applications have been retrofitted in the field to accommodate round burners, although in most cases burner retrofits and upgrades involve modifying or replacing the fuel components and buckets with components that fit into the existing burner geometry.

In some applications, the burners are designed to be tilted up and down by plus or minus 30° from level. The burners are all tilted at the same angle, which allows the fireball to be moved higher or lower in the firebox. By controlling the location of the fireball relative to the super heater tubes located at the top of the furnace, superheated steam temperature can be controlled. This can also be used to control the residence time of the combustibles in the furnace to assure carbon monoxide (CO) burnout on harder-to-combust fuels.

1.8 Air Heaters

Air heaters (see Chapter 16) are used in a wide range of industries—for preheating of process heaters in the petrochemical and refining industries, for detergent, coal or fertilizer drying, and for other heating and drying applications, for example, in the chemical, soap, paper, food, and cement industries. They are used mainly for high-temperature drying, where the combustion products mix with air and are used to heat the product directly. Typical applications include drying of detergents, minerals, fertilizers, animal feeds, and coal. Air heaters are also used as an indirect source of heat for drying of foodstuffs such as milk powder and dried potatoes, roasting of coffee beans, and production of food-grade chemical additives.

The most common type of air heater is the Peabody twin shell design. This type of air heater is used for conventional drying applications where the inlet air stream is at a low temperature, less than 100°C (212°F) and the required outlet temperature is no more than 800°C (1500°F). The twin shell design gets its namesake from an annular passage through which diluted air passes between the boiler outer shell and the combustion chamber, before mixing with hot combustion products to achieve the final outlet temperature. Burners for air heaters are generally round, require high turndown, and sometimes must operate with very high excess air. The high excess air used in air heaters can make low NO_x operation a challenge. On the other hand, lean premix burners can be easily employed to reduce NO_x.

1.9 Duct Burners

Duct burner systems (see Chapter 15) can be loosely described as large cross-sectional ducts with high flows that require uniform heat addition for relatively small temperature increases. The flows can be air, fumes, or oxygen-depleted streams. The burners used are also called ribbon burners, linear burners, or duct burners designed so that the heat input can be distributed over a relatively large cross section. The typical location of this type of burner can be seen in Figure 1.10.

Linear and in-duct burners were used for many years to heat air in drying operations before their general use in cogeneration systems. Some of the earliest systems premixed fuel and air in an often complicated configuration, which fired into a recirculating process air stream. The first use for high-temperature, depleted oxygen streams downstream of gas turbines in the early 1960s was to provide additional steam for process use in industrial applications and electrical peaking plants operating steam turbines. As gas turbines have become larger and more efficient, duct burner supplemental heat input has increased correspondingly. Duct burners are suitable for a wide variety of direct-fired air heating applications where the physical arrangement requires mounting inside a duct.

1.10 Burners

The burner is the device that is used to combust the fuel with an oxidizer to convert the chemical energy in the fuel into thermal energy. A given combustion system may have a single burner or many burners, depending on the size and type of the application. A typical round low NO_x burner is shown in Figure 1.11. Boilers and other combustion chambers come in various sizes and configurations. It is the design and orientation of the burner that will define proper operation of the equipment. There are many factors that go into the design of a burner. This section will briefly consider some of the important factors that are considered in designing burners. A detailed discussion on burners is given in Chapter 14.

1.10.1 Competing Priorities

There have been many changes in the traditional designs that have been used in burners, primarily because of

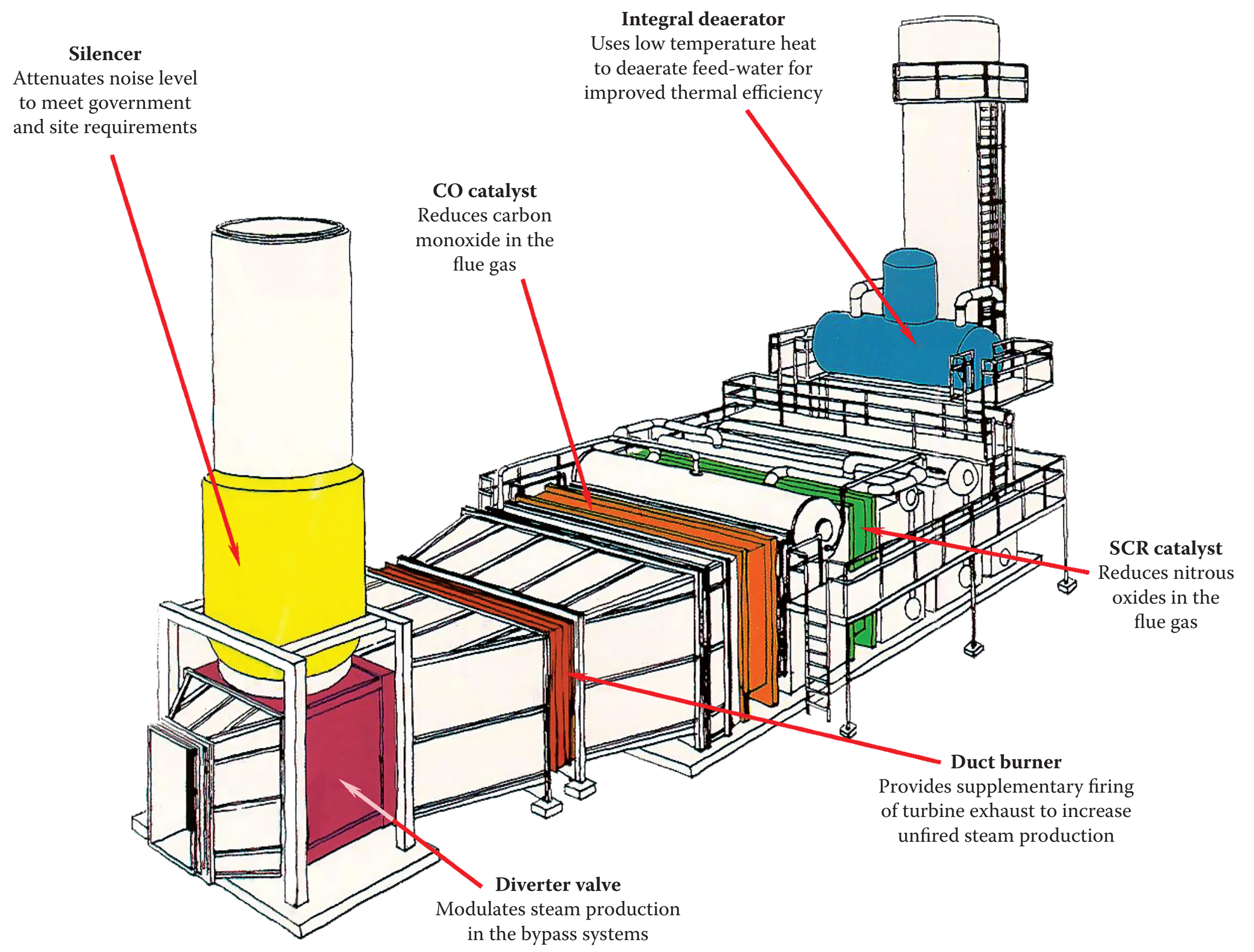

FIGURE 1.10
Typical duct burner location. (Courtesy of Hamon Deltak.)

FIGURE 1.11
Ecojet burner in an HRSG.

the recent interest in reducing pollutant emissions. In the past, the burner designer was primarily concerned with efficiently combusting the fuel and transferring the energy to a heat load. New and increasingly more stringent environmental regulations have added the need to consider the pollutant emissions produced by the burner (see Chapter 10). In many cases, reducing pollutant emissions and maximizing combustion efficiency are at odds with each other. For example, a well-accepted technique for reducing NO_x emissions is known as staging, where the primary flame zone is deficient of either fuel or oxidizer.[4] The balance of the fuel or oxidizer may be injected into the burner in a secondary flame zone or, in a more extreme case, may be injected somewhere else in the combustion chamber. Staging reduces the peak temperatures in the primary flame zone and also alters the chemistry in a way that reduces NO_x emissions because fuel-rich or fuel-lean zones are less conducive to NO_x formation than near stoichiometric zones.[5] NO_x emissions increase rapidly with the exhaust product temperature. Since thermal NO_x is exponentially dependent on the gas temperature, even small reductions in the peak flame temperature can dramatically reduce NO_x emissions. However, lower flame temperatures often reduce the radiant heat transfer from the flame since radiation is dependent on the fourth power of the absolute temperature of the gases. Another potential problem with staging is that it may increase CO emissions, which is an indication of incomplete combustion and reduced combustion efficiency. However, it is also possible that staged combustion may produce soot in the flame, which can increase flame radiation. The actual impact of staging on the heat transfer from the flame is highly dependent on the actual burner design.[6]

In the past, the challenge for the burner designer was to maximize the mixing between the fuel and the oxidizer to ensure complete combustion. If the fuel was difficult to burn, as in the case of low heating value fuels such as waste liquid fuels or process gases from chemical production, the task could be very challenging. Now, the burner designer must balance the mixing of the fuel and the oxidizer to maximize combustion efficiency while simultaneously minimizing all types of pollutant emissions. This is no easy task as, for example, NO_x and CO emissions often go in opposite directions. When CO is low, NO_x may be high and vice versa. Modern burners must be environmentally friendly, while simultaneously efficiently transferring heat to the load.

1.10.2 Design Factors

There are many types of burner designs that exist due to the wide variety of fuels, oxidizers, combustion chamber geometries, environmental regulations, thermal input sizes, and heat transfer requirements. Additionally, heat transfer requirements include, for example, flame temperature, flame momentum, and heat distribution. Garg[7] lists the following burner specifications that are needed to properly choose a burner for a given application: burner type, heat release and turndown, air supply (natural draft, forced draft, or balanced draft), excess air level, fuel composition(s), firing position, flame dimensions, ignition type, atomization media for liquid fuel firing, noise, NO_x emission rate, and whether waste gas firing will be used.[7] Some of these design factors are briefly considered next.

1.10.2.1 Fuel

Depending upon many factors, certain types of fuels are preferred for certain geographic locations due to cost and availability considerations. Gaseous fuels, particularly natural gas, are commonly used in most industrial heating applications in the United States. In Europe, natural gas is also commonly used along with light fuel oil. In Asia and South America, heavy fuel oils are generally preferred although the use of gaseous fuels is on the rise.

Fuels also vary depending on the application. For example, in incineration processes, waste fuels are commonly used either by themselves or with other fuels like natural gas. In the petrochemical industry, fuel gases often consist of a blend of several fuels, including gases like hydrogen, methane, propane, butane, propylene, nitrogen, and carbon dioxide.[8]

The fuel choice has an important influence on the heat transfer from a flame. In general, solid fuels like coal and liquid fuels like oil produce very luminous flames, which contain soot particles that radiate like blackbodies to the heat load. Gaseous fuels like natural gas often produce nonluminous flames because they burn so cleanly and completely without producing soot particles. A fuel like hydrogen is completely nonluminous because there is no carbon available to produce soot.

In cases where highly radiant flames are required, a luminous flame is preferred. In cases where convection heat transfer is preferred, a nonluminous flame may be preferred in order to minimize the possibility of contaminating the heat load with soot particles from a luminous flame. Where natural gas is the preferred fuel and highly radiant flames are desired, new technologies are being developed to produce more luminous flames. These include processes like pyrolyzing the fuel in a partial oxidation process,[9] using plasma to produce soot in the fuel,[10] and generally controlling the mixing of the fuel and oxidizer to produce fuel-rich flame zones that generate soot particles.[11]

Therefore, the fuel itself has a significant impact on the heat transfer mechanisms between the flame and the load. In most cases, the fuel choice is dictated by the end user as part of the specifications for the system and is not chosen by the burner designer. The designer must make the best of whatever fuel has been selected. In most cases, the burner design is optimized based on the choice for the fuel.

In some cases, the burner may have more than one type of fuel. An example is shown in Ref. [12]. Dual-fuel burners are designed to operate typically on either gaseous or liquid fuels. These burners are used, usually for economic reasons, where the customer may need to switch between a gaseous fuel like natural gas and a liquid fuel like oil. These burners normally operate on one fuel or the other, and sometimes on both fuels simultaneously. Another application where multiple fuels may be used is in waste incineration. One method of disposing of waste liquids contaminated with hydrocarbons is to combust them by direct injection through a burner. The waste liquids are fed through the burner, which is powered by a traditional fuel such as natural gas or oil. The waste liquids often have very low heating values and are difficult to combust without auxiliary fuel. This further complicates the burner design where the waste liquid must be vaporized and combusted concurrently with the normal fuel used in the burner.

1.10.2.2 Oxidizer

The predominant oxidizer used in most industrial heating processes is atmospheric air. This can present challenges in some applications where highly accurate control is required due to the daily variations in the barometric pressure and humidity of ambient air. The combustion air is sometimes preheated to increase the overall thermal efficiency of a process. Combustion air is also sometimes blended with some of the products of combustion, a process usually referred to as *flue gas recirculation* (FGR). FGR is used to both control boiler superheat or reheat and reduce NO_x emissions.

1.10.2.3 Custom-Engineered Solutions

From the early beginning of the company, Coen has been a leader in innovation. New products were regularly developed and introduced to the market place. These products were the beginning of "custom-engineered solutions." This was an informal process until 1978 when Coen organized a standalone R&D department. Why?—because everyone was too busy working on projects to spare time to develop new ones. One of the co-editors of this book (Steve) was hired that year into the new R&D department.

New products were released on the average of 3–4 per year, such as the dual zone burner kiln burner, biomass firing, electronic products, control systems, low NO_x burners, larger burners, and much more. Many new products were, in fact, custom-engineered solutions to solve unique customer applications. The existing test facility was slowly modernized and CFD was first utilized for a duct burner project in 1985.

R&D grew and was subdivided into R&D and staff engineering as the complexity of projects and applications grew. This set the stage for a significant increase in "custom-engineered solutions."

At the time, the Clean Air Act was passed in the United States and new environmental rules were being proposed, requiring reduced emissions. Alternative fuels and more efficient unit operation were becoming a customer priority. Coen was continuously being asked by its customers, "How can I solve this?," thus the phrase was coined: "custom-engineered solutions." Since then, Coen has conducted hundreds of studies resulting in custom solutions to customer problems.

What is a custom-engineered solution? It is generally as follows:

1. Coen is approached by a customer with a combustion problem of some kind.
2. Coen does not have an "off-the-shelf" solution.
3. The company conducts a study of the problem and produces a proposal to solve the problem.

The study may involve a site visit, measurements, and possibly a CFD study. In some cases, a scale burner/system may be constructed and tested. A report is issued with a quote for equipment to solve the problem. Historically, all of these custom-engineered solutions have been successful and arrived at an economical solution where none existed.

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2

Engineering Fundamentals

Stephen B. Londerville

CONTENTS

2.1 Introduction

The NASA Mars Climate Orbiter case is a monumental example of the significance of units and conversions for practicing engineers. The Mars Climate Orbiter was set to land on the surface of Mars on September 23, 1999, to study the Martian climate, atmosphere, and surface. The orbiter trajectory was planned to be 226 km (140 miles) above the surface so that the gravitational acceleration of Mars could pull the Orbiter through the atmosphere at safe speeds. Instead, the trajectory was only 57 km (35 miles) and the orbiter was disintegrated by the atmospheric stresses. The magnitude of error was off by a factor of 4.45, the exact conversion from Newtons to lb-force. The trajectory was programmed for force inputs in metric Newtons; however, the crew at the controls was entering trajectory data in imperial units of lb-force. Fortunately, the Orbiter was unmanned; however, the incident cost NASA well over $600 million.[1] Despite the infinite complexity in the engineering of the Orbiter, it was a simple conversion error that was ultimately the source of failure. This holds true for all engineers as it is easy to overlook such basic fundamentals.

2.2 Time, Length, and Mass

Since the existence of early civilization, setting up a standard for weights and measures was vital for trade and construction. The earliest establishment of the modern universal measurement system was set forth by the Magna Carta of 1215, which proposed that "there shall be one unit of measure throughout the realm." Later, the growing development of the sciences during the eighteenth century created a need for a more extensive and universal measurement system and thus ushered the creation of the original metric system, which was drafted in France throughout the 1790s.[2]

A set of units describes and quantifies the physical properties of the universe. Properties such as time, distance, velocity, and power are examples of units. Many of these quantities can be related through physical laws as will be exemplified throughout this chapter. Fundamental units, however, are units that describe physical quantities from which all other units can be derived. There are seven fundamental units; however, strictly speaking, all units can be derived with three of these fundamental units:

1. Mass
2. Length
3. Time

One early establishment of mass was the kilogram, which was defined as 1 kg to equal the mass of 1000 cm^3 of water.

Length was originally defined in the metric system to be one ten-millionth of the distance from the Earth's equator to the North Pole. This measurement was very challenging to reproduce when necessary, so in 1889 a precision bar that consisted of 90% platinum and 10% iridium was created and marked so that it would precisely represent 1 m at 0°C (32°F). Authorized metrologists were allowed to travel to the International Bureau of Weights and Measurements to measure and mark their own bars for regional prototypes. The meter was then redefined more precisely in 1960 as 1,650,763.73 wavelengths emitted by krypton-86 in a vacuum.[2]

From classic antiquity, the day was divided into 12 h of daylight and 12 h of night. During the medieval period, the minute was introduced as the 60th part of an hour and the second was introduced as the 60th part of a minute. Today, a second is related to the radiation of a specific quantum transition in cesium-133.[2]

2.2.1 English Units

The English unit system is a product of the early developments of standardization in medieval England. It is also commonly called the system of imperial units. This system of units was officially declared in 1824 by the British Weights and Measures Act and was later refined and reduced until 1959. The unit system is still used by England and much of its former empire.[3] Table 2.1 shows the basic units of this system.

TABLE 2.1

Common English Units

Length	Feet
Mass	Pound-mass
Time	Second
Temperature	Rankine

2.2.2 SI Units

The SI unit system is the modern form of the metric system created in 1960. It is often called the International System of Units and is abbreviated from French: Systeme international d'unites. Originally, the system was developed around the meter and is used in most countries today.[3] The common SI units are shown in Table 2.2.

TABLE 2.2

Common SI Units

Length	Meter
Mass	Kilogram
Time	Second
Temperature	Kelvin

2.2.3 Absolute English and SI Units

It is important to highlight the differences between weight and mass. While mass is the measure of the amount of matter in an object, weight is the force of an object due to gravity. An absolute unit is a unit that does not include the gravitational acceleration. In the English system the absolute unit of mass is the pound-mass as opposed to pound. Similarly, in the SI system the absolute unit of mass is simply the kilogram or kilogram-mass while weight is measured in units of Newtons or kilogram-force. By definition, weight and mass are related by the following:

$$w = m\frac{g}{g_c} \tag{2.1}$$

where
w is weight
m is mass (absolute unit of mass)
g is gravitational acceleration
g_c is proportionality constant

Applying the previous equation to Newton's second law yields

$$F = m\times\frac{dv}{dt}\times\frac{1}{g_c} = ma\times\frac{1}{g_c} \tag{2.2}$$

where
F is force
v is velocity
t is time
a is acceleration
g_c is proportionality constant