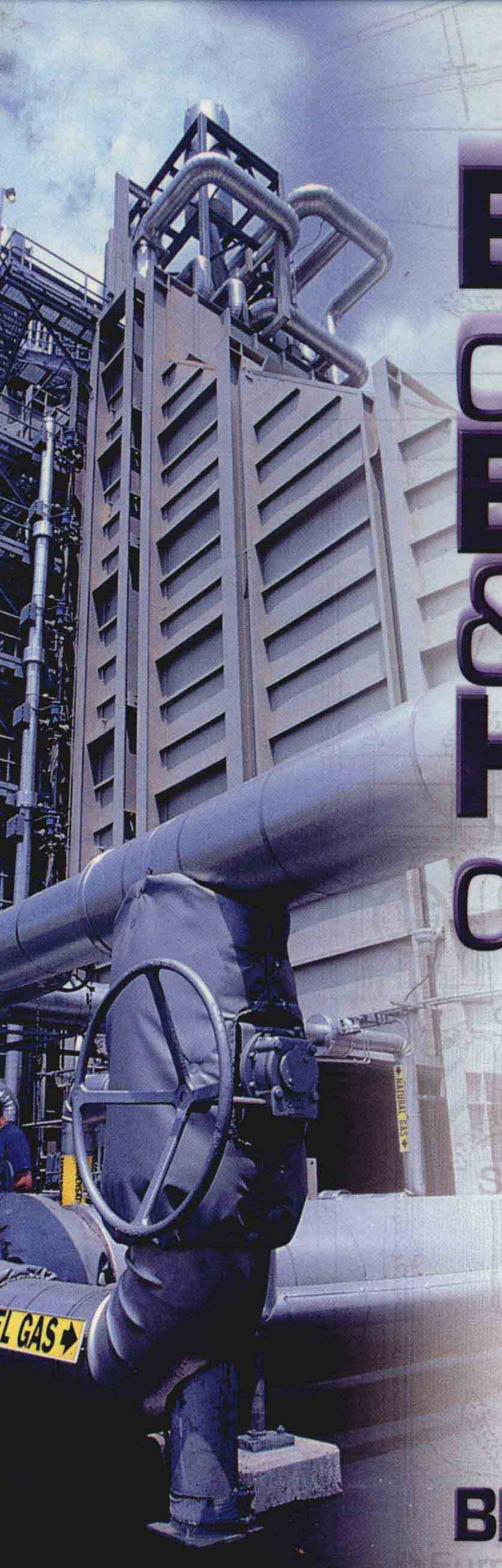

BASICS of BOILER & HRSG design

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Basics of Boiler and HRSG Design

Dedication

This book is dedicated to the special colleagues with whom it has been a pleasure to work and know for many years. I wish to particularly recognize Todd Hill, Karl Kohlrus, Doug Dorsey, Ellis Loper, Dave Arnold, John Wofford, Ron Axelton, and Sean MacDonald. Not forgotten are all of my other friends at City Water, Light & Power, Burns & McDonnell Engineering, UCB Films and CEDA.

List of Acronyms

ACFB	atmospheric circulating fluidized bed
ASME	American Society of Mechanical Engineers
ASTM	American Society of Testing & Materials
BACT	best available control technology
BCC	body-centered cubic
BFB	bubbling fluidized bed
Btu	British thermal unit
CAAA	Clean Air Act Amendment
CFB	circulating fluidized bed
COHPAC	compact hybrid particulate collector
DBA	dibasic acid
DNB	departure from nucleate boiling
DOE	United States Department of Energy
DP	dolomite percentage
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
ESP	electrostatic precipitator
FAC	flow-assisted corrosion
FBHE	fluidized-bed heat exchanger
FCC	face-centered cubic
FEGT	furnace exit gas temperature
FGD	flue gas desulfurization
FT	fluid temperature
HAP	hazardous air pollutant
HCP	hexagonal close packed
HHV	higher heating value
HP	high pressure
HRSG	heat recovery steam generator/generation
HT	hemispherical temperature
ICGCC	integrated coal gasification combined-cycle
IFB	inclined fluidized-bed
IP	intermediate pressure
IT	initial deformation temperature
kV	kilovolt
LAER	lowest achievable emission rate
LHV	lower heating value
LNB	low-NOx burners
LP	low pressure
MW	megawatt

NAAQS	National Ambient Air Quality Standards
NACE	National Association of Corrosion Engineers
NiDI	Nickel Development Institute
OFA	overfire air
PC	pulverized coal
PM2.5	particulate matter less than 2.5 microns in diameter
PPM	parts-per-million
PPMV	parts-per-million by volume
PRB	Powder River Basin
RDF	refuse-derived fuel
SCR	selective catalytic reduction
SD	softening temperature
SNCR	selective non-catalytic reduction
STP	standard temperature and pressure
UNC-CH	University of North Carolina-Chapel Hill
WESP	wet electrostatic precipitator

FOREWORD

The genesis of this project can be traced to several colleagues who asked me if there was a book on the market describing the basic aspects of fossil-fired steam generator design. I could think of two excellent but very detailed books, Babcock and Wilcox's *Steam* and Combustion Engineering's (now Alstom Power) *Combustion*, but it appeared that a need existed for a condensed version of this material. This book is also "generated" in part by changes in the utility industry, and indeed in other industries—the "do more with less" philosophy. Plants are now being operated by people who have to wear many hats, and may not have extensive training in areas for which they are responsible. The book therefore serves as an introduction to fundamental boiler design for the operator, manager, or engineer to use as a tool to better understand his/her plant. It also serves as a stepping-stone for those interested in investigating the topic even further.

I could not have completed this book without the assistance of many friends who supplied me with important information. These individuals include Mike Rakocy and Steve Stultz of Babcock & Wilcox, Ken Rice and Lauren Buika of Alstom Power, Stacia Howell and Gretchen Jacobson at NACE International, Jim King of Babcock Borsig Power, Jim Kennedy of Foster Wheeler, and Pat Pribble of Nooter Eriksen. All supplied illustrations or granted permission to reproduce illustrations.

The structure of the book is as follows:

- Chapter 1 discusses fundamentals of steam generation and conventional boiler design
- Chapter 2 discusses some of the "newer" (in terms of large-scale use) technologies, including fluidized-bed combustion and heat recovery steam generation (HRSG). For the latter subject, I had the aid of a fine book published by PennWell, *Combined Cycle Gas & Steam Turbine Power Plants, 2nd ed.* For those who really wish to examine combined-cycle operating characteristics in depth, I recommend this book
- Chapter 3 looks at fuel and ash properties
- Chapter 4 examines typical fossil-fuel plant metallurgy. This is very important with regard to plant design and successful operation

- Chapter 5 reviews many important topics regarding air pollution control—a constantly evolving issue. Utility managers will most certainly be faced with new air emissions control challenges in the years and decades to come

I hope you enjoy this book. I spent a number of years at a coal-fired utility, where practical information was of great importance. I have always tried to follow this guideline when writing so the reader can obtain useful data without having to wade through a mountain of extraneous material. I hope this comes through in the book.

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Chapter 1

Fossil-Fired Boilers–Conventional Designs

INTRODUCTION

People throughout much of the world have become dependent upon electricity to operate everything from home lighting systems to the most advanced computers. Without electricity, industrial societies would collapse in short order. A very large part of electric power production comes from steam-driven turbine/generators, and even though other sources of energy are becoming more popular, steam-produced electricity will meet our needs for years to come.

Steam also powers many industrial processes that produce goods and services, including foods, pharmaceuticals, steel, plastics, and chemicals. Yet issues related to global warming, acid rain, conservation of resources, and other economic and environmental concerns require that existing plants be operated with the utmost efficiency, while better energy production technologies are being developed.

This chapter provides information about fundamental boiler designs, many of which are still in use today. Knowledge of these basics provides a stepping-stone for understanding newer steam generation technologies, such as the heat recovery steam generator (HRSG) portion of combined-cycle plants.

The steam generating process can be rather complex, especially when electrical generation is part of the network. Consider Figure 1-1. The boiler produces steam to drive both an industrial process and a power-generating turbine. Condensate recovered from the industrial plant is cleaned, blended with condensed steam from the turbine, and the combined stream flows through a series of feedwater heaters and a deaerator to the boiler. The superheater increases steam heat content, which in turn improves turbine efficiency. The turbine itself is an intricate and finely tuned machine, delicately crafted and balanced to operate properly (see Appendix 1-1).

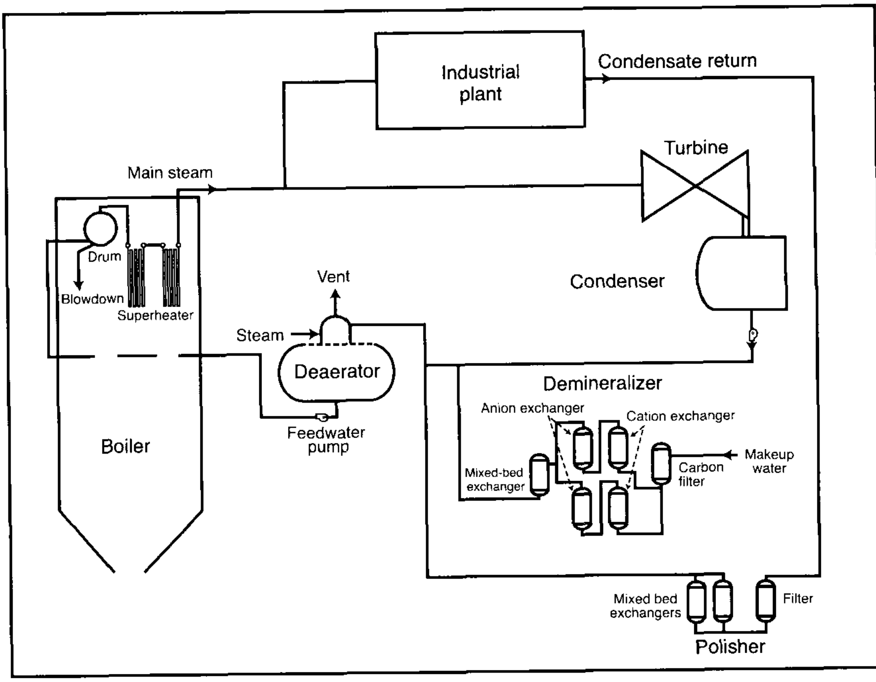

Fig. 1-1: Possible water/steam network at a co-generation plant

How did steam-generating units evolve into such complex systems? The process has taken several hundred years.

Early history of steam generation

The Industrial Revolution of the eighteenth and nineteenth centuries drove a spectacular increase in energy requirements throughout Western Europe, the U.S., and other areas of the world. Some of the industries that blossomed, such as steel making, utilized a great deal of direct heating. However, many processes also required what might be termed *indirect* or *step-wise* heating, in which combustion of fossil fuels in a pressure vessel converts water to steam. It is then transported to the process for energy transfer. Water is used as the energy transfer medium for many logical reasons. It is a very stable substance, available in great abundance, and because of its abundance, is inexpensive.

The first chapter of Babcock & Wilcox's book, *Steam,* outlines the early history of steam generation. The French and British developed practical steam applications in the late 1600s and early 1700s, using steam for food processing and operating water pumps, respectively. The boilers of that time were very simple devices, consisting of kettles heated by wood or charcoal fires.

Technology slowly progressed throughout the 1700s, and by the end of the century and into the early 1800s, several inventors had moved beyond the very basic, and very inefficient, kettle design, developing simple forms of water tube boilers (Fig. 1-2). This period also witnessed the development of fire tube boilers, in which combustion gases flow through boiler tubes with the liquid contained by the storage vessel. The fire tube design had one major disadvantage—the boiler vessel could not handle very high pressures. Many lives were lost due to fire tube boiler explosions in the 1800s, and the design lost favor to water tube boilers. Since the latter dominate the power generation and most of the industrial market, this book will focus exclusively on water tube boilers.

The world changed forever with the invention of practical electrical systems in the early 1880s and development of steam turbines for power generation around the turn of the twentieth century. Ever since, inventors and researchers have worked to improve generation technology in the quest for more efficient electricity production. This chapter looks at conventional boiler types from the late 1950s onward.

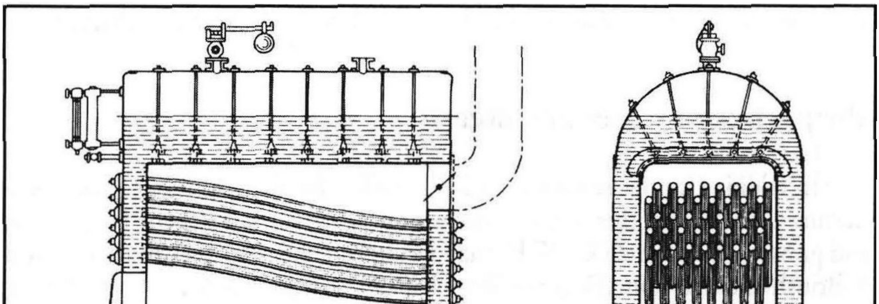

Fig. 1-2: An early steam boiler developed by Stephen Wilcox (Reproduced with permission from *Steam*, 40th ed., published by Babcock & Wilcox, a McDermott Company)

Steam generating fundamentals

This section first examines the basics of heat transfer, beginning with the three major types of energy transfer in nature, providing a basis for understanding heat transfer in a boiler.

Radiant energy, conduction, and convection

Consider a summer day after sunrise. *Radiant energy* from the sun directly warms the soil. The soil re-radiates some of this energy in the infrared region, but it also heats air molecules that vibrate and agitate other air molecules. This heating process is *conduction*. As the air warms, it rises, and cooler air flows in to take its place. This flow of fluids due to density difference is *convection*.

All three energy transfer mechanisms—radiant energy, conduction, and convection—are at work in a boiler. Radiant heat is obvious—burning fuel emits energy in the form of light and heat waves that travel directly to boiler tubes and transfer energy. Conduction is another primary process wherein the heat produced by the burning fuel greatly agitates air and the combustion-product molecules, which transfer heat to their surroundings. Conduction is also the mode of heat transfer through the boiler tubes; but in this case, the vibrating molecules are those of the tubes. Convection occurs both naturally and mechanically on the combustion and waterside of the boiler. Fans assist convection on the gas side, while waterside convection occurs both naturally and assisted by pumps. Waterside and combustion-side flow circulation are examined in more detail in this chapter and chapter 2.

Properties of water and steam

In addition to the reasons mentioned earlier for the selection of water as a heating medium, another is its excellent heat capacity. At standard temperature and pressure (STP) of 25°C (77°F) and one atmosphere (14.7 psi), heat capacity is 1 British thermal unit (Btu) per lbm-°F (4.177 kJ per kg-°C). Other physical aspects are also important. Between the freezing and boiling points, any heat added or taken away directly changes the temperature of the liquid. However, at the freezing and boiling points, additional mechanisms come into play. Consider the scenario in which water is heated at normal atmospheric pressure, and the temperature reaches 212°F (100°C). At this point, further energy input does not raise the temperature, but rather is used in converting the liquid to a gas. This is known as the latent heat of vaporization. Thus, it is possible to have a water/steam mixture with both the liquid and vapor at the same temperature. At atmospheric pressure, it takes about 970 Btu to convert a pound of water to steam (2,257 kJ/kg). Once all of the water transforms to steam, additional heating again results in a direct temperature increase. Likewise, when water is cooled to 32°F, additional cooling first converts the water to ice before the temperature drops any lower. This is known as the latent heat of fusion.

As a closed pressure vessel, a boiler allows water to be heated to temperatures much higher than those at atmospheric conditions. For example, in a boiler that operates at 2,400 psig (16.54 mPa), conversion of water to steam occurs at a temperature of 663°F (351°C). Thus, it is possible to add much more heat to the water than at atmospheric pressure. This in turn gives the fluid more potential for work in a heat transfer device. The following discussion of boiler designs illustrates how the boiler components extract energy from burning fuel to produce steam.

Fundamental boiler design

Figure 1-3 is the simple outline of a natural circulation, drum-type boiler. While this is an elementary diagram, the essentials of water/steam flow are illustrated in this drawing.

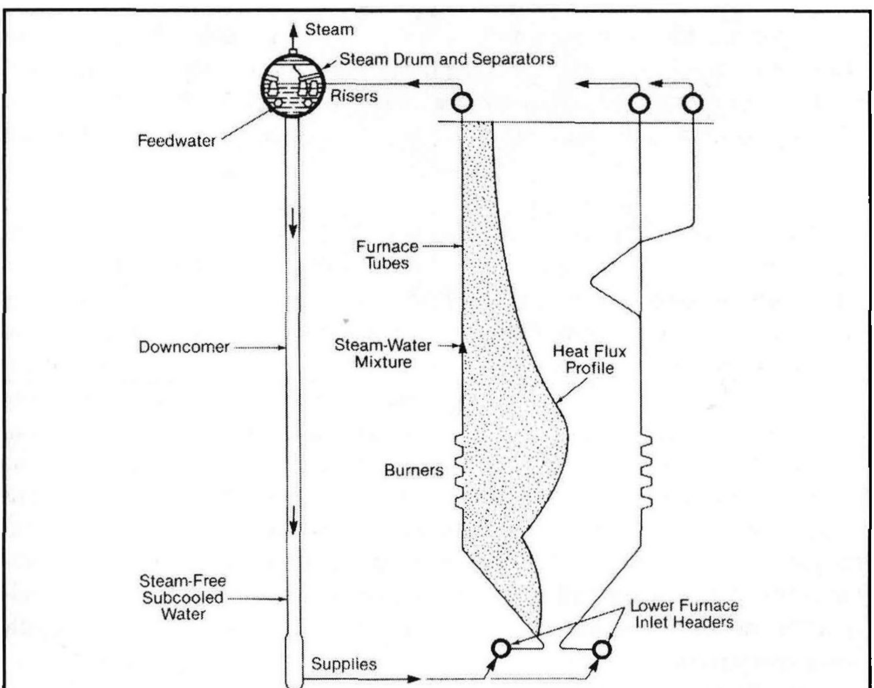

Fig. 1-3: A simplified view of water flow in a drum-type, natural-circulation boiler (Reproduced with permission from *Steam*, 40th ed., published by Babcock & Wilcox, a McDermott Company)

Steam generation begins in the waterwall tubes located within the furnace area of the boiler. As the boiler water flowing into the tubes absorbs heat, fluid density decreases and the liquid rises by convection. Conversion to steam begins as the fluid flows upwards through the waterwall tubes, known as risers. (As Appendix 1-2 outlines, a smooth transition of water to steam in the tubes is important.) The water/steam mixture enters the drum, where physical separation