EDITION: 41

Steam

its generation and use

Sample Pages

The Babcock & Wilcox Company
a McDermott company

a McDermott company

The Babcock & Wilcox Company

Preface

Dear Reader:

The founders of our company, George Babcock and Stephen Wilcox, invented the safety water tube boiler. This invention resulted in the commercialization of large-scale utility generating stations. Rapid increases in generation of safe, dependable and economic electricity literally fueled the Industrial Revolution and dramatically increased the standard of living in the United States and industrialized economies worldwide throughout the twentieth century.

Advancements in technology to improve efficiency and reduce environmental emissions have continued for nearly 140 years, creating a unique and valuable body of applied engineering that represents the individual and collective contributions of several generations of employees. As in other areas of science and engineering, our field has continued to evolve, resulting in an extensive amount of new material that has been incorporated into our 41st edition of *Steam/its generation and use.* This edition required an extensive amount of personal time and energy from hundreds of employees and reflects our commitment to both our industry and our future.

Today it is clear that the challenge to generate power more efficiently from fossil fuels, while minimizing impacts to our environment and global climate, will require significant technological advancements. These advances will require creativity, perseverance and ingenuity on the part of our employees and our customers. For inspiration, we can recall the relentless drive and imagination of one of our first customers, Mr. Thomas Alva Edison. For strength, we will continue to embrace our Core Values of Quality, Integrity, Service and People which have served us well over our long history as a company.

I thank our shareholders, our employees, our customers, our partners and our suppliers for their continued dedication, cooperation and support as we move forward into what will prove to be a challenging and rewarding century.

To help guide us all along the way, I am very pleased to present *Edition: 41*.

David L. Keller

David L. Keller
President and Chief Operating Officer
The Babcock & Wilcox Company

Table of Contents

Section I – Steam Fundamentals

Section II – Steam Generation from Chemical Energy

Section III – Applications of Steam

Section IV – Environmental Protection

Section V – Specification, Manufacturing and Construction

Section VI – Operations

Section VII – Service and Maintenance

Section VIII – Steam Generation from Nuclear Energy

Appendices

Editors' Foreword

When we completed the 40th edition of *Steam* in 1992, we had a sense that perhaps our industry was stabilizing. But activity has again accelerated. Today, efficiencies are being driven even higher. Emissions are being driven even lower. Many current technologies are being stretched, and new technologies are being developed, tested and installed. We have once again changed much of *Steam* to reflect our industry's activity and anticipated developments.

Recognizing the rich history of this publication, we previously drew words from an 1883 edition's preface to say that *"we have revised the whole, and added much new and valuable matter."* For this new 41st edition we can draw from the 1885 edition to say *"Having again revised Steam, and enlarged it by the addition of new and useful information, not published heretofore, we shall feel repaid for the labor if it shall prove of value to our customers."*

We hope this new edition is of equal value to our partners and suppliers, government personnel, students and educators, and all present and future employees of The Babcock & Wilcox Company.

Introduction to *Steam*

Throughout history, mankind has reached beyond the acceptable to pursue a challenge, achieving significant accomplishments and developing new technology. This process is both scientific and creative. Entire civilizations, organizations, and most notably, individuals have succeeded by simply doing what has never been done before. A prime example is the safe and efficient use of steam.

One of the most significant series of events shaping today's world is the industrial revolution that began in the late seventeenth century. The desire to generate steam on demand sparked this revolution, and technical advances in steam generation allowed it to continue. Without these developments, the industrial revolution as we know it would not have taken place.

It is therefore appropriate to say that few technologies developed through human ingenuity have done so much to advance mankind as the safe and dependable generation of steam.

Steam as a resource

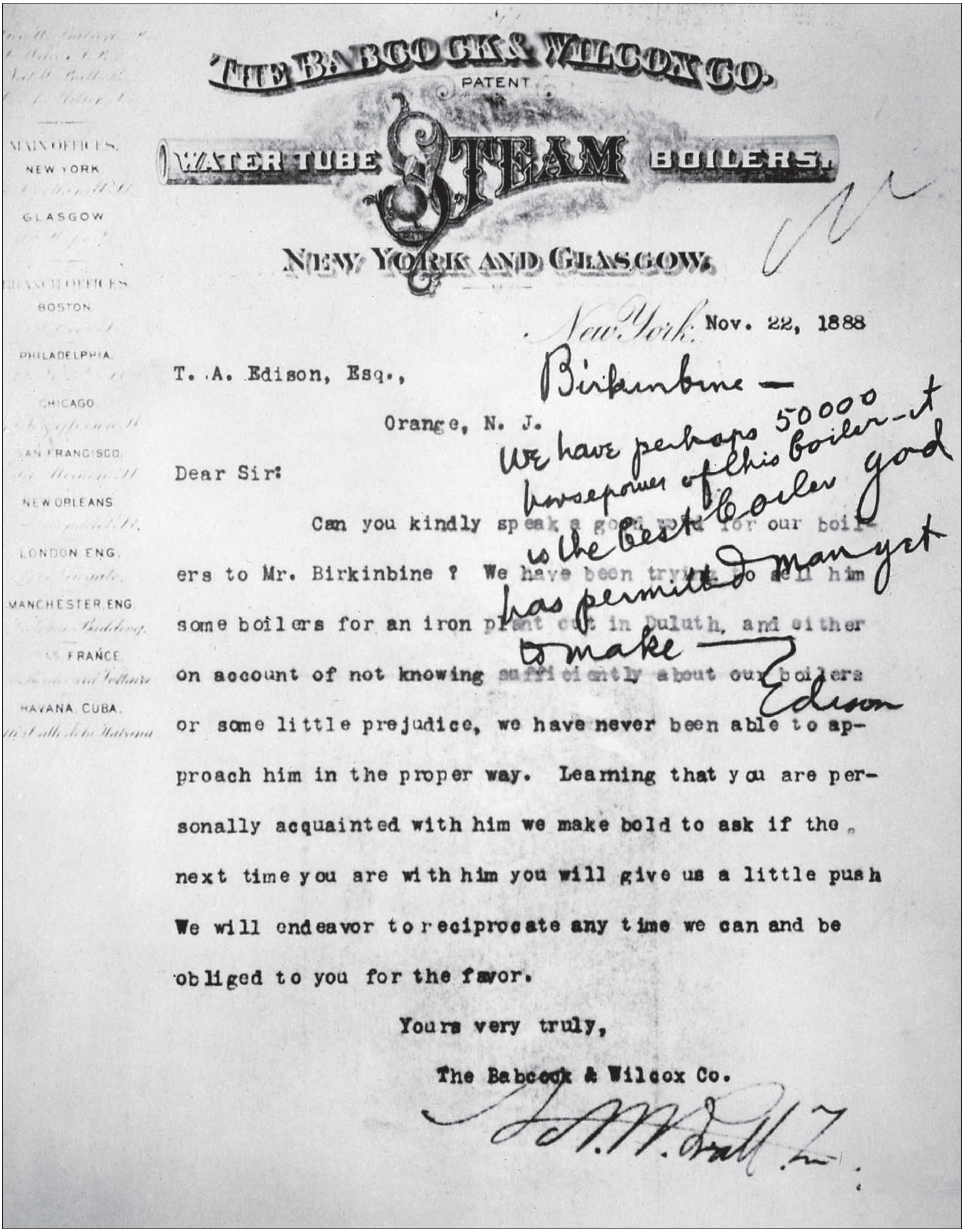
In 200 B.C., a Greek named Hero designed a simple machine that used steam as a power source (Fig. 1). He began with a cauldron of water, placed above an open fire. As the fire heated the cauldron, the cauldron shell transferred the heat to the water. When the water reached the boiling point of 212F (100C), it changed form and turned into steam. The steam passed through two pipes into a hollow sphere, which was pivoted at both sides. As the steam escaped through two tubes attached to the sphere, each bent at an angle, the sphere moved, rotating on its axis.

Hero, a mathematician and scientist, labeled the device *aeolipile*, meaning rotary steam engine. Although the invention was only a novelty, and Hero made no suggestion for its use, the idea of generating steam to do useful work was born. Even today, the basic idea has remained the same – generate heat, transfer the heat to water, and produce steam.

Intimately related to steam generation is the steam turbine, a device that changes the energy of steam into mechanical work. In the early 1600s, an Italian named Giovanni Branca produced a unique invention (Fig. 2). He first produced steam, based on Hero's aeolipile. By channeling the steam to a wheel that rotated, the steam pressure caused the wheel to turn. Thus began the development of the steam turbine.

The primary use of steam turbines today is for electric power production. In one of the most complex systems ever designed by mankind, superheated high-pressure steam is produced in a boiler and channeled to turbine-generators to produce electricity.

Fig. 1 Hero's aeolipile.



THE BABCOCK & WILCOX CO.
PATENT
WATER TUBE STEAM BOILERS.
NEW YORK AND GLASGOW.

MAIN OFFICES.
NEW YORK
GLASGOW
BRANCH OFFICES
BOSTON
PHILADELPHIA
CHICAGO
SAN FRANCISCO
NEW ORLEANS
LONDON ENG.
MANCHESTER ENG.
FRANCE
HAVANA CUBA.

New York. Nov. 22, 1888

T. A. Edison, Esq.,
Orange, N. J.

Dear Sir:

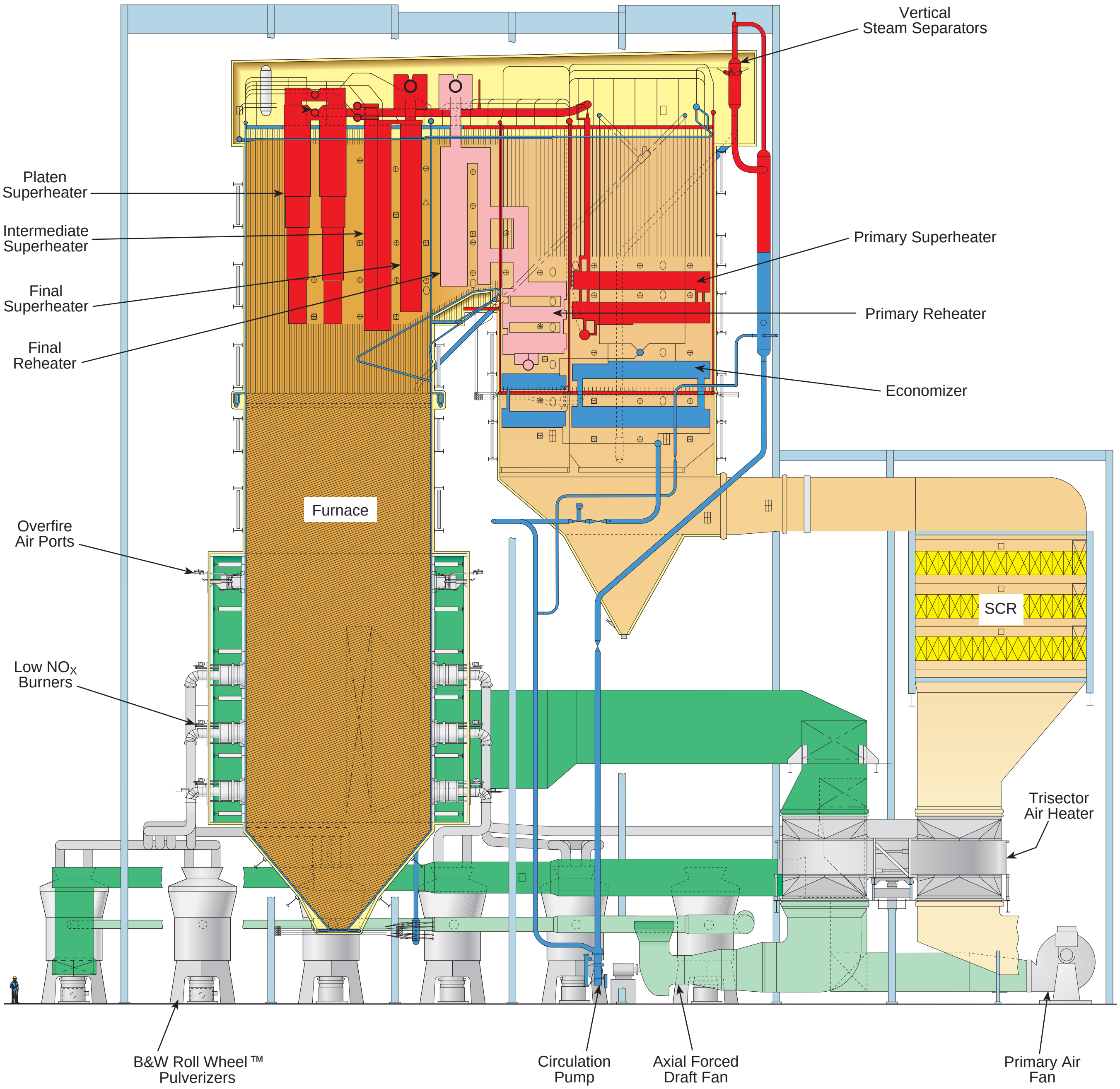
Can you kindly speak a good word for our boilers to Mr. Birkinbine ? We have been trying to sell him some boilers for an iron plant out in Duluth, and either on account of not knowing sufficiently about our boilers or some little prejudice, we have never been able to approach him in the proper way. Learning that you are personally acquainted with him we make bold to ask if the next time you are with him you will give us a little push We will endeavor to reciprocate any time we can and be obliged to you for the favor.

Yours very truly,

The Babcock & Wilcox Co.

Birkinbine —
We have perhaps 50000 horsepower of this boiler — it is the best Boiler god has permitted man yet to make —
Edison

Fig. 15 Thomas Edison's endorsement, 1888.



B&W supercritical boiler with spiral wound Universal Pressure (SWUP™) furnace.

Chapter 6

Numerical Modeling for Fluid Flow, Heat Transfer, and Combustion

Numerical modeling – an overview

Continuous and steady advances in computer technology have changed the way engineering design and analyses are performed. These advances allow engineers to deal with larger-scale problems and more complex systems, or to look in more detail at a specific process. Indeed, through the use of advanced computer technology to perform engineering analysis, numerical modeling has emerged as an important field in engineering. While this chapter focuses on fluid flow and heat transfer, Chapter 8 provides a brief discussion of numerical modeling for structural analysis.

In general, the term *numerical method* describes solving a mathematical description of a physical process using a numerical rather than an analytical approach. This may be done for a number of reasons, including the following:

1. An analytical means of solving the equations that describe the system may not exist.
2. Even though an analytical method is available, it may be necessary to repeat the calculation many times, and a numerical method can be used to accelerate the overall process.

A small-scale replica of an apparatus is considered a *physical model* because it describes the full-size apparatus on a smaller scale. This model can incorporate varying levels of detail depending on need and circumstances. A mathematical description of a physical system (referred to as a *mathematical model*) can also incorporate varying levels of detail. Similar to a physical model, the amount of detail is often determined by the accuracy required and the resources available to use the model. This creates a need to strike a balance between accuracy, complexity and efficiency.

There are two basic approaches to mathematical modeling.

1. *Model the behavior of a system*. Network flow models and heat exchanger heat transfer correlations are examples of a system model.
2. *Model the fundamental physics of a system to determine the behavior*. Computational fluid dynamics (CFD) and chemical reaction models fall into this category.

The term *numerical modeling* usually refers to the use of numerical methods on high-powered computers to solve a complex system of mathematical models based on the fundamental physics of the system. In this respect, it describes the second approach identified above.

As an example, consider analysis of hot air moving through a length of duct composed of several different components all in a cold environment.

The first type of analysis would involve a network model. This model would describe the pressure drop and heat loss along the duct based on the length, shape, number of turns, etc. This model is based on extensive flow measurements taken on the individual components (i.e., straight sections, turns, reductions, etc.) that make up the duct. A set of empirical and fundamental correlations is used to analyze the flow rate through the duct. The computation can be set up quickly and with minimal effort. Results and multiple variations can be rapidly obtained. While results are reasonably accurate, they are limited to the components for which a flow correlation already exists. A unique component design that has not been described by a correlation may not be accurately evaluated with this type of model.

The second type of analysis would involve a CFD model of the same duct. The detailed behavior of the flow through the entire duct is modeled. From this information, pressure drop and heat loss along the length of the duct may be determined. However, unlike the first analysis, this type of model provides additional details. For example, the first model does not consider how the flow through a bend differs if it is followed by another bend or a straight section; the first model may result in the same pressure drop regardless of how the components are arranged. The second analysis would account for these differences. In addition, variation in heat loss from one side of the duct to the other can be determined. Most importantly, this model is not restricted to duct components where extensive experimental data is available. New concepts can easily be evaluated.

These two approaches have both benefits and limitations. The appropriate use of each is determined by the information needed and the information available. While both approaches are important engineering tools, the remaining discussion here will focus on the second, specifically on CFD and combustion modeling, and how they relate to furnaces, boilers and accessory equipment.

through the unit. Fig. 5a shows the case without the tray. The lowest profile shows how non-uniform flow develops as the high velocity flue gas is introduced into the tower, is decelerated, and makes a sharp right-angle turn to flow up the tower. In the absence of a tray, the high velocity (red) and low velocity (blue) regions persist as the flue gas moves through the middle of the tower (middle velocity profile) entering the first level of spray headers. Some of the non-uniformity persists even up to the mist eliminators. With the addition of the tray (Fig. 5b), the large high and low velocity regions are effectively eliminated. The resulting more-uniform velocity profile and the gas/reagent mixing on top of the tray permit higher levels of SO_2 control at reduced slurry recirculation rates.

This model has also been used to explore design changes to meet site-specific new and retrofit requirements.[25] These have included alternate flue gas exit geometries, flue gas inlet conditions, tower diameter transitions, header locations, slurry recirculation rates or other factors while still achieving the desired performance. It has also been used to investigate internal design alternatives to boost performance and reduce pressure drop.

Popcorn ash

Situation Popcorn, or large particle, ash forms under certain conditions from the combustion of coal and is light, porous, irregularly shaped, and often forms in the upper boiler furnace or on the convective heat transfer surface. This ash can plug the top catalyst layer in selective catalyst reduction (SCR) NO_x control systems, increasing pressure drop and decreasing catalyst performance. Modifications to both the economizer outlet hoppers and the ash removal systems can increase ash capture to address this situation.

Accurately predicting how the popcorn ash behaves within the economizer gas outlet requires detailed knowledge of the aerodynamic properties of the ash particles and sophisticated modeling techniques. Key ash properties include the particle density, drag coefficient, coefficients of restitution, and its coefficient of friction with a steel plate. CFD models involve solving the gas flow solution, then calculating the particle trajectories using B&W's proprietary CFD software.

Analysis Most CFD programs that handle particle-to-wall interactions are not adequate to accurately predict the complex behavior seen in the popcorn ash physical experiments. These deficiencies have been remedied by adding capabilities to B&W's proprietary CFD software. First, the coefficient of restitution is separated into its normal and tangential components. Next, a particle-to-wall friction model is used for particles sliding along the wall and experiencing a friction force proportional to the coefficient of friction measured in the physical tests. Also, the ability to set

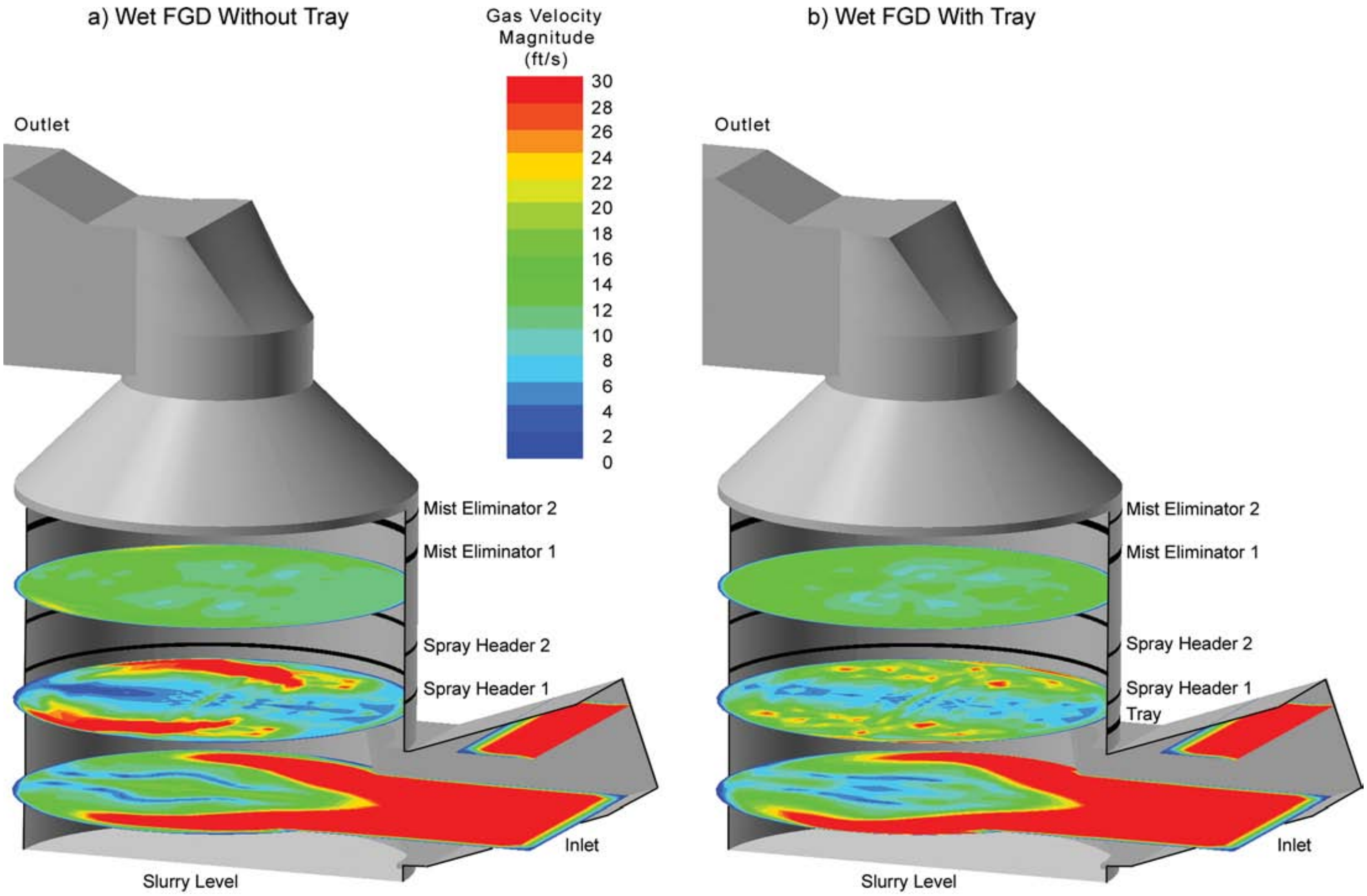


Fig. 5 Effect of B&W's tray design on gas velocities through a wet flue gas desulfurization system – numerical model results on a 650 MW absorber.

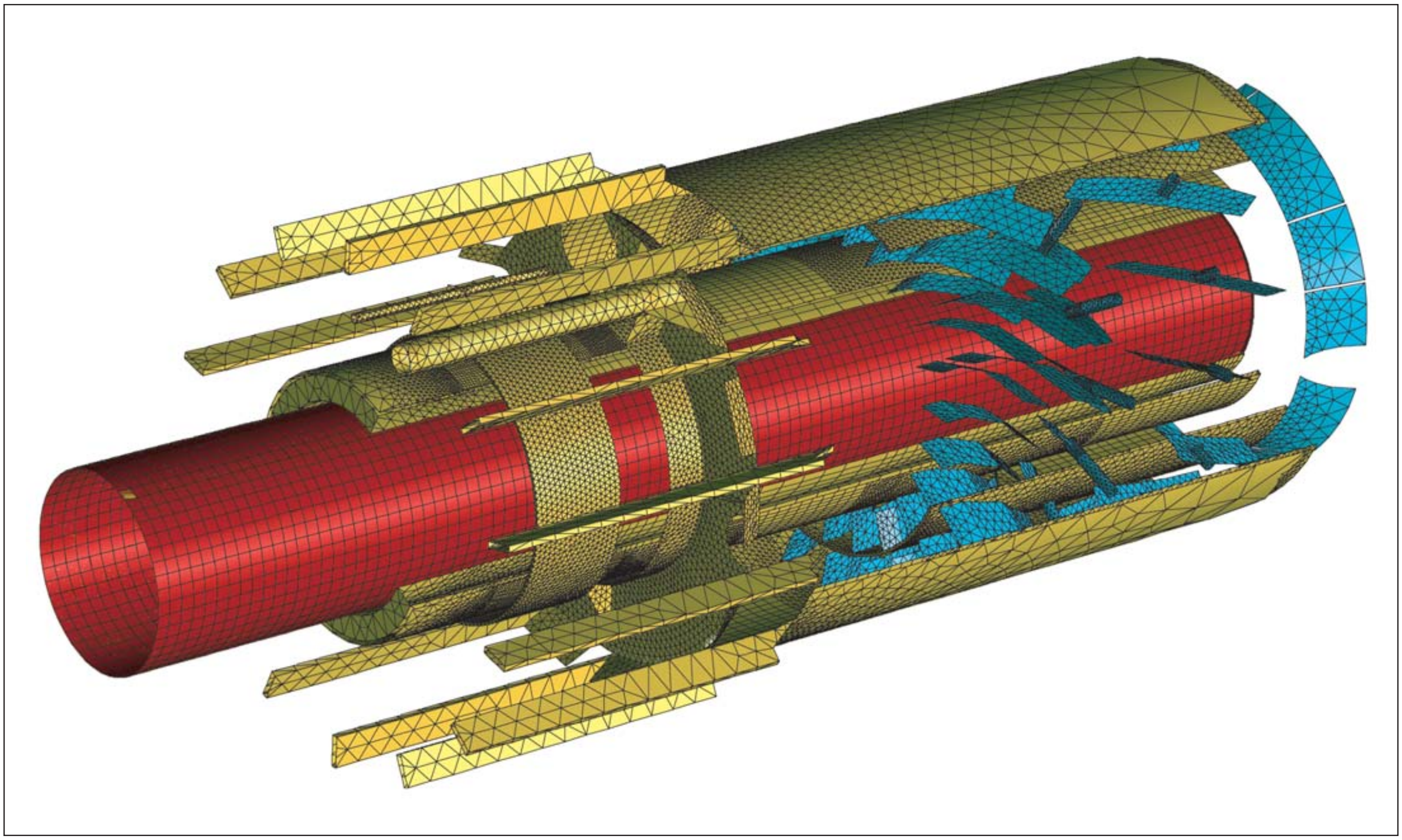


Fig. 23 Detailed numerical model evaluation grid for an advanced coal burner.

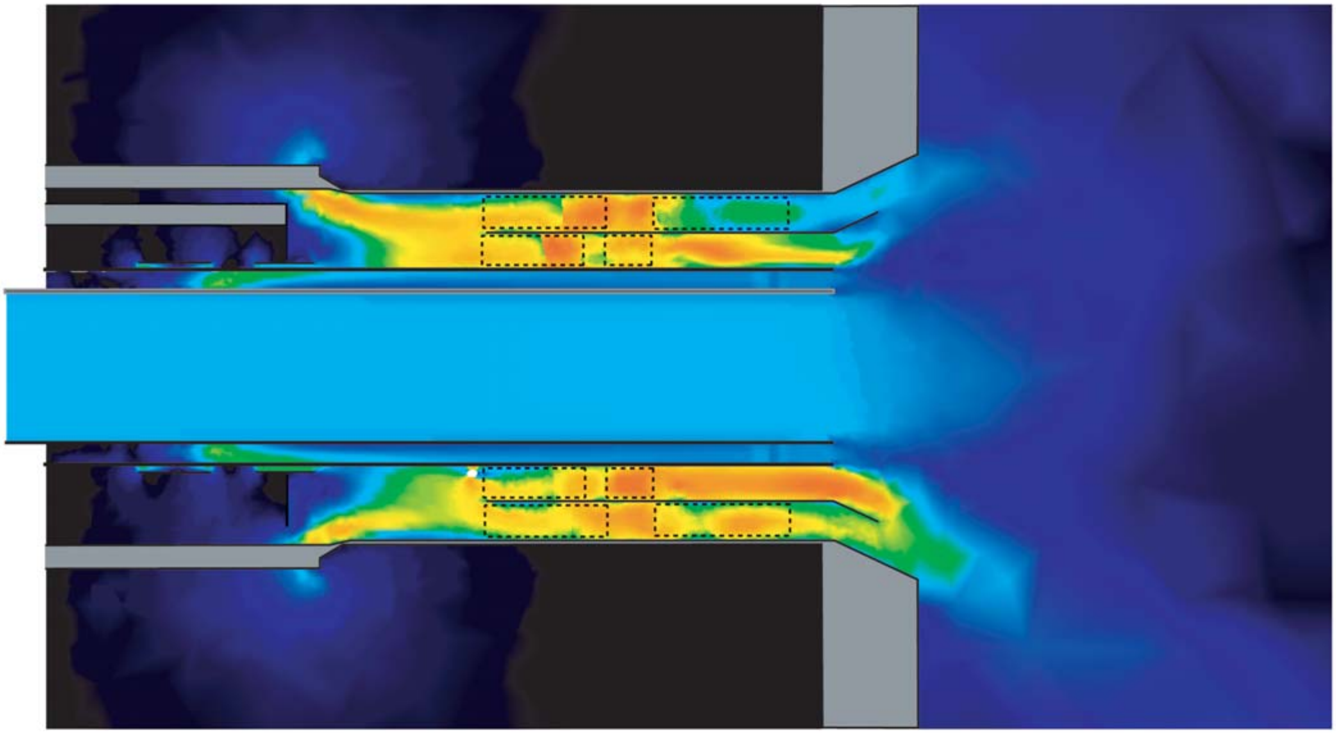


Fig. 24 Gas velocity model for the coal burner shown in Fig. 23.

Chapter 26

Fossil Fuel Boilers for Electric Power

Most of the electric power generated in the United States (U.S.) is produced in steam plants using fossil fuels and high speed turbines. These plants deliver a kilowatt hour of electricity for each 8500 to 9500 Btu (8968 to 10,023 kJ) supplied from the fuel, for a net thermal efficiency of 36 to 40%. They use steam driven turbine-generators of up to 1300 MW capacity with boilers generating from one million to ten million pounds of steam per hour. A typical coal-fired facility is shown on the facing page.

Modern fossil fuel steam plants use reheat cycles with nominal steam conditions of 3500 psi/1050F/1050F (24.1 MPa/566C/566C) for supercritical pressure systems, and 2400 psi (16.5 MPa) with superheat and reheat steam temperatures ranging from 1000 to 1050F (538 to 566C) for subcritical pressure systems. For some very small units, lower steam conditions may be applied. In selected global locations where higher cycle efficiencies are required, supercritical pressure steam conditions on the order of 4300 psi/1075F/1110F (29.6 MPa/579C/599C) and 3626 psi/1112F/1130F (25.0 MPa/600C/610C) have been used.

Most power plants in the U.S. and around the world are owned and operated by: 1) investor owned electric companies, 2) federal, state or local governments, or 3) finance companies.

These owners, whether public or private, have been generally known as *utilities*. During the 1980s and 1990s, there was a trend toward new types of companies supplying significant portions of new generation. However, the fundamental approach to selecting power generation equipment will remain unchanged.

Selection of steam generating equipment

The owner has several technologies to choose from based upon fuel availability, emissions requirements, reliability, and project timing. One of the common choices for modern electric power generation is the high pressure, high temperature steam cycle with a fossil fuel-fired boiler.

Each new electric generating unit must satisfy the user's specific needs in the most economical manner. Achieving this requires close cooperation between the equipment designers and the owner's engineering staff or consultants. The designers, owner and engineering group must identify those equipment features and characteristics that will reliably produce low cost electricity. The primary costs of electricity include: 1) capital equipment, 2) financing charges, 3) fuel, and 4) operation and maintenance. The owner, prior to issuing equipment specifications, reviews and surveys all cost factors. (See Chapter 37.)

The capital cost survey must include all direct costs such as the boiler, steam turbine and electric generator, emissions control equipment, condenser, feedwater heaters and pumps, fuel handling facilities, buildings, and real estate. In addition, finance charges, including interest rates, loan periods, source of funds and tax considerations must be added. Fuel and emission control reagent costs need to be evaluated based on the initial costs, plant capacity variations expected during the life of the plant, and forecasts of cost changes during plant lifetime. The operation and maintenance costs should be estimated based on other current plants with similar equipment, fuels and operating characteristics. Operating and maintenance costs are heavily affected by personnel requirements, and consideration should be given to the availability of skilled labor as well as to the cost of retaining the skilled staff during the plant lifetime.

Plant efficiency, fuel use and capital cost are critically related. Higher plant thermal efficiency obviously reduces annual fuel costs; however, fuel savings are partially offset by the associated higher capital costs. Therefore, selection of the desired plant efficiency should carefully consider the economic tradeoffs between capital and operating costs.

Other important criteria are the location of the electric generating plant with respect to fuel supply and the areas where electricity is used. In some cases, it is more economical to transport electricity than fuel. Some large steam generating stations have been built at the coal mine mouth to generate electricity which is then used several hundred miles away. If the user is a member of a broader grid of interconnected util-

Chapter 27

Boilers for Industry and Small Power

Most manufacturing industries require steam for a variety of uses. Basic plant heating and air conditioning, prime movers such as turbine drives for blowers and compressors, drying, constant temperature reaction processes, large presses, soaking pits, water heating, cooking and cleaning are all examples of how steam is used.

Steam produced by industrial boilers can also be used to generate electricity in a cogeneration mode which uses a conventional steam turbine for electric power generation and low pressure extraction steam for the process. The electricity is then used by the plant or sold to a local electric utility company. As an alternate cogenerating system, a gas turbine can be used for power generation with a heat recovery steam generator for steam.

Thousands of boilers are installed in industrial and municipal plants, providing lower pressure and temperature steam than utility boilers dedicated to large, central station electric power generation. In an industrial plant, the dependability of steam generating equipment is critical. Most often, the industrial operation has a single steam plant with one or more boilers. If the steam flow is interrupted, production can be seriously impacted. Accordingly, industrial boilers must be very reliable because plant productivity relies so heavily on their availability. Loss of a boiler for a short time can stop production for days if, for example, materials cool and solidify in process lines. For this reason, some industries prefer multiple smaller units.

The principles governing the selection of boilers and related equipment are discussed in Chapter 37. Proper equipment selection can be accomplished only in the framework of a sound technical and cost evaluation. This requires a working knowledge and understanding of the performance of the different steam generating unit components under various conditions, including the significance of the many different arrangements of heat absorbing surfaces, the characteristics of available fuels, combustion methods and ash handling. The owner must also establish the present and future steam conditions and requirements. All pertinent environmental regulations must also be considered. A brief summary of boiler specifications is provided in Table 1.

Industrial boiler design

Industrial boilers generally have different performance characteristics than utility boilers. These are most apparent in steam pressures and temperatures as well as the fuel burning equipment.

Industrial units are built in a wide range of sizes, pressures and temperatures – from 2 psig (13.8 kPa) and 218F (103C) saturated steam for heating to 1800 psig (12.4 MPa) and 1000F (538C) steam for plant power production.

In addition, industrial units often supply steam for more than one application. For some applications, steam demand may be cyclic or fluctuating, thereby complicating unit operation and control of the equipment.

The Babcock & Wilcox Company (B&W) industrial boilers, such as the unit shown in Fig. 1, are water tube design and generally rely upon natural circulation for steam-water circulation.

Most utility boilers are designed to burn pulverized or crushed coal, oil, gas, or a combination of oil or gas with a solid fuel. Industrial boilers can be designed for the above fuels as well as coarsely crushed coal for stoker firing and a wide range of biomass or byproduct fuels.

Table 1
Typical Industrial Boiler Specification Factors

1. Steam pressure
2. Steam temperature and control range
3. Steam flow
    - Peak
    - Minimum
    - Load patterns
4. Feedwater temperature and quality
5. Standby capacity and number of units
6. Fuels and their properties
7. Ash properties
8. Firing method preferences
9. Environmental emission limitations — sulfur dioxide (SO_2), nitrogen oxides (NO_x), particulate, other compounds
10. Site space and access limitations
11. Auxiliaries
12. Operator requirements
13. Evaluation basis

Chapter 28

Chemical and Heat Recovery in the Paper Industry

In the United States (U.S.), the forest products industry is the third largest industrial consumer of energy, accounting for more than 11% of the total U.S. manufacturing energy expenditures. In 2002, 57% of the pulp and paper industry relied on cogeneration for their electric power requirements.

Approximately one-half of the steam and power consumed by this industry is generated from fuels that are byproducts of the pulping process. The main source of self-generated fuel is the spent pulping liquor, followed by wood and bark. The energy required to produce pulp and paper products has been significantly reduced. Process improvements have allowed U.S. pulp and paper manufacturers to reduce energy consumption to 2.66×10^{12} Btu (2806.5×10^{12} J), a significant reduction.

Pulp and paper mill electric power requirements have increased disproportionately to process steam requirements. This factor, coupled with steadily rising fuel costs, has led to the greater cycle efficiencies afforded by higher steam pressures and temperatures in paper mill boilers. The increased value of steam has produced a demand for more reliable and efficient heat and chemical recovery boilers.

The heat value of the spent pulping liquor solids is a reliable fuel source for producing steam for power generation and process use. A large portion of the steam required for the pulp mills is produced in highly specialized heat and chemical recovery boilers. The balance of the steam demand is supplied by boilers designed to burn coal, oil, natural gas and biomass.

Major pulping processes

The U.S. and Canada have the highest combined consumption of paper and paperboard in the world (Fig. 1), consuming 105.6 million tons each year. With a base of more than 800 pulp, paper and paperboard mills, the U.S. and Canada are also the leader in the production of paper and paperboard. North America accounts for 32% of the total world output; pulp production is nearly 43%.

Total pulp production in the U.S. is divided among the following principal processes: 85% chemical, groundwood and thermomechanical; 6% semi-chemical; and 9% mechanical pulping. The dominant North America pulping process is the sulfate process, deriving its name from the use of sodium sulfate (Na_2SO_4) as the makeup chemical. The paper produced from this process was originally so strong in comparison with alternative processes that it was given the name *kraft*, which is the Swedish and German translation for strong. Kraft is an alkaline pulping process, as is the soda process which derives its name from the use of sodium carbonate, Na_2CO_3 (soda ash), as the makeup chemical. The soda process has limited use in the U.S. and is more prominent in countries pulping nonwood fiber. Recovery of chemicals and the production of steam from waste liquor are well established in the kraft and soda processes. The soda process accounts for less than 1% of alkaline pulp production and its importance is now largely historic.

Kraft pulping and recovery process

Kraft process

The kraft process flow diagram (Fig. 2) shows the typical relationship of the recovery boiler to the overall pulp and paper mill.[1] The kraft process starts with feeding wood chips, or alternatively a nonwood fibrous material, to the digester. Chips are cooked under pressure in a steam heated aqueous solution of

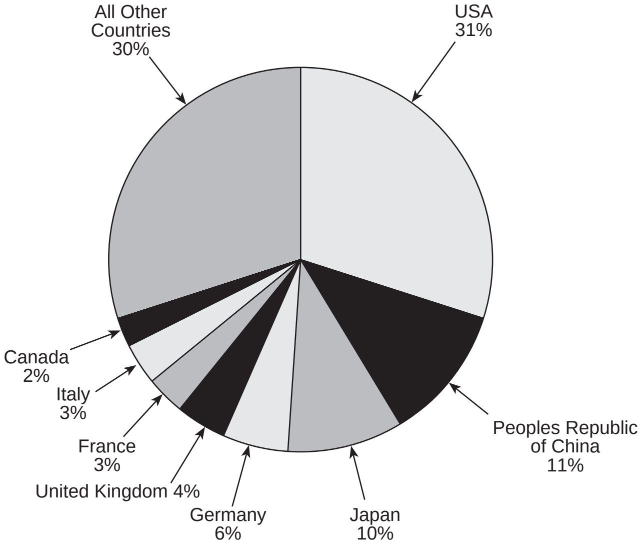


Fig. 1 World paper and board consumption by country, 2000.

Chapter 32

Environmental Considerations

Since the early 1960s, there has been an increasing worldwide awareness that industrial growth and energy production from fossil fuels are accompanied by the release of potentially harmful pollutants into the environment. Studies to characterize emissions, sources and effects of various pollutants on human health and the environment have led to increasingly stringent legislation to control air emissions, waterway discharges and solids disposal.

Comparable concern for environmental quality has been manifest worldwide. Since the 1970s, countries of the Organization for Economic Cooperation and Development have reduced sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emissions from power plants in relation to energy consumption. In at least the foreseeable future, emission trends are expected to continue downward due to a combination of factors: change in fuel mix to less polluting fuels, use of advanced technologies, and new and more strict regulations. In Japan, the reductions in SO_2 emissions were particularly pronounced due to strong environmental measures taken in the 1970s. As an example, in the United States (U.S.) between 1980 and 2001, electricity generation increased by 56%, while SO_2 emissions declined 38%.

Environmental control is primarily driven by government legislation and the resulting regulations at the local, national and international levels. These have evolved out of a public consensus that the real costs of environmental protection are worth the tangible and intangible benefits now and in the future. To address this growing awareness, the design philosophy of energy conversion systems such as steam generators has evolved from providing the lowest cost energy to providing low cost energy with an acceptable impact on the environment. Air pollution control with emphasis on particulate, NO_x, SO_2, and mercury emissions is perhaps the most significant environmental concern for fired systems and is the subject of Chapters 33 through 36. However, minimizing aqueous discharges and safely disposing of solid byproducts are also key issues for modern power systems.

Sources of plant emissions and discharges

Fig. 1 identifies most of the significant waste streams from a modern coal-fired power plant. Typical discharge rates for the primary emissions from a new, modern 615 MW coal-fired supercritical pressure boiler are summarized in Table 1.

Atmospheric emissions arise primarily from the byproducts of the combustion process (SO_2, NO_x, particulate flyash, and some trace quantities of other materials) and are exhausted from the stack. A second source of particulate is fugitive dust from coal piles and related fuel handling equipment. This is especially significant for highly dusting western U.S. subbituminous coals. Some low temperature devolatilization of the coal can also emit other organic compounds. A final source of air emissions is the cooling tower and the associated thermal rise plume which contains water vapor.

Solid wastes arise primarily from collection of the coal ash from the bottom of the boiler, economizer and air heater hoppers, as well as from the electrostatic precipitators and fabric filters. Pyrite collected in the pulverizers (see Chapter 13) is usually also included. Most of the ash is either transported wet to an ash settling pond where it settles out or is transported dry to silos from which it is taken by truck for beneficial use (e.g., cement additive). The chemical composition and characteristics of various ashes are discussed in Chapter 21.

The second major source of solids is the byproduct from the flue gas desulfurization (FGD) scrubbing process. Most frequently, this is a mixture containing primarily calcium sulfate for wet systems and calcium sulfite for dry systems. After dewatering, the wet system byproduct may be sold as gypsum or landfilled. Additional sources of solids include the sludge from cooling tower basins, wastes from the water treatment system and wastes from periodic boiler chemical cleaning.

Aqueous discharges arise from a number of sources. These include once-through cooling water (if used), cooling tower blowdown (if used), sluice water from the ash handling system (via the settling pond), FGD waste water (frequently minimal), coal pile runoff from rainfall, boiler chemical cleaning solutions, gas-side water washing waste solutions, as well as a variety of low volume wastes including ion exchange regeneration effluent, evaporator blowdown (if used), boiler blowdown and power plant floor drains. Many of these streams are chemically characterized in Chapter 42. Additional discussions of these systems as well as the controlling regulations are provided in References 1 and 2.

Air pollution control

U.S. legislation – Clean Air Act

The Federal Clean Air Act (CAA) is the core driving force for all air pollution control legislation in the United States (U.S.). The original CAA was first en-

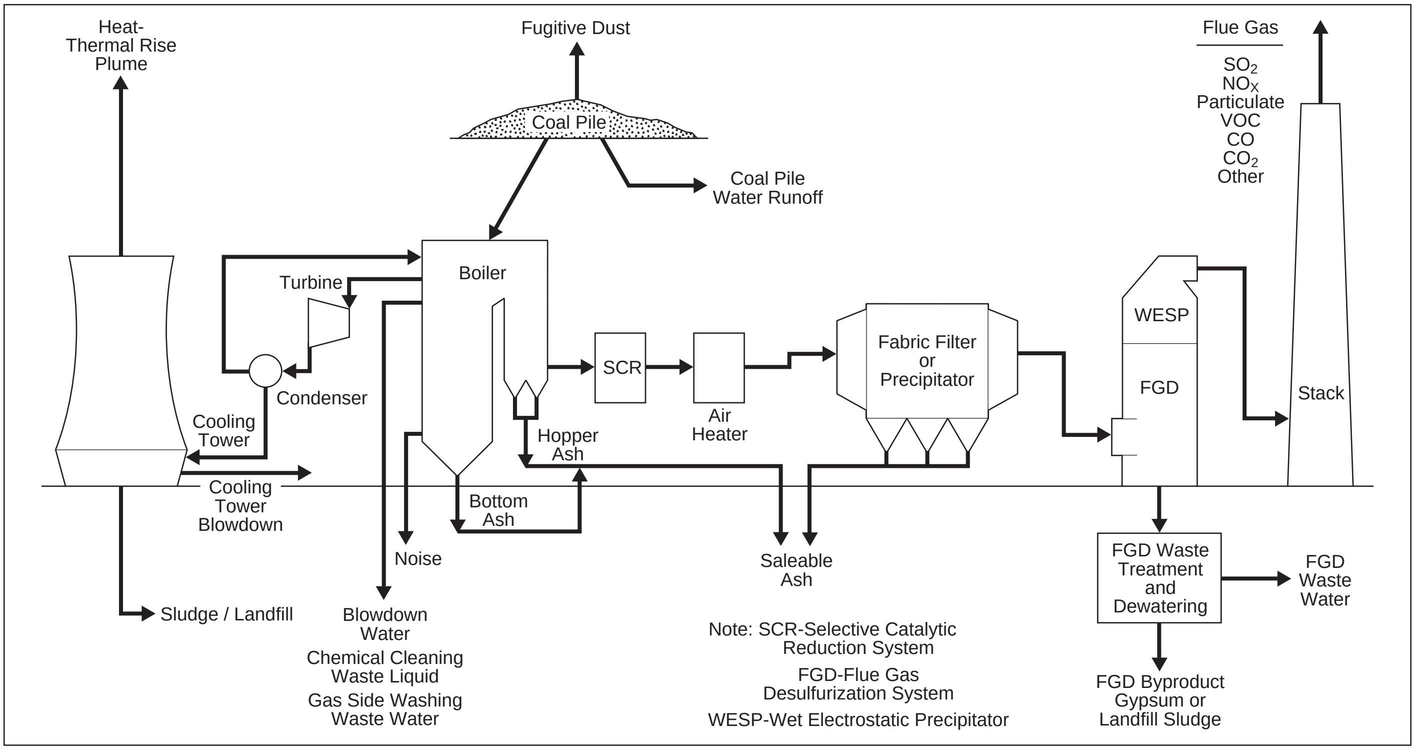


Fig. 1 Typical bituminous coal-fired power plant effluents and emissions.

acted in 1963, and since that time the Act has evolved through five significant amendment cycles in 1965, 1967, 1970, 1977, and 1990.

The primary objective of the CAA is to protect and enhance the quality of the nation's air resources to promote the public health and welfare and the productive capacity of its population.[3] The legislation generally provides for the U.S. Environmental Protection Agency (EPA) to set national air quality standards and other minimum regulatory requirements through federal regulations and guidance to state and local regulatory agencies. The individual states are required to develop state implementation plans (SIPs) to define how they will meet the minimum federal requirements. However, state and local government agencies may also develop and implement more stringent air pollution control requirements. The CAA as amended prior to 1990 included the following regulatory elements of potential interest to boiler owners and operators.

National Ambient Air Quality Standards (NAAQS) Federal standards were developed to define acceptable air quality levels necessary to protect public health and welfare. The EPA promulgated National Ambient Air Quality Standards for six *Criteria Pollutants*: sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), ozone (O_3), particulate matter and lead. Two levels of standards have been established: primary standards aimed at prevention of adverse impacts on human health and secondary standards to prevent damage to property and the environment. All geographic areas of the country are divided into a number of identifiable areas known as air quality control regions which are classified according to their air quality. Air quality control regions that meet or better the NAAQS for a designated pollutant are classified as attainment areas for that pollutant, and regions that fail to meet the NAAQS are classified as nonattainment areas for that pollutant.

New Source Performance Standards (NSPS) Federal New Source Performance Standards were established for more than 70 categories of industrial processes and/or stationary sources. The NSPS rules set source-specific emission limitations and corresponding monitoring, recordkeeping and reporting requirements that must be met by new sources constructed on or after the effective date of an applicable standard. Sources constructed prior to the promulgation of an applicable NSPS are generally *grandfathered* and are not subject to the standards until such time that the source undergoes major modification or reconstruction. The EPA's NSPS regulations are published under Title 40, Part 60 of the Code of Federal Regulations.[4] Table 2 provides reference to select Subparts of 40 CFR 60 applicable to a variety of industrial and utility boilers. The various NSPS rules governing fossil fuel-fired boilers include emission limitations for NO_x, SO_2, particulate and opacity. The NSPS emission limits are based on the EPA's evaluation of best demonstrated technology, and these limits are subject to periodic review and revision. Finally, the NSPS rules generally establish the least stringent emission limitation a new source would have to meet. Typically, more stringent emission limitations are necessary to meet other federal, state or local permitting requirements. For example, any significant new source or major modification to an existing source of emissions may be subject to the federal *New Source Review* rules discussed below.

New Source Review (NSR) New Source Review regulations were established to: 1) preserve existing air quality in areas of the U.S. that are in compliance with

Chapter 44

Maintaining Availability

The design of boiler systems involves the balancing of near-term and long-term capital costs to maximize the availability and useful life of the equipment. Fossil fuel-fired boilers operate in a very aggressive environment where: 1) materials and technology are pushed to their economic limits to optimize efficiency and availability, and 2) the erosive and corrosive nature of the fuels and combustion products result in continuous and expected degradation of the boiler and fuel handling components over time. As a result, the original boiler design is optimized to balance the initial customer capital requirement and the long-term expected maintenance, component replacement, and service costs for a possible operating life of many decades.

When a new power plant is started up, there is a relatively short learning period when the operators and maintenance crews learn to work with the new system and resolve minor issues. This period may be marked by a high forced outage rate, but this quickly declines as the system is broken in and operating procedures are refined.

As the plant matures, the personnel adapt to the new system, and any limitations in the plant design are either overcome or better understood. During this phase, the forced outage rate remains low, availability is high, and the operating and maintenance costs are minimal. The power plant is usually operated near rated capacity with high availability.

As the plant continues to operate, a number of the major boiler pressure part components reach the point where they are expected to be replaced because of erosion, corrosion, creep, and fatigue. Without this planned replacement, increasingly frequent component failures occur resulting in reduced availability. In some instances such as waste-to-energy systems, this period can be as short as one to three years for superheaters because of the very corrosive flue gas composition. However, for most fossil fuel-fired utility boilers operating on their design fuels, major pressure part components are economically designed for more than two decades of operation before economic replacement. Failures of major components such as steam lines, steam headers and drums can cause major, prolonged forced outages. Significant capital expenditures are normally required to replace such components.

A strategic availability improvement program that includes capital expenditures to replace or repair this equipment before major forced outages occur can smooth out and raise the availability curve. Higher availabilities usually require higher maintenance, higher capital expenditures, and better strategic planning. The large expenditures needed for high availability in older plants require a strategic plan to yield the best balance of expenditures and availability.

Strategic plan for high availability

Mature boilers represent important resources in meeting energy production needs. A systematic strategic approach is required to assure that these units remain a viable and productive resource. The more efficient, but older boilers in the system can be the backbone of the commercially available power for a utility.

Emphasis on high availability

Today, the need for high commercial availability is of prime importance to the financial livelihood of a power supplier. This means that the low- cost units in a system must be available for full capacity power production during critical peak periods, such as hot summer days. Competition in the electrical supply industry requires that low-cost units be available so that the system can supply power to the grid at low overall costs. Usually, the large fossil powered units are the lowest cost units in the system. Lost revenue associated with having a large, low-cost unit out of service for repairs can be in excess of one million U.S. dollars per day. Owners are attempting to maintain availability levels of 90% or more on these large workhorses in the system.

The emphasis on maintaining or even improving availability means that a strategic plan must be put in place. Times between planned outages have been

Chapter 46

Steam Generation from Nuclear Energy

Since the early 1950s, nuclear fission technology has been explored on a large scale for electric power generation and has evolved into the modern nuclear power plants. (See frontispiece and Fig. 1.) Many advantages of nuclear energy are not well understood by the general public, but this safe, environmentally benign source of electricity is still likely to play a major role in the future world energy picture. Nuclear electric power generation is ideally suited to provide large amounts of power while minimizing the overall environmental impact.

First generation power plants

The concept of an energy generating plant using nuclear fission was first considered by nuclear physicists in the 1930s. However, peaceful use of the atom was delayed until after World War II. The United States (U.S.) had a head start on nuclear technology because of its work in the atomic weapons program. The U.S. Atomic Energy Commission (AEC) took the lead in research and development for a controlled chain reaction application to energy generation. Many concepts were hypothesized and several promising paths were explored, but the real momentum developed when U.S. Navy Captain Hyman G. Rickover established a division in the AEC to develop a nuclear power plant for a submarine. This program, established in 1949, was to become the forerunner of commercial generating stations in the U.S. and the world. Rickover's design succeeded in 1953. Technology and materials developed by his team became the cornerstone of future U.S. nuclear plants. Concurrently, the AEC established a large testing site in Arco, Idaho where, in 1951, the fast neutron reactor produced the first electricity (100 kW) generated by controlled fission.

The world's first civil nuclear power station became operational in Obninsk in the former Soviet Union (FSU) in mid-1954, with a generating capability of 5 MW. This was about the same energy level produced in the U.S. submarine design.

In 1953, the Navy canceled Captain Rickover's plans to develop a larger nuclear power plant to be used in an aircraft carrier. However, he subsequently transformed this project into a design for the first U.S. civilian power stations. Duquesne Light Company of Pittsburgh, Pennsylvania agreed to build and operate the conventional portion of the plant and to buy steam from the nuclear facility to offset its cost of operation. On December 2, 1957, the Shippingport, Pennsylvania reactor plant was placed in service with a power output of 60 MW. This event marked the beginning of the first generation U.S. commercial nuclear plants.

Several basic concepts were being explored, developed and demonstrated throughout the world during this period. The U.S. submarine and Shippingport plants were pressurized water reactors (PWR) that used subcooled water as the fuel coolant and moderator. The FSU developed enriched uranium, graphite-

Fig. 1 Indian Point Station, New York.

Index