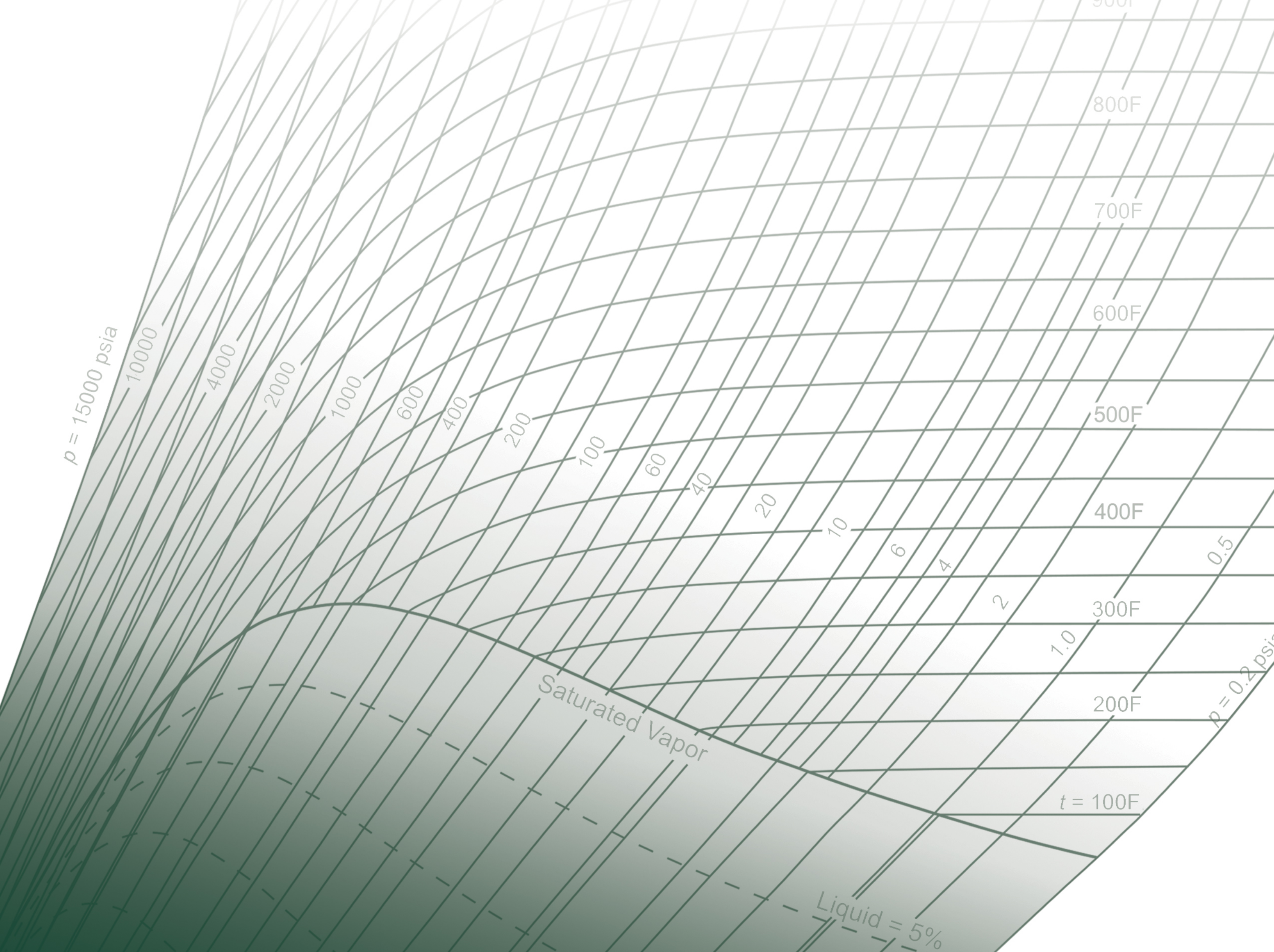
The Babcock & Wilcox Company

# STEAM

FORTY-SECOND EDITION

## ITS GENERATION AND USE



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# Editor's Foreword

As we began the process of updating this text, the focus was on the ever-changing power industry. New technologies currently under development were unheard of only a few years ago. A continued increase in public awareness of the environment, along with expanding governmental regulations in response to the push for cleaner air, present increasing challenges for power plant owners and operators. Other stakeholders are demanding, more than ever, an increase in profits and substantial returns on investment.

This new edition provides the latest information to address the challenges faced by those directly and indirectly involved with generating and using steam power. Completely new chapters address carbon emissions and hazardous air pollutant considerations. Significant updates cover emissions control technologies, numerical modeling, fossil and renewable applications, and steam generation from nuclear energy. All other material, including the fundamentals of steam generation, is now thoroughly reviewed and revised as necessary.

Beyond the actual content of the book, however, it became clear that there was an underlying factor that provided a foundation for new technologies, and for the drive and willingness to share this wealth of knowledge with others … our people. It is B&W people who engineer advanced materials for even higher steam temperatures and pressures. It is B&W people who are the face of our company to plant personnel. And it is B&W people who help users get the most out of their existing assets.

Many individuals donated their personal time to carry on the tradition of *the longest continually published engineering textbook of its kind in the world*. We applaud their dedication. Working alongside these professionals proved immensely satisfying.

B&W has been a big part of this industry for nearly 150 years. Since the first edition of *Steam* in 1875, just eight years after the founding of our company by George Babcock and Stephen Wilcox, a lot has changed. What has not changed is the dedication, integrity and expertise of countless B&W employees. On their behalf, we proudly present the 42nd edition of *Steam/its generation and use.*

# Section I
# Steam Fundamentals

Steam is uniquely adapted, by its availability and advantageous properties, for use in industrial and heating processes and in power cycles. The fundamentals of the steam generating process and the core technologies upon which performance and equipment design are based are described in this section of eight chapters. Chapter 1 provides an initial overview of the process, equipment and design of steam generating systems, and how they interface with other processes that produce power and use steam. This is followed by fundamental discussions of thermodynamics, fluid dynamics, heat transfer, and the complexities of boiling and steam-water flow in Chapters 2 through 5. Chapter 6 is dedicated to exploring the use of advanced computational numerical analysis in the design of modern steam generators and environmental systems. The section concludes with Chapters 7 and 8 discussing key elements of material science and structural analysis that permit the safe and efficient design of the steam generating units and components.

# Chapter 1

## Steam Generation – An Overview

Steam generators, or boilers, use heat to convert water into steam for a variety of applications. Primary among these are electric power generation and industrial process heating. Steam is a key resource because of its wide availability, advantageous properties and nontoxic nature. Steam flow rates and operating conditions are the principal design considerations for any steam generator and can vary dramatically: from 1000 lb/h (0.1 kg/s) in one process use to more than 10 million lb/h (1260 kg/s) in large electric power plants; from about 14.7 psi (0.1013 MPa) and 212F (100C) in some heating applications to more than 4500 psi (31.03 MPa) and 1100F (593C) in ultra-supercritical (USC) power plants. Work is underway to develop advanced USC cycles with steam temperatures as high as 1400F (760C).

Fuel use and handling add to the complexity and variety of steam generating systems. The fuels used in most steam generators are coal, natural gas and oil. However, nuclear energy also plays a major role in the electric power generation area. Also, an increasing variety of biomass materials and process byproducts have become heat sources for steam generation. These include peat, wood and wood wastes, bagasse, straw, coffee grounds, corn husks, coal mine wastes (culm), and waste heat from steelmaking furnaces. Even renewable energy sources, e.g., solar, are being used to generate steam. The steam generating process has also been adapted to incorporate functions such as chemical recovery from paper pulping processes, volume reduction for municipal solid waste or trash, and hazardous waste destruction.

Steam generators designed to accomplish these tasks range from a small package boiler (Fig. 1) to large, high capacity utility boilers used to generate 1300 MW of electricity (Fig. 2). The former is a factory-assembled, fully automated, gas-fired boiler, which can supply saturated steam for a large building, such as a hospital. It arrives at the site with all controls and equipment assembled. On the other hand, the large field-erected utility boiler will produce more than 10 million lb/h (1260 kg/s) steam at 3860 psi (26.62 MPa) and 1010F (543C). Such a unit, or its comparably rated nuclear option (Fig. 3), is part of some of the most complex and demanding engineering systems in operation today. Other examples illustrating the range of combustion systems are shown by the 1000 t/d (907 $t_m$/d) mass-fired refuse power boiler in Fig. 4 and the circulating fluidized-bed combustion boiler in Fig. 5.

The central job of the boiler designer in any of these applications is to combine fundamental science, technology, empirical data and practical experience to produce a steam generating system that meets the steam supply requirements in the most economical package. Other factors in the design process include fuel characteristics, environmental protection, thermal efficiency, operations, maintenance and operating costs, regulatory requirements, and local geographic and weather conditions, among others. The design process involves balancing these complex and sometimes competing factors. For example, the reduction of pollutants such as nitrogen oxides ($NO_x$) may require a larger boiler volume, increasing capital costs and potentially increasing maintenance costs. Such a design activity is firmly based upon the physical and thermal sciences such as solid mechanics, thermodynamics, heat transfer, fluid mechanics and materials science. However, the real world is so complex and variable, and so interrelated, that it is only by applying the art of boiler design to combine science and practice that the most economical and dependable design can be achieved.

Steam generator design must also strive to address in advance the many changes occurring in the world to provide the best possible option. Fuel prices can be expected to escalate over time while fuel supplies become less certain, thereby enforcing the need for continued efficiency improvement and fuel flexibility. Increased environmental protection will drive improvements in combustion, efficiency and emissions control technology capabilities. Demand growth continues in many areas where steam generator load may have to cycle up and down more frequently and at a faster rate. Also, modularization and further standardization will help

**Fig. 1** Small shop-assembled package boiler.

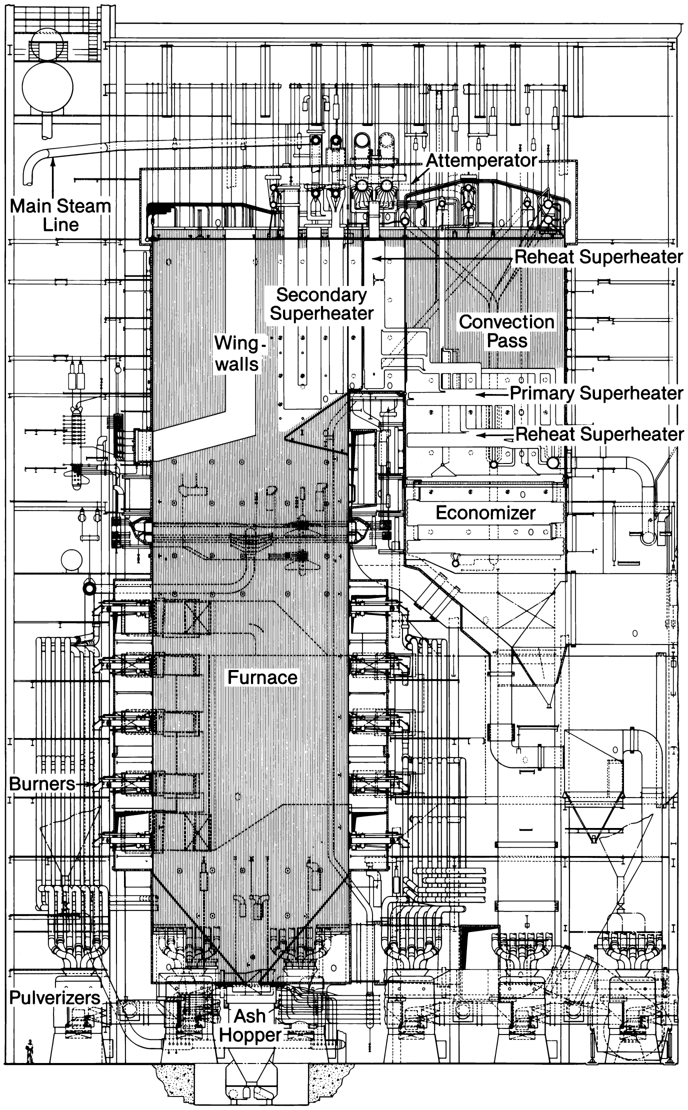


**Fig. 2** 1300 MW coal-fired utility steam generator.

reduce fabrication and erection schedules to meet more dynamic capacity addition needs.

## Steam Generation Fundamentals

### Boiling

The process of boiling water to make steam is a familiar phenomenon. Thermodynamically, instead of increasing the water temperature, the energy used results in a change of phase from a liquid to a gaseous state, i.e., water to steam. A steam generating system should provide a continuous process for this conversion.

The simplest case for such a device is a kettle boiler where a fixed quantity of water is heated. (See Fig. 6.) The applied heat raises the water temperature. Eventually, for the given pressure, the boiling (*saturation*) temperature is reached and bubbles begin to form. As heat continues to be applied, the temperature remains constant, and steam escapes from the water surface. If the steam is continuously removed from the vessel, the temperature will remain constant until all of the water

**Fig. 3** 900 MW nuclear power system.

is evaporated. At this point, heat addition would increase the temperature of the kettle and of any steam remaining in the vessel. To provide a continuous process, all that is needed is a regulated supply of water to the vessel to equal the steam being generated and removed.

Technical and economic factors indicate that the most effective way to produce high pressure steam is to heat relatively small diameter tubes containing a continuous flow of water. Regardless of whether the energy source is nuclear or fossil fuel, two distinct boiling systems are used to accomplish this task: those that include a steam drum

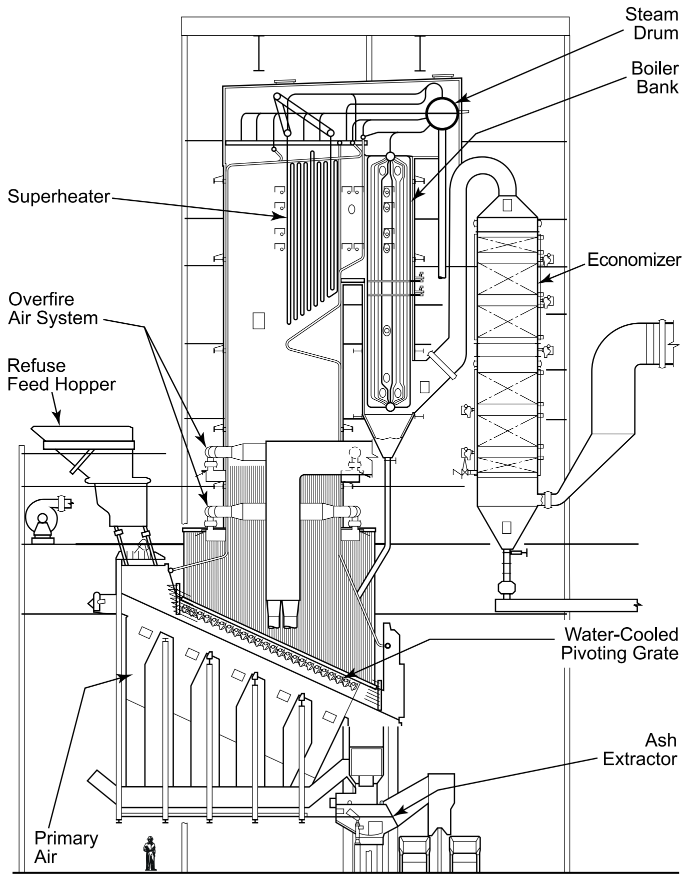


**Fig. 4** B&W 1000 ton per day mass-fired refuse power boiler.

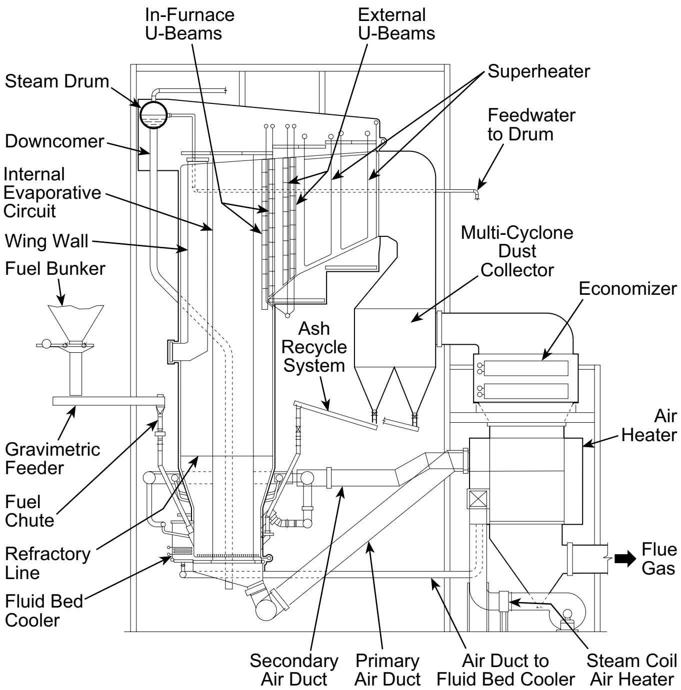


**Fig. 5** Coal-fired circulating fluidized-bed combustion steam generator.

(see Fig. 7a), or fixed steam-water separation point, and those that do not (see Fig. 7b), identified as once-through steam generators (OTSG).

The most common and simplest to control is the steam drum system. In this system, the drum serves as the point of separation of steam from water throughout the boiler's load range. Subcooled water (less than boiling temperature) enters the tube to which heat is applied. As the water flows through the tube, it is heated to the boiling point, bubbles are formed, and *wet* steam is generated. In most boilers, a steam-water mixture leaves the tube and enters the steam drum, where steam is separated from water. The remaining water is then mixed with the replacement water and returned to the heated tube.

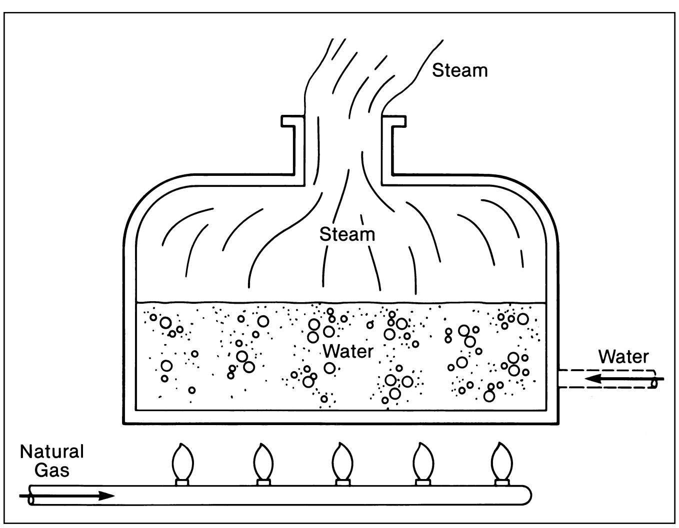


**Fig. 6** Simple kettle boiler.

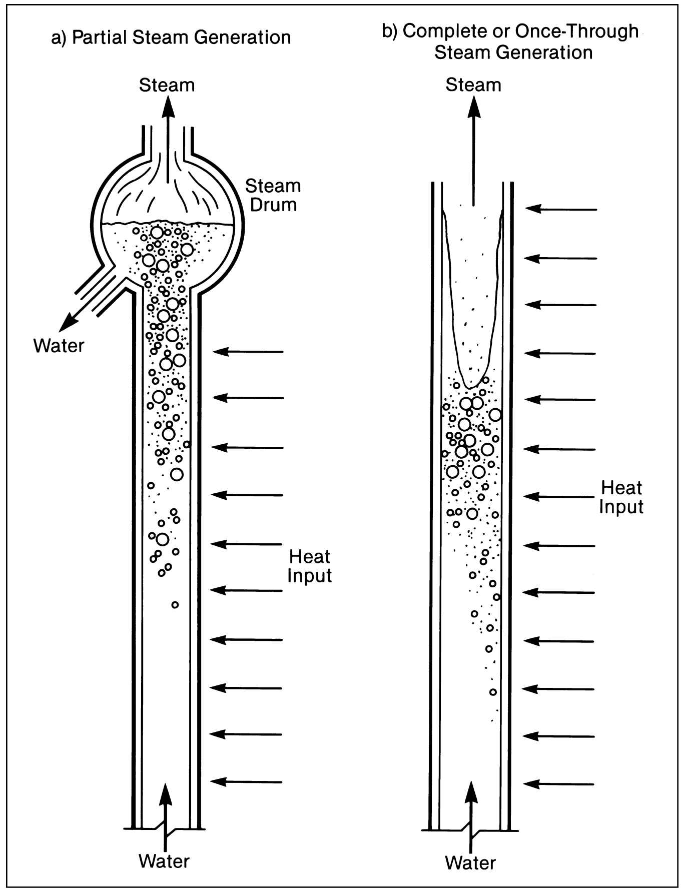


**Fig. 7** Boiling process in tubular geometries.

Without a steam drum, i.e., for an OTSG system, subcooled water also enters the tube to which heat is applied, but the flowing water turns into steam somewhere along the flow path (length of tube), dependent upon water flow rate and heat input rates. Shown in Fig. 7b, the flow rate and heat input are closely controlled and coordinated so that all of the water is evaporated and only steam leaves the tube. There is no need for the steam drum (fixed steam-water separation point).

## Circulation

For both types of boiling systems described above, water must continuously pass through, or circulate through, the tubes for the system to generate steam continuously. For an OTSG, water makes one pass through the boiler's tubes before becoming steam to be sent to the turbine-generator. However, for those boilers with a fixed steam-water separation point or steam drum, a molecule of water can make many passes through a circulation loop before it leaves as steam to the turbine-generator. Options for this latter system are shown in Fig. 8.

Two different approaches to circulation are commonly used: natural or thermal circulation, and forced or pumped circulation. Natural circulation is illustrated in Fig. 8a. In the *downcomer*, unheated tube segment A-B, no steam is present. Heat addition generates a steam-water mixture in segment B-C. Because the steam and steam-water mixture in segment B-C are less dense than the water segment A-B, gravity will cause the water to flow

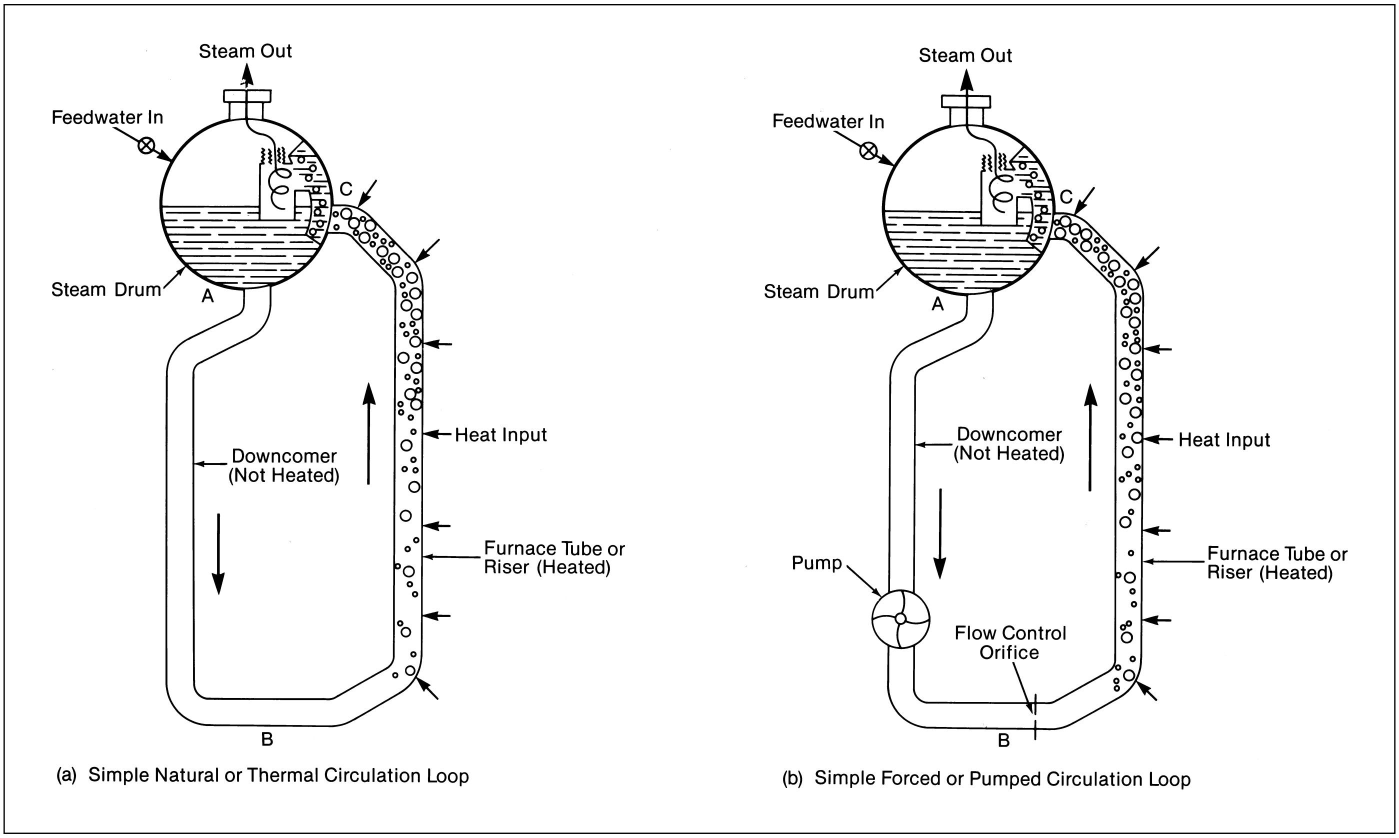


**Fig. 8** Simple circulation systems.

downward in segment A-B and will cause the steam-water mixture (B-C) to move upward into the steam drum. The rate of water flow or circulation depends upon the difference in average density between the unheated water and the heated steam-water mixture.

The total circulation rate in a natural circulation system depends primarily upon four factors: 1) the height of the boiler, 2) the operating pressure, 3) the heat input rate, and 4) the free flow areas of the components. Taller boilers result in a larger total pressure difference between the heated and unheated legs and therefore can produce larger total flow rates. Higher operating pressures provide higher density steam and higher density steam-water mixtures. This reduces the total weight difference between the heated and unheated segments and tends to reduce flow rate. Higher heat input typically increases the amount of steam in the heated segments and reduces the average density of the steam-water mixture, increasing total flow rate. An increase in the cross-sectional (free flow) areas for the water or steam-water mixtures may increase the circulation rate. For each unit of steam produced, the amount of water entering the tube can vary from 3 to 25 units.

Forced or pumped circulation is illustrated in Fig. 8b. A mechanical pump is added to the simple flow loop and the pressure difference created by the pump controls the water flow rate.

The steam-water separation in the drum requires careful consideration. In small, low pressure boilers, steam-water separation can be easily accomplished with a large drum approximately half full of water. Natural gravity steam-water separation (similar to a kettle) can be sufficient. However, in high capacity, high pressure units, mechanical steam-water separators are needed to economically provide moisture-free steam from the drum. With such devices installed in the drum, the vessel diameter and cost can be significantly reduced.

At very high pressures, a point is reached where water no longer exhibits boiling behavior. Above this critical pressure [3200.1 psi (22.1 MPa)], the water temperature continuously increases with heat addition, and the fluid changes phase from water to steam in a continuous fashion. Steam generators can be designed to operate at pressures above this critical pressure, during which drums and steam-water separation are no longer required for higher load operation, and the steam generator operates effectively on the once-through principle.

There are a large number of design methods used to evaluate the expected flow rate for a specific steam generator design and set of operating conditions. In addition, there are several criteria which establish the minimum required flow rate and maximum allowable steam content or quality in individual tubes, as well as the maximum allowable flow rates for the steam drum.

## System Arrangement and Key Components

Most applications of steam generators involve the production of electricity or the supply of process steam. In some cases, a combination of the two applications, called *cogeneration*, is used. In each application, the steam generator is a major part of a larger system that has

# Section II
# Steam Generation from Chemical Energy

This section containing 17 chapters applies the fundamentals of steam generation to the design of boilers, superheaters, economizers and air heaters for steam generation from chemical or fossil fuels (coal, oil and natural gas). As discussed in Chapter 1, the fuel and method of combustion have a dramatic impact on the size and configuration of the steam producing system. Therefore, Chapters 9 and 10 begin the section by exploring the variety and characteristics of chemical and fossil fuels, and summarize the combustion calculations that are the basis for system design.

The variety of combustion systems available to utilize these fuels and the supporting fuel handling and preparation equipment are then described in Chapters 11 through 18. These range from the venerable stoker in its newest configurations to circular burners used for pulverized coal, oil and gas, to fluidized-bed combustion and coal gasification. A key element in all of these systems is the control of atmospheric emissions, in particular oxides of nitrogen ($NO_x$) which are byproducts of the combustion process. Combustion $NO_x$ control is discussed as an integral part of each system. It is also discussed in Section IV, Chapter 33.

Based upon these combustion systems, Chapters 19 through 22 address the design and performance evaluation of the major steam generator heat transfer components: boiler, superheater, reheater, economizer and air heater. These are configured around the combustion system selected with special attention to properly handling the high temperature, often particle-laden flue gas. The fundamentals of heat transfer, fluid dynamics, materials science and structural analysis are combined to provide the tradeoffs necessary for an economical steam generating system design. The boiler enclosure and auxiliary equipment, such as sootblowers, ash handling systems and fans, which are key elements in completing the overall steam system, conclude this section in Chapters 23 through 25.

# Section III
# Applications of Steam

The five chapters in this section illustrate how the subsystems described in Section II are combined to produce modern steam generating systems for specific applications. A number of steam generating unit and system designs for various applications are described and illustrated.

Chapter 26 begins the section with a discussion of large fossil fuel-fired equipment used to generate electric power. Both large and small industrial units, as well as those for small electric power, cogeneration, combined cycle and other specialty applications, are then described in Chapter 27. The next three chapters address specialized equipment for specific applications. Unique designs for steam producing systems are used in pulp and paper mills, waste-to-energy plants, and biomass-fired units. These systems are receiving increased interest as renewable energy resources grow in importance.

# Section IV
# Environmental Protection

Environmental protection and the control of solid, liquid and gaseous effluents or emissions are key elements in the design of all steam generating systems. The emissions from combustion systems are tightly regulated by local and federal governments, and specific rules and requirements are constantly changing. At present, the most significant of these emissions are sulfur oxides ($SO_x$), nitrogen oxides ($NO_x$), fine airborne particulate, mercury and other hazardous air pollutants (HAPs). All of these require specialized equipment and systems for control. Emerging concern about climate change will also affect the design and application of new technologies and solutions.

Chapter 31 begins this section with an overview of current regulatory requirements and overall emissions control technologies. The chapter concludes with a discussion of water pollution and solid waste disposal. Following this overview, Chapters 32 through 35 discuss multi-pollutant control technologies and systems to reduce atmospheric emissions of particulate, $NO_x$, $SO_x$, mercury and HAPs. The $NO_x$ discussion focuses on post-combustion technologies; combustion-related control options are addressed in Chapter 11 and Chapters 14 through 18.

Chapter 36 is completely new for the 42nd edition of *Steam* and covers carbon dioxide ($CO_2$) considerations. Both combustion and post-combustion technologies for concentrating and capturing $CO_2$ are discussed. Significant progress has been made in laboratory and pilot-scale tests, with commercial-scale applications in development.

Finally, a key element in a successful emissions control program is measurement, monitoring and reporting. Chapter 37 addresses a variety of issues and outlines a number of technologies for flue gas monitoring.

# Section V
# Specification, Manufacturing and Construction

This section begins with an in-depth discussion of the specification, evaluation and procurement process for large capital expense items. This includes discussions about project scope, terms and conditions, and general bid evaluation. Also discussed are power system economics, and procedures for the evaluation of equipment characteristics in terms of justifiable expenditures. Examples and calculations are included for both utility and industrial units, and emissions control equipment.

This is followed by a discussion of the manufacturing processes for fossil fuel-fired equipment. Welding and metal removal techniques, as well as fabrication of the various components and component parts, are covered. Examination and quality control are also discussed. The section ends with a chapter covering various construction techniques, labor requirements, on-site considerations, safety issues, and post-construction testing, as well as a discussion on the special considerations for nuclear plant construction.

# Section VI
# Operations

With proper design, manufacture and construction, modern steam generating systems are capable of operating efficiently for long periods of service. However, successful operation requires adherence to basic operating principles. These principles begin with the careful monitoring of operating conditions so that a system functions within design limits. Chapter 41 describes the instrumentation for monitoring pressures, temperatures and flows — the key process parameters. These operating parameters then serve as the inputs to the control system. The fundamentals of control theory and modern integrated control systems are reviewed in Chapter 42. These systems have become more automated to provide greater operator knowledge and flexibility to optimize plant performance.

Successful long-term operation of steam producing systems requires careful attention to water treatment and water chemistry control. Chapter 43 provides a discussion of water treatment practices from startup through operation and chemical cleaning. Drum and once-through boilers have different requirements, and each boiler requires individual consideration.

General operating principles and guidelines outlined in Chapter 44 conclude this section. Each steam generating system is unique and requires specific operating guides. However, a number of general principles covering initial operations serve as a basis.

# Section VII
# Service and Maintenance

This section describes the last element of a successful steam generating system life cycle plan — service and maintenance. As owners and operators of steam plants search for optimum performance, efficiency, and life cycle for all equipment, issues of maintenance and availability have become increasingly important.

The section begins with Chapter 45 and a discussion of service and maintenance encountered with all plants, both utility and industrial. A well-crafted service and maintenance program is essential in sustaining the availability of critical steam generating assets and maximizing overall performance and output. Condition assessment is then addressed in Chapter 46 with detailed discussion about examination techniques, assessment of various components, and analysis techniques for determining remaining life. The effects of cycling operation are also addressed.

# Section VIII
# Steam Generation from Nuclear Energy

Nuclear power generation provides a critical element in the energy supply of virtually all developed nations, and offers the continued promise to address growing power needs in an environmentally acceptable and safe manner. This section describes the application of steam generation fundamentals to the design of nuclear steam supply systems (NSSS) in which steam is generated by heat released from nuclear fuels.

Chapter 47 begins this section with an overview of nuclear installations, concentrating on the pressurized water reactor. It also discusses the emerging interest in small modular reactors. The nuclear fuel cycle, followed by the principles of nuclear reactions are then explored in Chapters 48 and 49. Chapter 50 is dedicated to nuclear steam generators. Operating experience indicates that this component is a particularly challenging and important part of the NSSS. As nuclear power plants age, the steam generators are increasingly being replaced to optimize plant performance and extend the operating plant life.

Chapter 51 provides an overview of the highly specialized manufacturing requirements and capabilities that are necessary for successful component fabrication. Chapter 52 explores the key service, maintenance and life extension strategies and activities of a nuclear steam system that can optimize long-term performance and availability. The section concludes with Chapter 53 and a discussion of nuclear waste management.