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FAILURE INVESTIGATION OF BOILER TUBES

A COMPREHENSIVE APPROACH

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Preface

Power plants are the backbone of industrial development for most countries and their failures impact economic growth. When failures or forced shutdowns in power plants occur, they are often due to boiler failure, and particularly failure of boiler tubes. The many causes of boiler tube failures include overheating, creep, erosion, corrosion, fatigue, manufacturing and material defects, and operational issues. Boiler tube failures lead to unscheduled shutdowns, increased maintenance and repair costs, reduced plant load factors, and loss of available power. To prevent interruptions in the supply of power, it is critical to investigate the root cause of boiler tube failures and the resultant forced outages and to develop remedial measures for preventing the recurrence of similar failures in the future. Such investigations are also aimed at assessing the remaining life of the boiler tubes.

We have long-standing experience in the field of metallurgy and materials technology, failure investigations, remaining life assessment, and reviewing fitness for service of industrial plants and equipment, including power plants. We have performed a large number of failure investigations of boiler tubes and have made effective recommendations of remedial measures in problem solving for power and utility boilers. An attempt has been made in this book to share our knowledge and expertise in failure investigation of boiler tubes, for the benefit of user industries.

For non-metallurgists, a chapter has been devoted to basics of material science, metallurgy of steels, heat treatment, and structure-property correlation. Without adequate knowledge of physical metallurgy fundamentals of steels and related materials, understanding the mechanisms of boiler tube failure is almost impossible. A chapter on materials for the manufacture of boiler tubes deals with composition and application of different grades of steels and high-temperature alloys currently in use as well as future materials to be used in supercritical, ultra-supercritical, and advanced ultra-supercritical thermal power plants. A comprehensive discussion on different mechanisms of boiler tube failure is the heart of the book. A large number of case studies based on actual failures from the field have been cited along with photographs and microstructures in order to facilitate the discussion of the underlying theory behind the respective failure mechanisms. Chapters dealing with the role of advanced material characterization techniques in failure investigation and the role of water chemistry in tube failures are key contributions to the book.

This book will help not only the novice but also practicing engineers in the operation and maintenance departments of power plants, boiler tube manufacturers, research and development personnel concerned with power plants, academicians, and students. This book will not make plant personnel experts in analysis of boiler tube failures; however, it will certainly increase their awareness, and help them effectively communicate with specialists and experts from failure investigation agencies as well as with their own management. For academicians and research and development personnel, it will act as a valuable ready reference.

Finally, we have great pleasure in acknowledging the support and encouragement received from the Indian power industry, users of industrial boilers, and allied organizations. Our special thanks to the management of the power plants for whom we have performed failure investigations, for permitting us to use the data, especially in writing the case studies.

We would like to thank the editorial and production staff at ASM International, especially Karen Marken, senior managing editor, for her guidance and valuable contribution at various stages of manuscript preparation.

We are grateful to the late V.K. Bafna, founder of the TCR Group of companies, for his vision and relentless efforts in building a world-class investigation center. We would also like to thank our colleagues at TCR Advanced Engineering, Vadodara, India, for their support in preparation of the manuscript for this book.

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Paresh Haribhakti is the managing director of TCR Advanced Engineering Pvt. Ltd. in Vadodara, India (a TCR Engineering Services partner company), director of TCR Arabia, Dammam, and global technical consultant to the TCR group of companies. Mr. Haribhakti is a graduate in metallurgical engineering and has a master's degree in materials technology from The Maharaja Sayajirao University of Baroda, Vadodara, India. With more than two and half decades of experience in the field of metallography, microstructural evaluation, and failure investigation, Mr. Haribhakti has been instrumental in solving more than 4000 industrial problems. He has investigated approximately 400 cases of boiler tube failures. He has expertise in areas such as failure investigation, remaining life assessment and fitness for service, and material development and import substitution for power plants, fertilizers, chemical and petrochemical complexes, the oil and gas industry, and other engineering and manufacturing industries. He is a member of the Institution of Engineers (India), Institute of Indian Foundrymen, Indian Institute of Metals and Indian Institute of Welding, and ASM International.

Dr. P.B. Joshi

Dr. P.B. Joshi, the former professor and head of the department of metallurgical and materials engineering of The Maharaja Sayajirao University in Baroda, Vadodara, India, has more than 30 years of teaching and research experience and five years of industrial experience. His areas of teaching and research have been physical metallurgy, alloy steels, failure analysis and material selection, material characterization, and powder metallurgy. He has published papers in more than 60 journals of national and international repute. He has worked as principal investigator/co-investigator and chief coordinator on various research projects funded by the Government of India. He authored a book, *Materials for Electrical and Electronic Contacts*, with Professor P. Ramakrishnan of IIT, Mumbai, India. The book was jointly published by Oxford & IBH Publishers, New Delhi, and Science Publishers, USA, in 2004. Currently, he is working as a consultant to TCR Advanced Engineering Pvt. Ltd., Vadodara.


Dr. Rajendra Kumar

Dr. Rajendra Kumar earned his Ph.D. from the University of Sheffield (United Kingdom), and started his career as a member of the teaching faculty at IIT, Kharagpur and Banaras Hindu University, Varanasi, India. He was honored with the Commonwealth Visiting Professorship at the University of Austin, Birmingham, United Kingdom during 1979 to 1980. He also served as scientist director at National Metallurgical Laboratory, Jamashedpur, India, and director of Regional Research Laboratory, Bhopal, India. Dr. Kumar has been intimately connected with the thermal power sector in India as well as abroad. He was the expert coordinator for a national level project for improving the plant load factor for power boilers sponsored by the Central Board of Irrigation and Power, India. He was a member of a committee appointed by the government of India formulated for drafting the VIII Plan proposal for research and development in the thermal power sector. He was invited by the United Nations Commission for Science and Technology to prepare a scenario for decentralized thermal power generation to reduce global warming. He has served as an expert to the boiler industry and power plants in India for more than three decades. He is the author of two books, *Operation and Maintenance of Steam Power Boilers*, published in 2008, and *Physical Metallurgy of Iron and Steel*, published in 1969.

CHAPTER 1

Introduction to Boiler Technology

1.1 Introduction

A boiler is an enclosed vessel in which water is heated to produce hot water, steam, superheated steam, or any combination of these under pressure by the application of heat. The necessary heat is produced by burning solid, liquid, or gaseous fuel under a controlled supply of air in the combustion chamber of the boiler. Thus, the boiler is an appliance to convert the chemical energy in fuel into thermal energy to generate steam or hot water. The steam or hot water so produced is then circulated out of the boiler for end use for power generation, or in various manufacturing processes for the captive supply of steam/heat. In projects such as refineries, petrochemical plants, paper mills, food and pharmaceutical industries, and the textile industry, boilers are used for power generation and/or for providing process steam and process heat.

1.2 Classification of Boilers

Because the areas of application of boilers are very diverse, there is a need for their classification. Functionally, two main categories of boilers are utility boilers and industrial/commercial/institutional (ICI) boilers. Utility boilers are used in thermal power plants to produce steam at a constant rate. Utility boilers are very large in size and work with pulverized coal, fuel oil, or natural gas at high pressure and temperature to produce high-pressure, high-temperature, superheated steam for power generation. On the other hand, ICI boilers have markedly different purposes and applications. Industrial boilers are used for producing hot water or steam for industrial process applications including food processing, paper production, chemical processing, petrochemicals and refining, and the textile and allied industries. Commercial boilers provide steam and/or hot water for

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commercial establishments such as hotels, restaurants, office buildings, and apartments. Institutional boilers are used in establishments such as hospitals, schools, colleges, and government buildings to provide steam, hot water, and/or electricity. ICI boilers are flexible in terms of their ability to produce steam output and are generally designed with regard to the plant space limitations. In general, ICI boilers work at much lower annual operating loads than typical utility boilers.

1.2.1 Utility Boilers

There are different forms of utility boilers based on the method used for fuel combustion. Utility boilers with different combustion arrangements (Ref 1.1) include:

- Tangentially fired boilers: The air-fuel mixture is introduced into the furnace from the four corners of the furnace, tangentially.
- Wall-fired boilers: Multiple burners are located along a single wall or on opposite walls of the furnace.
- Cyclone-fired boilers: The air-fuel mixture is burned in horizontal cylinders.
- Stoker-fired boilers: The fuel is combined in relatively thin layers on top of a grate.
- Fluidized bed combustion boilers: A fluidized bed of sand particles is used under atmospheric conditions for efficient combustion.
- Pressurized fluidized bed combustion boilers: Similar to fluidized bed combustion, but at pressure greater than atmospheric and with higher efficiency.

1.2.2 Industrial Boilers

Industrial boilers are normally identified by the method of heat transfer and the combustion system utilized. Based on the mode of heat transfer, there are two types of industrial boilers: watertube and firetube boilers. Further discussion on each one of them is covered in succeeding paragraphs. On the basis of the combustion system, industrial boilers may be grouped as burner- or stoker-type boilers.

Further classification of the boilers may be done based on the fuel used, working pressure and temperature, firing practice, draft method, size and capacity, method of fabrication, and portability.

Criteria on which the boilers may also be classified (Ref 1.2) include:

- Horizontal, vertical, or inclined boiler based on the axis of the boiler
- Method of firing, variables being horizontal firing, vertical firing, down shot firing, front and rear wall firing, and tangential firing
- Externally or internally fired boiler based on whether the fire is inside or outside the shell. In other words, a boiler is classified as a *firetube*

or *watertube* boiler based on the relative location of the water and fuel inside or outside the tube.

- Single tube or multitube boiler based on the number of tubes in firetube boilers
- Boilers can be classified as natural circulation, forced or controlled circulation, combined circulation, and once-through types.
- Heat source as coal-fired or solid fuel-fired, oil-fired, gas-fired, or lignite-fired boilers. Electric boilers use resistance- or immersion-type heating elements.
- They are also classified as subcritical, supercritical (SC), and ultrasupercritical (USC) boilers. The basic difference between the three types is the operating temperatures and pressures. Subcritical boilers operate below the critical point of water (374.15 °C and 22.1 Mpa, or 705.45 °F and 3.21 ksi), whereas SC and USC boilers operate above the critical point. Supercritical and USC boilers are characterized by the absence of a steam drum, which is normally present in subcritical boilers.
- Stationary or portable boiler
- Based on the method of fabrication as shop-assembled, field-erected, and package boilers. Shop-assembled boilers are built from a number of individual parts or subassemblies. After these parts are aligned, connected, and tested, the entire unit is shipped to the site in one piece. Field-erected boilers are too large to be transported as an entire assembly. Hence, they are constructed at the site from a series of individual components.

1.3 Types of Boilers

Various types of boilers used throughout the world for power and steam generation are discussed (Ref 1.3, 1.4).

1.3.1 Firetube Boilers

A typical example of a firetube boiler is a locomotive boiler. In this type of boiler, the combustion gasses pass through tubes that are surrounded by water. The basic design of a firetube boiler consists of a series of straight tubes that are housed inside a water-filled outer shell (i.e., on the tube side there are hot combustion gases, whereas on the shell side there is water). The tubes are submerged in water so that the hot combustion gases can pass through the tubes several times, thereby transferring their heat across the tube walls to the water filling the outer shell. As a result of this, the water in the shell heats up, boils, and finally transforms to steam. Firetube boilers are generally used for relatively small steam capacities and applications involving low to medium steam pressures. Figure 1.1 shows a cutaway view of a firetube boiler.

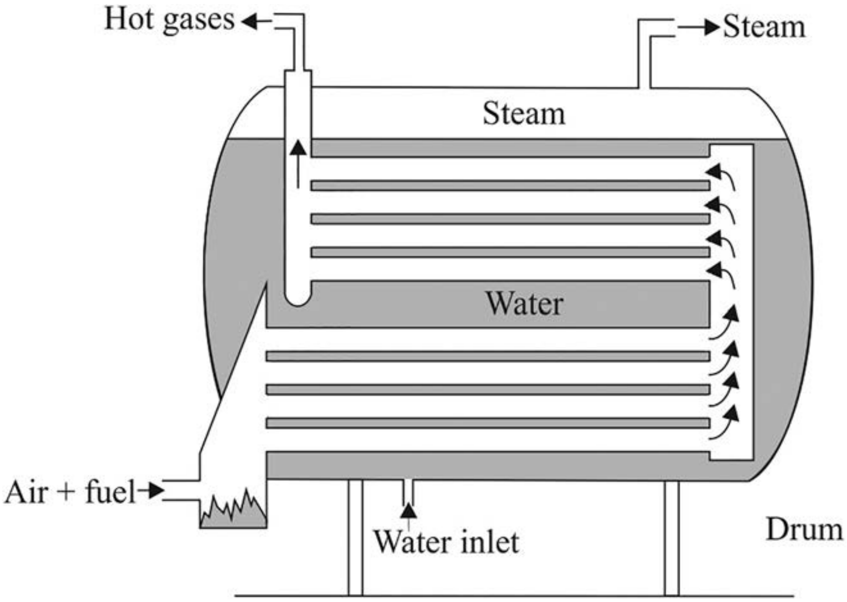

Fig. 1.1 Schematic showing basic principle of a firetube boiler

1.3.2 Watertube Boilers

Watertube boilers are designed to circulate hot combustion gases around the outer surface of a large number of water-filled tubes. In other words, on the tube side there is water, whereas on the shell side there are hot combustion gases. In watertube boilers, the fuel is combusted in a central chamber (furnace, bed, or grate) and the combustion gas transfers heat energy, through radiation and convection, to the water circulating through the tubes. The water tubes are connected to a steam drum at the top and one or more lower drums (also known as a mud drum) at the bottom. The necessary heat is produced by means of fire in the combustion chamber as shown in the schematic (Fig. 1.2). The circulated water is heated by the combustion gases and converted into steam at the vapor space in the steam drum.

Almost any solid, liquid, or gaseous fuel can be burned in a watertube boiler. Commonly used fuels include coal, oil, natural gas, and biomass. These boilers can be used under forced, induced, and balanced draft conditions so as to offer higher thermal efficiency. The only concern is that the water must be treated to improve the water quality, which incurs additional expenditure.

1.3.3 Electric Boilers

Electric boilers are used as an efficient source of hot water or steam. They are available in ratings from 5 to over 50,000 kW. Heating is ensured by

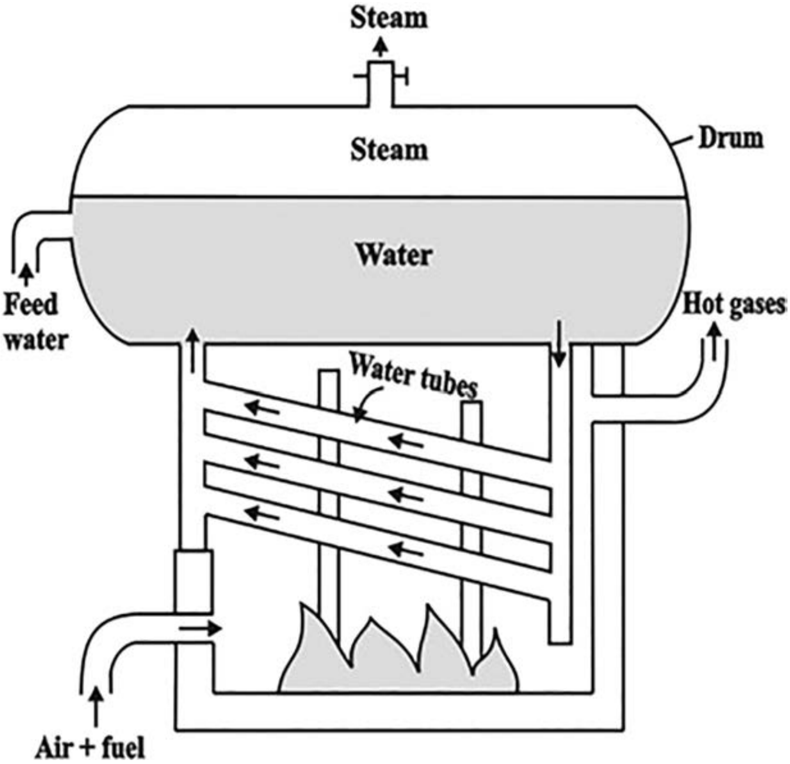

Fig. 1.2 Schematic showing basic principle of a watertube boiler

means of resistance or immersion heaters. They are much cleaner in operation than firetube and watertube boilers.

1.3.4 Packaged Boilers

Packaged boilers are small, self-contained boiler units. Packaged boilers can be either watertube or firetube, and they are generally of the shell type with a firetube design so as to achieve high heat transfer rates by both radiation and convection. They are installed with a large number of small-diameter tubes offering good convective heat transfer with a forced or induced draft system. The small size of the combustion chamber and high heat release rate impart higher thermal efficiency levels to package boilers compared with other boilers.

The major benefits of using packaged boilers are compact design, short installation time, and low installation cost.

1.3.5 Fluidized Bed Combustion Boilers

In principle, a fluidized bed combustion (FBC) boiler is one in which a fire bed is produced by means of finely divided solid particles, such as

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silica sand, through which an evenly distributed stream of air or fluidizing gas is passed upward such that the sand particles remain in suspension. Fluidization improves mixing of fuel and air. When the initial velocity of the fluidizing medium (i.e., air or gas) is low, the sand particles are undisturbed. However, as the air velocity increases, a stage is reached when the individual particles are suspended in the air stream, forming a bed called a *fluidized bed*.

With further increase in air velocity, there is vigorous turbulence resembling bubble formation in a liquid. The solid particles within the bed start behaving as bubbles in a boiling liquid and assume the appearance of a fluid, known as a *bubbling fluidized bed*. Depending on the velocity of the combustion air, the layer acquires different types of fluid-like characteristics such as the fixed bed, bubbling bed, circulating bed, and turbulent bed.

If the sand particles in the fluidized state are heated to the ignition temperature of coal, and coal is injected continuously into the bed along with the introduction of air for combustion from the bottom of the bed, the coal will burn rapidly, forming a combustion bed. Fluidized bed combustion takes place at about 850 to 950 °C (1560 to 1740 °F). Because this temperature is below the ash fusion temperature, melting of ash and associated problems are avoided.

Fluidized bed combustion has several advantages over the conventional firing system (Ref 1.4):

- Compact boiler design
- Permits use of many different types of fuels including coal, biomass, rice husk, bagasse, and other agricultural wastes. Inferior-quality fuels containing a high concentration of ash, sulfur, and nitrogen can also be used. Natural gas or fuel oil is used primarily as a start-up fuel to preheat the fluidized bed.
- Higher combustion efficiency
- Lower combustion temperature because of a high coefficient of heat transfer due to rapid mixing in the fluidized bed leads to lower NOx emissions
- Reduced emission of other noxious pollutants such as SOx by desulfurization during combustion

Fluidized bed combustion boilers can be further grouped as atmospheric or pressurized units.

In atmospheric fluidized bed combustion (AFBC) boilers, the fuel, such as coal, is crushed to a size of 1 to 10 mm (0.04 to 0.4 in.) and is fed into the combustion chamber. Atmospheric air, which acts as both the fluidization air and the combustion air, is then delivered at pressure and flows through the bed after being preheated by the exhaust flue gases. The energy so produced is utilized in heating the water circulating through the tubes located within and above the fluidized bed so as to produce steam. Atmospheric fluidized bed boilers are also known as *bubbling bed boilers*. Figure 1.3 shows an AFBC boiler.

Atmospheric FBC boilers are further divided into bubbling fluidized bed combustion (BFBC) and circulating fluidized bed combustion (CFBC) units; the fundamental difference between these two is the fluidization velocity. In the BFBC type, because the velocity of the air is low, the medium particles are not carried above the bed. The fluidizing velocity is lower than the terminal velocity of individual bed particles. The combustion in this type of boiler is generated in the bed.

The CFBC boiler incorporates a cyclone filter to separate solid material from the hot flue gases that leave the exhaust of the furnace. The solids from the filter are recirculated into the bed, hence the name. In the CFBC type, the velocity of air is high, so the medium-sized particles are carried out of the combustor. Here, the fluidizing velocity exceeds the terminal velocity of individual bed particles. The carried particles are continuously captured by a cyclone installed in the outlet of the combustor and sent back to the bottom part of the combustor to combust unburned particles. This helps to ensure full combustion.

A pressurized fluidized bed combustion (PFBC) boiler is a variation of FBC technology that is meant for large-scale coal burning applications. In a PFBC boiler, a compressor supplies forced draft air, which improves the combustion efficiency. The PFBC system can be used for cogeneration or combined cycle power generation.

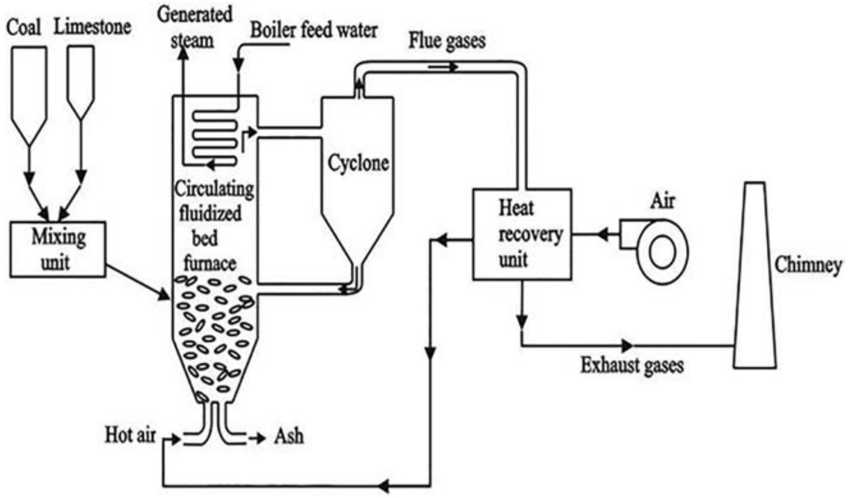

Fig. 1.3 Schematic diagram of a fluidized bed combustion boiler

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1.3.6 Oil- and Gas-Fired Boilers

Both oil- and gas-fired boilers use controlled combustion of the fuel to heat water. Oil-fired boilers are used for heating water for domestic and industrial applications. In this type of boiler, the oil is mixed with air and burns by means of a burner to produce heat. The heat of the flame created by burning the oil and air mixture is directed over coiled copper pipe through which the water is flowing, such that the water flowing through the copper coils is heated by conductive heat transfer.

Natural gas boilers employ either atmospheric burners (also known as natural draft burners) or forced draft burners. Both types of boiler can be used for combustion of oil as well as gas because they have some common properties; both contain practically no moisture or ash, and both produce the same amount of flue gas during combustion.

1.3.7 Waste Heat Boilers

The operational efficiency of a boiler is measured by the percentage of the fuel input energy that is eventually delivered as useful heat output. Major sources of heat loss from steam boilers are the flue gas, blow down, and radiation to the boiler's surroundings.

Waste heat recovery steam generators (HRSGs) use the heat from exhaust gases from combustion processes of gas turbines and diesel engines, or from hot exhaust air from industrial processes, to produce hot water or steam. Waste heat recovery boilers are generally conventional watertube boilers. Here, the heat from the hot exhaust gases from gas turbines or any industrial process equipment is recovered by passing them over a set of parallel tubes through which the normal water (ambient temperature) flows. The heat transfer across the tube walls ensures vaporization of water and in turn its transformation to steam, which is then collected in a steam drum for subsequent end use as heating or processing steam. Efficiency of heat transfer can be further improved by using finned tubes instead of tubes with plain surfaces. The water can be circulated through the tubes a number of times for better results. If the waste heat in the exhaust gases is insufficient for generating the required amount of process steam, auxiliary burners may be used. The black liquor recovery boiler is a classic example of a waste heat recovery boiler.

1.3.8 Black Liquor Recovery Boilers

Recovery boilers were first invented in the early 1930s and play a key role in the kraft process of pulping. Kraft recovery boilers (also known as BLRBs) are used to efficiently convert wood chips into paper in pulp and paper mills. The wood chips are first cooked in an aqueous solution (known as white liquor) in a digester for manufacturing pulp. The digested pulp is then separated from the residual liquor, which is relatively dilute in nature with a solid concentration of about 15%. Multistage evaporation converts "white liquor" to "black liquor," where the concentration of solids is raised to 70 to 75%. The black liquor consists of more than 50% organic matter, wood lignin, and inorganic compounds, and includes mainly sodium and sulfur compounds.

Black liquor recovery boilers perform a dual function. First, they recover the valuable cooking chemicals used in the pulp digester, and second, they produce steam that can be used to generate electricity or for heating purposes in the kraft process. There are two main sections in a BLRB: the fire side, or furnace, where the black liquor is burned, and the heat transfer section, where steam is produced. Accordingly, in the furnace part of a BLRB, the spent cooking chemicals in the black liquor are burned to recover the inorganic salts (mainly sodium and sulfur compounds) while simultaneously generating steam through the combustion of the organic matter in the liquor in the heat transfer section. During the process, inorganic solids such as sodium sulfate, sodium sulfide, sodium carbonate, sodium chloride, and sodium hydroxide are melted on the furnace bed. Combustion of black liquor under reducing conditions converts sulfur compounds to sulfides and recovers the inorganic chemicals in molten form. For example, sodium sulfate is converted to sodium sulfide. The total sulfur in black liquor amounts to about 6%. The black liquor as a fuel has a very low calorific value as compared with conventional fossil fuels, and also has very high ash content.

In a BLRB furnace, the black liquor is introduced through a spray into the lower part of the furnace along with air for combustion. The black liquor is thus atomized to form small droplets to enable complete combustion. The size of the droplets is controlled in order to avoid their carryover to the upper portions of the furnace where they may otherwise deposit on the tubes. Such carryover deposits are particularly found in the superheater section, and may consist of soot, ash, and slag. Deposits decrease the boiler efficiency by reducing heat transfer. The heat transfer surfaces are therefore required to be periodically cleaned using air, steam, water, or mixtures thereof. On account of the very nature of this fuel, BLRBs suffer from various forms of fire-side corrosion, erosion-corrosion, and erosion related problems. The fact remains that black liquor fly ash is not as abrasive as the fly ash produced from combustion of coal in power boilers.

1.4 Operation and Working Principle of Utility or Power Plant Boilers

The fuels used in large utility or power plant boilers include fossil fuels (coal, oil, and natural gas), nuclear fuels (uranium and, sometimes, plutonium), and renewable biomass (wood, straw, and manure). Though each type of fuel has its own advantages and limitations, coal is the most

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commonly used fuel. Coal-fired boilers using pulverized coal as the fossil fuel dominate the electric power industry, even today.

Unless otherwise specified, a power plant based on coal-fired boilers belongs to the category of subcritical boilers.

1.4.1 Conventional or Subcritical Boilers

Conversion of water to steam involves transition from a liquid to a gaseous state; this is associated with a substantial increase in volume. The volume of one unit mass of steam at atmospheric pressure is sixteen hundred times that of water, because the atoms and molecules in steam are spaced further apart from one another than those in water. Therefore, when water is converted to steam in a closed vessel, the pressure of the steam formed will increase. This is the underlying principle on which a boiler works.

The three stages in conversion of water to steam are (Ref 1.5):

1. Heating the water from room temperature (i.e., cold condition to boiling point or saturation temperature by addition of sensible heat). Further addition of sensible heat is ensured by preheating the high-pressure boiler feed water using extracted heat from the steam recycled by the low-pressure turbine.
2. Boiling of water at saturation temperature to produce steam as a result of addition of latent heat.
3. Heating steam from saturation temperature to a higher temperature, called the superheated temperature, to improve plant efficiency.

As shown in Fig. 1.4, the important components of the boiler are burners, the combustion chamber, the steam drum, heat exchangers such as waterwalls, and economizers. Finely ground coal is mixed with air and fed to the burners, where it ignites to form a fireball in the combustion chamber. The combustion takes place at 1300 to 1700 °C (2370 to 3090 °F) and the heat generated is transferred to the feedwater that flows through the waterwall tubes that form the walls of the furnace. The feedwater consists of condensate or condensed steam returned from the processes and make-up water (i.e., treated raw water), which comes from a source such as a river, reservoir, or lake. For higher boiler efficiencies, an economizer preheats the feedwater using the waste heat in the flue gas. A mixture of water and steam is formed in waterwall tubes as a result of heat transferred by the fireball in the combustion chamber/furnace. This mixture then moves up into the steam drum located at the top end of the boiler, as it has a lower density than the water flowing through downcomers. The liquid water and steam are separated in the steam drum. The separated liquid water is then recirculated to waterwall tubes through downcomers. The downcomers and the waterwall tubes form the two legs of a water

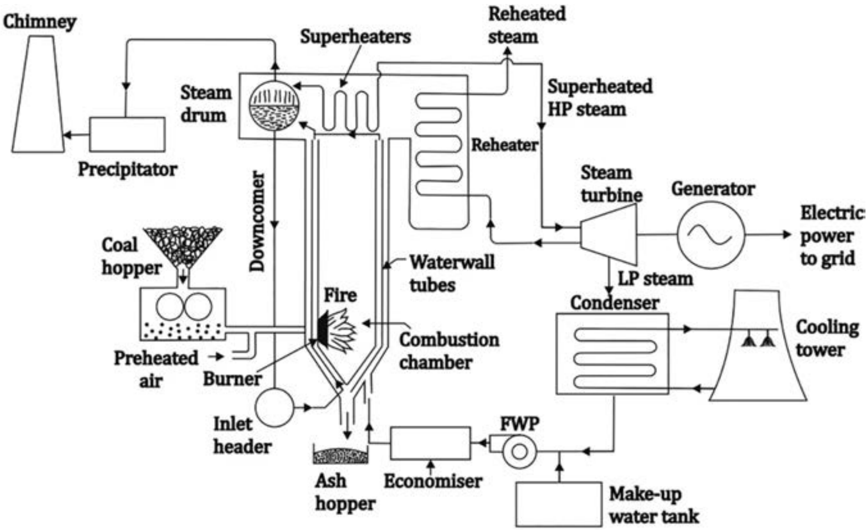

Fig. 1.4 Schematic showing working principle of a boiler

column. The steam collected in the upper half of the steam drum is separated and fed to primary and secondary superheaters to further raise its temperature and pressure. In the secondary superheaters, steam comes across the hot gases exiting the top of the boiler and is heated to its final temperature and pressure before leaving the boiler. The typical temperature and pressure of the final superheated steam are 530 to 570 °C (990 to 1060 °F) and up to 175 bar (2.5 ksi). This steam is then fed to a high-pressure steam turbine to drive a generator, which produces electricity. Steam exiting the high-pressure steam turbine is called *cold reheat*. It is reheated in the reheater tubes and sent back to the low-pressure steam turbine for improving the thermal efficiency of the process. By the time the flue gases exit the boiler, most of their energy is transferred to water in the boiler. Finally, the hot gases are cleaned up before they are sent to a stack, to control pollution.

1.4.2 Advanced Boiler and Power Plant Technologies

Pulverized coal-fired boilers are the most commonly used technology in thermal power plants, based on many decades of experience. This technology is well developed, and there are thousands of units around the world. However, conventional coal-fired plants operate at very low plant efficiency (typically 35 to 38%), making power generation very expensive. Additionally, they are one of the largest sources of air pollution. Emissions such as CO_2, SO_2, NO_x, and dust particles due to burning of fossil fuels are some of the largest contributors to global climate change. Studies reveal that improvement in the plant efficiency, apart from lowering the cost of electricity production, results in significant reduction in CO_2 emission as well. One way to increase the efficiency of a steam power plant is to increase steam pressure and temperature, and this has been the basis of development of SC, USC, and advanced USC (A-USC) boilers.

1.4.2.1 Supercritical, Ultra-Supercritical, and Advanced Ultra-Supercritical Boilers. A conventional or subcritical boiler is characterized by a maximum operating pressure of 19 MPa (2.8 ksi). Under this condition there is a nonhomogeneous mixture of water and steam in the evaporator (i.e., waterwall tubes) and thus the boiler design requires a steam drum to separate steam from water before it is fed to the superheater and then to the turbine. However, in the supercritical (SC) condition for any system, there is no distinction between its liquid and gaseous states. Thus, for water in the SC state, there is no clear distinction between liquid water and steam, and the system behaves as a homogeneous fluid (dry steam) with homogeneous properties.

Subcritical steam boilers operate at relatively low pressures such that water boils first and is then converted to superheated steam. At SC pressures, water is heated to produce superheated steam without boiling. Incidentally, water reaches this state at a pressure above 22.1 MPa (3.21 ksi) and a temperature of 374.15 °C (705.45 °F). These are the critical temperature and pressure for water (called the critical point of water), and at the critical point of latent heat (enthalpy of steam minus enthalpy of water), they become zero. In physical terms, at this pressure, water transforms to steam spontaneously.

Thus, if the operating pressure in the evaporator part of the boiler is in excess of 22.1 MPa, such a boiler is referred to as an SC boiler. In this type of boiler, cycle fluid does not exist as two phases, liquid water and steam, so there is no question of separation of steam from water. Therefore, SC boilers do not have any steam drum. The heat-absorbing surface is one continuous tube that the water and steam generated in the furnace waterwalls pass through only once; such boilers are called *once through boilers*. The underlying difference in functioning between subcritical and SC once-through boilers is demonstrated in Figure 1.5; there is no recirculation of water in a SC boilers as there is in the case of a subcritical boiler.

As previously mentioned, the efficiency of plants using a subcritical boiler is around 35 to 38%, and increases in plant efficiency lead to reduction in coal consumption and in the level of emission of noxious gases in the environment. Advancements in boiler technology over the past several decades have therefore been mainly focused in the direction of increasing plant efficiency, which can be achieved by raising the operating steam pressure and temperature beyond the critical point of water. This increases the efficiency of the Rankine steam cycle used in power generation. Based on the operating steam temperatures and pressures, there

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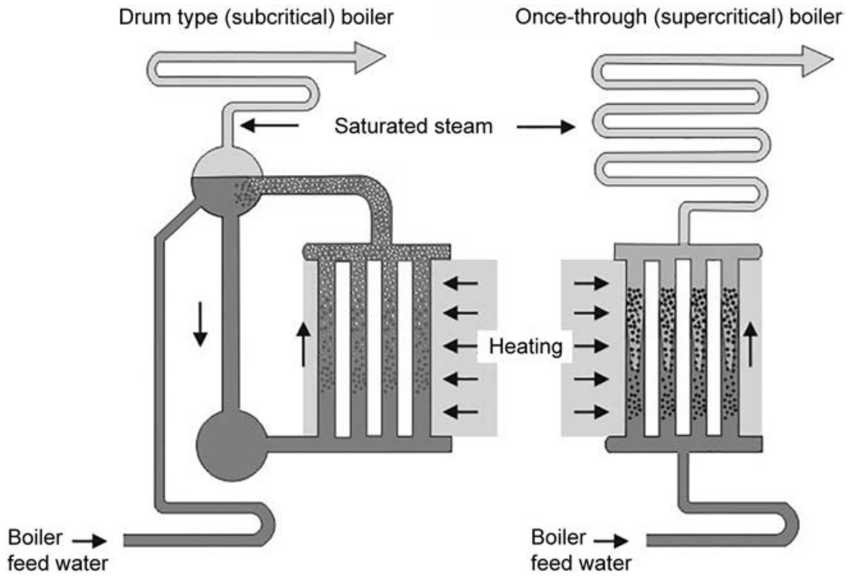

Fig. 1.5 Difference in functioning between subcritical and supercritical boilers

are four types of pulverized coal boilers, namely subcritical, SC, USC, and advanced ultra-supercritical (A-USC) boilers. Table 1.1 gives the classification of various types of boilers on the basis of their operating temperature and pressure and the plant efficiency they offer (Ref 1.6).

Ultra-supercritical boilers work at SC pressure of >22.1 MPa (typically around 27 MPa, or 3.9 ksi) with a steam temperature of 565 °C (1050 °F) or more and plant efficiency around 40 to 42%. Advanced ultra-supercritical coal-fired power plants are characterized by an inlet steam temperature to the turbine of 700 to 760 °C (1290 to 1400 °F), with average metal temperatures of the final superheater and final reheater running as high as about 815 °C (1500 °F). A-USC plants can offer a plant efficiency of up to 47%.

Further discussion on SC power plant technology is given in Chapter 2, *An Overview of the Functioning of a Thermal Power Plant*, in this book.

Table 1.1 Typical data on boiler operating parameters versus efficiency

Type of boiler	Steam pressure and temperature	Typical plant efficiency, %
Subcritical	<22.1 MPa, 538 °C, (3.2 ksi, 1000 °F)	35.0–38.0
Supercritical	24.7 MPa, 538–565 °C, (3.6 ksi, 1000–1050 °F)	38.0–40.0
Ultra-supercritical	27 MPa, 565–625 °C, (3.9 ksi, 1050–1155 °F)	40.0–42.5
Advanced ultra-supercritical	>30 MPa, above 700 °C, (4.4 ksi, above 1290 °F)	42.5–47.0

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1.4.2.2 Integrated Gasification Combined Cycle Technology.

Gasification of pulverized coal in a conventional coal-fired plant coupled with a combined cycle process has emerged as an alternative to achieving higher plant efficiency. This novel approach, known as an integrated gasification combined cycle (IGCC), is a technology that uses a gasifier to transform pulverized coal under a given set of pressures and temperatures into a synthesis gas termed *syngas*. The gasification process involves a reaction between pulverized coal particles and oxygen and/or steam to produce syngas. The syngas so produced mainly consists of hydrogen and carbon monoxide, besides certain impurities. The syngas is subjected to cleaning to remove impurities such as sulfur. The cleaned syngas is fired in a combustion gas turbine that drives a generator to produce electricity. The waste heat from the gas turbine is recovered by passing the hot exhaust gases of the gas turbine through an HRSG to produce steam. The resultant steam is further used to drive a second steam turbine-generator set to produce electricity.

The burning of gas in a gas turbine not only produces power but also hot exhaust gases that, when routed through an HRSG, yield steam for running a steam turbine to produce power; the process is termed a *combined cycle*. Figure 1.6 shows the block diagram of an IGCC process.

In an IGCC process, the thermal efficiency can be extended to approximately 50–60%. Instead of coal, other carbon-based materials such as diesel or natural gas may also be used as fuel. When natural gas is used as a fuel to produce syngas, the process is called a natural gas combined cycle (NGCC).

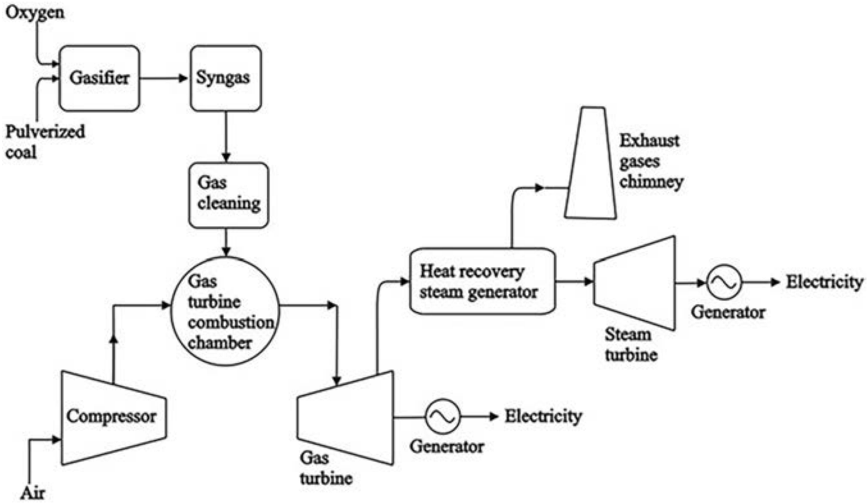

Fig. 1.6 Block diagram of integrated gasification combined cycle process

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1.4.2.3 Cogeneration/Combined Heat and Power. *Cogeneration*, also known as combined heat and power (CHP), may be defined as the simultaneous production of electrical and thermal energy from a single fuel. The basic principle of a cogeneration system is that if the waste heat from one process is utilized in the production of the other, a substantial improvement in energy efficiency can be achieved. For example, the waste heat (i.e., heat discarded from a conventional power generation unit such as a steam turbine) is recovered and subsequently utilized as thermal energy for applications such as space heating and cooling, water heating, or industrial process heat. The two main components of any cogeneration facility are a power generator and a heat recovery system. As a result of the CHP approach, it becomes possible to ensure an overall system efficiency of between 50 and 70%. Thus, there is a significant improvement over the efficiency of a fossil-fuel-fired power plant, whose average efficiency is approximately 35%. Cogeneration also leads to reduced energy costs and reduced greenhouse gas emissions. The underlying basic principle of cogeneration is shown in Fig. 1.7.

As shown in the schematic, a heat source (i.e., a boiler) converts water to high-pressure steam. The high-pressure steam is further heated to the boiling temperature and then most frequently superheated to a temperature above the boiling temperature. This high-pressure superheated steam is fed to a steam turbine, where the thermal energy of the steam is utilized to rotate a turbine. The turbine in turn drives a generator to produce electricity, which is then supplied to a plant utility or grid. Waste heat in the form of low-temperature, low-pressure steam at the exit end of the turbine is utilized as hot water or steam for subsequent consumption by an industrial or commercial application. Thus, a CHP plant recovers waste heat and supplies it to local buildings for heating or cooling purposes and thereby improves the process efficiency.

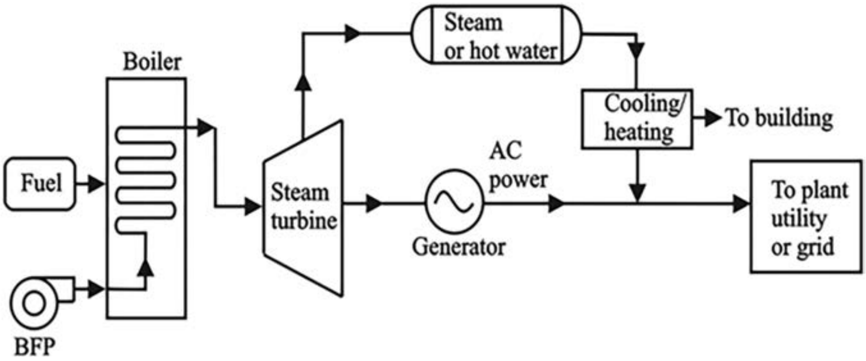

Fig. 1.7 Schematic showing principle of cogeneration using a steam boiler and steam turbine

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