西安交通大學"十五"规划教材

锅 炉

——理论、设计及运行

Boilers——Theory, Design and Operation

(英文版)

车得福 著
Defu CHE

西安交通大学出版社
XI'AN JIAOTONG UNIVERSITY PRESS

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Preface

It has long been my wish to write a textbook concerning boiler in English for senior college students.

There are quite a few reasons for me to write this textbook. Xi'an Jiaotong University (XJTU) is the first institute in which the specialty of boiler was established in 1950s in China. Since then, a great number of students have graduated from this university, and they have become and will become the eminent engineers and scientists. Historically, the textbooks compiled by the staff of this university have been adapted to the Chinese students. Both the graduates and the textbooks from this university have been widely recognized over the whole society of China. XJTU should continue to keep the leadership in textbook compilation and teaching reforms. English has in fact become a very international language. The writing of academic papers and technical reports in English is almost inevitable for the graduates, in particular, as China has become a member of WTO. It will be of great significance for the students to be familiar with the English terminology and expressions related to boiler as early as possible. Good English proficiency can be very helpful in job seeking.

The Chinese edition of *Boilers* appeared in 2004. In this English edition, many features have been reserved. Nevertheless, the contents associated with material strength of pressure part, boiler setting and framework, auxiliary equipment have been eliminated, and a new chapter, *Operation of Boiler* has been added. The notation system throughout this book is retained for convenient reading of Chinese readers.

This book can be used as a textbook after the students have learned fluid mechanics, engineering thermodynamics and heat transfer as prerequisites. I do not intend this book to be scientifically and technically complete. In particular, neither the correlations and diagrams nor the methods for design or operation of boiler presented in this book are of absolute authority. They are not the sole choice whenever a boiler is designed or operated. Any practical design or operation of a boiler shall refer to relevant handbooks or manuals. Besides, English is not my native tongue. Although I have the visiting, studying, working and living experiences in English-speaking countries, more or less inappropriate or incorrect expressions might have occurred throughout this book. I am very anxious about any possible misleading and misunderstanding. I am looking forward to having the corrections from all the readers of this book.

Prof. Tongmo XU, the former president of Xi'an Jiaotong University, Prof. Dongping TIAN, the former head of Teaching Affairs Department, who initiated the writing of this

textbook, are highly appreciated. My thanks also go to Prof. Zhengning ZHUANG, Prof. Dong WANG and Prof. Jun LI, who are the co-authors of the Chinese edition of this book. Their contributions to the book should be greatly appreciated.

I appreciate the many comments and suggestions from Prof. Guoxiang WANG of The University of Akron, USA, who reviewed this book word by word. Both the content and mode of presentation of the material has been influenced here and there throughout the book. Although the author has been teaching the course for over fifteen years, the lack in practical experiences of designing and operating a boiler might have led to many shortcomings or even errors in this book. Further criticisms, comments and suggestions are all welcome.

I would like to gratefully acknowledge the writing grants from XJTU. I also express my gratitude toward all those at Xi'an Jiaotong University Press, who have made the production of this book possible.

Last, but not least, I would like with all my heart to thank my wife, Dr. Yanhua LIU, who works also in XJTU as a professor, and my lovely daughter, Chang CHE, who seems thoughtful a little bit earlier as a middle school student. It is not imaginable to accomplish this book without their patience and understanding. Long-time facing to the computer monitor is painful to me. But, whenever I am back to home, a cup of hot coffee or a piece of fruit handed to me is always capable of relieving my tiredness physically as well as mentally. It is absolutely true that there is no place like home. Every word or sentence from them is always encouraging, which had become an impetus for me to be determined to complete this book.

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Chapter 1

Introduction

1.1 Status of energy utilization

Energy resource is the substance in nature which can be transformed into heat, light, electrical and mechanical energy etc.

Since our ancestors started to take advantage of fire (one kind of heat source), human beings had bidden adieu to the primitive lives in which raw birds and beasts were eaten. Of course, the prehistoric civilizations mainly consumed (burned) wood to get heat. With the evolution of civilization, heat can be obtained in many different ways, that is, many kinds of energy resources have been found.

The energy resource existing in a ready form in nature, which need not be processed or transformed and can be used directly, is known as natural energy or primary energy, e.g., coal, crude oil, natural gas, flowing water, biomass, nuclear fuel, solar energy, geothermal energy, tidal energy etc. The energy resource which has been processed or transformed is known as secondary energy, e.g., coke, gasoline, electricity, steam etc.

Brushwood, coal and oil were the major energy resources firstly used by mankind. Until 19th century, wood and grass as fuels have been providing the most part of energy for the lives and productive activities of mankind. Since 80's of 19th century, the energy from coal became the most important, exceeding that from wood. From 60's of 20th century, oil has become the most dominating resource in world-wide consumption of energy. Currently, natural gas has also become a widely used energy resource.

Coal, oil, natural gas and water and so on, which have been widely used with the aid of modern technologies, are known as conventional or traditional energy. The energy from nuclear fusion, solar, wind, geothermal, tidal, biomass, hydrogen and ocean, which are still being developed and have not been used on a large scale, are known as new energy resource. The new energy resource is tremendous in amount, various in type, and clean while utilized, hardly detrimental to the environment. Because a balance between consumption and replenishment can be maintained, these energy sources are referred to as consecutive energy sources or renewable energy sources. Hydropower is also one of renewable energy sources.

With the depletion of conventional energy, mankind has got to turn to the energy sources that are renewable and have no pollution to the environment, inclusive of solar, wind, geothermal, ocean, biomass and nuclear. Since nuclear energy has not been used as a main energy resource in China, it is usually classified into the category of new energy resource. But, the energy from nuclear fission has been employed for many years in the countries such as France, Belgium, Japan, Sweden, Germany, Korea and Hungary, and the electricity from nuclear energy takes 30%～77% of total amount in these countries. Therefore, the nuclear fission energy is not considered as a new energy. The nuclear energy in new energy resources refers to nuclear fusion energy only.

In comparison with fossil fuels, it was generally considered that new energy is not harmful to the environment during the process of being consumed. However, the widespread use of new energy can lead to a detrimental impact on both the human being and the environment, although the impact may be limited. For example, some noxious substances have to be used during the production of solar energy batteries, noise will be generated from a windpower equipment, H_2S will go out from the deep earth with geothermal water stream. Thus, much attention must also be paid to the environmental protection when new energy resource is developed and used.

China is plentiful in primary energy, and takes a most part in the world. The total proven reserves (technically recoverable) of conventional energy resources (including coal, oil, gas and hydropower (that is renewable and calculated on a basis of 100 years) is over 8230×10^8 tce (tons coal equivalent, the coal that has a calorific value of 29 300 kJ/kg, i.e., 7000 kcal/kg, is known as coal equivalent). The total proven and economically-recoverable reserves is 1392×10^8 tce, approximately 10.1% of the total global reserves.

Table 1 - 1 Reserves and constituents of conventional energy resources of China[2]

Energy Resource	Total ($\times 10^8$ tce)	Coal ($\times 10^8$ t)	Oil ($\times 10^8$ t)	Natural Gas ($\times 10^8$ m^3)	Water ($\times 10^8$ kW·h)
Total energy	40 466.4	50 592.2	1000.0	381 400.0	59 221.8
Constituent /%	100.0	89.3	3.5	1.3	5.9
Globally Total	1 048 809.7	1 195 748.4	51 172.8	79 330 827.1	413 095.0
China /%	3.9	4.2	2.0	0.5	14.3
Total proved reserves (exploitable in technology)	8231.0	10 077.0	160.0	20 606.0	19 233.0
Constituent /%	100.0	87.4	2.8	0.3	9.5
Globally Total	329 697.5	352 749.6	25 674.6	26 630 075.2	117 549.0
China /%	2.5	2.9	0.6	0.1	16.4
Proved Rate /%	20.3	19.9	16.0	5.4	
Warranted Years	766.8	1007.7	98.2	74.3	
Production in 2000	10.9	10.0	1.6	277.3	2224.0
Constituent /%	100.0	67.2	21.4	3.4	8.0
The total proved and economically-exploitable reserves	1391.9	1145.0	32.7	13 668.9	12 600.0
Constituent /%	100.0	58.8	3.4	1.3	36.5
Globally Total	13 832.9	9842.1	1402.8	1 493 811.0	73 053.0
China /%	10.1	11.6	2.3	0.9	17.2
Warranted Years	129.7	114.5	20.1	49.3	

China can be considered to be among the countries possessing plentiful energy resources. However, taking into account variety, distribution and population, there are some inherent contradictions or problems in the exploration and drillings and exploitation of energy resources, which should be solved with effective strategies and concrete measures.

The possession of energy resource per capita is small in China, saving of energy is a national long term task.

China is a power with huge energy resource, but also a power with a big population. The total amount of energy resources ranks forefront in the world, in which, water energy ranks No.1, and recoverable reserves of coal takes the third place. But, in 2000, the recoverable reserves of coal, oil and natural gas per capita are only 90 t, 3 t and 1080 m^3 respectively, correspondingly 54.9%, 11.0% and 4.3% of global averages (165 t, 23 t and 24 988 m^3), and 9.7%, 23.1% and 6.3% of America (903 t, 13 t and 17 025 m^3), 22.3%, 30.0% and 9.0% of OECD (Organization for Economic Cooperation and Development) countries. Obviously, China is relatively impoverished in energy resources. It is absolutely of great significance to advocate saving energy, and to take energy-saving as No.5 resource after coal, oil, natural gas and water. The utilization efficiency and the economic benefit of energy should be promoted, the sustainable development of energy and economy must be adhered to.

A serious regional imbalance of energy distribution exists, and it is of difficulty to transport energy resources over long distance.

There are more energy resources in the north part than in the south part, and the west area is richer in resources than the east. There are more coals in the north, more hydropower in the south, and more oil and gas in the west. However, there are greater demands for the resources in the east and coastal areas. The contradiction between the resource distribution and economy development has determined that the energy resource should flow from the west to the east and from the north to the south. The pattern that the coals in the north are transported to the south is inevitable. The projects "West electricity transmission to the east" and "West gas transport to the east" will play crucial roles for the sustainable and fast development of national economy.

Coal has been the major conventional energy. Various possible measures should be taken to optimize the production and consumption of this energy resource.

Compared to other resources, the utilization efficiency of coal is lower, and the induced pollution is more serious. Thus, much more attention must be paid to the clean coal utilization.

In order to solve the problems of environmental protection, the consumption of clean energy resources such as oil, gas and hydropower should be appropriately increased. Hydropower is clean and renewable energy resource, and it ranks No. 2 among all the resources of China, the proportion of hydropower in the quantity of remaining recoverable reserves of energy resources is over 36.5%,. But, in the year of 2000, only 17.6% of the economically exploitable hydropower had been utilized. This figure is much lower than the average of the hydropower-rich developed countries. Therefore, priority shall be given to the further survey and exploitation of hydropower.

Nevertheless, in China many difficulties exist in developing hydropower resource. Since the major sources are far from the coastal electricity load centers, how to make the electricity transmission more efficient and how to ensure the stability of electrical power systems are challenging scientists and engineers.

There are plenty of new energy resources and renewable energy resources in China, their development and utilization should be considered to be an important composition of sustainable development strategy of the country, which will be of positive and far-reaching significance to the environmental protection and the optimization of the energy resource structure.

The excessive dependence on coal in the consuming structure of energy in China has led to an aggravation of environmental pollution. The production and utilization of coal are the major influential factors of the regionally environmental problems such as atmospheric pollution, acidic rain and the globally environmental problem such as climate change. The Chinese coals are characterized as high sulfur content and high ash content. The ash content of raw coals is mostly around 20%, about 13% of raw coals have a sulfur content of more than 2%, and the production of high sulfur coals has been increasing.

The major atmospheric pollutants in China are soot and dust, sulfur dioxide and nitrogen oxides, which originate mostly from the combustion of fossil fuels and the industrial processes. In 2000, The soot and dust, SO_2 emitted in China amounted to 1165×10^4 t and 1995×10^4 t (see Table 1-2) respectively. The emissions of soot and dust, sulfur dioxide were much more in the production regions of high sulfur coal and in the regions where energy resources were produced and consumed in a great amount. In these regions, the air pollution was relatively serious. In addition, the emission of soot and dust, sulfur dioxide was remarkably different from industry to industry. The sulfur dioxide emitted due to power generation, gas and hot water supplies roughly accounted for 50.6% of the total emission.

Table 1-2 Emissions of major pollutants in China in 2000[2] $\times 10^4$ t

Pollutant	Total amount	From industry	From daily activities
Soot and Dust	1165.4	953.3	212.1
SO_2	1995.1	1612.5	382.6

In China, air pollution happens mostly in urban areas. Over last few years, the deterioration of air quality has been greatly mitigated, and the air quality of some cities has been considerably improved. Generally speaking, the pollutions in the winter and the spring are more serious than in the summer and the autumn, more serious in the northern cities, and in large and medium sized cities. The total suspended particulates or respirable dusts are the major pollutants affecting the air quality in the city, the air pollution due to sulfur dioxide is serious in some regions, and the concentration of nitrogen oxides is high in a few metropolitans. Nevertheless, the acidic rain extent and frequency have been maintained to be stable, and the acidic rain area has been over 30% of the territory, and China has become one of the three large acidic rain areas in the world. The pH value of the rain in some cities in 2000 reached 3.98. The proportion of cities with lower than 5.6 of pH value of rain is 70.6%.

According to the monitored results in 2000, the daily averaged concentration of TSP (Total Suspended Particulates) of all the cities was 336 $\mu g/m^3$ for northern cities, and 186 $\mu g/m^3$ for southern cities, both are much higher than the reference value of 60~90 $\mu g/m^3$ provided by WHO (World Hygiene Organization).

1.2 Boiler and its role playing in national economy

A boiler is a closed vessel in which water, under pressure, is transformed into steam by the application of heat. In China, usually those devices generating steam and/or hot water at atmospheric pressure are also considered to be boilers.

A boiler has emerged as an important tool of industry with a high degree of versatility. In addition to the generation of electricity, as a source of hot water and/or steam it has found applications in a variety of industries like aluminium, automobiles, concrete block and bricks, ceramic glass, inorganic and organic chemicals, copper primary and secondary, lumber, pulp and paper, selected plastics, rubber, textiles and sugar etc.

In its essentials a boiler consists of a furnace in which any fuel—oil, coal, wood, husk, or gas are burnt to produce combustion products and thereby generate heat and an arrangement of heating surfaces to contain and heat water or produce steam.

The people dealing with boiler are also called as water-heaters in folk Chinese language. Indeed, the boiler is mainly associated with water, although the working fluid of a boiler can be a liquid other than water in special circumstances.

As well known to all, water can exist in three states in nature, which are solid (ice), liquid (water) and gas (vapor) respectively. Being heated, the temperature of water will be elevated with the absorption of heat, and the water boils at certain temperature. The temperature at which the water boils is known as boiling point or saturation temperature. The boiling water is called as saturated water. The heat the water of 1 kg absorbs from 0℃ to saturation temperature is named as liquid heat.

If heat is exerted further after the saturation temperature is reached, the water starts evaporating, but the temperature does not continue to rise. The heat added makes water turn into steam. Actually, the boiling is a process in which a great number of vapor bubbles are formed and rise to surface. During this process, the temperature of the steam maintains unchanged at the saturation temperature, the vapor is known as saturated steam. The heat needed to change the saturated water of 1 kg into saturated steam completely is named as latent heat.

The temperature of saturated vapor will rise up if it continues to be heated at a constant pressure. The steam whose temperature is higher than saturation temperature has the name of superheated steam. The number of degrees beyond the saturated temperature is referred to as superheat. The heat for superheating the steam is named as superheating heat.

At different pressures, the saturation temperature, liquid heat and latent heat of water are quite different. Their values corresponding to several pressures are listed in Table 1 - 3. The state at which the latent heat is zero is known as critical state, and the corresponding parameters are called critical parameters.

Table 1 - 3 Thermophysical characteristics of water at different pressures

Absolute pressure /MPa	0.1	1	10	22.12
Saturation temperature /℃	99.6	179.9	310.9	374.15
Liquid heat /kJ · kg^{-1}	417.5	762.6	1409	2095
Latent heat /kJ · kg^{-1}	2258	2014	1316	0

If 1 kg of water at 0℃ is heated at constant pressure to certain state, the heat absorbed by the water is defined as the enthalpy of the water or the steam. If the water has been heated to superheated state, the enthalpy will be the sum of liquid heat, latent heat and superheat. The heat absorbed by 1 kg of water when heated by boiler is the difference between the enthalpy of the steam at the outlet and the enthalpy of the water entering the boiler.

In order to realize heating and evaporating the water and superheating the steam, a boiler shall have the equipment that can acquire heat energy from fuels, i.e., the furnace, the pressure vessel containing the water and the heating surface absorbing sufficient heat. Whether or not the heating surface is sufficient depends on the amount of the steam required, and the temperature and pressure.

If a strict definition is given for boiler, it may be described as: boiler is a device in which fuels are burned, the chemical energy is released as heat energy, and the heat is transferred to the water (or other working fluid), finally the water is transformed into the steam or hot water with certain pressure and temperature.

As mentioned above, current structure of global energy resources is that coal, crude oil and natural gas are given priority to. In addition, hydropower and nuclear energy are playing more and more important role. Up to now, solar, windpower, geothermal and tidal energy have also been rather highly developed. Whether or no, the main form of the energy utilized by the modern people is electricity, and various energy resources are being converted into the electricity.

The gross installation capacity of China has been over 6×10^8 kW. The changes of the installed capacity and the generation capacity are listed in Table 1 - 4 (The figures are exclusive of Hong Kong, Macao and Taiwan). Since 1996, both the installed capacity and the generation capacity of China have exceeded those of Japan, and ranked No. 2 in the world.

Table 1 - 4 The installation capacity and the generation capacity of China[2]

Year	Installed capacity ($\times 10^4$ kW)				Generation capacity ($\times 10^8$ kW · h)			
	Total	Hydropower	Thermal	Nuclear	Total	Hydropower	Thermal	Nuclear
1980	6 586.9	2 032.0	4 555.0		3 006	582	2 424	
1985	8 705.3	2 641.0	6 064.0		4 107	924	3 183	
1990	13 789.0	3 604.5	10 184.5		6 213	1 264	4 950	
1995	21 722.4	5 218.4	16 294.0	210	10 069	1 868	8 073	128
1996	23 654.2	5 557.8	17 886.4	210	10794	1 869	8 781	143
1997	25 423.8	5 973.0	19 240.8	210	11 342	1 946	9 249	144
1998	27 728.9	6 506.5	21 012.4	210	11 577	2 043	9 388	141
1999	29 876.8	7 297.1	22 343.4	210	12 331	2 129	10 047	148
2000	31 932.1	7 935.2	23 754.0	210	13 685	2 431	11 079	167
2005	51 718.48	11 738.79	39 137.56	684.60	24 975.26	3 963.96	20 437.30	530.88
2006	62 200	12 857	48 405	685	28 344	4 167	23 573	543

The energy resource structure determines the guidelines of electric power development. In China, the guidelines are as follows: thermal power generation shall be optimized, hydropower shall be developed actively, nuclear power shall be developed moderately, and new energy sources shall be developed by adjusting measures to local conditions. The development of new electrical grids and the upgrading of existent electrical grids shall be emphasized, equal attention shall be paid to the development and the conservation of energy resource, even more attention shall be paid to environmental protection and the efficiency of energy utilization shall be improved by all means.

Up to now, in China more than 80% of the gross electric power generation is from thermal power generation. The installed thermal gross capacity is about 75%. The proportions of the generation and the installation capacity of hydropower are 20% and 25%, respectively. The corresponding figures for nuclear power are 1.2% and 0.66%, respectively. Others are negligible. In the thermal power generations, coals are taken as the major fuels, whereas oil and natural gas are seldom used to generate electric power. Roughly speaking, 1/3 of the coal produced is for power generation, 1/3 for industrial and residential