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RESEARCH ARTICLE

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Air pollutant control and strategy in coal-fired power industry for promotion of China's emission reduction

Abstract Coal-fired power industry has always been the major power source in China. As coal-fired power industry consumes around a half of China's coal production, it is always thought to be a big air pollutant emission source. As more and more strict legislations in coal-fired power industry have been issued by the government, the emission performance in coal-fired power industry has been drastically reduced recently. Based on a brief review of the development of emission control in China's coal-fired power industry, the affecting mechanism among the development of installed capacities of emission control device, pollutant emission, and emission performances in coal-fired power industry is studied. According to a systematic study on the development of emissions of classified categories, the role of coal-fired power industry as a pollutant source is reevaluated. It is found that, coal-fired power industry has contributed the most to China's emission reduction, and the barycenter of air pollutant emission has been transformed to other high energy consumption industries, like heat, iron/steel, and cement. Then some development strategies are suggested, such as maintaining the current emission standard in coal-fired power industry; expending the coal-fired power emission standards to categories of heat generation and supply, nonmetallic mineral production and ferrous metals smelting and processing; and controlling other heavy metal by consulting the method of Hg control.

Keywords coal-fired power industry, energy intensive industries, pollutant emission control, NO_x, SO_2, soot

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1 Introduction

Limited by China's energy reservation of more coal, but less oil and natural gases, the primary energy consumption of China has to relay on coal, which accounts for approximately 70% of the national energy consumption [1,2]. Most of the coal is consumed through direct combustion in power and heat generation and other energy intensive industries such as iron/steal and cement [3,4]. Coal-fired power industry has consumed more than half of China's coal consumption [5,6], and supplied about 80% of the electricity in the past several decades[1)] . As large-scale coal is burnt directly, a great amount of dust, SO_2, and NO_x are produced, which are the main sources of fine particle pollution. This fine particle pollution contributed a lot to the forming of fog and haze [7,8]. Consequently, coal-fired power industry has always been accused as the biggest pollutant producer for a long period of time.

The first national standard involving pollutant emission control in coal-fired power plant was issued in 1973, named as "Industrial 'Three Wastes' Emission Standard Trial Edition (GB J4-73)" [9], hereafter referred to as "Three Wastes Standard." While the "Emission Standards of Air Pollutants for Coal-fired Power Plants (GB 13223-91)" issued in 1991 is the first emission standard specially developed for coal-fired power plants [10], hereafter referred to as "Emission Standard." As the environmental problem increasingly deteriorated, the "Emission Standard" was revised three times in 1996 [11], 2003 [12], and 2011 [13], respectively. The worldwide most stringent

1) National Energy Administration of China. National Power Industry Statistics Bulletin (1950–2018) (in Chinese)

"ultra-low emission" was proposed as the "Action Plan on Upgrading and Reconstruction of Coal-fired Power Industry for Energy Conservation and Emission Reduction (2014–2020)" ([2014] No.2093) [14] was jointly issued by three ministries in 2014, hereafter referred to as "Action Plan." According to the "Action Plan," the emission concentrations of dust, SO_2, and NO_x in newly installed coal-fired power plants are limited to 10, 35, and 50 mg/m^3 on the reference of 6% oxygen content in the 11 eastern provinces of China [14].

As the air quality in China has not been obviously improved in recent years, the concept of "near-zero" emission has caused widespread controversy [15]. Consequently, several applications including the demonstration project has been conducted in some plants [16], and an enterprise standard has been issued by a big power company [7]. However, considering the issues of cost-effectiveness, technologies, and coal resource conditions, it is argued that the emission standard in China should not be too stringent [17,18].

To solve the problem of severe air pollution in China, the development of air pollutant emission control in the power industry in China is briefly reviewed and discussed, including the evolution of emission standard, emission performance, installed capacity for emission control, as well as the total emission in China's power industry. Subsequently, the development of national classified emissions is thoroughly analyzed. Then the effect of pollutant control in the power industry on the national emission reduction is identified, and a national emission control receipt is prescribed accordingly.

2 Pollutant control in power industry

2.1 Soot control

The pollutant first controlled in power industry is soot, whose emission was first limited by mass flow rate according to the stack height in coal-fired power plant in the "Three Wastes Standard" since 1973 [9]. In 1991 when the first "Emission Standard" was issued [10], the soot concentration of newly installed units was first limited to 150–600 mg/m^3 according to different ash content of the supplied coal. Along with the fast development of industry, the nationwide air pollution increasingly deteriorated, consequently the emission standard was revised to be increasingly stricter. In the first two revised editions of the "Emission Standard," the soot emission was differentially treated according to the different conditions of construction time, unit capacity, location and coal type, as considering factors of the local environmental condition, soot removal techniques, as well as the economic issue. In the 2011 edition of the "Emission Standard," the consideration of construction time and coal type were deleted, the maximum soot emission concentration was reduced to 30 mg/m^3, and the emission concentration in key regions was even reduced to 20 mg/m^3. When the "Action Plan" was issued in 2014, the concentration of soot emission in newly installed coal-fired power plants is even limited to 10 mg/m^3 in the 11 eastern provinces of China [14].

The development of soot emission and corresponding emission performance in China's power industry is shown in Fig. 1[1)]. Along with the fast development of China's coal-fired power industry and its increasingly strict soot emission standard, the national soot emission in coal-fired power industry has experienced the stages of remaining stable in 2001–2010, a sudden drop from 2010 to 2011, a gradual decline in 2011–2013, a sharp decrease from 2013 to 2015, and another gradual decline afterward. As can be seen from Fig. 1, the national soot emission in power industry dropped drastically from 3.07 to 1.55 million tons in 2011 since soot emission concentration in all coal-fired power plants was limited to 30 mg/m^3 (20 mg/m^3 in key regions) by the 2011 edition emission standard. Subsequently, as the ultra-low emission standard was adopted in the 11 eastern provinces of China since 2014, the national soot emission in power industry sharply decreased to 0.4 million tons in 2015 and further to 0.35 tons in 2016 [19], which accounted for only 9.5% of the historical peak value. The soot emission in coal-fired power industry has been effectively controlled in recent years.

2.2 SO_2 control

The SO_2 emission in coal-fired power industry was first limited by mass flow rate according to the stack height in coal-fired power plant by the first edition of "Emission Standard" issued in 1991. The emission control of SO_2 concentration was first required in the first revised edition of the "Emission Standard" issued in1996, where the SO_2

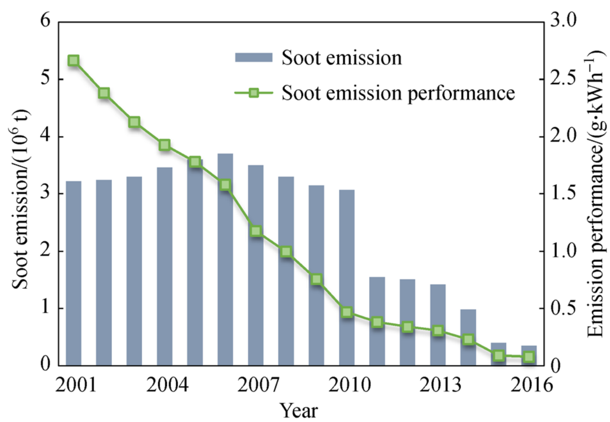

Fig. 1 Soot emission performance in China's coal-fired power industry

1) State Environmental Protection Administration of China. Annual Statistic Report on Environment in China (2001–2016) (in Chinese)

emission concentration of newly installed coal-fired power units was limited to 1200 mg/m^3. As the "Emission Standard" was revised again in 2003, the SO_2 emission concentration of newly installed coal-fired power units was limited to 400 mg/m^3. In the 2011 revised edition of the "Emission Standard," the SO_2 emission concentration of the newly installed coal-fired power units was limited to 100 mg/m^3 from the beginning of 2012, and that of in-service units was limited to 200 mg/m^3 from July 1st, 2014 (200 and 400 mg/m^3 respectively for Guangxi Zhuang Autonomous Region and other three south-western municipalities and provinces of Chongqing, Sichuan and Guizhou). Besides, the SO_2 emission concentration of all units was limited to 50 mg/m^3 in key regions. As the ultra-low emission limitation presented in the "Action Plan" was adopted in the 11 eastern province of China in 2014, the concentration of SO_2 emission in the newly installed coal-fired power plants is further limited to 35 mg/m^3 [14].

Influenced by the increasingly strict emission standard, more and more coal-fired power units have been equipped with desulfurization devices (De-SO_2). The developments of the installed capacity of De-SO_2 (the capacity of coal-fired power units equipped with De-SO_2) and the installed percentage of De-SO_2 (the installed capacity of De-SO_2 over the total capacity of coal-fired power units) over the total coal-fired power capacity from 2005 to 2016 are illustrated in Fig. 2[1)]. The first stage of the increases of De-SO_2 installed capacity and its percentage began from the implementation of the 2003 edition of "Emission Standard," in which the limitation of SO_2 emission for newly installed units could be achieved without De-SO_2. As can be seen from Fig. 2, the installed capacity of De-SO_2 sharply increases from less than 100 GW in 2005 to 631 GW in 2011, and its percentage also sharply increases from less than 10% in 2005 to about 79% in 2011. As the limitation of SO_2 emission became even stricter in the 2011 edition of "Emission Standard," more units, including the units with circulating fluidized bed (CFB) boilers, were forced to be equipped De-SO_2. The installed capacity of De-SO_2 further rapidly increases to 880 GW in 2016, and its percentage stably increases to approximately 97% in 2016.

The national SO_2 emission and its performance from 2001 to 2016 are depicted in Fig. 3[2)]. As the result of fast development of China's power industry, it can be seen from Fig. 3 that the national SO_2 emission increased sharply before 2005, when the De-SO_2 had not been widely installed. As the result of the continually fast increment of installed capacity of De-SO_2 and its percentage in coal-fired power industry, both the national SO_2 emission and unit performance have been reduced greatly since 2006. The reduction process could be generally divided into two stages, i.e., the "Eleventh Five-Year Plan" period (2006–2010) and the "Twelfth Five-Year Plan" (2010–2015) period. According to the Outline of the Eleventh Five-Year Plan for National Economic and Social Development of the People's Republic of China, the national SO_2 emission and that of coal-fired power industry should be controlled within 22.9 and 10 million tons, which are a reduction of 10% and 26% compared to those in 2005 respectively. Besides, the SO_2 emission performance in coal-fired power industry should be reduced by 50%. Consequently, affected by the increased De-SO_2 installed capacity and compensated desulfurization price for electricity generation, the SO_2 emission performance in coal-fired power industry decreased sharply in the "Eleventh Five-Year Plan" period, and the national SO_2 emission in this field was well controlled as can be seen from Fig. 3.

As the increasing ratio of installed percentage of De-SO_2 was gradually reduced as shown in Fig. 2, and the national capacity of coal power units continually increased, the

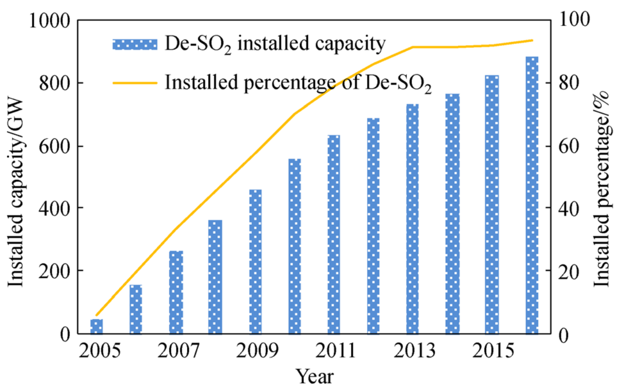

Fig. 2 Installed capacity and its percentage of De-SO_2 of coal-fired power plants in China

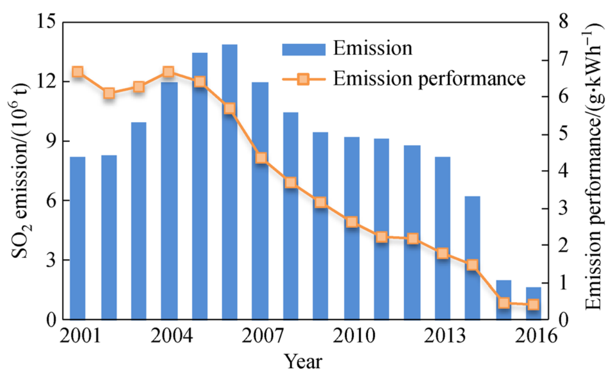

Fig. 3 Emission and its performance of SO_2 of coal-fired power plants in China

1) State Environmental Protection Administration of the People's Republic of China. Annual Statistic Report on Environment in China (2005–2016) (in Chinese)

2) State Environmental Protection Administration of the People's Republic of China. Annual Statistic Report on Environment in China (2001–2016) (in Chinese)

decreasing ration of SO_2 emission performance and SO_2 emission decreased in the first three years of the "Twelfth Five-Year Plan" period. While as the 2011 edition of "Emission Standard" took effect for the in-service units in 2014, followed closely by the ultra-low emission limitation for the 11 eastern emission concentrated provinces, the national SO_2 emission in coal-fired power industry decreased sharply in 2014, and plummeted in 2015. As can be seen from Fig. 3 that the SO_2 emission was reduced by 24% and 68% in 2014 and 2015 respectively. It has been well controlled below 1.7 million tons since 2016, which is only 12% of the historical peak value.

2.3 NO_x control

The emission control for NO_x in coal-fired power industry was first limited in the1996 edition of "Emission Standard," where the NO_x emission concentration of newly installed coal-fired power units was limited to 650 and 1000 mg/m^3 for dry and wet bottom boilers respectively. As the "Emission Standard" was revised in 2003, based on the low NO_x combustion technology, the NO_x emission concentration of newly installed coal-fired power units was limited to 450, 650, and 1100 mg/m^3 according to the different content of volatile matter since 2004 (relatively lower emission standards were adopted for previously installed units according to different installation times since 2005). In the 2011 revised edition of the "Emission Standard," the NO_x emission concentration of all coal-fired power units was limited to 100 mg/m^3 (200 mg/m^3 for W-type boiler, circulating fluidized bed boiler units and the units installed or licensed before 2004), in which the limitation for in-service units was executed from July 1st, 2014. While the limitation of 100 mg/m^3 for NO_x emission in key regions was executed with no exception of boiler type. As the ultra-low emission limitation was adopted in 2014, the concentration of NO_x emission in the newly installed coal-fired power plants is further limited to 50 mg/m^3 in the 11 eastern provinces of China [14].

The developments of the installed capacity of De-NO_x and its percentage over the total coal-fired power capacity from 2005 to 2016 are demonstrated in Fig. 4[1)]. As the NO_x emission concentration was limited basically based on the low NO_x combustion technology in 1996 and 2003 edition of "Emission Standard," the installed capacity and its percentage of denitration devices (De-NO_x) grew slowly before 2011. While in the 2011 edition of "Emission Standard," the limitation of NO_x emission was further limited to 100 mg/m^3, which normally cannot be achieved merely by the low NO_x combustion technology, most of the coal-fired power units have to be equipped with De-NO_x. As can be seen from Fig. 4, the installed capacity

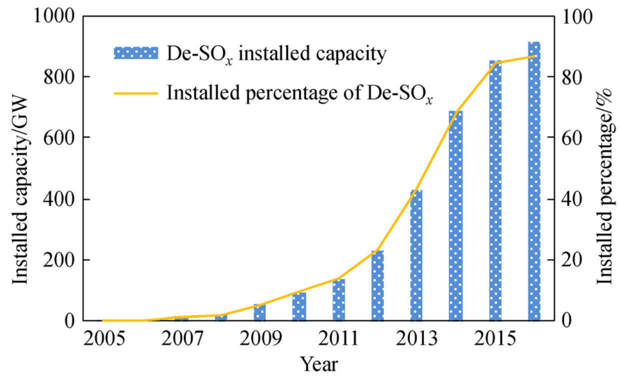

Fig. 4 Installed capacity and its percentage of De-NO_x of coal-fired power plants in China

of De-NO_x and its percentage skyrocketed from 100 GW and 14% to 850 GW and 85% respectively within four years from 2011 to 2015. The installed capacity of De-NO_x and its percentage had reached 910 GW and 87% respectively by the end of 2016.

The national NO_x emission and its performance from 2005 to 2016 are exhibited in Fig. 5[1)]. As the result of stricter NO_x emission limitations were adopted in the 2003 edition of "Emission Standard," the low NO_x combustion technology was widely adopted on the newly installed coal-fired power units and part of the in-service ones after 2004 and 2005 respectively. As Fig. 5 shows, the emission performance of NO_x decreased steadily from 2005 to 2011. However, as the result of the fast development of the national installed capacity of coal-fired units, the national NO_x emission in coal-fired power industry remained almost unchanged before 2011.

According to the Outline of the Twelfth Five-Year Plan for National Economic and Social Development of the People's Republic of China, the national NO_2 emission and that in coal-fired power industry should be controlled

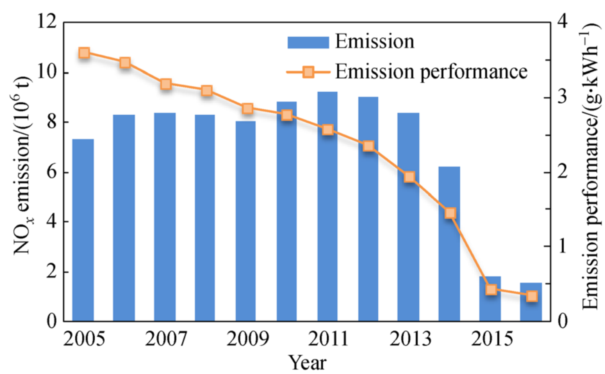

Fig. 5 Emission and its performance of NO_x of coal-fired power plants in China

1) State Environmental Protection Administration of the People's Republic of China. Annual Statistic Report on Environment in China (2005–2016) (in Chinese)

within 13.91 and 7.5 million tons in 2015, which are reductions of 15% and 29% compared to those in 2010 respectively. As the even stricter limitation of 100 mg/m^3 for NO_x emission concentration was executed in 2012, accompanied by the compensate denitration price for electricity generation, the emission performance of NO_x decreased sharply in the following three years, especially in 2014 when the 2011 edition of "Emission Standard" took effect for the in-service units. Consequently, the national NO_x emission was increasingly reduced simultaneously.

As the ultra-low emission limitation presented in the "Action Plan" was adopted in the 11 eastern emission concentrated provinces in 2014, the national NO_x emission in coal-fired power industry plummeted in 2015. As can be seen from Fig. 5, the NO_x emission was reduced by 26% and 71% in 2014 and 2015 respectively. The national NO_x emission has been further reduced to 1.6 million in 2016, which is only 17% of that in 2011.

2.4 Heavy metal control

There are many trace heavy metal elements contained in coal, including plumbum, Hg, arsenic, cadmium, chrome, etc. When coal is burnt in the industrial process, the heavy metals are released to the environment through the flue gas [20], waste water or slag, and then concentrated in the body of human beings, animals, and plants, which is harmful to the health of human beings and the environment. Consequently, the emission control for heavy metals was first asked to be controlled by the "Guiding Opinions on Strengthening Prevention and Control of Heavy Metal Pollution" in 2009[1)], and was comprehensively put into practice in the "Comprehensive Prevention and Control of Heavy Metal Pollution in the Twelfth Five-Year Plan"[2)]. In Chinese coal, the content of Hg ranges from 0.10 to 0.31 mg/kg [21], which is relatively high compared to the coal in other countries. It is reported that more than 99% of the Hg in coal is released to the flue gas during combustion [22]. Then the emission control for Hg was first asked to be controlled in coal-fired power plant in the 2011 edition of "Emission Standard" [13], where the emission content of Hg in flue gas was restricted to within 30 μm/m^3 [13].

Accordingly, a lot of research has been conducted by removing Hg from the flue gas. Generally, there are two methods. The most common one is oxidizing the Hg to be Mercy chloride, and then removing it by electrostatic precipitator (ESP), bag filter or wet flue gas desulfurization (WFGD) [23]. It is found that the removing efficiencies of Mercy chloride through ESP, bag filter or WFGD could be 29%, 67%, or 80%, respectively [22]. If selective catalytic reduction (SCR) is installed, and the Hg is oxidized by halogens or ozone, the Hg could be removed by WFGD with an efficiency of up to 89% [23]. The other method is to capture the Hg by effective sorbents [24].

3 Pollutant control in China

3.1 Classification of air pollutants in China

According to the statistical method adopted by the Ministry of Environmental Protection of the People's Republic of China[3)], the air pollutants of dust, SO_2, and NO_x are collected according to the five classifications of power/heat generation and supply, ferrous metals smelting and processing, nonmetallic mineral production, other industries and life. For the convenience of discussion, the category of power/heat generation and supply is divided into power generation and supply category and heat generation and supply category in some parts.

The category of heat generation and supply basically refers to the process of adopting devices like boiler to utilize the energy resources of coal, oil, gas etc. for steam/hot water generation, the supply process of steam/hot water, and the maintenance and management of the heat supply facilities. The category of ferrous metal smelting and processing mainly refers to ironmaking, steelmaking, steel calendering and ferroalloy smelting. The category of nonmetallic mineral production mainly refers to the production of cement, glass, ceramics, plaster etc.

3.2 Development of soot emission

By referring to the Annual Statistic Report on Environment in China (2005–2015), the development of national classified soot emission from 2005 to 2015 is displayed in Fig. 6[4)], where the sudden increase in 2011 was generally resulted from the expanded statistical scopes, combined survey of soot and dust as well as the revised indicators, method of survey, and related technologies in statistical system, while the sudden increase in 2014 was basically resulted from the extended survey of amorphous soot (dust) in iron/steel smelting and cement production. Besides, the soot emission in coal-fired power industry is also shown in Fig. 6 by the green line as referred from the Annual Development Report of China's Power Industry (2015–2017) [6,19,25].

1) Ministry of Environmental Protection of the People's Republic of China. Guiding Opinions on Strengthening Prevention and Control of Heavy Metal Pollution (in Chinese)
2) Environmental Protection of the People's Republic of China. Comprehensive Prevention and Control of Heavy Metal Pollution in Twelfth Five-Year plan (in Chinese)
3) State Environmental Protection Administration of the People's Republic of China. Annual Statistic Report on Environment in China (2008–2015) (in Chinese)
4) State Environmental Protection Administration of the People's Republic of China. Annual Statistic Report on Environment in China (2005–2015)

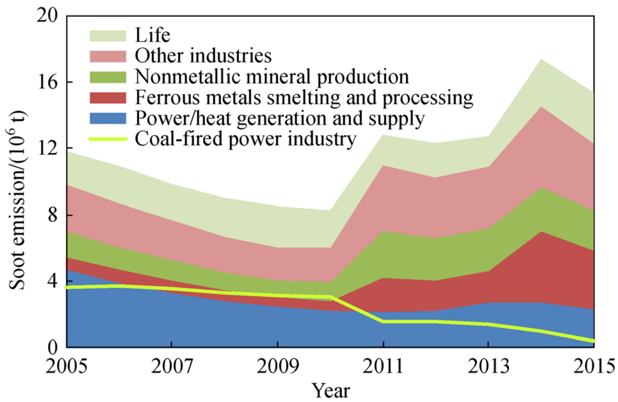

Fig. 6 Development of soot emission in China

As shown in Fig. 6, the soot emission in power/heat generation and supply category dominated the national soot emission before the dust was combined into the national survey of soot emission in 2011. As the survey of dust emission was combined into that of the soot emission in 2011, the national total soot (dust) emission increased by 54% in comparison with the soot emission in 2010. However, as the result of the sharp decrease of soot emission in coal-fired power industry in 2011, the soot (dust) emission in power/heat generation and supply category not only did not increase, but also reduced a bit. As a consequence, the percentage of soot (dust) emission in power/heat generation and supply category decreased suddenly from 26% to 17%.

It can also be found that in the "11th Five-Year Plan" period, the soot emission in all of the industrial categories experienced obvious declines, and the decline in power/heat generation and supply category, with a total decline of 53%, is the most significant one; while the soot emission in life category is seen to have an increase of 14%. However, in the "12th Five-Year Plan" period, a slight increase of soot emission can be found in the first four years of industrial categories, while a sharp decrease is seen in the last year. The soot emission in life category increased by 35% in total, but fluctuated during the process.

In comparison with the soot emission in coal-fired power industry and that in power/heat generation and supply category, it is found that soot emission in coal-fired power industry has been the majority of that in power/heat generation and supply category for a long time. As the 2011 edition of "Emission Standard" was adopted step by step, the contribution of soot emission in coal-fired power industry to the power/heat generation and supply category was greatly reduced after 2011. Subsequently, as the ultra-low emission standard was further adopted in eastern provinces of China, the soot emission in coal-fired power industry was correspondingly reduced to 0.4 million tons in 2015, which accounted for only 18% of that in the power/heat generation and supply category, and 3% of the national soot emission. Then, by removing the soot emission in coal-fired power industry from the category of power/heat generation and supply, the rest of the soot emission (basically from heat generation and supply) was around 1.88 million tons in 2015, which independently became a major industrial soot emission source.

Meanwhile, the soot emission limitations for other industries have not been reduced correspondingly compared to coal-fired power industry. The soot emission standards for the main industries are shown in Fig. 7 [13,26–30], where the soot-limitation-6% O_2 represents the corresponding limitation value on oxygen content of 6%. As can be seen from Fig. 7, the soot emission limitations for other categories are at least four times of that for coal-fired power industry in the 6% O_2 condition. The limitations for heat generation and steel are as high as 7–10 times of coal-fired power industry soot emission limitation in the 6% O_2 condition.

Based on the national statistical data in 2015, as shown in Fig. 6, the soot emission in categories of other industries and life are 4.07 and 3.05 million tons respectively, accounting for 26% and 20% of the national soot emission correspondingly. In addition, it is found that the biggest industrial soot emission source is the ferrous metals smelting and processing (mainly referring to steel), whose emission is about 3.57 million tons, and accounts for 23% of the national soot emission. Meanwhile, the emission limitation for steel is the highest one. If it is reduced to the same level of coal-fired industry, the total soot emission could be reduced by more than 3 million tons. The second biggest industrial soot emission source is nonmetallic mineral production (including mainly cement, glass and ceramics), whose emission is 2.4 million tons, and accounts for 16% of the national soot emission. Referring to the emission standard of the coal-fired power industry, the soot emission of the nonmetallic mineral production could be reduced by about 2 million tons. The soot emission in the category of heat generation and supply

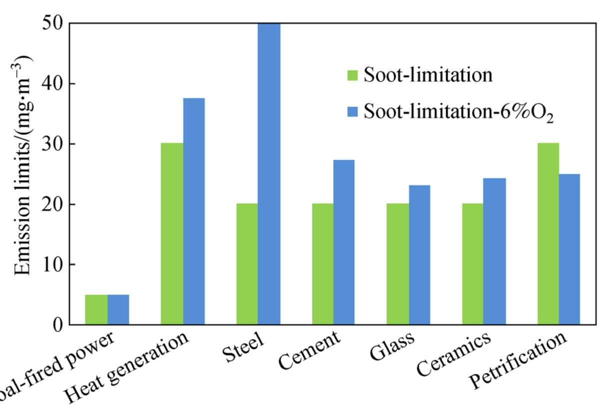

Fig. 7 Soot emission standard of different categories

accounts for 12% of the national soot emission, and takes the third place in industrial field.

3.3 Development of SO_2 emission

Figure 8 shows the development of the national classified SO_2 emission from 2001 to 2015 on reference of the Annual Statistic Report on Environment in China (2001–2015). The SO_2 emission in coal-fired power industry is also shown in Fig. 8[1)] by the green line as referred from the Annual Development Report of China's Power Industry (2015–2017) [6,19,25]. As shown in Fig. 8, the SO_2 emission in the power/heat generation and supply category has always dominated the national SO_2 emission, and took a share of above 50% for a long time before 2011. As the national statistical scopes was expanded, and the indicators, method of survey and related technologies were revised in the national statistical system in 2011, the share of SO_2 emission in the power/heat generation and supply category experienced a sudden decline from 53% to 41%, and that in the category of other industry experienced a sudden increase from 15% to 30%.

By excluding the influence of the statistical methods, the SO_2 emission in the power/heat generation and supply category exhibits a steady decline as the result of the strict SO_2 emission control over the past ten years. The share of the SO_2 emission in the power/heat generation and supply category in the national total emission has been reduced from about 59% in 2006 to 27% in 2015,while the SO_2 emission of other categories keep almost unchanged.

According to a joint analysis of SO_2 emission in coal-fired power industry and that in power/heat generation and supply category, it is obviously observed that the SO_2 emission in coal-fired power industry had always been the majority of that in power/heat generation and supply category before 2014, where the excess part during 2012–2013 could be thought as the statistical error resulted from different survey methods. By referring to the SO_2 emission control analyzed previously, a conclusion can be drawn that the continual steady decline of SO_2 emission in power/heat generation and supply category is mainly achieved by the great achievement in the reduction of SO_2 emission in coal-fired power industry in the past decades.

As the ultra-low emission standard was adopted in the eastern provinces of China, the SO_2 emission in coal-fired power industry was further reduced to 2 million tons in 2015, which was only 40% of that in the power/heat generation and supply category, and 11% of the national SO_2 emission. Similarly, by removing the SO_2 emission in coal-fired power industry from the category of power/heat generation and supply, the rest of the SO_2 emission (basically from the heat generation and supply) was around 3.06 million tons in 2015, which independently became the largest industrial SO_2 emission source.

The SO_2 emission standards for the main industries are shown in Fig. 9 [13,26–30]. The SO_2-limitation-6% O_2 represents the corresponding limitation value on oxygen content of 6%. As can be seen from Fig. 9, the SO_2 emission limitation for heat generation is about 7 times of that for coal-fired power industry. Except ceramics and petrification industries, the SO_2 emission limitation for other industries, like steel, cement, and glass are also more than three times of that of coal-fired power industry on 6% O_2 condition.

Based on the national statistical data in 2015, the SO_2 emission in categories of other industries and life are 6.74 and 3.02 million tons, and accounts for 36% and 16% of the national SO_2 emission respectively. Then, the divided category of heat generation and supply is found to be the biggest industrial SO_2 emission source, which is about 3.06 million tons, accounting for 16% of the national SO_2 emission. By referring to the SO_2 emission standard of coal-fired power industry, the SO_2 emission of heat generation could be reduced by 2.6 million tons. The second industrial source is the nonmetallic mineral production (including mainly cement, glass and ceramics),

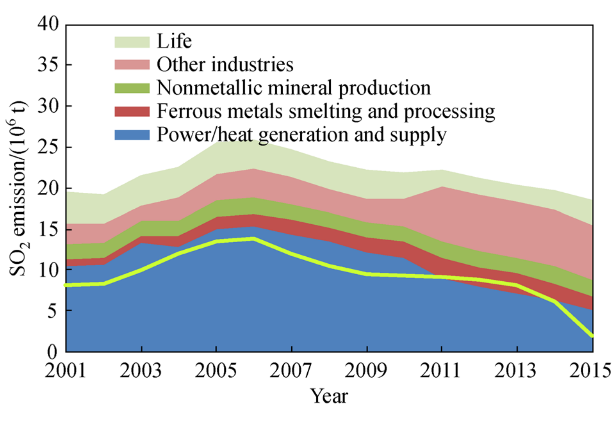

Fig. 8 Development of SO_2 emission in China

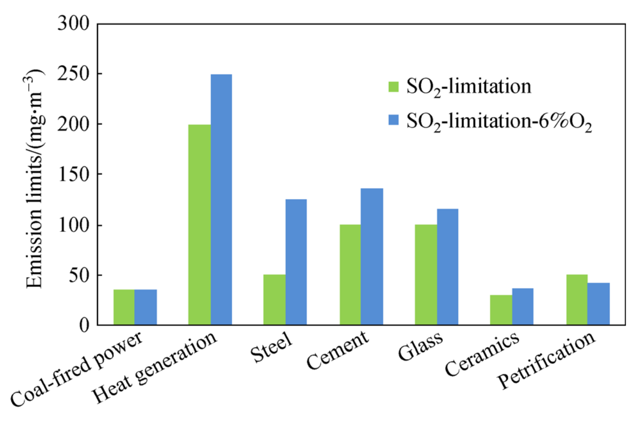

Fig. 9 SO_2 emission standard of different categories in China

1) State Environmental Protection Administration of the People's Republic of China. Annual Statistic Report on Environment in China (2001–2015)

whose SO_2 emission is 2.04 million tons, accounting for 16% of the national SO_2 emission. By referring to the SO_2 emission standard of coal-fired power industry, the SO_2 emission of heat generation could be reduced by 1.3 million tons. The SO_2 emission in coal-fired power industry, with a close SO_2 emission to the nonmetallic mineral production category, ranks the third in industrial field.

3.4 Development of NO_x emission

The development of national classified NO_x emission from 2005 to 2015 is shown in Fig. 10[1)] , where the sudden increase in 2011 was also resulted from the expanded statistical scopes, the revised indicators, the method of survey, and the related technologies in statistical system. The NO_x emission in coal-fired power industry is also shown in Fig. 10 by the green line as referred from the Annual Development Report of China's Power Industry (2015–2017) [6,19,25]. As can be seen from Fig. 10, the NO_x emission in the power/heat generation and supply category always took a share of above 40% of the national NO_x emission before 2013.

As discussed previously in Section 2.3, the NO_x emission in coal-fired power industry decreased gradually since the execution of the 2011 edition of "Emission Standard" in 2012. As the "Emission Standard" was further executed on in-service units in 2014 and afterward, a much stricter ultra-low emission limitation was adopted in the eastern provinces on the NO_x emission in coal-fired power industry plummeted in 2015. Then, the NO_x emission in the power/heat generation and supply category decreased simultaneously. As the NO_x emission in coal-fired power industry decreased to 1.8 million tons in 2015, it was not the main part of the NO_x emission in the power/heat generation and supply category any more. By removing the NO_x emission in the coal-fired power industry, the NO_x emission in the heat generation and supply category was about 3.18 million tons in 2015, which accounted for about 17% of the national NO_x emission, and became the largest part in the industrial field.

The NO_x emission standards for other typical industries are shown in Fig. 11 [13,26–30]. The NO_x-limitation-6% O_2 represents the corresponding limitation value on oxygen content of 6%. As can be seen from Fig. 11, the NO_x emission limitation for cement and glass are more than 9 times of that for coal-fired power industry. The SO_2 emission limitation for other industries, like heat generation and steel are also 5–6 times of that of coal-fired power industry in the 6%O_2 condition. The limitations for ceramics and petrification are about 2 times of that for coal-fired power industry soot emission limitation in the 6%O_2 condition.

As could be observed from Fig. 10, the NO_x emission in coal-fired power industry not only accounted for the largest part before 2014, but also dominated the national NO_x emission. As the NO_x emission in coal-fired power industry was increasingly reduced to 2 million tons in 2015, the NO_x emission in the life category, with a value of 6.71 million tons and a share of 36%, accounted for the largest part. According to the national statistics [35], the NO_x emission from transportation in the life category contributed 5.86 million tons in 2015, which independently became the biggest NO_x emitter. Since the transportation industry consumes mainly oil fuel, it is not included in the scope in this paper.

Then the NO_x emission in heat generation and supply, with a value of 3.18 million tons, became the largest contributor in industrial field. If the NO_x emission limitation of coal-fired power industry is adopted in heat generation industry, the NO_x emission could be reduced by about 2.3 million tons annually. The categories of nonmetallic mineral production follow up with NO_x emissions of 2.67 million tons. By adopting the NO_x emission limitation of coal-fired power industry in

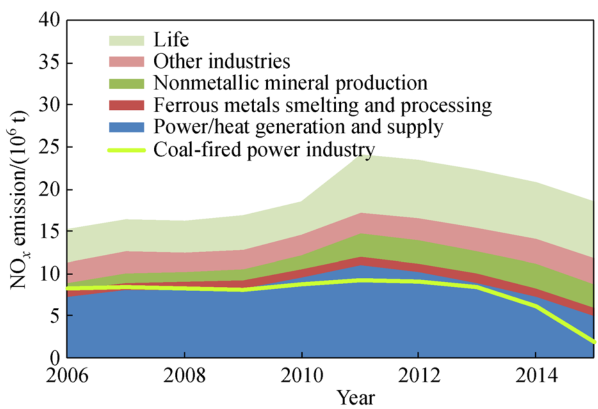

Fig. 10 Development of NO_x emission in China

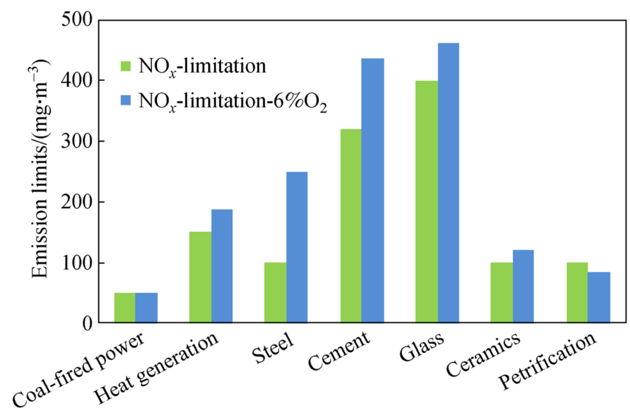

Fig. 11 NO_x emission standard of different categories in China

1) State Environmental Protection Administration of the People's Republic of China. Annual Statistic Report on Environment in China (2001–2015) (in Chinese)

nonmetallic mineral production categories, the NO_x emission could be further reduced by about 2.3 million tons.

3.5 Development of heavy metal discharge

Promoted by the "Comprehensive Prevention and Control of Heavy Metal Pollution in the 12th Five-Year Plan"1), around 3 billion US dollars were spent on the prevention and control of heavy metal pollution by the central government of China. By the end of 2015, the annual total emission of heavy metal, including plumbum, Hg, arsenic, cadmium, and chrome, was reduced by 27.7%.

Flue gas of coal combustion is always thought to be the biggest source of Hg emission. In 2010–2012, the national total anthropogenic atmospheric Hg emissions is about 545 t, where the coal combustion contributes 352 t [31], in which coal-fired power industry contributes 90–145 t [32,33], accounting for 27% of the total anthropogenic atmospheric Hg emission. However, as the emission control of Hg was adopted in the 2011 edition of "Emission Standard," the Hg emission in coal-fired power industry was reduced to 43 t in 2015, accounting for only 8% of the total anthropogenic atmospheric Hg emission. In spite of this, the Hg emission from other coal-combustion process, like heat generation, ferrous metals smelting and processing, nonmetallic mineral production, is still as high as around 200 t.

4 Conclusions and proposed strategies

Based on studies of the air pollutant control in coal-fired power industry, its effect on the national emission reduction, and the development of classified pollutant emission, it is found that coal-fired power industry has been the biggest air pollutant emission source before 2010, no matter the emission is of dust, SO_2, NO_x, or Hg. However, as the increasingly strict "Emission Standard" was gradually adopted in coal-fired power industry, the emissions, emission performances, and emission shares have experienced a decline, though in different procedures. The emission reduction in coal-fired power industry contributes the most in the national emission reduction of air pollutants. Generally speaking, coal-fired power industry consumes more than 35% of the fossil energy, but only contributes less than 10% of the air pollutant emission after 2015. It is not one of the largest air pollutant emitters any more.

Nevertheless, by removing the coal-fired power industry from the category of power/heat generation and supply, the heat generation and supply category left has been highlighted as a major air pollutant emitter. Besides, the categories of nonmetallic mineral production (cement as a major contributor) and ferrous metals smelting and processing are also major air pollutant emitters with different emphasis on different pollutants. Some strategies are proposed as follows:

The emission standard in coal-fired power industry is strict enough, which should not be even stricter any more in the near future.

Corresponding emission standards in categories of heat generation and supply, nonmetallic mineral production and ferrous metals smelting and processing are called for.

The NO_x emission in the transportation field should be treated with stricter emission standard.

The SO_2 emission in the category of other industry should be surveyed with more detailed classifications, and corresponding stricter emission standard should be exerted on the main emitter.

Hg emission could be well controlled by a combination of SCR, ESP, and WFGD, which is supposed to be extended to other heavy metal emissions

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