Frontiers of Engineering Management
DOI 10.15302/J-FEM-2016053

Ke Liu

The Major Root Causes of Smog in China and Technologies and Solutions to Reduce It

Abstract This paper discusses the two major root causes of smog in China. The first one is the distributed coal combustion in many small and medium sized boilers which have no emission control systems installed. To resolve this problem, there are several ways, such as increasing the centralized coal combustion for heat and power cogeneration; or converting coal to SNG in areas where there is enough water resource and removing the pollutants of the coal in the centralized coal to SNG plant, or refining the coal and making it cleaner first before combustion. The second major cause of smog is the low quality diesel and outdated diesel engines used in China. To solve this problem, there are some ways, such as improving the diesel quality to meet the national V standard, and meanwhile, enhancing the law enforcement to eliminate these outdated diesel engines that do not meet the national emission standards; in addition, combusting cleaner and cheaper fuel such as methanol or DME in the diesel engines is also an option for certain areas where there are abundant alternative fuels such as methanol to replace diesel.

Keywords: smog, emissions, coal refining, coal utilization, solutions

1 Cause of smog

1.1 Distributed coal combustions in small & medium size boilers

Recently, smog has become one of the hottest topics. The public, relevant industries and government all express frustration and strong complains about it. The top priority is finding out the main causes of smog, and then the solutions accordingly.

Smog refers to the particulates hanging in the air which block the sun when the concentrations get too high. Those particulates could be classified into two types: the "primary particulates" and the "secondary particulates". As shown in *Figure 1*, the particulates directly emitted from combustion of fossil fuels, such as diesel engines, are "primary particulates", which account for about 24% of the total amount of the smog. What contribute the most to smog are the "secondary particulates", which account for about 50% of the total amount of the smog. The "secondary particulates" are the particulates generated from aerosol reaction happened after the gaseous pollutants (such as NO_x, SO_x) and volatile organic compounds (VOCs) from fossil fuels combustion getting into the atmosphere, with ammonia from the fertilizers and VOC in the air at certain mist conditions. Therefore, in order to reduce smog, the emission of pollutants NO_x, SO_x, VOC, and NH_3 must be reduced.

The chemical fertilizer used per acre of land in China is 4 times more than that of Denmark. Due to the vast utilization of ammonia based chemical fertilizers, there are always ammonia in the air. The heavy utilization of fossil fuels such as coal, diesel and gasoline emitted a large amount of SO_x, NO_x, and VOCs. The SO_2 and NO_2 in the air can be oxidized into SO_3 and NO_3 which will become sulfuric acid and nitric acid when there is moisture in the air. The acids can further react with ammonia and VOC in the air to form the particulates of salts such as ammonia sulfates and ammonia nitrates and some other organic salts. These are the main causes of smog, and the formation mechanism of the "secondary particulates" is as shown in *Figure 2*.

The amount of SO_x and NO_x emission can easily be estimated based on the total amount of coal and oil consumed based on their sulfur content and NO_x emission concentration by simple mass-balance. The annual petroleum consumption in China was around 470 million tons in 2010, and increased to approximately 570 million tons in 2015, while the annual coal consumption was 3.6–3.8 billion tons in 2014 (Work Group for the Consultant Research in the Field of Energy, 2015). The coal-dominant energy structure in China could not be changed in a short-term, so the pollution control of coal combustion becomes

Manuscript received February 27, 2016; accepted September 15, 2016

Ke Liu (✉)
The Dean of Clean Energy Institute of Southern University of Science & Technology, Shenzhen 518055, China
Email: liuk@sustc.edu.cn

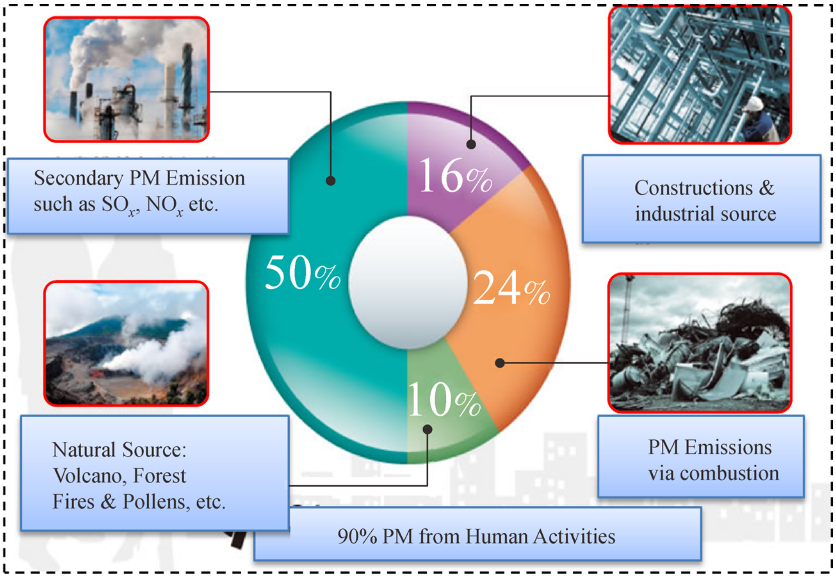

Figure 1. Smog distribution from Panasonic Corporation (Hao, Chen, & Wang, 2012).

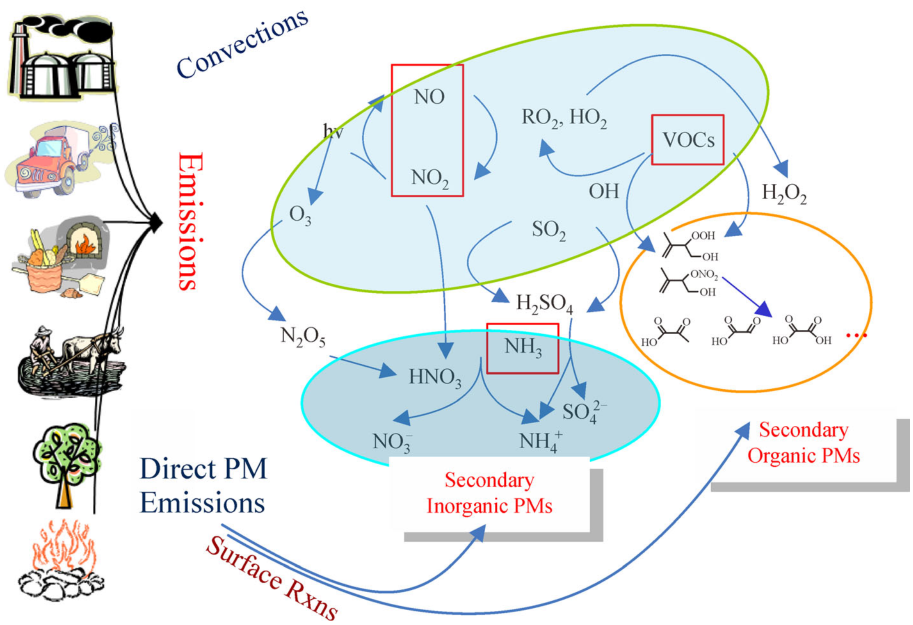

Figure 2. Mechanisms of smog formation from Professor Hao of Tsinghua University (Jang, Czoschke, Lee, & Kamens, 2002).

the primary issue currently. Desulfuration, de-NO_x and dust removal technologies are required in large-scale coal power plants, and the removal rate could reach over 90%. For coal centralized utilization, the amount of pollutants in emission can be controlled close to, or even lower than that of natural gas combustion. The global average coal utilization centralization degree is around 60%, and it could reach over 90% in Europe, USA, and Japan, but it is less than 50% in China. There are nearly about 700,000 small and medium-sized boilers burning several hundreds of million tons of coal in China. There is no accurate amount of this part of coal consumption due to the discrepancy of the statistical data, but it is estimated to be around 600~800 million tons of coal that is burned in those small and medium sized boilers without any exhaust gas treatment (Work Group for the Consultant Research in the Field of Energy, 2015).

It is impossible to install the desulfuration, de-NO_x and particle removal devices for each small and medium sized boilers. The pollutants emitted from burning one ton of coal in these boilers without exhaust treatment is about 10–20 times of that of coal burned in a large-scale boiler with ultra-clean emission treatment. Thus, the pollution from 600 million tons of coal burned in these small to medium sized boilers is equivalent to the pollution generated by almost 6 to12 billion tons of coal burned in large coal power plants. As there is a huge population base in China, the energy consumption and emission per capita in China is much lower than that in Europe and USA, this "per capita" methodology cannot explain the smog pollution problem in China. However, environment capacity may explain this problem. The environment capacity depends on the emission amount per square kilometer (or energy density), and it is irrelevant to the emission per capita since there could be 10 people or 10,000 people live in one square kilometer. If focusing only on regional city data for smog problem does not help much, since air flows. From a macroscopic point of view, Europe has about the same geographical size as China. However, most of Chinese people are centralized in the east coast within around two million square kilometers, while European people are distributed in area about four million square kilometers. Compared with the 3.6 billion tons of coal consumption in China, the total coal consumption in Europe is only about 580 million tons, and most of Europe's coal consumption is in the large coal power plants with emission treatment. Not only is the total coal consumption in China much greater than that in Europe, but also a great amount of coal in China is burned in those small to medium sized boilers, so the emission per square kilometer in China is significantly greater than that in Europe. This explains why smog happens frequently in China but rarely in Europe, although there are a large number of automobiles in both regions.

The author believes that the coal combustion in those small and medium sized boilers without any exhaust treatment is one of the primary cause of smog. To solve this problem, many propose that natural gas should be used in small boilers instead of using coal. But why replace the coal with natural gas in those small boilers? Is it feasible? The total amount of natural gas in China is not enough. The total amount of natural gas consumed in China is about 205 billion cubic meter which in heat value is equivalent to less than 300 million tons of coal, and the heat value supplied by this amount of natural gas is less than 10% of the heat value supplied by coal in China (~3.6 billion tons of coal). This limited amount of natural gas supply has to be used in large and medium sized cities for heating and cooking first, thus left little to replace those in small and medium sized boilers. Recently, the price of natural gas in China has dropped, which leads to a speculation of a natural gas surplus in China. This speculation is misleading and baseless. The natural gas in China is not too much but too expensive and its price is two mines more than that in the USA. From the viewpoint of environment protection and smog abatement, the very limited natural gas left after supplying the cities for heating and cooking should be used in the small and medium-sized boilers to reduce emission first. However, the government is forced to shut-down a few very big coal power plants and converted them into natural gas power plants. As a result, the very limited natural gas, instead of being utilized in small and medium sized boilers, is used in those huge coal power plants that already have the emission reduction units installed. As mentioned above, even if all the natural gas (equivalent to 300 million tons of coal) in China is used for converting the small and medium-sized coal boilers to gas burners, the natural gas is not enough. It is well-known that it is impossible for all small and medium-sized coal fired boilers to be equipped with desulfuration, de-NO_x and dedusting units after the combustion. Thus, in the foreseeable future, a practical and feasible way to reduce the pollution of those small and medium sized boilers, is coal refining technology. Develop "coal refining" industry, remove the pollutants in the coal before the combustion, and then supply the cleaner coal to the small and medium-sized boilers.

1.2 Coal refining process to reduce the emission of small and medium sized coal boilers

As shown in *Figure 3*, the "coal refining" process includes the following steps: 1) the inorganic sulfur in the coal can be removed by coal washing. Most of the inorganic sulfur are in the ash as sulfonates, and most of the ash could be removed and hence the inorganic sulfur could be removed by the washing process. 2) After coal washing, the coal could be heated to ~300°C to remove the moisture of the coal, and then further heated the coal to around 525°C, and at this temperature, not only do the oil and gas volatiles in the coal come out, but most of the organic sulfur compounds also comes out. 3) The volatiles coming out of the coal then condense, and the liquid product which is called pyrolysis oil can further be hydro-treated to produce clean diesel and gasoline; and the gas product is called pyrolysis gas which can further be converted and purified to produce H_2 that is needed for upgrading the pyrolysis oil, or going through a methanation process to produce the synthesis natural gas (SNG) as clean gas fuel. Thus, the coal refining process could not only make the coal cleaner, but also co-produces cleaner liquid and gas fuels which can help to recover part of the investment in this coal refining process. After the moisture and volatiles of the coal are removed by drying and pyrolysis, the porosity of the coal particles increases significantly, which makes the coal combustion much more uniform and thus could reduce the NO_x emission significantly as well.

In addition, the quality of the coal used for small and medium-sized boilers should be regulated with higher standards (e.g. sulfur $< 0.2\%$, and heat value

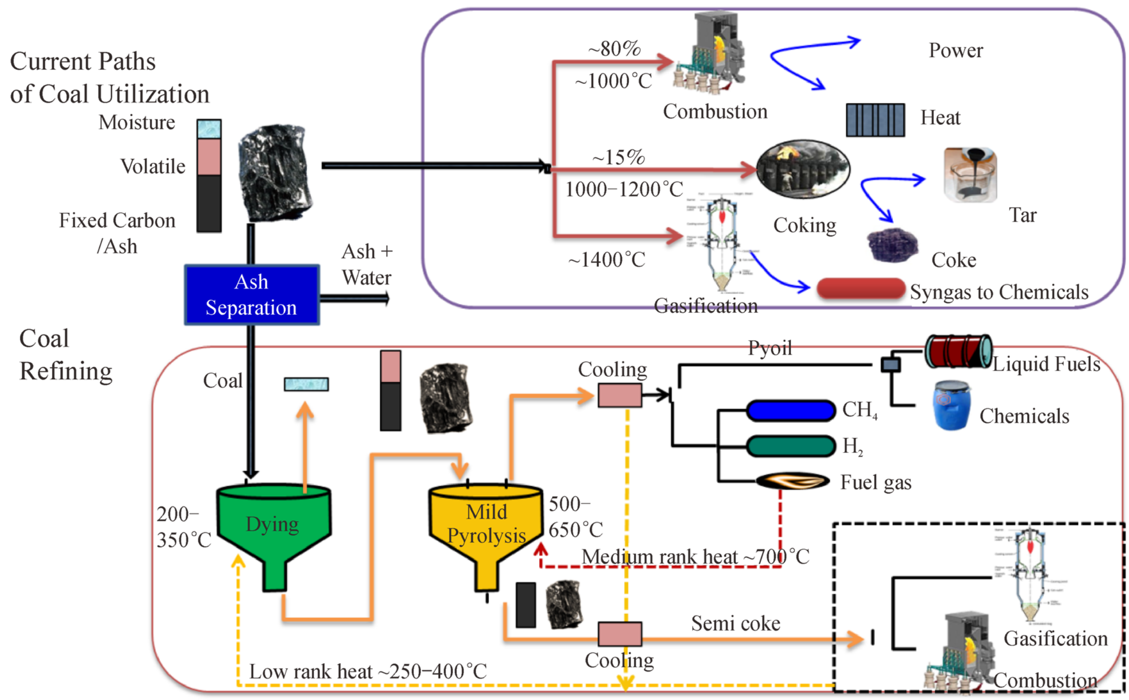

Figure 3. Coal refining- A new approach for coal utilization.

>6000 kcal/kg), and other regulations shall be established to control the pollution caused by small and medium-sized boilers too. There is no doubt that coal fired large-scale power plants can reduce all their emissions except CO_2 to the equivalent level of natural gas fired power plants, or even lower, as long as the investment is enough, and the technology is mature. In recent years, China has made a lot of efforts in large-scale coal power plants pollution reduction, which is positive and deserves recognition. Some companies even have invested heavily on building ultra-clean coal fired power plants, which are cleaner than natural gas fired power plants (Cen et al., 2015). In fact, these desulfuration, de-NO_x and dedusting technologies of ultra-clean emission are off-the-shelf. The key argument is whether it is worthy to spend so much money on raising the pollutant removal level from 95% to 99% or even higher. The current situation is that on one hand no treatment is done in small and medium-sized boilers with 100% pollutants emitted because small and medium-sized enterprises and individuals are unable to replace coal with gas, and on the other hand, the large-scale power plants, already equipped with devices with desulfuration rate of over 90%, are pursuing ultra-clean emissions lower than those of natural gas fired plants by investment a huge amount of money. Those large state-owned enterprises spend heavily to upgrade larger-scale coal power plants already equipped with pollutant removal to pursue ultra-clean emission (lower than that of natural gas fired power plant), and on the other hand, no investment goes to "coal refining" technology to provide cleaner coal to the small and medium sized boilers. As a result, smog abatement is ineffective, because even though China has spent a huge amount of money on the renovation and upgrading of large-scale coal power plants, the main source of smog is from those small and medium sized coal boilers, rather than from large coal power plants with desulfuration, de-NO_x and dedusting devises already installed.

1.3 Approaches to reduce the emissions from distributed coal combustion

In conclusion, the pollutant emitted from those decentralized coal combustion in those small and medium size boilers is one of the main causes of smog, and the methodology of achieving clean "renovation" of nearly 700,000 small and medium-sized boilers is the key to mitigate the smog problem. On this issue there are three solutions on different levels:

First, try to provide the heat and power by coal combustion in large boilers with exhaust treatment, expand heat and power cogeneration, intensify the law enforcement of environment protection, keep centralized coal combustion emission treatment devices in compliance with the national standard on emission, enhance environment protection law execution by legislation, and push step-by-step innovation and gradually reduce those small and medium coal fired boilers as much as possible by increasing the centralized coal utilization.

Second, it is unlikely to achieve 100% coal centralized burning with large boilers due to the vast area of China.

"Coal to SNG" could be implemented in areas where there is no centralized coal utilization with suitable conditions. The natural gas supply in China will remain below the demand, although the natural gas supply contract with Russia may be implemented smoothly in 2018 according to the plan. The natural gas imported from Russia will only account for approximately 20% of domestic gas consumption. Thus, another option of reducing pollution from decentralized coal consumption is converting coal to natural gas by "coal to SNG" technology in regions with abundant coal and water resources. By doing so, all pollutants are removed altogether, and clean natural gas products could be delivered to thousands of households and small plants through local pipeline network. "Coal to SNG" maybe not applicable to all regions, but it is more feasible than installation of desulfuration and de-NO_x devices in each small and medium-sized boilers.

Third, "coal refining" should be promoted at the places where neither above solution can be done. As mentioned in section 1.2 of this paper, Coal Refining includes first washing out the inorganic sulfur and ash in coal, and this will remove most of the inorganic sulfur in the coal. After coal washing, most of the organic sulfur could be removed by coal pyrolysis. The pyrolysis liquid products could be further hydrogenated to produce clean diesel, and the gas product (coke-oven gas) could be further converted to SNG, and the solid product is clean desulfurized coal (semi coke). Due to its blue colored flame while burning, which is the same color as natural gas flame (also blue), semi coke is also called "blue coal"(in Chinese). The "coal refining" technology could convert coal to clean gaseous, liquid and solid fuels, and then the pollution from coal combustion will be substantially reduced. Although "coal refining" will increase the usage cost, it is still more economical and efficient than installing emission treatment devices in each small and medium-sized boiler, and it is the last option when neither of the two previous solutions works. In fact, "coal refining" is much cheaper than importing LNG, wind energy, solar energy and nuclear energy considering that valuable clean liquid and gas fuels could be produced from the coal (mainly diesel and SNG) as well.

2 Approaches to reduce the emissions from diesel

China is a major consumer of diesel fuel. The second main source of smog is a great amount of diesel fuel used in China which is of low quality and many outdated diesel engines are still in use especially in the countryside of China. But the law enforcement of eliminating the old diesel engine could not reach the remote countryside. The pollutants from all kinds of vehicles account for about 25% of smog (including primary and secondary particulates). Due to the usage of high sulfur diesel fuel and the absence of emission treatment system on certain old diesel engines, the pollutant emission from diesel engines is remarkably high domestically. The annual diesel fuel consumption is around 170 million tons in China, and emission from diesel engine is the second source of smog listed behind the small and medium size coal boilers.

2.1 Two ways to reduce emission from diesel engines

There are two ways to reduce emission from diesel engine. The first one is clean ultra-low sulfur diesel. Almost 50% of European new vehicles are diesel based, but due to the wide application of ultra-low sulfur diesel fuel (<10 ppm), pollution is quite low. However, the sulfur concentration of diesel in China is much higher than that in Europe and the US. Under such circumstances, it is difficult to control pollutant emission, even though vehicles are equipped with particulate filter and de-NO_x system. Inferior diesel could even damage the emission treatment system, so oil up gradation is the key to control the pollution from diesel engines. Currently, there are some mature technologies available for Chinese refineries to produce ultra-low sulfur diesel fuel products, which conform to China V Standard and brought economic and social benefits.

In addition to the diesel desulfuration mentioned above, another way of the diesel engine emission treatment is NO_x and particulate removal. This requires diesel particulate filter and SCR de-NO_x system installed. The latest de-NO_x catalyst helps reducing fuel consumption, and due to its light weight, further reducing vehicle weight and improving the whole vehicle fuel efficiency. In Europe, the research and development on diesel engine technologies have made great achievements recently, and it is reported that there are sample vehicles that could drive 268 miles per gallon of diesel. China should pay more attention to the efficient diesel engine technology from Europe in addition to developing the EVs. Currently, nearly half of the new vehicles manufactured in Europe are diesel cars. However, it is difficult to ensure that the NO_x and PM2.5 emission from diesel engine is in compliance with the standard as long as it burns diesel, and this is one of the reasons why Volkswagen cheats in diesel engine tests. Therefore, another potential way to reduce diesel pollution in the future is to apply cleaner and cheaper fuels, such as methanol, DMMN and dim ethyl ether (DME), or other methanol based fuels, in diesel engine. There have been breakthroughs on this development recently. The emission from burning these clean fuels in diesel engine is much lower than that of diesel oil, and this type of technologies could be first tested in diesel based power generators mines, oilfields and rural areas, and then gradually moved to diesel vehicles after all the performance demoed and all the concerns addressed by long term usage of those cleaner fuels.

Another aspect of reducing smog and contaminations of oils is reducing the amount of chemical fertilizers utilized in per acre of land in China. This requires more organic fertilizers. This is a subject of another research, and will not be discussed too much here. Since all the farm land and grasses are utilizing chemical fertilizers, and it is not practical to reduce them dramatically in short time. Thus in the foreseeable future, the SO_x, NO_x, and VOCs emissions from burning fossil fuels such as coal, diesel, gasoline in boilers and engines should be controlled to reduce smog.

While it is very important to further develop wind power, solar power, hydro energy, and nuclear energy and let these clean energy play much important role, in the foreseeable future, we believe that the solutions provided above are suitable for China in next decade or two, and they are more economical, feasible and sustainable at this stage. Although there are many strategies for smog reduction, it is not easy to change the current situation in short-term. Firstly, it requires clear understanding of the main causes of smog, and then targets to the root causes accordingly. While government carries out top-level framework with strong determination and persistence of reformation, each citizen's active coordination is appreciated as well. As long as the above economically practical technologies such as coal refining are fully applied, corresponding policies are well designed according to the main causes of smog, replacement of coal by gas for small and medium-sized boilers is promoted, regional coal to gas industry is supported, supplement to diesel duel with cleaner and cheaper fuels is encouraged, research on high efficiency diesel technologies are enhanced, environment protection law is well established and executed, public awareness on environment protection are increased, and blue sky and clean water will reappear on vast China land as a natural consequence of common wish and joint efforts national wide.

References

Cen, K., Ni, M., Gao, X., Luo, Z., Wang, Z., & Zheng, C. (2015). Progress and prospects on clean coal technology for power generation. *Chinese Journal of Engineering Science*, 17(9), 49–55.

Hao, J., Chen, Z., & Wang, S. (2012). The research on China's present condition of environmental pollution and its control measures. *Environmental Protection*, (09), 16–20.

Jang, M., Czoschke, N.M., Lee, S., & Kamens, R.M. (2002). Heterogeneous atmospheric aerosol production by acid-catalyzed particle-phase reactions. *Science*, 298, 814–817.

Work Group for the Consultant Research in the Field of Energy. (2015). *Strategic research on clean, efficient, sustainable exploitation and utilization of coal in China* (Results of the Chinese Academy of Engineering Priority Consultant Research Project, 2011-ZD07). Beijing: Science Press.