Chinese Sulphur Dioxide Emissions and Local Environment Pollution

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Abstract. During the last 30 years Chinese economy has increased rapidly. The pollution of air in many Chinese cities exceeds both national and international standards due to rapid urbanization, industrialization and increased energy consumption. Present China becomes the highest sulphur dioxide emitter in the world due to its reliance on coal for energy generation. Breathing in sulphur dioxide can irritate the nose, throat and the lungs, causing phlegm, coughing, shortness of breath, development of bronchitis and other respiratory diseases, as well as aggravation of existing cardiovascular disease. Long-term contact to sulphur dioxide at lower concentrations can cause temporary loss of smell, headache, nausea and dizziness. In this paper an attempt has been taken to discuss sulphur dioxide emissions of China and stresses on desulphurization processes.

Keywords: SO$_2$ control policy, Human health, Acid rain, Desulphurization.

1. INTRODUCTION

People’s Republic of China is situated in the Eastern Asia on the western shores of the Pacific Ocean. Beijing is its capital city and Shanghai is its largest city. Its area is 9,640,821 km$^2$ and it is considered as the 3rd largest country (after Russia and Canada) in the world. In 2010, its population becomes about 1,339,724,852, which is in the 1st position in the world (20% of the world’s total) and density of population is 138.96/km$^2$, which is the 53rd in the world. The landforms of China’s vast territories are extremely varied and include mountains, hills, plateaus, plains, basins, and deserts. Coasts of China are on the East China Sea, Korea Bay, Yellow Sea, and South China Sea. It has a continental coastline extending over 18,000 km and an adjacent sea area of 4.73 million km$^2$. China has administrative control over 22 provinces (excluding Taiwan Province) (Mohajan, 2014).

The country holds the largest and highest plateaus, most of the highest mountains, and the world’s two longest rivers, the Yellow and Yangtze Rivers. Due to its various landforms and large land area, spanning tropical, sub-tropical, temperate and boreal zones, China contains a remarkable range of different ecosystems (Liu and Diamond, 2005). Mountainous regions in China occupy about 66% of the total area. Only 16% of the territory has an altitude lower than 500 meters; the areas with an altitude higher than 1,000 meters occupy 65% of China’s total land area (Jiang et al., 2007).

The economy of China has grown with an average 10% per annum during the last two decades. Its per capita gross domestic product (GDP) in Purchasing Power Parity (PPP) has increased more than 20 times from $379 in 1980 to $7,632 in 2010 (Cai and Lu, 2013). As a result people migrate to urban areas and energy demand has increased. China is now the world’s largest energy consumer (British Petroleum, BP, 2011a) and energy demand is expected to continue growing rapidly through 2030 (BP, 2011b). The quality of air in many Chinese cities exceeds both national and international standards due to rapid urbanization, industrialization and increased energy consumption (Huang et al., 2009). Coal-dominated energy consumption structure in China faces some of environmental problems such as acid rain, air pollutions and a large amount of greenhouse gas (GHG) emissions (National Bureau of Statistics (NBS), 2010).

Sulphur dioxide is a chemical compound with the formula SO$_2$ and chemical structure is O=S=O. It belongs to a family of sulphur oxide gases (SO$_x$). It is a poisonous gas that released by volcanoes and in various industrial processes (by roasting metal sulphide ores). It has a variety of industrial applications, from refining raw materials for preserving food. The poisonous gas SO$_2$ is considered as a local pollution problem worldwide. It is emitted...
in the atmosphere from both anthropogenic and natural sources. It is estimated that anthropogenic sources account for more than 70% of SO$_2$ global emissions, half of which are from fossil-fuel combustion (Whelpdale et al., 1996). SO$_2$ is the main product from the combustion of sulphur compounds and is of significant environmental concern.

At room temperature under normal conditions, SO$_2$ is a colorless gas. SO$_2$ is often described as the ‘smell of burning sulphur’ but is not responsible for the smell of rotten eggs. SO$_2$ forms sulphate aerosols that are thought to have a significant effect on global and regional climate. Sulphate aerosols reflect sunlight into space and also act as condensation nuclei, which tend to make clouds more reflective and change their lifetimes.

At present China becomes the highest SO$_2$ emitter in the world due to its reliance on coal for energy generation. When SO$_2$ combines with moisture in the atmosphere, it can form sulphuric acid (H$_2$SO$_4$), which is the main component of acid rain. Acid rain destroys various living organisms (harmful for humans, animals and vegetation) and structures (paints, buildings, infrastructure and cultural resources). Atmospheric SO$_2$ emissions are a major contributor to particular matter (particles or droplets (aerosols) suspended in the air) PM$_{2.5}$, (whose particles are less than 2.5 $\mu$m in diameter, $1 \mu$m = $10^{-6}$ m) in China (Mohajan, 2014).

Zheng et al. (2011) examined the issue of ancillary benefits by linking SO$_2$ emissions to CO$_2$ emissions using a panel of 29 Chinese provinces over the period 1995–2007. They inspected both the long-run and short-run elasticities of SO$_2$ with respect to CO$_2$.

Some countries, for example, Australia, Greece, India and China experienced a rise of SO$_2$ emissions during 1990–2007 (United Nations (UN), 2010) and at the same period the UK, Germany, the USA, Italy, and Spain experienced a decline of SO$_2$ emissions (European Environment Agency (EEA), 2010).

The Government of China has established national goals to reduce SO$_2$ emissions by 10% in the 10$^{th}$ and 11$^{th}$ Five-Year Plan periods, 2001–2005 and 2006–2010, respectively. Five-Year Plans of China are a series of social and economic development initiatives. During the 10$^{th}$ Five-Year Plan period, economy-wide SO$_2$ emissions increased at an average rate of 5.5% annually. After the adaption of a number of policies and introducing new instruments during the 11$^{th}$ Five-Year Plan, SO$_2$ emissions were declined by 14% (Schrefels et al., 2012). The World Health Organization (WHO) (WHO, 2004) estimated that acid rain seriously affects 30% of China’s total land area. Tianbao et al. (2012) indicate that China is one of the countries in the world which suffers from severe acid rain contamination. Acid rain causes many hazards to the environment, affects the standard of living, and is even harmful to human health. Due to China’s SO$_2$ emissions, both Japan and Korea are experiencing increases in acid rain (Mohajan, 2014).

2. IDENTIFICATION OF SO$_2$

SO$_2$ is a colorless gas or liquid with a strong odor, which affects the human respiratory system and aggravates cardiovascular disease. Its molecular weight is 64.06, vapor pressure is 2.538 mm-Hg at 21.1º C, vapor density is 1.43 g/ml (water is 1 g/ml at 4º C), boiling point is −10º C at 760 mm-Hg, freezing point is −72.7º C, it is soluble in water (11.3 g/100 ml at 20º C) and non-flammable.

Since it is a colorless gas that can be detected by taste and smell in the range of 1,000 to 3,000 micrograms (1 $\mu$g = $10^{-6}$ g) per cubic meter ($\mu$g/m$^3$). At concentrations of 10,000 $\mu$g/m$^3$, it has a pungent, unpleasant odor. Thermal power plants burning high-sulphur coal or heating oil are generally the main sources of anthropogenic SO$_2$ emissions worldwide (for the cleaner fuel the sulphur compounds are removed before burning the fuel), followed by industrial boilers and non-ferrous metal smelters. Emissions from domestic coal burning and from vehicles can also contribute to high local ambient concentrations of SO$_2$ (World Bank Group, 1998).

2.1. Structure and Bonding of SO$_2$

SO$_2$ is a bent molecule with $C_2v$, symmetry point group. In terms of electron-counting formalism, the sulphur atom has an oxidation state of +4 and a formal charge of +1. It is surrounded by 5 electron pairs and 8 lone pairs. In terms of the VSEPR model, SO$_2$ is planar with a bond angle of 92°.

The Lewis structure of SO$_2$ consists of an O=S=O double bond. From the perspective of molecular orbit theory, most of these valence electrons are engaged in S=O bonding (dative bond) without utilizing d-orbitals, resulting in a bond order of 1.5 (Cunningham et al., 1997).

2.2. Preparation of SO$_2$

Atomic structure of SO$_2$ that is produced by the burning of sulphur directly or of burning materials that contain sulphur is as:

$$S_8 + 8O_2 \rightarrow 8SO_2.$$ 

SO$_2$ is typically produced in large amounts by the burning of common sulphur-rich materials including wool, hair, rubber, and foam rubber such as are found in mattresses, couch cushions, seat cushions, carpet pads and vehicle tires.
SO₂ is produced by the combustion of hydrogen sulphide (H₂S) and organosulphur compounds as:

\[ 2\text{H}_2\text{S} (g) + 3\text{O}_2 (g) = 2\text{H}_2\text{O} (g) + 2\text{SO}_2 (g). \]

SO₂ is produced by the roasting of sulphide ores such as, pyrite (ferrous sulphide, FeS₂), sphalerite (zinc blend, zinc sulphide, ZnS) and cinnabar (mercury sulphide, HgS) as (Atkins, 2010):

\[
\begin{align*}
4\text{FeS}_2 (s) + 11\text{O}_2 (g) &= 2\text{Fe}_2\text{O}_3 (s) + 8\text{SO}_2 (g) \\
2\text{ZnS} (s) + 3\text{O}_2 (g) &= 2\text{ZnO} (s) + 2\text{SO}_2 (g) \\
\text{HgS} (s) + \text{O}_2 (g) &= \text{Hg} (l) + \text{SO}_2 (g).
\end{align*}
\]

SO₂ is found as a by-product in the manufacture factory when calcium silicate cement (CaSO₄) is heated with coke (C) and sand (SiO₂) as:

\[ 2\text{CaSO}_4 (s) + 2\text{SiO}_2 (s) + \text{C} (s) = 2\text{CaSiO}_3 (s) + 2\text{SO}_2 (g) + \text{CO}_2 (g). \]

Action of hot sulphuric acid on copper turnings produces SO₂:

\[ \text{Cu}(s) + 2\text{H}_2\text{SO}_4 (aq) = \text{CuSO}_4 (aq) + \text{SO}_2 (g) + 2\text{H}_2\text{O} (l). \]

Since coal and petroleum often contain sulphur compounds, their combustion generates SO₂ unless the sulphur compounds are removed before burning the fuel. SO₂ is the predominant form found in the lower atmosphere. Further oxidation of SO₂, usually in the presence of a catalyst such as NO₂, forms H₂SO₄, which creates acid rain.

### Table 1: According to World Bank list of most polluted cities in 2004 (Slanina, 2008).

<table>
<thead>
<tr>
<th>Rank</th>
<th>City</th>
<th>Country</th>
<th>Part. Matter (µg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cairo</td>
<td>Egypt</td>
<td>169</td>
</tr>
<tr>
<td>2</td>
<td>Delhi</td>
<td>India</td>
<td>150</td>
</tr>
<tr>
<td>3</td>
<td>Kolkata</td>
<td>India</td>
<td>128</td>
</tr>
<tr>
<td>4</td>
<td>Tianjin</td>
<td>China</td>
<td>125</td>
</tr>
<tr>
<td>5</td>
<td>Chongqing</td>
<td>China</td>
<td>123</td>
</tr>
<tr>
<td>6</td>
<td>Not Found (N/F)</td>
<td>N/F</td>
<td>N/F</td>
</tr>
<tr>
<td>7</td>
<td>Kanpur</td>
<td>India</td>
<td>109</td>
</tr>
<tr>
<td>8</td>
<td>Lucknow</td>
<td>India</td>
<td>109</td>
</tr>
<tr>
<td>9</td>
<td>Jakarta</td>
<td>Indonesia</td>
<td>104</td>
</tr>
<tr>
<td>10</td>
<td>Shenyang</td>
<td>China</td>
<td>101</td>
</tr>
<tr>
<td>11</td>
<td>Zhengzhou</td>
<td>China</td>
<td>97</td>
</tr>
<tr>
<td>12</td>
<td>Jinan</td>
<td>China</td>
<td>94</td>
</tr>
<tr>
<td>13</td>
<td>Lanzhou</td>
<td>China</td>
<td>91</td>
</tr>
<tr>
<td>14</td>
<td>Taiyuan</td>
<td>China</td>
<td>89</td>
</tr>
<tr>
<td>15</td>
<td>N/F</td>
<td>N/F</td>
<td>N/F</td>
</tr>
<tr>
<td>16</td>
<td>Beijing</td>
<td>China</td>
<td>88</td>
</tr>
<tr>
<td>17</td>
<td>Chengdu</td>
<td>China</td>
<td>86</td>
</tr>
<tr>
<td>18</td>
<td>N/F</td>
<td>China</td>
<td>83</td>
</tr>
<tr>
<td>19</td>
<td>Anshan</td>
<td>China</td>
<td>82</td>
</tr>
<tr>
<td>20</td>
<td>Wuhan</td>
<td>China</td>
<td>79</td>
</tr>
</tbody>
</table>

### 2.3. Use of SO₂

SO₂ has several agricultural and industrial uses. It can serve as a warning marker and fire retardant for liquid grain fumigants. Every year more than 300,000 tons of SO₂ are used globally for the manufacture of sulphur containing chemicals, particularly hydrosulphites. The bleaching of wood pulp and paper is another common use along with processing, disinfecting, and bleaching food products. There are also uses in metal, ore and oil refining as well as in waste and water treatment. It is used in small amounts as a food and wine preservative (Agency for Toxic Substances and Disease Registry (ATSDR), 2004).

### Table 2: Blacksmith List of most polluted cities and areas (The Blacksmith Institute, 2007).

<table>
<thead>
<tr>
<th>Rank</th>
<th>City</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sumgayit</td>
<td>Azerbaijan</td>
</tr>
<tr>
<td>2</td>
<td>Linfen</td>
<td>China</td>
</tr>
<tr>
<td>3</td>
<td>Tianying</td>
<td>China</td>
</tr>
<tr>
<td>4</td>
<td>Sukinda</td>
<td>India</td>
</tr>
<tr>
<td>5</td>
<td>Vapi</td>
<td>India</td>
</tr>
<tr>
<td>6</td>
<td>La Oroya</td>
<td>Peru</td>
</tr>
<tr>
<td>7</td>
<td>Dzerzhinsk</td>
<td>Russia</td>
</tr>
<tr>
<td>8</td>
<td>Norilsk</td>
<td>Russia</td>
</tr>
<tr>
<td>9</td>
<td>Chernobyl</td>
<td>Ukraine</td>
</tr>
<tr>
<td>10</td>
<td>Kabwe</td>
<td>Zambia</td>
</tr>
</tbody>
</table>
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Table 3: Estimated SO2 emissions scenario accordance with GDP growth rate in China (Su et al., 2013).

<table>
<thead>
<tr>
<th>GDP growth Scenarios</th>
<th>Electricity generation (TWh)</th>
<th>Gross SO2 emissions (MT)</th>
<th>Household SO2 emissions</th>
<th>SO2 emission control target</th>
</tr>
</thead>
<tbody>
<tr>
<td>5%</td>
<td>5,306</td>
<td>60.6</td>
<td>2.1</td>
<td>69.9%</td>
</tr>
<tr>
<td>7%</td>
<td>5,893</td>
<td>65</td>
<td>2.2</td>
<td>72.1%</td>
</tr>
<tr>
<td>9%</td>
<td>6,434</td>
<td>69</td>
<td>2.2</td>
<td>73.8%</td>
</tr>
<tr>
<td>11%</td>
<td>8,193</td>
<td>80.7</td>
<td>2.3</td>
<td>77.8%</td>
</tr>
</tbody>
</table>

Table 4: Installation, operation and SO2 removal rates for plants with SO2 control in 11th Five-Year Plan in China.

<table>
<thead>
<tr>
<th>Year</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating and absorption rate (%)</td>
<td>57</td>
<td>57</td>
<td>57</td>
<td>57.6</td>
<td>57.7</td>
</tr>
<tr>
<td>Installation rate (%)</td>
<td>30</td>
<td>43</td>
<td>60</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Removal rate of all plants (%)</td>
<td>17</td>
<td>24.6</td>
<td>34.4</td>
<td>46</td>
<td>46</td>
</tr>
</tbody>
</table>

Table 5: SO2 reduction targets and results in the previous Five-Year Plans in China (Su et al., 2013).

<table>
<thead>
<tr>
<th>Plan</th>
<th>10th (2001–05)</th>
<th>11th (2006–10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO2 reduction targets</td>
<td>10% below 2000 levels</td>
<td>10% below 2005 levels</td>
</tr>
<tr>
<td>SO2 reduction results</td>
<td>27.8% above 2000 levels</td>
<td>14.3% below 2005 levels</td>
</tr>
<tr>
<td>Industrial emissions meeting discharge standards</td>
<td>79.4%</td>
<td>97.9%</td>
</tr>
<tr>
<td>Industrial desulphurization rate</td>
<td>33.5%</td>
<td>66.0%</td>
</tr>
</tbody>
</table>

Fig. 1: Kuznets curve: pollution versus economic development (Slanina, 2013).

3. EFFECTS OF SO2 ON HUMAN HEALTH

SO2 is considered as severe health effect ingredient, both in short-term and long-term. It is a major pollutant that has a relatively short lifetime in the atmosphere and has negative effects that are local in nature. The negative effects of SO2 on health have been well documented in toxicological, human clinical and epidemiological studies (Electric Power Research Institute (EPRI, 2009). The human lungs are particularly susceptible to both the chronic and acute effects of SO2. After entering upper portion of lungs it immediately passes through the mucous membranes into the blood (Petrucci et al., 1994). In blood it becomes associated with the alpha-globulin fraction of plasma (Toxicology Update, 1995). In the moist pulmonary environment, SO2 produces sulphurous acid (H2SO3), which is a severe irritant. In addition it produces H+, bisulphate (H2SO3−), sulphite (SO3−), which in turn affects the smooth muscles and nerves involved in bronchoconstriction (Gunnison and Jacobsen, 1987; ATSDR, 2004; Miller et al., 2004). SO2 increases lipid peroxidation of cell membranes and interferes with antioxidative processes by decreasing the levels of superoxide dismutase, catalase and glutathione peroxidase.
The health effects caused by a short-term (a few minutes) exposures to SO2 are as follows (Bureau of Community and Environmental Health (BCEH), 2001):

(a) difficulty in breathing; (b) coughing; (c) irritation of the nose, throat, lungs; (d) fluid in lungs; (e) shortness of breath, and; (f) forms sulphuric acid in lungs.

The health effects caused by long-term exposure to SO2 are as follows (BCEH, 2001):

(a) temporary loss of smell; (b) headache; (c) nausea; (d) dizziness; (e) irritation of lungs; (f) phlegm; (g) coughing; (h) shortness of breath; (i) bronchitis, and; (j) reduced fertility.

The people who may be more sensitive to SO2 than others are as follows (BCEH, 2001):

(a) children; (b) elderly; (c) people with asthma; (d) people with chronic lung disease, and; (e) people with cardiovascular diseases.

A healthy people exposed to 1.5 parts per million (ppm) (1 ppm = 2.616 mg/m³) of SO2 for a few minutes may have temporary difficulty in normal breathing. Breathing in SO2 can irritate the nose, throat and the lungs, causing phlegm, coughing, shortness of breath, development of bronchitis and other respiratory diseases, as well as aggravation of existing cardiovascular disease. Asthmatics can be particularly susceptible to the pulmonary effects of SO2. Long-term contact to SO2 at lower concentrations can cause temporary loss of smell, headache, nausea and dizziness. More than 400 ppm concentrations of SO2 can cause severe shortness of breath and a build-up of fluid in the lungs. The great problem is that SO2 can go deep into the lungs where it combines with moisture to form H2SO4, possibly causing permanent lung damage. Long-term exposure to SO2 may decrease fertility both in males and females (BCEH, 2001).

In its untransformed, acidic, and particulate state, SO2 has adverse effects on human health and the environment. Inhaling SO2 is associated with increased respiratory symptoms and disease, difficulty in breathing and premature death. High levels of SO2 emissions can cause problems of breathing difficulty, respiratory illness, emphysema, asthma, acute broncho spasm, chronic bronchitis and heart diseases.

Fine particles PM2.5 penetrates deeply into sensitive parts of the lungs, where it can worsen respiratory disease, such as emphysema and bronchitis, and can worsen existing heart disease, can increase pulmonary disorders, and can increase morbidity and mortality rate. As a result increased of hospital admissions and sometimes caused premature death. At the cellular level, SO2 decreases levels of antioxidant enzymes, increases membrane permeability, causes chromosome breakage and is mutagenic or co-mutagenic.

A 2011 systematic review concluded that exposure to sulphur dioxide is associated with preterm birth (Shah and Balkhair, 2011). Children take more air in breathing for their body weight than adults. So, they can be more sensitive to the effects of SO2 than those of adults. Long-term exposure to SO2 increased respiratory illness and wheezing fits.

In the winter months when weather inversions occur, air pollution due to SO2 is trapped close to the ground and cannot escape to the upper atmosphere and the pollution reaches in unhealthy levels.

4. EFFECT OF SO2 WITH DOSE WISE

Effects of SO2 in human body are dose dependent. Typical levels of human susceptibility act as follows (Toxicology Update, 1995):

1) At 5 ppm, dryness of the nose and throat can be felt and resistance to bronchial airflow significantly increases.

2) At 6–8 ppm, tidal respiratory capacity may evidently decrease.

3) At 10 ppm, sneezing, coughing and wheezing may be seen, possibly accompanied by eye, nose and throat irritations. In this situation nose bleeding may also be seen. At this level, asthmatics are likely to experience asthmatic paroxysm, lasting possibly for several days.

4) At 20 ppm, bronchospasms be inclined to begin and eye irritation is a common matter.

5) At 50 ppm, discomfort becomes inclined, but permanent injury is unlikely if exposure is less than 30 minutes duration.

6) Above 50 ppm, reflex closure of the glottis can happen and last for a period of minutes.

7) Disclosure to SO2 at a concentration of 400 ppm will likely constitute an immediate danger to life.

8) Concentrations above 1,000 ppm, are usually fatal within 10 minutes; the proximate cause of death is assumed to be respiratory depression.

9) For asthmatics, experiences as low as 0.1 ppm for as short duration as 10 minutes during tiring physical activity, can result in significant respiratory changes and asthmatic attacks.

5. SO2 STANDARDS

The existing primary SO2 standards were established in 1971, which include a 24-hour standard at a level of 140 parts per billion (ppb) (SO2 conversion factor for ppb to μg/m³ is 2.616) and an annual average standard of 30 ppb.

WHO (2005) expressed that “Controlled studies involving exercising asthmatics indicate that a
proportion experience changes in pulmonary function and respiratory symptoms after periods of exposure to SO₂ as short as 10 minutes.”

The European Union Air Quality Standards (EUAQS) and The United States Environmental Protection Agency (USEPA) established a new 1-hr standard for SO₂ at 350 μg/m³ and 196 μg/m³ (75 ppb), respectively. The USEPA estimates that the health benefits associated with this rule range between $13 billion and $33 billion annually, which include preventing 2,300 to 5,900 premature deaths and 54,000 asthma attacks in a year. The estimated cost in 2020 to fully implement this standard is around $1.5 billion (Sulphur Dioxide Standards in Asia, 2010).

6. GLOBAL SO₂ EMISSIONS

Scientist calculated that human beings release about one-third of all sulphur compounds into the atmosphere. SO₂ is released when fossil fuels such as, coal, oil, gasoline, and diesel fuel are burned (commonly containing 1–2% sulphur by weight), from deforestation and agricultural activities and from traditional biomass combustion. Main source of SO₂ emissions are from fertilizer manufacturers, power plants, refineries, wood and paper mills, metal smelters, and other industrial processes.

Fossil fuel combustion at power plants (73%) and other industrial facilities (20%) are the main sources of SO₂ emissions. Other sources of SO₂ emissions are extracting metal from ore, and the burning of high sulphur fuels by locomotives, large ships, and non-road equipment.

Global SO₂ emissions peaked in the early 1970s and decreased until 2000 and then increased from 2000 to 2005 due to increased emissions in China, international shipping, and developing countries in general. At present China represents one-third of global SO₂ emissions from man-made sources. Between 2000 and 2010, SO₂ emissions in North America and Europe continued to decrease. But SO₂ emissions in India, the second largest source in Asia (China is the highest SO₂ emitter in Asia, as well as in the world), are rising, largely due to an increase in coal consumption and the absence of laws requiring flue-gas desulphurization. In 2010, Indian SO₂ emissions exceeded those of the USA and were about one-third of China’s total.

In 2006, China became the world’s largest SO₂ polluter, with 2005 emissions estimated to be 25.49 million tons (MT). This amount represents a 27% increase since 2000, and is roughly comparable with the US emissions in 1980 (United Press International, 2006).

7. AIR POLLUTION IN CHINA

Ambient concentrations of SO₂ in some regions of China are several times higher than air quality standards. Rapid economic growth of China has been increased emissions of SO₂ (a major air pollutant), NOₓ, and CO₂, due to increase of burning of fossil fuels. These three gases pollute air and environment, which increase human morbidity and mortality rates. Approximately 40% of China’s land area is affected by acid rain. The proportion of SO₂ emissions from the industrial sector grew from 76% to 85% between 1998 and 2006. Since 1990, SO₂ generated in China has been responsible for about one-fourth of the global emissions and more than 90% of the East Asian emissions. In 2006, Coal-fired power plants emitted about 11.12 MT of SO₂, which is about half of the total SO₂ emissions in China.

Between 1980 and 2006, total coal consumption in China increased from 0.6 billion tons (BT) to 2.58 BT, and SO₂ emissions reached 25.89 MT in 2006.
The SO$_2$ related pollution has momentous adverse impacts on human health, ecosystems, and cultural resources, and has caused direct economic loss of China in each year (Zheng et al., 2010). Zhang et al. (2008) have estimated that the total particular matters (PM) concentrations in 111 key Chinese cities contributed to more than 280,000 premature deaths and 680,000 cases of chronic bronchitis at a cost to the economy of more than 187.7 billion RMB ($29.2 billion) annually.

In China’s thermal power industry emits more than 50% Chinese SO$_2$. From 2000 to 2006, total SO$_2$ emission in China increased by 53%, from 21.7 trillion gram (Tg) to 33.2 Tg, which is an annual growth rate of 7.3%. Emissions from power plants are the main sources of SO$_2$ in China. These plants have increased from 10.6 Tg to 18.6 Tg in the same period.

Particulate matter, especially the smaller particles, has harmful effects on human health. Estimates of deaths due to respiratory and heart diseases caused by air pollution in China vary between 200,000 and 600,000 per year (HEI International Scientific Oversight Committee, 2004).

From 2000 to 2006 SO$_2$ emissions from north China increased by 85%, but in the south increased by only 28%. The anthropogenic SO$_2$ emission in China is of increasing global concern, as it contributed to about one-fourth of the global SO$_2$ emissions and more than 90% of Eastern Asia emissions since the 1990s (Streets et al., 2009; Ohara et al., 2007). Air pollution due SO$_2$ emissions of China are effecting larger regions from the Asian continent to the Northwestern Pacific, North America, and the rest of the northern hemisphere. Because of the harmful effects of SO$_2$, plants cannot grow robustly and some also die in severely polluted industrial areas.

SO$_2$ emissions vary accordance with the regions of China, depending with different sectors and characteristic of fuels. The relative emissions of SO$_2$ are defined as emissions energy thermal consumption multiplied by emission factors, considering corresponding removal efficiency. SO$_2$ emissions in specific region are calculated as follows (Su et al., 2013):

$$ E = \sum_s \sum_e 2Q_{se}S_se(1-\delta_e) $$ (1)

where the multiplication factor 2 in the right hand side of (1) indicates that the atomic weight of SO$_2$ is twice as S, the suffices $s$ and $e$ indicate sector and energy source, respectively. $Q_{se}$ is the energy thermal consumptions in specific region, sector and energy source, $S_s$ is the sulphur content in specific region and energy source, $\alpha_e$ is the SO$_2$ emission factor in...
specific region and energy source, $\delta_r$ is the desulphurization rate in specific region and energy source.

SO$_2$ creates acid rain. The Chinese Central government’s environment agency has estimated that the economic costs of acid rain at more than 83 billion RMB ($13 billion) per year (Hao et al., 2007).

8. SO$_2$ EMISSIONS CONTROLLING POLICY IN CHINA

To control SO$_2$ emissions, in 1998 the Chinese Government implemented Two Control Zone (TCZ) policy (the Acid Rain and Sulphur Dioxide Emission Control Zones Policy). The policy package contains the following two conditions (Li and Gao, 2002):

(a) Any new coal mine with sulphur content greater than 3% will be shut down and will be limited.

(b) The construction of new thermal power plants will not be approved in large and medium-size cities or their suburbs; for newly built or rebuilt thermal power plants, if the sulphur content in burning coal exceeds 1%, desulphurization facilities must be installed.

Since 2006, China has taken steps to reduce energy intensity, emissions, and pollutants in multiple guidelines and in the Five-Year Plans. Government of China takes various steps to control SO$_2$ emission. In the 4th plenary session of the 10th National People’s Congress, the central Government explicitly mandated a 10% reduction in national SO$_2$ emissions to be accomplished by 2010. Unfortunately during this period SO$_2$ emissions have increased by about 28% in the 10th Five-Year Plan (2001–2005) (National Bureau of Statistics (NBS), 2010). Desulphurization devices are required to be installed in most power plants, which had 52% of total coal consumption in China (NBS, 2009) and has effectively reduced SO$_2$ emission in China (Cao et al., 2009). SO$_2$ emissions began to decrease in China after 2006 mainly due to the wide application of flue-gas desulfurization (FGD) devices in power plants (Lu et al., 2010). The Ministry of Environmental Protection (MEP) of China resolved in its 11th Five-Year Plan (2006–2010) to cut the national SO$_2$ emissions by 10% and total SO$_2$ emissions declined by more than 14.3% by the end of 2010 (NBS, 2010).

Chinese Government has planned to reduce SO$_2$ emissions by 8% in the new 12th Five-Year Plan (2011–2015). China has targeted to popularize of wet-type SO$_2$ scrubbers and to improve the environmental emission standards, which plays an important role in the achievement of SO$_2$ control target by 2015 (State Council of China (SCC), 2011).

The maximization discounted consumption of each decision variables in equation (1) can be calculated as (Su et al., 2013):

$$ D = 5\sum_{r=1}^{R} \sum_{t=1}^{T} \prod_{j=0}^{t-1}(1 - d_{j,r})^5 \ln C_{r,t}. \quad (2) $$

5 in equation (2) indicates 5 years per period, $C$ is annual consumption and $d$ is utility discount rate. During the 12th Five-Year Plan five possible desulfurization rates in China are 50%, 60% 70%, 80% and 90%, covering the desulfurization rate in 2010 of 66%. In the planned 7% GDP growth scenario, China generates 5,893 TWh electricity and the gross SO$_2$ emissions reaches to 65 MT in 2015. The corresponding figures for 5%, 9% and 11% GDP growth scenarios are given in Table 3.

The provinces of China that emit SO$_2$ seriously like Shandong, Jiangsu and Guangdong are assigned high emission reduction targets, as 14.9%, 14.8% and 14.8%, respectively, comparing to 2010 levels. On the other hand, the most important industrial and commercial municipalities in China, Shanghai and Beijing are also allocated relatively severe SO$_2$ emission control targets, reducing 13.7% and 13.4% below 2010 levels, respectively. But some provinces of China are even allowed to increase the SO$_2$ emissions due to previous lower emissions, such as Hainan, Qinghai and Gansu, which are able to raise the SO$_2$ emissions by 34.9%, 16.7% and 2% above 2010 levels, respectively (Su et al., 2013).

The ancillary benefits of damage of per ton of SO$_2$ are different in different countries.

9. DESULPHURIZATION IN CHINA

The desulphurization rate is calculated based on the historic trend of the emission intensity, given the installation rate of the technology, an actual operating rate of the technology and the derived absorption rate. The installation rate was 2% in 2000, and increases to 6% in 2005. After the initiation of the 11th Five-Year Plan, it surged to 60% in 2008, and 80% in 2009 (China Electricity Council (CEC), 2009). The absorption rate remained at only 79% in 2009 in difference to the technical maximum removal rate of 95–98% of the technologies (Yang, 2009). Based on an overall 46% removal rate derived from the SO$_2$ emission intensity (Table 4), the ratio of the operating facility is estimated to be around 70% in 2009 (Zhou et al., 2011).

According to the 11th Five-Year Plan to reduce energy intensity by 20% by 2010, the State Council also approved a plan to close 50 Giga-watt (GW) of small coal-fired power plant capacity (small plants are
considered those with less than 100 MW of capacity). By the end of 2009, a total of 60.38 GW of capacity of small coal-fired power plants has already been shut down since 2006 (Ministry of Industry and Information Technology (MIIT), 2010). It is forecasted that removal rate in China will be 81% by 2015 and 98% in 2020 (Zhou et al., 2011).

Desulphurization rate in China in the 10th Five-Year Plans was not satisfactory but in the 11th Five-Year Plans it was in progress (Table 5). Industrial desulphurization rate was 33.5% in 2005 and 63.9% in 2010 in the 11th Five-Year Plan (Figure 2). The thresholds of desulphurization for different growth scenarios, namely 5%, 7%, 9% and 11% scenarios, to achieve the SO\(_2\) emission control target be 69.9%, 72.1%, 73.8% and 77.8, respectively (Su et al., 2013).

10. RECOMMENDATIONS

Desulphurization rates of China should be raised above 70% in 12th Five-Year Plan due to the uncertainty of GDP growth in urban areas. Desulphurization equipment should be installed in the petrochemical sector for catalytic cracking units with sulfur recovery rate in excess of 99%.

The popularization of wet-type SO\(_2\) scrubbers and improvement of the environmental emission standards play an important role in the achievement of SO\(_2\) control target by 2015. The improvement in energy consumption structure contributes to SO\(_2\) and other energy related emission controls effectively, as well as the sustainable development of energy.

Strength then flue gas treatment in mid- to large-sized coal-fired boilers, so that the boilers with capacity above 20 tons per hour should have sulphur removed, and the desulphurization rate will be greater than 70%. Desulphurization equipment should be installed in all coal-fired power units of the country, and substandard desulphurization equipment should be upgraded and reconstructed. The overall desulphurization efficiency in thermal power should be greater than 90%.

11. CONCLUSION

Global rapid urbanization and industrial development increased wealth and welfare. On the other hand pollution also increased due to emissions GHGs and SO\(_2\). In this study we have not included GHG emissions and discuss only SO\(_2\) emissions and reduction policies of China. We have stressed on SO\(_2\) emissions of China, as it is the world’s largest SO\(_2\) emitting country. In this article we have discussed some properties of SO\(_2\) and then discussed Chinese SO\(_2\) situations.

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