Air dispersion modelling for emission mitigation of power plant technology

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Abstract. Emission is a serious environmental problem worldwide due to the toxic gaseous emitted from industrial sectors and transportation. These can harm human health and the environment. One of industrial activities mentioned as the major contributor to poor air quality level is electricity generation. Air dispersion modeling has been developed and used for assessing the emission dispersion at a certain distance. The purpose of this study is to estimate the concentrations of emissions dispersion in surrounding area of the plants by simulating three different power plant technologies in West Java using Gaussian Plume Model. Hence air pollution can be reduced. The result found that the power generations in West Java did not significantly contribute to poor ambient air quality due to the emission concentrations were still below the threshold of ambient air standard.

1. Introduction
Energy is an essential input to modern life due to people's dependence on energy supply for most of everyday activities that increase significantly every year [1]. To fulfill the rising demand for energy consumption, a huge amount of money in energy generation was invested by government and private sector. Energy production offers not only great advantages but also causes severe impact on the environment and human health due to pollutant emissions emitted from power plants, which have high contribution to air quality levels [2]. Industry in China released 88.15% of Sulphur Dioxide emissions, of which coal-fired power generation was responsible for around 35.62% [3]. The International Energy Agency (IEA) predicted that electricity production in 2015 contributed nearly one-third of global Sulphur Dioxide (SO2), 14% of Nitrogen Oxide (NOx), and 5% of fine particulate matter (PM2.5) [2]. Not only energy sector, however, industrial activities and transportation also contribute to poor air quality levels.

Iron and steel industry, for instance, emitted SO2, NOx, PM, and volatile organic compound (VOC) as emissions in each process and 56% of SO2 and NOx emissions were nationwide emissions of iron and steel industries in five provinces of China [4]. In 2013, India has established iron and steel and non-metallic minerals industries to be major contributors to greenhouse gas emissions which represent 38% and 29% respectively [5]. Emissions from coal mines were environmental problem worldwide, which is predicted to increase by 20 percent in the next 12 years [6]. The common air pollutants in mining area consist of SO2, NOx, Carbon Dioxide (CO2), and powder [7]. Additionally, a study in Yunnan stated that a key for emission reduction is vehicle emissions control due to air pollution, such as carbon oxide (CO), CO2, SO2, NOx, Methane (CH4), PM2.5, PM10, VOC, Zinc and Cadmium that emitted. The result showed that private cars and heavy-duty trucks stayed ahead on vehicular emissions and CO2 was the major pollutant emitted in the road [8]. Likewise, in Indonesia, the main source of air pollutants was...
transportations and industries. The vehicles contributed nearly 71% of NOx, 15% of SOx, and 70% of PM$_{10}$ [9].

The number of air emissions depends on the fuels (coal, oil, natural gas, biomass) used during combustion process, the type and design of combustion unit, the emission control measures, and the overall system efficiency [10]. To prevent air pollution, the stringent regulation constructed by most countries to determine the maximum value of emission which may be permitted to release into the air and ambient air quality to monitor the ambient air surrounding the sources area. Hence, this study aims to estimate the major toxic emissions concentration of power plants mentioned as the main source contributed to the air pollution among industrial sectors using air dispersion model.

2. Method
Two main methods were used in this study, namely case study, and air dispersion modeling. These two methods are presented in section 2.1 and 2.2.

2.1 Study approach
The three studied power plants were 1x280 MW combined cycle power plant, 1x250 MW open cycle power plant, 3x315 MW coal-fired power plant located in West Java, Indonesia. West Java is an urban area where the economic and population grow fast. The population in the vicinity of these power plants were affected by the emissions of the power generations.

Hence, air dispersion modeling was carried out on emission data of these plants to find the dispersion of the emissions from the plants and their impact on air quality level in West Java area. The 3-month emissions measurement for each plant was taken for dispersion modeling to predict the concentration of pollutants, with ranges from 200 m to 15 km. The emissions data processed for air dispersion modeling were the values of SO$_2$, NOx, and PM$_{2.5}$. For dispersion modeling input, the meteorological data were collected from two stations that represent each area of these power generations: a) Jakarta station and b) Tangerang station. Combined cycle and open cycle power plants used Jakarta station as the meteorological data input, while Tangerang station applied for coal-fired power plants. In order to run the model, the 20-years of data (1998-2018) were required to draw the meteorological condition.

2.2 Air dispersion modeling
Air dispersion model used to estimate how much the reduction occurred during the pollutant dispersion from the point source to the ground level [11]. The models commonly incorporate meteorological data (wind speed, wind direction, temperature, humidity, atmospheric pressure), stack configurations (stack height, stack diameter, gas discharge velocity, stack gas temperature), terrain, chemical characteristics of the effluent [12].

Gaussian dispersion model is the most widely used model for dispersion and computational basis model distributed by U.S. EPA [11] due to extremely fast response time whereas it solves a single formula [13]. The illustration of Gaussian plume dispersion model is shown in Figure 1.

![Gaussian plume dispersion illustration](image-url)
The Gaussian formula can be written as follows:

\[
C(x, y, z) = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp \left( \frac{-y^2}{2\sigma_y^2} \right) \left[ \exp \left( \frac{-(z-H)^2}{2\sigma_z^2} \right) + \exp \left( \frac{-(z+H)^2}{2\sigma_z^2} \right) \right]
\]  

(1)

Where \(C\) is the concentration (\(\mu g/m^3\)), \(Q\) is the emission rate of the pollutant from the source (g/s). It obtained from emission flow rate multiplied by the emission value of point source. \(u\) is wind speed (m/s), \(y\) is crosswind (m), \(z\) is vertical direction (m), \(H\) is effective stack height (m), \(\sigma_y\) is a standard deviation of plume concentration distribution in horizontal (m), \(\sigma_z\) is a standard deviation of plume concentration distribution in vertical (m). \(\sigma_y\) and \(\sigma_z\) can be calculated based on formula that discovered and developed by Pasquil and Gifford as follow [14]:

\[
\sigma_y = ax^{0.894}
\]

(2)

\[
\sigma_z = cx^d + f
\]

(3)

Assuming at the ground level \((z = 0)\), the equation can be simplified as follows:

\[
C(x, y, 0) = \frac{Q}{\pi \sigma_y \sigma_z u} \exp \left( -\frac{y^2}{2\sigma_y^2} \right)
\]

(4)

Table 1. Dispersion coefficients

| Atm. Stability | a   | \(x \leq 1\) km | \(x \geq 1\) km |
|----------------|-----|-----------------|-----------------|
|                | c   | d   | f   | c   | d   | f   |
| A              | 213 | 440.8 | 1.941 | 9.27 | 459.7 | 2.094 | -9.6 |
| B              | 156 | 106.6 | 1.149 | 3.3  | 108.2 | 1.098 | 2.0  |
| C              | 104 | 61.0  | 0.911 | 0    | 61.0  | 0.911 | 0    |
| D              | 68  | 33.2  | 0.725 | -1.7 | 44.5  | 0.516 | -13.0 |
| E              | 50.5| 22.8  | 0.678 | -1.3 | 55.4  | 0.305 | -34.0 |
| F              | 34  | 14.35 | 0.740 | -0.35 | 62.6  | 0.180 | -48.6 |

The value of dispersion coefficients varies for each classification of atmospheric stability which shown in Table 1. Atmospheric stability is a parameter for characterizing turbulent status of atmosphere that ranges into six classes (A-F), from “very stable”, class F, to “neutral”, class D, up to “very unstable”, class A [15]. It can be seen in Table 2.

Table 2. Atmospheric stability classes

| Surface Wind Speed (m/s) | Day-time insolation | Night-time cloud cover |
|-------------------------|---------------------|------------------------|
|                         | Strong | Moderate | Slight | \(\geq 4/8\) | \(< 3/8\) |
| < 2                     | A      | A-B      | B      | -          | -        |
| 2-3                     | A-B    | B        | C      | E          | F        |
| 3-5                     | B      | B-C      | C      | D          | E        |
| 5-6                     | C      | C-D      | D      | D          | D        |
| >6                      | C      | D        | D      | D          | D        |
3. Result and Discussion

The simulation output of air dispersion model estimates the concentrations of emission released from power plants into the atmosphere at a certain distance in hourly. In this study, the output compared to the regulation of Indonesia air pollution control number 41 in the year 1999 which establishes ambient air threshold. Table 3 provides the maximum threshold for each pollutant [16].

Table 3. The Indonesian ambient air threshold

| Pollutant                  | Maximum Value (μg/Nm$^3$) |
|----------------------------|----------------------------|
| Sulfur Dioxide (SO$_2$)    | 900 (1 hour) 365 (24 hours) |
| Nitrogen Dioxide (NO$_2$)  | 400 (1 hour) 150 (24 hours) |
| Particulate Matter (PM$_{2.5}$) | 65 (24 hours)         |

3.1 Wind rose plot

Wind rose is a speed distribution diagram that indicates the wind direction is coming from [13]. The wind rose on Figure 2 showed the conditions of wind direction at a height of 10 m. Figure 2a shows that the most dominant wind direction in Jakarta station was in the east, in the amount of 14%. The wind speeds between 3 to 6 m/s are the most common. Similarly, east is the most common wind direction in Tangerang station, approximately 13% of the time. The most dominant wind speed frequency on Figure 2b is 0 to 3 m/s.

![Figure 2. Wind Rose Plot: a) Jakarta station, b) Tangerang station](image)

3.2 Predicted sulphur dioxides concentration

High concentrations of SO$_2$ in the atmosphere are associated with adverse human health and environmental effects. For environmental effects, high SO$_2$ contributes to acidic disposition, harms vegetation, decreases plant growth, accelerates materials corrosion [17]. Short-term exposure to SO$_2$ can be harmful to the respiratory system, especially for children, elderly, and those who have asthma will make them breathing difficult [18]. SO$_2$ emissions come from fossil fuels burning which contain sulfur, such as coal and fuel oil that mainly released from industrial process. Among industrial sectors in a few countries, power plants, particularly coal-fired power generation, contributes to the largest amount of
SO₂ emissions. It is proved by Figure 3 which shows coal-fired power plant gets the highest concentrations of SO₂ than the others about 240 μg/m³ at a distance of 200 m. The SO₂ concentrations decrease with increasing the distance due to air dilution. Nevertheless, the finding also indicates that the predicted values are below the threshold of SO₂ ambient air quality of Indonesia.

![Figure 3. SO₂ Concentrations](image)

![Figure 4. NOₓ Concentrations](image)

### 3.3 Predicted nitrogen oxide concentration

The graph presented in Figure 4 is the simulation output of predicted NOₓ values. The maximum concentration of NOₓ predicted is about 170 μg/m³ at a distance of 200 m from the point source of open cycle power generation. This complies with stringent limit of ambient air quality of Indonesia. Figure 4 shows that open cycle power plant has the greatest concentration value than two other power plants due to high temperature during combustion process. Automobile contributes about half of the NOₓ emissions, electric power plants 20%, and substantial emission (industrial boilers, incinerators, gas turbines, cement manufacture, petroleum refineries) 30% [19]. According to European Environment Agency, in 2013, 39% of NOₓ concentration came from road transport which was also the major contribution of the existence of NOₓ [20]. The excess NOₓ in the air can cause respiratory disorders, corrosion of materials, visibility reduction and vegetation damaged [21].

![Figure 5. PM₂.₅ Concentrations](image)
3.4 Predicted PM$_{2.5}$ concentration

PM$_{2.5}$ can be released directly from stationary or moving sources and formed from reactions of gaseous pollutants, such as SOx, NOx, NH$_3$, and VOCs. Due to their small size, PM$_{2.5}$ can be inhaled into human respiratory systems causing health problems [20]. The result (Figure 5) shows that coal-fired power plant has the highest value of PM$_{2.5}$ emission about 183 μg/m$^3$ for a distance of 200 m. Conversely, the lowest value was found on open cycle power generation. It was supported by the data emission in China that PM emissions from coal-fired power plants accounted for 44.6% of total PM emissions [20]. However, it was still below the threshold for PM$_{2.5}$ that has been established by the Ministry of Environmental and Forestry of Indonesia.

4. Conclusion

Emission is the result of fossil fuel combustion that emits toxic gaseous which can be harmful to human health and environmental. One of the common fuels combustions is coal burning as a result of coal-fired power plant activity. The result showed that the highest SO$_2$ and PM$_{2.5}$ emissions were released by coal-fired power plants. While open cycle has NOx as the dominant emissions than two other plants due to high temperature during combustion process. Nevertheless, the concentrations are still below the threshold of ambient air quality of Indonesia. This can be implied that power generations in West Java did not significantly contribute to the poor air quality level. In addition, further research is required to assess the other potential sources that impact ambient air quality.

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