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Effect of Boiler Chimney Design on Particulate Emission Dispersion Using Aermod Modelling

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Abstrak

Dalam operasional pembangkit listrik, proses pembakaran merupakan salah satu penghasil emisi partikulat. Emisi partikulat sendiri diketahui dapat memberikan dampak negatif bagi kesehatan, seperti menyebabkan gangguan pernapasan. Pola sebaran emisi partikulat dari cerobong boiler perlu dipelajari untuk meminimalisir sebaran polusi yang sampai ke lingkungan Model dispersi emisi partikulat yang dihasilkan dari cerobong boiler dapat diketahui dengan menggunakan alat bantu pemodelan aermod dimana melalui pemodelan ini, konsentrasi emisi partikulat yang diterima oleh lingkungan di sekitar dapat dipelajari. Desain cerobong boiler juga diketahui dapat mempengaruhi konsentrasi partikulat yang terdispersi selain faktor iklim seperti kecepatan angin, kelembapan, curah hujan dan lain-lain sebagai faktor eksternal. Penelitian ini bertujuan untuk mengetahui pengaruh desain cerobong terhadap sebaran emisi partikulat dari boiler. Model dispersi partikulat dilakukan dengan menggunakan alat bantu pemodelan aermod dengan variabel bebas adalah variasi ketinggian cerobong 21 meter dan 25 meter. Dari hasil analisis dispersi terlihat bahwa cerobong dengan ketinggian 21 meter menghasilkan konsentrasi emisi yang lebih tinggi pada jarak dekat dibandingkan dengan cerobong dengan ketinggian 25 meter. Hal ini disebabkan cerobong yang lebih rendah menyebabkan dispersi yang kurang optimal dan cenderung memberikan dampak lokal yang lebih signifikan karena konsentrasi emisi yang lebih tinggi di dekat sumber. Cerobong 25 meter memberikan hasil dispersi yang lebih baik dan lebih efektif dalam menyebarkan polutan ke area yang lebih luas. Hasil penelitian ini sesuai dengan teori plume rise dan model dispersi Gaussian, yang menyatakan bahwa semakin tinggi cerobong asap, maka semakin besar potensi gas buang dan partikulat yang dilepaskan untuk terdispersi.

Kata Kunci: partikulat, cerobong, pemodelan, boiler, dispersi

Abstract

In the power plants operation, the combustion process will produce particulate emissions. Particulate emissions themselves are known have a negative impact on health, such as causing respiratory problems. The pattern of particulate emissions from boiler chimneys needs to be studied to minimize the spread of pollution to the environment. The particulate emission dispersion model generated from the chimney of a boiler can be known using the aermod modeling tool, through this model, the concentration of particulate emissions received by the environment around the activity can be studied. The design of the boiler chimney is also known to affect the concentration of particulate matter that is dispersed. This study aims to determine the effect of chimney design on the distribution of particulate emissions from boilers. The particulate dispersion model was carried out using the aermod modeling tool with the independent variables were variations in chimney heights of 21 meters and 25 meters. From the dispersion analysis, it can be seen that the 21-meter chimney results in higher emission concentrations at close range because the lower chimney causes less optimal dispersion and tends to have a more significant local impact due to higher emission concentrations near the source. The 25-meter chimney provides better dispersion results more effective in dispersing pollutants over a wider area. The result of this research is consistent with plume rise theory and the Gaussian dispersion model, which states that the higher the stack, the more potential for the released flue gas and particulates to disperse vertically and horizontally before reaching ground level. Taller chimneys allow emissions to be released at a higher altitude, which can reduce particulate concentrations in the area around the plant or industrial installation. As the stack height increases, emissions are dispersed more widely in the atmosphere, so the potential for pollutant accumulation in areas near the source is reduced

***Key words**: particulate, chimney, aermod modelling, boiler, disperse*

INTRODUCTION

One of the main units in a steam power plant is a boiler, boiler is a high-pressure closed vessel that functions to convert water into steam (Siriwardena, 2020; Sunaryanto, 2023). The steam formed in the boiler is then flowed into the turbine to drive the turbine, this motion power is then converted into electric power. To convert water into steam, heat is needed from the combustion process in the furnace section of the boiler (Tawil, 2016). The fuel used in the combustion process can be fossil or non-fossil fuels. The combustion process will produce flue gas in the form of SO_2 and NO_2 gases which are released as emissions through the boiler chimney. In addition to the combustion gases, emissions generated from the boiler in the form of particulates derived from ash carried by the fuel. Most of ash will come out as bottom ash, while light ash will be included with the flue gas and enter the emission control system installed in the boiler, and will come out as fly ash while a small portion will come out through the chimney as particulate emissions (Xu et al., 2000; Firstanti et al., 2022; Thad Godish, 2014). The condition of particulate emissions produced by a boiler depends on several things, including: 1) type of fuel, where fuels with high ash content (such as Coal) will produce more particulates; 2) boiler design and condition, boilers that are not maintained or operate with low efficiency tend to produce more emissions; and 3) the efficiency of emission control devices such as electrostatic precipitators, bag filters, multi cyclone dust collectors or wet scrubbers will affect the amount of emissions released. Based on their size, particulate emissions can be divided into several types, namely: PM10 are particles with aerodynamic diameter less than or equal to 10 micrometres, PM2.5 are particles with aerodynamic diameter less than or equal to 2.5 micrometres. These particles are more dangerous because they can penetrate deep into the respiratory tract. In terms of chemical composition, particulate emissions generally consist of carbon from incomplete combustion, residual fuel combustion containing minerals such as silica, alumina, iron and calcium, heavy metals derived from fuel and organic compounds such as polycyclic aromatic hydrocarbons which are carcinogenic. The concentration of flue gas emission from boilers are regulated in the Minister of Environment Regulation.

Flue gas emissions generated by the boiler will form a distribution pattern that will affect the surrounding air quality. The distribution of these emissions is influenced by several factors, including climatic factors such as wind speed, rainfall, humidity, air temperature, surface pressure, solar radiation, altitude and cloud cover are variables that greatly affect the emission distribution pattern. Atmospheric stability will affect the vertical movement of air. In stable air, vertical air movement is inhibited and particulates tend to concentrate near the chimney and spread horizontally near the ground. While unstable air will encourage vertical movement so that particulates will be dispersed vertically and horizontally quickly and diluted quickly and reduce the concentration near the chimney (Ramadhan et al., 2017; Sutasoma et al., 2023; Atthoriq & Sitagosa, 2023). Atmospheric stability will affect the shape of the smoke coming out of the chimney, known as the plume. Wind direction and speed will generally affect the direction and distance of particulate dispersion. Wind speed will also affect how long particulates stay in the air before falling to the ground. Strong winds will reduce the residence time of particulates in the air. Solar radiation has a significant influence on the dispersion of particulates from boiler flues, mainly through two main mechanisms, namely: 1) the formation of plume rise, where solar radiation will heat the surface of the earth and its surroundings when it meets with hot air from the boiler chimney, the hot air around it will smoke it up higher (plume rise phenomenon). The higher the plume rise, the further the particulates can be carried before finally falling to the ground; 2) Photochemical reactions, solar radiation will trigger photochemical reactions in the atmosphere and can change the chemical composition of particulates released from the boiler flue. Some particulates can decompose, while others can react with gases in the atmosphere to form secondary particulates that differ in nature and size (Sharma et al., 2005; Abril et al., 2016)

In addition to climatic factors as external factors, the distribution of boiler flue gas emissions is also influenced by internal factors in the form of chimney design (Thad Godish, 2014). Boiler chimney design is a crucial aspect of efficient and environmentally friendly boiler operation. The main objective of chimney design is to safely and effectively discharge the combustion gases from the boiler to the atmosphere, and minimize the impact of air pollution. Some important factors in chimney design include: 1) Chimney height, in accordance with the Decree of the Head of Bapedal No. 205 of 1996 Appendix III states that the height of the chimney should be 2 - 2.5 times the height of the surrounding buildings so that the surrounding environment is not exposed to turbulence with gas flow velocity from the chimney should be greater than 20 m/sec (Republik Indonesia, 1995) so that the gases coming out of the chimney will avoid turbulence.

The height of boiler chimney can be affected by its capacity but not the main factor of its design. The formula that expresses the relation between chimney height and boiler capacity indicates that an increase of boiler capacity does not lead to a comparable increase in chimney height, but there is still a significant effect. The formula applies in the context of power generation systems and industrial boilers using conventional fuels such as coal, gas or biomass. In practical terms, the formula is used by engineers to design a chimney that matches the energy capacity produced by the boiler. The height of the chimney will determine how far pollutants can be dispersed in the atmosphere. A taller chimney allows pollutants to be carried further and diluted before reaching ground level; 2) Chimney diameter, where the size of the chimney diameter should match the volume and flow rate of the flue gases from the boiler. A diameter that is too small can cause the gas velocity to be too high, increasing friction and energy loss. Conversely, too large a diameter can reduce gas velocity and cause pollutant buildup.

The dispersion pattern of emissions emitted from boiler chimneys can be studied using the Aermod modelling tool introduced by the American Meteorological Society (AMS) and the U.S. Environmental Protection Agency (EPA) Regulatory Model. This modelling system is a dispersion modelling system in steady state conditions and is a development of the Gaussian Plume Model system (Cimorelli et al., 2015; Prabasari & Pusparani, 2022). The Aermod modelling tool is an atmospheric model used to predict the dispersion of air pollutants from point sources (such as boiler or factory chimneys), area sources, or linear sources to the atmosphere (Hasibuan et al., 2015; Riko Ferdinand Abdillah & Yayok Suryo Purnomo, 2024). The model is often used for air quality impact assessment in the vicinity of emission sources and to predict pollutant concentrations in the atmosphere based on various meteorological parameters, topography, and emission source characteristics. It is a physics-based numerical model designed to handle complex atmospheric conditions, including changing wind fields, temperature, and humidity (Anaam A. Sabri, 2011; Aggarwal & Haritash, 2018) It is particularly useful for analysis of compliance with air quality regulations and spatial planning. The dispersion process of pollutants using AERMOD models is more realistic way compared to other similar modelling.

This research aims to study the dispersion pattern of particulate emissions influenced by the design of the boiler chimney height. This study specifically analyzes the impact of variations in stack height (21 m and 25 m) on the dispersion of particulate emissions from biomass-fired boilers in the context of Indonesia's tropical environment which has typical meteorological conditions (wind, solar radiation, humidity). Many similar studies have been conducted in subtropical countries or with a generalized approach without explicitly highlighting variations in stack design in tropical conditions. In addition, although AERMOD is not new, its use in simulating emissions from biomass boilers in Indonesian plants with ERA5 meteorological data and WRPlot-AERMET-AERMAP integration is still relatively limited in the national literature. The model is used to assess the impact of emissions on specific receptor points (based on settlement locations), not just generalized predictions. This study also provides local empirical data to support the implementation of regulations such as BAPEDAL Head Decree No. 205 Year 1996 on chimney height. The results can be used for decision-making on the design of new chimneys or improvement of emission systems in operating factories.

RESEARCH METHOD

Identification of Emission Sources

The emission source comes from the combustion process in the boiler unit of the steam power plant. The boiler is a biomass-fired boiler with a capacity of 25 tons/hour and is located at coordinates 1° 44' 53.00" S and 103° 53' 53.00" E. Around the boiler there are residential areas at a distance of 586 meters to the northeast and 572 meters to the north. In addition, around the boiler is an oil palm plantation. The emission database that will be used in this study is secondary data in the form of particulate parameters derived from calculations using a mass balance with a resulting concentration of 4.08 mg/Nm^3. The boiler chimney height can also be calculated using the formula below (Atthoriq & Sitagosa, 2023).

$$H = 14 (Q)^{0.33} \text{ .... (1)}$$

where H is the height in meters and Q is the boiler capacity in kW

Meteorological Data

The meteorological analysis used as input for the Aermet tool comes from the cds.climate.copernicus.eu/ERA5 website including cloud cover data, temperature, humidity, air pressure, wind direction, wind speed, ceiling height, rainfall, and solar radiation. From the results of the meteorological analysis, the dominant wind direction is obtained as shown in Picture 2. Where the wind direction from the emission source leans towards the Southeast and Northeast.

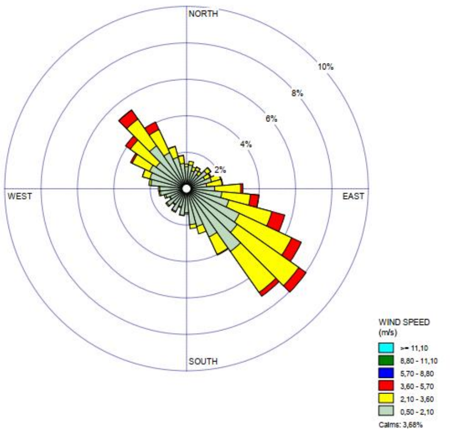


Figure 1. The dominant wind direction

Dispersion Simulation Analysis

Emission dispersion simulations use the Aermod air modelling tool issued by the American Meteorological Society (AMS) and the U.S. Environmental Protection Agency (EPA) Regulatory Model. The processes in aermod are: 1) Data collection including emission sources (number, type, stack height, and other parameters), meteorological data, topographic and land use data (topographic map and local barrier data); 2) Determination of Receptor Points: Receptor points are locations where pollutant concentrations will be calculated, such as around industrial facilities or in residential areas; 3) Running the Model: Once the data is ready, AERMOD is run to calculate the pollutant concentrations at the reception points over a certain period of time. The results can be used to assess whether the pollutant concentrations meet the air quality standards set by the government or regulatory agencies; 4) Analyse Results: After the model is run, the results need to be analysed to verify whether the predicted emissions may exceed safe limits. If necessary, mitigation or emission reduction measures can be proposed.

The aermod modelling tool is integrated with several other supporting software such as WRPlot to process meteorological data so that it can be processed by other supporting tools, namely AERMET View. AERMET view is a data processing tool output from WRPlot so that it can be read by AERMAP View. Another supporting device is AERMAP View, in this device will be displayed topographic information of the study area. The flowchart of the Aermod simulation is described as follows (Hadlocon et al., 2015; Prabasari & Pusparani, 2022).

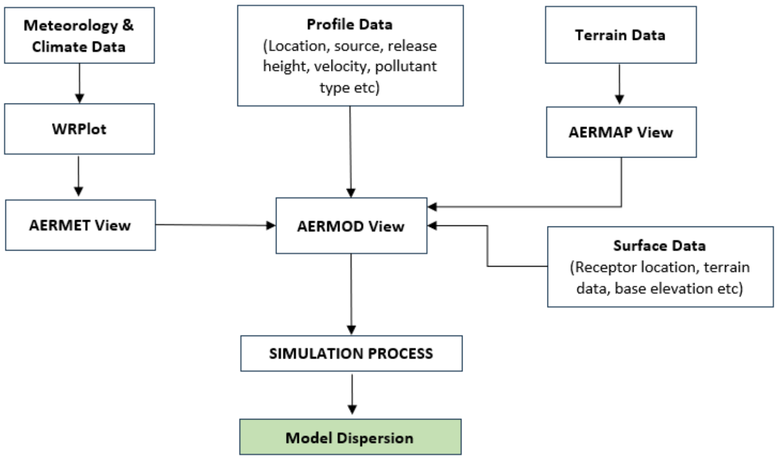


Figure 2. Flowchart of the Aermod simulation

The source parameters are base elevation 21 meters, gas exit temperature 200°C, gas exit velocity 12 m/s and chimney diameter 2 meters. There are 3 receptors that are determined based on the wind direction and the location of the nearest residents with the following coordinates. The position of emission sources and receptors according to the coordinates presented above shown in Figure 3 below.

Table 1. Receptors Location

No	Receptor	Coordinate	Distance from emission source (m)
1	Receptor-1	1° 44' 42.19" S; 103° 54' 09.29" E	607
2	Receptor-2	1° 44' 33.48” S; 103° 53' 58.86" E	630
3	Receptor-3	1° 45' 04.69” S; 103° 53' 57.93" E	396

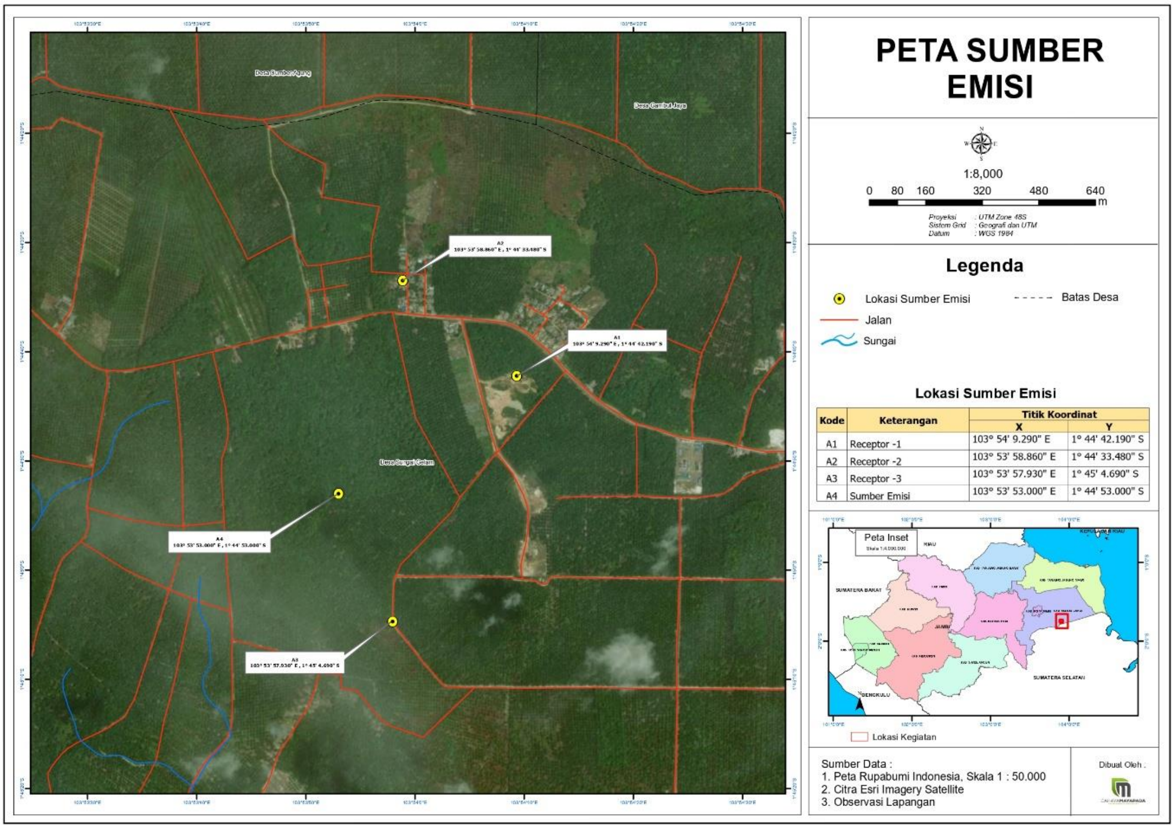
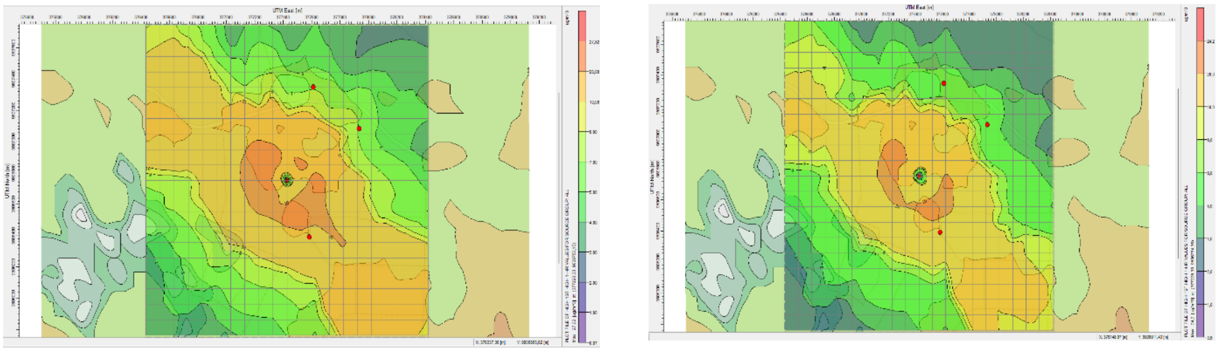


Figure 3. Emission source and the receptors location (Google Earth, 2024)

The independent variable is the height of the chimney, which is 21 meters and 25 meters. The chimney height variable has taken into account the provisions of the chimney height of 2 - 2.5 meters from the tallest building around the emission source (Republik Indonesia, 1995) and by using the above chimney height formula, for a boiler capacity of 25 tons/hour with a steam and power production ratio of 7, the minimum chimney height is 21 meters.

RESULTS AND DISCUSSIONS

From the simulation results, the particulate emission distribution model for each chimney height was obtained. The distribution pattern of particulate emissions at a stack height of 21 and 25 meters is depicted in Picture 4 below.



(a) (b)

Picture 4. Distribution pattern of particulate emissions at different stack height (a) 21 meters and (b) 25 meters

From the modelling, particulate emissions received at each receptor with varying chimney heights are shown in the table below. It can be seen from the table that Receptor 3 experienced the largest particulate concentration in absolute value. This indicates that the location of Receptor 3 is more affected by the change in stack height, while Receptor 1 and Receptor 2 show the lower concentration. Increasing the stack height is effective in reducing particulate concentrations, but the impact varies depending on the receptor location. Graphs of particulate emission distribution against distance from the emission source for each reseptors are shown in the figures below.

Table 2. Particulate emission at each reseptor

No	Chimney Height (m)	Receptor	Particulate Emission Level (mg/m^3)
1		Receptor-1	6,90
2	21	Receptor-2	6,70
3		Receptor-3	16,77
4		Receptor-1	6,83
5	25	Receptor-2	6,61
6		Receptor-3	16,07

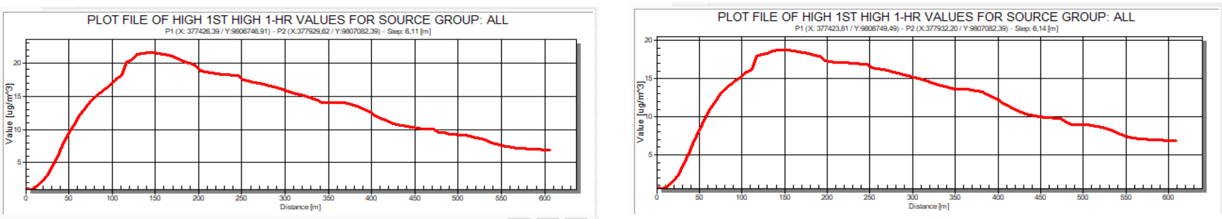
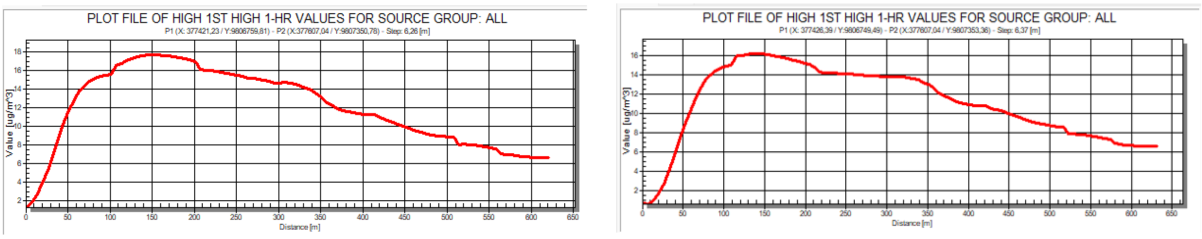


Figure 5. Particulate emission distribution against distance from the emission source to Receptor-1 at different stack height (a) 21 meters and (b) 25 meters

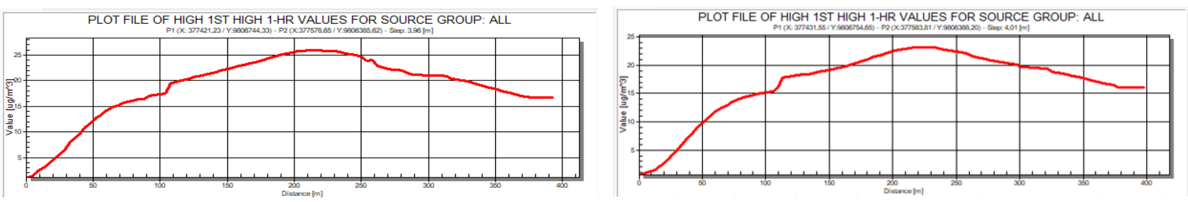
From the figure above, it can be seen that at a stack height of 21 meters, the particulate emission concentration is higher at a closer distance to the stack (the peak looks sharper) while there is a stack height of 25 meters, the maximum concentration is slightly lower, but the distribution looks more even or spread over a longer distance. The peak particulate concentration occurs closer to the emission source, around 100-150 meters at a stack height of 21 meters where the decrease in concentration after the peak is faster indicating a more focused distribution of emissions, while at a stack height of 25 meters the peak particulate concentration also occurs at the same distance (around 150 meters), but the value is smaller and the decrease in concentration is slower, so the pollutants spread further with lower concentrations.



(a) (b)

Figure 6. Particulate emission distribution against distance from the emission source to Receptor-2 at different stack height (a) 21 meters and (b) 25 meters

The figure above shows that at a stack height of 21 meters the peak concentration reaches about 18 μg/m^3 at a distance of about 150 meters, while at a stack height of 25 meters the peak concentration is slightly lower, about 16 μg/m^3, at almost the same distance of 150 meters. This suggests that with a higher stack height (25 meters), particulate emissions are more dispersed, resulting in lower maximum concentrations. Judging from the distribution pattern, at a stack height of 21 meters the concentration decreases gradually after a distance of 150 meters, but at a distance of more than 500 meters, it is still above 4 μg/m^3 and the distribution of emissions is more concentrated with high concentration values near the stack. At the 25-meter stack the concentrations also decreased after the peak, but faster than at the 21-meter stack and at a distance of more than 500 meters, the concentrations were close to 3 μg/m^3, and the emission distribution was wider with lower concentrations, indicating that higher stacks increase the dispersion of emissions.



(a) (b)

Figure 7. Particulate emission distribution against distance from the emission source to Receptor-3 at different stack height (a) 21 meters and (b) 25 meters

The figure shows that the particulate emission concentration at the 21-meter-high stack increases significantly until it peaks at a distance of about 200 meters from the source and then gradually decreases as the distance increases. The same is true for the 25-meter chimney but shows a smaller concentration peak. In both graphs, the decrease in concentration after the peak is gradual. However, the concentration at long distances is lower at a stack height of 25 meters, indicating more effective dispersion due to the higher stack height. The higher the chimney, the wider the particle distribution and the lower the maximum concentration.

The results of this study can be further explained based on atmospheric dispersion theory, specifically the Gaussian plume model that is the basis of the AERMOD software. This theory explains that air pollutants, such as particulates from boiler flues, will spread horizontally and vertically following a normal distribution pattern. The shape of this distribution is strongly influenced by various parameters such as wind speed, air temperature, atmospheric stability, and emission source characteristics, including stack height and diameter. It shown that variations in stack design, particularly the height of the boiler stack, have an effect on particulate emission dispersion patterns. The 25-meter high chimney produced lower particulate concentrations around the emission source than the 21-meter high chimney. This concentration difference was most significant at the receptor closest to the source. This result is consistent with plume rise theory and the Gaussian dispersion model, which states that the higher the stack, the more potential for the released flue gas and particulates to disperse vertically and horizontally before reaching ground level. This reduces localized concentrations and reduces direct exposure to surrounding communities (Ilaboya et al., 2011; Cimorelli et al., 2015; Thad Godish, 2014). Comparison with some previous studies also shows concordance. For example, studies by Binti Mokhadzir & Ramli (2020) and Matacchiera et al. (2019b) concluded that increasing the height of the chimney has a significant effect in reducing the particulate concentration in the area around the chimney. (Fadavi et al., 2016) also found that lower height chimneys tend to cause concentration peaks to occur near the chimney with a sharp decline thereafter, as also seen in the scatter graph results in this study (Holmes & Morawska, 2016). Conversely, higher chimneys allow for greater plume rise. Hot gases from the boiler will be pushed upwards and undergo more optimal dilution, so suspended particles spread further with lower concentrations near the source.

Boiler stack height can affect the distribution of particulate emissions generated by the combustion process in several ways. In general, stack height has some impact on the distribution of particulate emissions, both in terms of air pollution around the industrial area and on the dispersion of pollutants in the atmosphere. Taller chimneys allow emissions to be released at a higher altitude, which can reduce particulate concentrations in the area around the plant or industrial installation. As the stack height increases, emissions are dispersed more widely in the atmosphere, so the potential for pollutant accumulation in areas near the source is reduced. This also reduces direct exposure to human health and the surrounding environment (Matacchiera et al., 2019; Binti Mokhadzir & Ramli, 2020). Particulate emissions coming out of taller chimneys may be dispersed by winds at higher altitudes, depending on meteorological conditions such as wind speed and direction. In other words, taller chimneys can help "transport" pollutants over a wider area, reducing local concentrations but potentially increasing pollution over more distant areas, depending on wind patterns. At certain heights, wind speeds can be higher and more stable, which can help reduce airborne particulate concentrations. The higher the chimney, the more likely it is that particulate emissions can be pushed further before they settle to the surface. This finding is reinforced by the results of Fattal et al. (2021), which showed that increasing the height of the chimney can expand the distribution of PM10 and PM2.5 particulates in the atmosphere and reduce local concentrations, although it can increase the potential for exposure in more distant areas. It can potentially reduce the accumulation of dust and particulates on the ground or on vegetation around the site (Fattal et al., 2021).

However, while taller stacks can reduce localized concentrations, wider dispersion can lead to increased air pollution in more distant areas, which can contribute to long-term air quality problems, especially if there are multiple emission sources in the same region. In some cases, increasing the height of the stack can exacerbate air quality problems in areas further away from the source. Taller chimneys can affect the dynamics of fog or smoke formation, as higher and more dispersed emissions can mix with lower and cooler layers of the atmosphere, creating conditions that favour the formation of fog or other microscopic particles (Holmes & Morawska, 2016; Fadavi et al., 2016). For example, pollutants can react with water vapor or other particles in the air to form new chemicals that can increase air pollution over a wider area.

The study by Binti Mokhadzir & Ramli (2020) also found that the use of the AERMOD model on a biomass plant showed that a chimney with optimal height can significantly reduce particulate concentrations in nearby residential zones. This study underscores the importance of integration between stack design and dispersion simulation in air pollution control. Furthermore, Abril et al. (2016) in their study of industries and cities found that the AERMOD model was quite accurate in predicting particulate dispersion based on meteorological parameters and stack design. They also emphasized that increasing the stack height not only decreases the concentration near the source, but also changes the lateral distribution pattern (horizontal spread), which is important in the spatial planning of industrial areas.

In terms of regulation, the simulation results show that the particulate concentration of 4.08 mg/Nm^3 is far below the emission quality standard threshold set in the Minister of Environment Regulation No. 07 of 2007, which is a maximum of 230 mg/Nm^3 for biomass-fired boilers. This indicates that the boiler system and emission control mechanisms used generally meet the environmental requirements. However, according to Bapedal Chief Decree No. 205 of 1996, it is stated that the minimum flue gas velocity at the chimney should be more than 20 m/s to avoid turbulence and ensure efficient gas release. In this study, the flue gas velocity was 12 m/s, which is relatively lower than the standard. Although the concentration results are still below the quality limit, this can be a concern for future technical improvements to the emission system design to optimize the dispersion process.

CONCLUSIONS

The dispersion of particulate emissions is influenced by the height of the chimney. From the results of the particulate emission distribution analysis that has been carried out, it can be seen that the particulate concentration received by each receptor is lower in chimneys with a height of 25 meters than 21 meters. However, this difference is not too significant, for a height difference of 4 meters, the average difference in concentration at each Receptor1 and 2 is 1%, while for Receptor 3 with the closest position to the emission source has a greater difference of 4%. Overall, it can be seen that the 21-meter chimney results in higher emission concentrations at close range because the lower chimney causes less optimal dispersion and tends to have a more significant local impact due to higher emission concentrations near the source. The 25-meter chimney provides better dispersion results because the taller chimney allows particles to be carried further by the wind, resulting in lower concentrations at close range and more even dispersion, and is more effective in dispersing pollutants over a wider area, reducing the impact on the area around the source but increasing the potential for distribution over more distant areas.

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