Characterization of suspended PM2.5 and PM10 concentration and radioactivity around rembang steam power plant

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Abstract. Around Rembang Power Plant, ambient air samples of PM2.5 and PM10 has been taken. Result of this study can be useful as information for stakeholder and also people around Rembang power plant. Total characterization of average mass concentration in 6 locations for PM 2.5 and PM10 are 17.08 µg/m³ and 27.38 µg/m³ respectively. Those values are below air quality requirement by WHO. According to WHO, PM 2.5 should not exceed 25 µg/m³ and PM10 is not more than 50 µg/m³. Mass of PM 2.5 was around 63% from PM10 mass. This data shows that fossil fuel is main source of suspended particulate matter around Rembang power plant. Radioactivity analysis was done using gamma spectrometry, HPGe detector, radioactive sources (Eu-152 and Cs-137) and also Maestro 2 software. Radioactivity of Ra-226 for PM2.5 and PM10, are 5.72 µBq/m³ and 7.30 µBq/m³ respectively. Radioactivity of Th-232 for PM2.5 and PM10 are 1.17 µBq/m³ and 2.59 µBq/m³ respectively, while radioactivity of K-40 for PM2.5 and PM10 are 17.68 µBq/m³ and 25.58 µBq/m³, respectively. Those values of radioactivity are below recommended values released by Regulation of Nuclear Regulatory Agency Head Number 7 Year of 2017 About Radioactivity Level in Air. According to this law, radioactivity of Ra-226 is below 1800 µBq/m³ and for Th-232 is below 2300 µBq/m³.

1. Introduction
Coal is one of flammable minerals. Coal combustion results on radionuclides that found in bottom ash and fly ash, except in the flue gas and minerals that evaporate because radionuclides are carried by the flue gas stream. In large scale power plant, 20% of ash is bottom ash and the remaining 80% is fly ash [1], [2]. Due to the activity of using organic components of coal, there is an increase of activity in coal that become ash. Some of the radionuclides contained in coal include K-40, U-238, Ra-226, Pb-210, Po-210, Th-232, Th-228 and Ra-228 with activities around 10 Bq/kg to 600 Bq/kg [1, 3]. Naturally occurring radionuclides such as U-238, Th-232 and K-40 and their offspring in air, water and soil cause radiation exposure to populations [4].

The increase of concentration of natural radionuclide activity that occurs due to the dispersion of fly ash through the disposal of smoke from coal combustion needs further study because it has the potential to increase environmental radioactivity [5]. Suspended Particulate Matter (SPM) in air is generally a complex matter of a multi-phase system of liquid and solid particles at low pressure. SPM has aerodynamic particle sizes from 0.01-100 micrometers to larger. The aerodynamic particle size fraction is described as follows, particulate matter 2.5 (PM2.5) with particle size ≤ 2.5 µm, particulate matter 10 (PM10) with particle size ≤ 10 µm, both are easily inhale and causing serious health problems. SPM measurements have concentrated on Total Suspended Particulate (TSP) without size
selection preferences [6], [7]. In general, PM10 is derived from mineral dust, whereas finer PM2.5, which has more serious health effects compared to PM10, has various sources, usually dominated by combustion [7].

The pollution of particulate matter in the atmosphere is mainly composed of micron and sub-micron which are anthropogenic, because of human activity, transportation, biomass, fossil fuel, and natural resources [8], [9], [10]. Air pollution is defined as external existence in atmosphere, consists of one or several substances introduced by humans in such a way that it affects the health and well-being of human [9]. The purpose of this research is to identify and characterize the environmental impact of PM emissions with different aerodynamic particle size (PM2.5 and PM10) around Rembang steam power plant. The results of this study can provide valuable information about radiation threats and also serve as a baseline in monitoring environmental radioactivity in Indonesia.

2. Methodology

2.1. Materials

The materials used in this study were filters of particulate matter size 10 μm (PM10) and 2.5 μm (PM2.5) for six sampling locations and air sampling machine. To determine gamma spectrometry, Eu-152, Co-60 and Cs 137 were used.

2.2. Sampling Locations

![Figure 1. Map of sampling locations around Rembang steam power plant in Central Java](image)

Location 1 (L-1) of sampling located in Trahan, village of Trahan, is 1.2 km from the chimney of Rembang power plant with geographical coordinates of 06°38'03.20"S and 111°29'10.85"E. Location 2 (L-2) of sampling located in Tawang Rejo, Sluke Village, is 2.1 km away from the chimney of Rembang power plant with geographical coordinates of 06°37'59.13"S and 111°29'41.19"E. Location 3 (L-3) of sampling located in Pangkalan Kulon, Pangkalan village, is 1.3 km from the chimney of Rembang power plant with geographical coordinates of 06°37'53.10"S and 111°29'08.70"E. Location 4 (L-4) of sampling located in Pangkalan Wetan, Pangkalan village, located 2 km away with geographical coordinates of 06°37'47.30"S and 111°41.30"E. Location 5 (L-5) of sampling located in Pangkalan Kulon, Pangkalan village, is 1.3 km away from the chimney of Rembang power plant with geographical coordinates of 06°37'41.90"S and 111°29'05.20"E. Location 6 (L-6) of sampling located...
in Krajan Hamlet, Pangkalan Village, is 2.3 km away from the chimney of Rembang power plant with geographical coordinates 6°37'33.00"S and 111°29'39.60"E.

2.3. Tools and Sampling Technique
For ambient air sampling techniques PM 10, SIBATA HV-500R High Volume Air Sampler (HVAS) with a flow rate of 500 L/min was used. For PM 2.5, Environmental Sampler (E-Sampler) with PM2.5 Cyclone at 2.0 L Met One Instruments with a flow rate of 2 L/min was used. Air sampler of PM10 and PM2.5 were running for 24 hours simultaneously. Sampling was conducted in July 2016. Samples were transported from the sampling location to Radiochemistry laboratory in Centre for Accelerator Science and Technology and stored in a desiccator at temperature of 20°C to minimize volatilization. Correction blank was done by preparing an empty filter using the same procedure as for suspended particulate samples.

2.4. Radioactivity Determination Technique
All samples were inserted into vials, labelled and left for about 30 days to achieve radioactive equilibrium before counting for radium and thorium decays (IAEA 2004) [5]. Concentrations of Ra-226, Th-232, Ra-228 and K-40 in the PM 2.5 and PM 10 filter material samples were measured by gamma ray spectrometry equipped with a High Pure Germanium (HPGe) detector, with a relative efficiency of 35,0% and a resolution of 1.88 keV at 1332 keV Co-60 energy. The detector chamber was protected with three layers of copper, cadmium and lead with 30 mm, 3 mm, and 100 mm thick respectively. Energy and efficiency calibration were carried out using the multi-nuclide standard of Eu-152, Cs-137 and Co-60 sources.

Ra-226 activity was determined using U-238 decays of 214-Pb with the energy of 295.2 and 351.9 keV and 214-Bi with the energy of 609.3 keV. Activity for 232-Th was measured from 212-Pb with the energy of 238.6 keV and also 228-Ac with the energy of 338.3 and 911.1 keV, and 208-Tl with the energy of 583.2 keV. The 40K was measured from the gamma line energy of 1460.8 keV. The activity concentrations (Bq/kg) of Ra-226, Th-232 and K-40 in samples were calculated using analytical equations (1) [4], [5].

\[ A = \frac{C_{\text{net}}}{P_{\gamma} \cdot E \cdot t \cdot m} \]  

(1)

The method used for detector efficiency determination was point source method, as stated in equation (1), where Cnet is sample counts after blank deduction, Py is probability of radionuclide absolute emission, E is absolute efficiency, t is counting time, m is weight of dry sample, kg

2.5. Radiological Hazards Estimation
Radium equivalent (Ra\text{eq}) activity was used to assess radiological hazards associated with irradiated environmental health status. Radium equivalent activity (Ra\text{eq}) is a general index used to compare specific activities of materials containing Ra-226, Th-232 and K-40, taking into account the radiation hazards associated with it. Ra\text{eq} activities are mathematically defined by equation (2) [11,12], where CRa is activity concentration of Ra-226, CTh is activity concentration of Th-232 and CK is activity concentration of K-40.

\[ \text{Ra}_{\text{eq}} = C_{\text{Ra}} + 1.43\ C_{\text{Th}} + 0.077 \ C_{\text{K}} \]  

(2)

3. Results and Discussion
Figure 2 is a graph showing the characteristics of suspended particulate matter (PM2.5 and PM10). Mass of suspended particulate matter presented in Table 1. The smallest PM2.5 concentration was 12.378 μg/m\(^3\) and the highest concentration was 20.27 μg/m\(^3\) with an average of 17.08 μg/m\(^3\). This value was below required value determined by WHO (2005) which is 25 μg/m\(^3\) and US EPA (2015) which is 35 μg/m\(^3\) [6, 13, 14]. The PM10 concentrations presented in Table 1 have the highest concentrations ranging from 22.25 μg/m\(^3\) to 33.37 μg/m\(^3\). PM10 particulate mass concentration was below WHO air quality guidelines with a value of 50 μg/m\(^3\) [14-15]. According to the Government
Regulation of the Republic of Indonesia Number 41 Year of 1999, regarding the control of air pollution, the standard ambient air quality standards for PM2.5 and PM10 are 65 μg/m³ and 150 μg/m³, respectively [17].

The mass of PM2.5 was around 63% of PM10. This shows that about 63% of particles come from fine fractions (PM2.5) and 37% come from coarse fractions (PM10), which shows the main source of airborne particle pollution comes from anthropogenic sources due to burning fossil fuels or from mechanical processes [15], [16].

| L-1  | L-2  | L-3  | L-4  | L-5  | L-6  | Average | Standard Deviation |
|------|------|------|------|------|------|---------|--------------------|
| PM10 | 27.903 | 33.375 | 22.250 | 30.861 | 23.125 | 26.778 | 27.382 | 4.32 |
| PM2.5 | 16.892 | 20.270 | 18.018 | 19.144 | 12.387 | 15.766 | 17.080 | 2.80 |

Figure 2. Mass concentration of PM2.5 and PM 10 on each sampling locations

The four most important radionuclides in the natural environment are Ra-226, Ra-228, Th-232 and K-40, where Ra-226 represents the uranium-238 series (U-238), which have long half-life, i.e. 1600 years [4, 18]. Figures 2 and 3 were histograms of radioactivity of each suspended particulate (PM2.5, PM10) which was analysed from the air sampling around Rembang power plant. Figure 3 was a radioactivity histogram contained in the PM2.5 suspended particulate filter at sampling location 1 (L-1) to location 6 (L-6).
**Table 2.** Radionuclides activity around Rembang steam power plant

| Radionuclides | Radionuclides Activity, μBq/m³ | L-1 | L-2 | L-3 | L-4 | L-5 | L-6 | Average |
|---------------|--------------------------------|-----|-----|-----|-----|-----|-----|---------|
| PM2.5         |                                |     |     |     |     |     |     |         |
| Th-232        |                                | 1.17| 1.45| 1.33| 2.06| 1.39| 3.10| 1.75    |
| Ra-226        |                                | 2.18| 4.41| 5.02| 11.18|3.89| 7.61| 5.72    |
| Ra-228        |                                | 3.53| 4.81| 8.45| 13.58|7.89| 9.53| 7.96    |
| K-40          |                                | 12.61|13.62|18.06|21.01|18.17|22.60|17.68    |
| PM10          |                                |     |     |     |     |     |     |         |
| Th-232        |                                | 1.82| 2.50| 2.39| 3.16| 2.34| 3.35| 2.59    |
| Ra-226        |                                | 4.87| 8.21| 5.61|12.60|6.31| 6.17| 7.30    |
| Ra-228        |                                | 6.13|11.81| 9.06|15.47|12.61|10.37|10.91    |
| K-40          |                                | 19.95|24.99|22.82|30.56|25.01|30.13|25.58    |

The histogram of Figure 3 shows that the suspended particulate PM2.5 has radioactivity for Th-232 from 1.17 μBq/m³ to 2.06 μBq/m³ with an average activity of 1.75 μBq/m³, this activity is still below the standard radioactivity level at air for Ra-266 of 1.8 Bq/m³, the recommendation of Regulation of Nuclear Energy Regulatory Agency Head Number 7 Year of 2017 explained that the standard level of radioactivity in the environment is the highest limit expressed in the concentration of radionuclide activity in the environment [19]. Ra-226 radionuclide has activities from 2.18 μBq/m³ to 11.18 μBq/m³ with an average of 5.72 μBq/m³, according to the maximum quality standard is 1.8x10⁻³ Bq/m³. Radionuclide of Ra-228 has the lowest activity of 3.53 μBq/m³ and the highest is 13.58 μBq/m³ with an average of 7.96 μBq/m³. From the four radionuclides in Figure 2, it can be seen that the K-40 activity is in the range of 12.61 μBq/m³ until 22.60 μBq/m³ with average value is 17.68 average μBq/m³.

**Figure 3.** Radioactivity histogram of PM2.5 on 6 sampling locations

Figure 4 is a suspended particulate histogram of PM10, the sequence of activity from the lowest is radionuclide Th-232 <Ra-266 <Ra-228 <K-40. Activity of Th-232 is ranging from 1.82 μBq/m³ to 3.35 μBq/m³ with an average of 2.59 μBq/m³, Ra-266 activity is ranging from 4.87 μBq/m³ to 12.60 μBq/m³ with an average of 7.30 μBq/m³ whereas Ra-288 activity is ranging from 6.13 μBq/m³ to 15.47 μBq/m³ with an average of 10.91 μBq/m³ and K-40 from 19.95 μBq/m³ to 30.56 μBq/m³ with an average of 25.58 μBq/m³. The concentration of activities of each radionuclide are all still below the recommended quality standard, according to Government Ordinance Number 41 Year of 1999.
The general distribution of radionuclides Ra-226, Th-232 and K-40 in samples of suspended particulate matter PM2.5 or PM10 was not uniform. To overcome the radionuclide uniformity, a general index called "radium equivalent activity (Ra_{eq})" is used to obtain radiological hazard assessments by the air around the Rembang power plant. As shown in Figure 4 the three natural radionuclides will determine the indication of radiation hazard in air samples.

Equation (2) was used to determine the radium equivalent activity value (Raeq). The lowest specific activity value (Raeq) of Ra-226, Th-232 and K-40 is 4.82 μBq/m3, found in PM2.5 at location 1 (L-1). The lowest average value of three radionuclides mentioned above is 9.8 μBq/m3. Whereas, the highest specific activity value (Raeq) of Ra-226, Th-232 and K-40 is 19.47 μBq/m3, found in PM10 at location 4 (L-4). The highest average value of three radionuclides mentioned above is 12.97 μBq/m3. The result of radium equivalent activity (Raeq) is still below the allowable value of the recommended radiological safety standard with a value of 1.8 \times 10^{-3} \text{ Bq/m}^3 [18]. These results indicate that the overall air of the Rembang power plant area is safe from radiological risks and not cause harmful effects to the environment. The results of this study can provide valuable information about radiation threats and also serve as a baseline in monitoring environmental radioactivity in Indonesia.

4. Conclusion
Average levels of suspended PM10 around Rembang steam power plant was 27.38 μg/m3 and PM2.5 was 17.08 μg/m3. Both are below the standard limits recommended by the US Environmental Protection Agency (US- EPA) and the World Health Organization (WHO), which are 50 μg/m for PM10 and 25 μg/m for PM2.5. The average radioactivity of Ra-226, Th-232, Ra-228 and 40K were
also far below the permitted level determined by Regulation of Nuclear Energy Regulatory Agency Head Number 7 Year of 2017. The value of specific activity (Ra\(_{eq}\)) for Ra-226, Th-232 and K-40 is ranging from the lowest with a value of Ra\(_{eq}\) 4.82 \(\mu\)Bq/m\(^3\) to the highest value of 19.47 \(\mu\)Bq/m\(^3\). These results indicate that the overall air of the Rembang power plant area is safe from radiological risks and not cause harmful effects to the environment.

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