Influence of wind and topography on distribution of H$_2$S concentration at Cirata hydropower plant and its impact on corrosion rate

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Abstract. Emission of hydrogen sulfide (H$_2$S) gas by diffusion and by bubbling into the atmosphere at tailrace of Cirata hydropower plant give an environmental impact on surrounding area, especially on corrosion of metal surfaces. Field study shows that the highest H$_2$S concentration and the highest corrosion rate are located at the location of Tailrace, with an average concentration of 152.63$x10^{-3}$ µg.m$^{-3}$, and corrosion rate of 0.5010 mm.yr$^{-1}$. Computational Fluid Dynamics is used to develop a simulation model that replicates the function of wind in the distribution of H$_2$S concentration over the complex three dimensional terrain. Results from this simulation are presented and compared with field study data to determine its impact on corrosion rate.

1. Introduction
Sediment transport along the Citarum river permanently accumulates at the end of the reservoir bed of the Cirata dam. Fishery productivity in the reservoir which produces sediment and nutrient does also directly and indirectly contribute to the accumulation of sediment. This sediment contains dissolved hydrogen sulfide (H$_2$S) gas which is produced by the decaying process of organic material [1] from the sediment.

Hydropower activities will create downstream of sediment, leading sediment to the penstock (water tunnel), turbine and tailrace (water outlet). Turbulence that occurs will produce bubbles and droplets which will increase the SSA (specific surface area) significantly [2]. As an air-water interface, SSA will emit H$_2$S into the air. In aerobic condition H$_2$S will be oxidized to H$_2$SO$_4$, as an catalytic compound in the process of electrochemical corrosion [3] that will increase corrosion rate significantly.

The main purpose of this work is to analyze how H$_2$S concentration distributes induced by wind and topography in the study area during 10 August 2013 until 11 November 2013. Computational Fluid Dynamics (CFD) software is used to generate simulated imagery inside the domain of interest, and compare this result with field study data.

2. Materials and Methods
In Figure 1, a rectangular region of the study area is located by four corners (107°19’40.18”E; 6°39’48.96”S; 107°22’12.00”E; 6°42’24.48”S), and covering about 22.4 square kilometers. H$_2$S, wind sample and placement of corrosion test coupons were observed and collected from four locations within boundary region: • A (Residencial, 6°40’13.19”S-107°20’58.81”E); • B (Intake, 6°41’24.96”S-107°20’45.86”E); • C (Tailrace, 6°40’53.94”S-107°20’52.00”E); • D (Office complex, 6°42’12.60”S-107°21’8.47”E).
Three dimensional topography was used in this work to simulate distribution of H₂S concentration using CFD. Digital Elevation Models (DEM) data were extracted from Google Earth at boundary region. The procedure of extracting includes: determining the region of the study area first, specifying the number of points to be extracted by a grid with given rows and columns, extracting the elevation of points column by column (x), tracing the elevation profiles (y,z), finally export point cloud data (x,y,z) into CFD to create 3-D geometry model.

Hourly wind data were extracted from online weather forecast station provided by Norwegian Meteorological Institute (http://www.yr.no), which is the data supplied by the European Organization for the Exploitation of Meteorological Satellites (http://www.eumetsat.int/website/home/index.html). This station was chosen because data from this station closely similar to the sample of wind data from in situ measurement, beside avoiding extrapolation caused by local effects such as the height of an anemometer, relief of the terrain, the land cover and other objects.

Air samples were observed and collected for hydrogen sulfide at four location (A, B, C and D) within the boundary region. The test was based on Standar Nasional Indonesia SNI 19-4844-1998 [4].

Corrosion test was using Carbon Steel Plate Coupon type SS400 from Krakatau Steel that has the following chemical composition by mass%; C (0.007%), Mn (0.311%), S (0.013%), P (0.006%), Si (0.018%), Cr (0.0097%), Mn (0.311%), A (0.039%), Cu (0.039%), Mo (0.021%), Ni (0.023%), V (0.00065%) and the rest is Fe (99.5%). Test coupons are individually mounted on a rack that were electrically insulated from surrounding and making an angle of 45° towards the horizontal plane.

These 24 pieces of test coupons are on average 40 mm wide, 60 mm long, and 1 mm thick and exposed outdoor during study period at four location (A, B, C and D) within the boundary region. After completion of exposed period (2250 hours), corrosion rate were calculate using weight loss method. The test was based on American Society for Testing and Materials (ASTM) G50-76, Standard Practice for Conducting Atmospheric Corrosion Tests on Metals (ASTM G50) [5].

The Comsol Multiphysics was used in this study. The computational model solves the steady-state Navier-Stokes equations which are formulations of mass, momentum and energy conservation laws for fluid flows. The fluid flow is described by the Navier-Stokes equations and the mass flux is given by diffusion and convection.
3. Results and Analysis

Wind speed and direction
The total amount of wind events collected during the study period is about 750 events (calm wind event: 18.86%). The northerly winds blow during the day and southerly winds blow during the night. Figure 2 shows that the northerly winds are predominantly from the N-NNE quadrant and southerly winds from S-SSE quadrant. Highest wind speeds are normally associated with winds from the NNE. In general, average wind speed is about 2 m.s\(^{-1}\) for both south and north direction.

![Figure 2. Wind direction (left-hand side) and distribution of wind speed (right-hand side).](image)

H\(_2\)S concentration and corrosion rate
H\(_2\)S is heavier than air, it will tend to accumulate near the ground when leaking into the atmosphere. H\(_2\)S gas is oxidized to H\(_2\)SO\(_4\) by thiobacillus bacteria living on the surface near the ground [6]. This acid subsequently condenses along the surface and creates significant corrosion to the iron surface exposed to the air.

| Location | Hydrogen Sulfide (H\(_2\)S) Measurement | Corrosion Rate Measurement |
|----------|----------------------------------------|----------------------------|
|          | I \(\mu g.m^{-3}\) | II \(\mu g.m^{-3}\) | III \(\mu g.m^{-3}\) | IV \(\mu g.m^{-3}\) | Average \(mol.m^{-3}\) | I \(mm.yr^{-1}\) | II \(mm.yr^{-1}\) | III \(mm.yr^{-1}\) | IV \(mm.yr^{-1}\) | Average \(mm.yr^{-1}\) |
| A        | 9.46  | 2.67  | 6.06  | 0.40  | 4.65  | 3.39.10^{-7} | 0.0181 | 0.0323 | 0.0379 | 0.0542 | 0.0356 |
| B        | 9.46  | 2.67  | 1.53  | 2.67  | 4.08  | 2.98.10^{-7} | 0.0335 | 0.0335 | 0.0350 | 0.0480 | 0.0375 |
| C        | 8.33  | 516.50 | 81.89 | 3.79  | 152.63 | 1.11.10^{-5} | 0.2203 | 0.4905 | 0.6419 | 0.6512 | 0.5010 |
| D        | 4.93  | 3.80  | n/d   | 3.79  | 4.17  | 3.04.10^{-7} | 0.0375 | 0.0637 | 0.0626 | 0.0536 | 0.0543 |

The concentration of H\(_2\)S and corrosion rate in location C is very high, far exceeding the three other locations (Table 1). This is because location C is a pollutant source, and the three other locations (A, B and D) can be assumed as dissemination areas.

Simulation of wind and H\(_2\)S concentration
North wind and south wind were chosen because they represent the typical wind direction in this area. Wind speed of 2 m.s\(^{-1}\) was chosen to present the average ability of wind speed to move the pollutant across this area. A cross section at location C (at 107°20'52.00"E, from 6°39'48.96"S to 6°42'24.48"S) was chosen because it represents the pollutant source, and also parallel and closely colinier to other cross section at location A, B and D.
Because H$_2$S is heavier than air, the wind near the surface is very influential in the spread of H$_2$S concentrations. Figure 3 shows the wind contour near the surface in a simulation with a north wind. Location C and B are lower in altitude and both getting wind with low speed (0 to 1 m.s$^{-1}$) which is potential for pollutants to be trapped inside. This condition is not much different with a south wind simulation. Noted that the models used in the simulation below (Figure 3, Figure 4, Figure 5) are scaled down by 10 for saving computation time.

![Figure 3. Contour of near surface wind.](image)

North wind simulation.

In the figure 4, it shows two basins that could cause pollutants to be trapped, at the location C where the H$_2$S gas emissions happen and location B above the surface reservoir. Wind speed in both locations plummet.

Most of the H$_2$S gas was trapped in the south walls of the basin (location C). Some of 8.65x10$^{-7}$ mol.m$^{-3}$ H$_2$S concentrations trapped above the surface reservoir (location B) due to turbulence at low wind speeds. An amount of 1.96x10$^{-7}$ mol.m$^{-3}$ H$_2$S concentration will reach the location D, by distance of more than 2,500 meters from the source.

![Figure 4. Wind magnitude, wind direction and distribution of H$_2$S concentration north wind simulation.](image)
South wind simulation.

Figure 5 shows that wind blows with low speed (0 to 1 m.s⁻¹) at the location C and location A.

![Wind magnitude, wind direction and distribution of H₂S concentration south wind simulation.](image)

In detail, turbulence with small wind speeds occurs in the basin (location C). Most of the H₂S gas will be trapped in the south walls of the basin. An amount of 4.91x10⁻⁷ mol.m⁻³ H₂S concentrations will reach the location A, by the distance of more than 1,500 meters from the source.

**H₂S concentration and corrosion rate**

From the results presented in Figure 6 it is apparent that the simulation of H₂S concentration will lead to a small deviation compared with H₂S concentration from measurement result. This is because the wind conditions are changing at the time of sampling H₂S, but in general the results showed the same pattern.

![Measured and simulated H₂S concentration and corrosion rate.](image)

Corrosion rate also showed a similar pattern as the H₂S concentrations, but there was some difference in location D. In this case, the corrosion rate is slightly higher than at location A and B, whereas the level of H₂S concentration in the location D is the lowest. This is probably caused by other...
physical parameters that affect the corrosion rate (such as dew point temperature, moisture, corrosive
gas, and other particulate matter) that are not included in this study.

4. Conclusion
Wind direction is predominantly from the N-NNE quadrant during the day, and from S-SSE quadrant
during the night. Highest wind speeds are normally associated with winds from the NNE. In general,
average wind speed is about 2 m.s$^{-1}$ for both south and north direction.

Low level of wind speed, wind direction and topography with a high slope angle lead to high
concentration of H$_2$S gas trapped in the basin, only less than 8% of H$_2$S concentration spread across
the hill. Consequently, high concentration of H$_2$S gas in the basin will increase corrosion rate in this
area significantly.

Field study of the H$_2$S concentration and corrosion rate illustrates the same pattern as the spread of
H$_2$S concentration using a CFD simulation. All the parameters are at the highest level at the tailrace
and three other locations are lowest, hence the presumption that the spread of H$_2$S concentration
derived from the location of Tailrace as a source, and three other locations as dissemination areas
could be proven.

References
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