The volcanic ash dispersion simulation of Soputan with PUFF Lagrangian method

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Abstract. Volcanic ash is dangerous for aviation because it can harm the plane engine. This study built a simulation of volcanic ash dispersion of Soputan in Indonesia, which erupted in December 2018 with the combination of the PUFF and Lagrangian methods. These combination methods gave a better result because it included the advection, diffusion, sedimentation vector, the geographic factor, wind area, eruption time and duration, and lifetime particle in the air. The simulation result was compared with the satellite image from Volcanic Ash Advisory and calculated the area ratio (AR) as well as the angular deviation ($\alpha$).

1. Introduction

Volcanic ash is produced from the erupting volcano with a diameter of less than 2 mm [1]. It is formed from rocks, minerals, and glasses. The volcanic ash can move far away from the erupting volcano because of carried away by the wind [2]. The shape and movement of the volcanic ash are varied depending on the volcano and eruption characteristics. Within a certain period, the volcanic ash falls on the ground [3] or disappear in the air [4].

The volcanic ash is dangerous for human health because this particle is hard and sharp. It irritates the eyes, nose, and lungs [1]. It is dangerous for aviation as well [5]. The particle of volcanic ash can enter the engine and cause damage. The particle is abrasive and able to scrape the compressor blade. Therefore, it causes a mall function in the compressor and an increment of the plane pressure [6]. The particle contains silica crystal, which is melting in the combustion chamber and turning into liquid glasses. When the liquid glasses are freezing up in the turbine, then the airflow will be bunged and off the engine.

Volcanic ash is a fluid particle; therefore, its physics can be explained by the fluid mechanic theory. The movement of volcanic ash in the air is able to be modelled with PUFF method while the fluid mechanics can be studied with the Lagrangian method. The PUFF method models the volcanic ash dispersion with include the geographic factor of the mountain, wind area, the diffusion, sedimentation, eruption time and duration, lifetime particle in the air. The PUFF method can produce a high-resolution image of volcanic ash dispersion [7]. While, the Lagrangian method draw the trajectory of volcanic ash particle, individually, as a function of area and time. The Lagrangian method is able to calculate the trajectory more efficient [8].
2. The methods

The study combined the PUFF and Lagrangian method to get a better volcanic ash dispersion simulation result. In the simulation, the particles of volcanic ash were considered as a ball with varies sizes. The radius of each particle was counted by log-normal distribution with deviation standard

$$\log a_i \in N(\log R, \log D)_i,$$

(1)

where $a_i$, $R$ and $D$ is the particle radius, the average and deviation standard. Furthermore, the particle trajectory and velocity are taken into account. The vector position $r$ of particle move as the function of time $t$ is denoted as follow

$$R = r(x, y, z, t),$$

(2)

the wind velocity or the advection vector which affected the particle position is denoted as follow

$$V = v(x, y, z, t).$$

(3)

whereas, the variable is the coordinate of horizontal position and is the coordinate of vertical position [9]. The wind velocity at the specified level can be obtained from weather data from meteorology agency such as Japan Meteorology Agency (JMA). JMA provides the Grid Point Value (GPV) or weather prediction in 312 hours further. The data have to be converted into wind velocity data; therefore, the data can be involved in the simulation. The vector position of each particle at time $t = 0$ can be denoted as follow

$$R_i(0) = S_i,$$

(4)

where $R_i(0)$ is the vector position of particle at time $t = 0$ and $S_i$ is a vector position the volcanic ash source or the initial position of the volcanic ash which is above crater of the volcanic. With the information of volcanic ash altitude from the satellite data, therefore the initial position of the volcanic ash can be denoted as

$$S_i = (x, y, z)_i,$$

(5)

where $(x, y, z)_i$ is the initial coordinate position of the particle. The initial vertical position of the volcanic ash was set randomly above the crater, in between the minimum and maximum altitude. The vertical position of the particle as the function of time can be denoted as

$$z(t) = z_2 - (z_2 - z_1)e^{-\frac{t}{\tau}}.$$

(6)

where $z_2$ is the maximum altitude of the particle, $z_1$ is the minimum altitude of the particle and $\tau$ is the attenuation time. In this study, the attenuation time was 30 seconds. In the time interval $\Delta t$, the vector position of each particle at the certain altitude from $t$ to $t + \Delta t$ can be denoted as

$$R_i(t + \Delta t) = R_i(t) + V(t)\Delta t + D(t)\Delta t + G(t)\Delta t, \quad i = 1 \sim M,$$

(7)

where $R_i(t)$ is particle position vector at time $t$, $V(t)$ is the advection vector or the wind velocity, $D(t)$ is the turbulent diffusion vector or the vector of particle diffusion velocity, $G(t)$ is the sedimentation vector which influenced by the gravitation and particle size [9], and $M$ is the particle number. In the
simulation, a significant number of particles will give a better result [10]. The vector of turbulent diffusion can be denoted as

\[ D = (c_h, c_h, c_v), \]  

where \( c \) is diffusion velocity, \( c_h \) and \( c_v \) are the horizontal and vertical diffusion velocity. The diffusion velocity can be denoted as

\[ c = \sqrt{\frac{2K}{\Delta t}}, \]  

where \( K \) is diffusion coefficient. The value of diffusion is gained from eruption analysis. The diffusion velocity is influenced by the particle altitude. The particle horizontal altitude can be denoted as

\[ c_h' = c_h \left(1 + \frac{z}{z_0} \exp\left\{-\left(\frac{r}{r_0}\right)^2\right\}\right), \]  

where \( z_0 \) and \( r_0 \) is the particle initial position. The sedimentation vector can be formulated by the Stokes Law

\[ G = (0,0,-w), \]  

where \( w \) is the final falling velocity which can be denoted as

\[ \frac{w}{w_0} = \frac{a_0}{a} \left( \left(\frac{a}{a_0}\right)^3 + \frac{1}{4} \right) \left( \frac{1}{4} \right)^{1/2} \]  

where \( a_0 = 150 \, \mu m \) is the particle size in viscous and inertia. Viscos means the particle is condensed, whereas inertia means the particle is inert. The parameter \( w_0 = 1.0 \, m/s \) is the final velocity of the particle \( a_0 \) [10]. The different of the particle size influence the volcanic ash dispersion in the air. More bigger of the particle size, then lifetime of the particle is shorter. Fig. 1 shows the graphic of particle size as the function of its falling velocity.

![Terminal Fall Speed](image_url)

**Figure 1.** Particle size as the function of its falling velocity [9].
This study simulated the volcanic ash dispersion of Soputan Mountain which erupted on 16 December 2018 Indonesian time or 15 December 2018 UTC. The simulation results were then compared with the satellite image. The area ratio (AR) and the angle deviation ($\alpha$) were analysed as follow

$$AR = \frac{A_{\text{simulation}}}{A_{\text{satellite image}}}$$  \hspace{1cm} (13)

3. Results and discussion

The simulation of volcanic ash dispersion headed to southwest after 6 hours of the first eruption. After while the dispersion dispersed to east. The altitude was measure in feet ($ft$). The simulation result was compared with the satellite image from Volcanic Ash Advisory (VAA) which was published by the VAAC Darwin. The simulation was analyzed by comparing the area (AR) and the angle deviation ($\alpha$). Fig. 2-5 showed the comparison of volcanic ash dispersion simulation with the satellite image.

**Figure 2.** (a) the area (b) the angle deviation at 15/19.30 UTC (FL120).

**Figure 3.** (a) the area (b) the angle deviation at 15/19.30 UTC (FL250).
Figure 4. (a) the area (b) the angle deviation at 15/23.45 UTC (FL120).

Figure 5. (a) the area (b) the angle deviation at 16/17.15 UTC (FL120).

The data was displayed based on four Coordinated Universal Time (UTC) and Flight Level (FL). They were 15/19.30 with FL120, 15/19.30 with FL250, 15/23.45 with FL120 and 16/17.15 with FL120. UTC 16/17.15 informed the date and time which were 16 and at 17.15, respectively. While the FL120 showed the flight level or the altitude at 1200 feet. In the Fig. 2-5, the red lines were the satellite image, while the green spots were the simulation results. The data in Fig. 2-5 were summarized in the numerical data as shown by table 1.

Table 1. The comparison of simulation and satellite data image.

| Date/Time (UTC) | Flight Level (FL) | AR  | The accuracy of area (%) | α (°) |
|-----------------|-------------------|-----|--------------------------|-------|
| 15/19.30        | FL120             | 1.05| 95                       | 2.5   |
| 15/19.30        | FL250             | 0.91| 91                       | 1.5   |
| 15/23.45        | FL120             | 1.12| 88                       | 2.5   |
| 16/17.15        | FL120             | 1.14| 86                       | 2     |
| **Average**     |                   |     | **90**                   | **2.15** |

The results showed that rate of the area accuracy and angle deviation were 90% and 2.15°. The accuracy was good, and the angle deviation was small. Therefore, the PUFF Lagrangian method was able to simulate the volcanic ash dispersion.

4. Conclusion

The simulation results of Soputan volcanics ash dispersion with PUFF Lagrangian method has been conducted. The simulation data taken from the volcanic ash dispersion of Soputan which erupted on 16 December 2018 in Indonesian time or 16 December 2018 UTC. The simulation results showed that the area dispersion accuracy rate was 90%, this value was good. While the angle deviation rate was 2.5°, it
means the angle difference was small. Therefore, the simulation of volcanic ash dispersion with PUFF Lagrangian method was acceptable.

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