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Design and Implementation of a Soiling Forecasting Tool for Parabolic Through Collector Mirrors

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Abstract. This study presents a new soiling forecasting algorithm that was designed to predict the deposition of dust on mirror of Parabolic Through Collector (PTC) plants. The PTC soiling model developed in this work is based on existing models for the dust dry deposition over geographic regions. The soiling forecast algorithm is characterized by specific mechanisms. The sedimentation mechanism, also known as "gravitational settling", is proportional to the sun's position. Brownian motion is defined as a diffusion process and depends on the air's wind speed and temperature. Impaction mechanism depends on the wind speed and wind direction and occurs when particles do not follow the curved streamlines of their flow due to the inertia. All three mechanisms depend also on aerosol's size. Two mechanisms contribute to the mirror's cleaning, namely rebound and washout. Soiling rate (*SR*) is the daily rate of dust accumulation on the mirror's surface and depends on deposition velocity, rebound, the number of particles and their size. The modelled reflectivity is a function of *SR* and the reflectivity of a cleaned mirror. The model was calibrated using reflectivity measurements which were acquired during a previous project campaign in the period July 2018 – May 2019. The validation of the model for June 2019 showed that it accurately captured the phasing and the magnitude of reflectivity. The results of this study can help the PTC's operator to choose the optimal cleaning strategy to minimize the energy loss and to reduce O&M cost.

Keywords: Soiling Forecast, Soiling Effect, Modelling, Particulate Matter, Parabolic Through Collector (PTC) Plants

1. Introduction

After the 20th century, many countries have focused on renewable energy sources for thermal and electricity production having the general objective to reduce the environmental impact due to the increased use of fossil fuels [3]. The most abundant renewable energy source available is solar energy, and many technologies were developed to exploit its resource, such as solar thermal plants and photovoltaic (PV) [3]. In order to decrease the use of fossil fuels and based on the European Union (EU) regulations, the use of renewable energy systems has increased during the last years, especially the solar energy-based systems [3]. Considering the large amount of fuel that is needed to cover the energy needs of the industrial sector, the Parabolic Through Collector (PTC) technology seems to be the best system to balance the needs of several industrial plants [3].

The PTC systems belong to the of solar concentrating systems called Concentrating Solar Power (CSP). PTC plants are being installed in dusty environments such as the Middle East and North Africa (MENA) regions [1]. The trade-off between minimizing soiling-induced losses and cleaning cost is a challenge for operators and project planners while reducing drastically the water amount dedicated to solar field cleaning is the final goal [1]. Measurement campaigns for the effect of soiling on PTC mirrors are time consuming and costly. There are no standardize methods to determine the soiling of PTC solar fields.

This study presents a soiling forecasting (SF) tool developed at the University of Patras in the frame of the Smart Solar System (S3) project (Horizon 2020 Solar-Era.net), to estimate the deposition of dust on PTC mirrors. The implementation of the tool's algorithm is based on an existing soiling model [1], adapted to estimate soiling on PTC mirrors. This model is developed based on the physical principles implemented in existing Atmospheric Dust Transport Models (ADTM).

2. Soiling model for dust accumulation on PTC mirrors

The SF estimation is derived from the ADTM models where the particle deposition on the ground from the atmosphere is presented as particle flux F. The particle flux towards the mirror surface is calculated in equation:

$$F_{mirr}(d_P)=v_D(d_p)\cdot C(d_p), \tag{1}$$

where d_p is the particle diameter, v_D is the deposition velocity (m/s), and $C(d_p)$ is the number of particles in a cubic meter (m^{-3}). Dust accumulation from sedimentation, Brownian motion and impaction are considered in the estimation of v_D. To estimate the rate of dust particles that can be accumulated on the surface of a PTC mirror, the computational procedure was divided in two different paths: the first one has the equations for the laminar flow regime and the second has the turbulent flow regime.

2.1 Deposition velocity and soiling mechanisms

In the laminar flow model, deposition velocity is calculated as a sum of velocities caused by the mechanisms of sedimentation, Brownian motion, and impaction [2].

$$v_D=v_S+v_B+v_I \tag{2}$$

The v_S term corresponds to sedimentation. Sedimentation of a particle is the result of the ratio between the gravity force exerted on the particle and the drag force that opposes the movement of the particle [4]. The deposition velocity from sedimentation of a spherical particle is perpendicular to the mirror's surface and the sun's position. The v_B term corresponds to Brownian motion which is defined as a diffusion process where the soil particles will tend to be spread evenly throughout the medium in a function of temperature and surrounding air molecules and other aerosol characteristics. The last term, v_I is called impaction and occurs when particles do not follow the curved streamlines of the flow due to their inertia, resulting in the collision with the obstacle. The small particles that are interacting with on obstacle, in this case the PTC mirror, are partly following the direction of surrounding air stream, if the transferred momentum can overcome their kinetic inertia, otherwise they hit or impact the mirror surface. Impaction is a function of particle size, wind speed and wind direction.

Turbulent flow must be considered when the wind speed exceeds the threshold value $6.8\ \mathrm{m/s}$, so the air volumes do not follow the main flow [7]. In this case, air shows turbulences and fluctuations that are described from equation 3 for particle removal and deposition velocity. The deposition velocity for a turbulent flow case is calculated as:

$$v_{D,turb}=\alpha_{turb} \cdot (1+u_{wind} \cdot b_{turb}) \cdot f_{reb,turb}, \tag{3}$$

where α_{turb} is the weighting factor for the adhesion of the particles on the PTC's surface and b_{turb} is the weighting factor that calibrates the impact of the wind speed to the deposition velocity. The $f_{reb,turb}$ term is a model parameter that was determined from [1]. According to literature [1], for wind speed values that exceed the threshold of $6.8\ \mathrm{m/s}$, the turbulent flow equations are selected to estimate soiling correctly.

2.2 Rebound and washout

Apart from the mechanisms that estimate the formation of dust layers on a mirror's surface, the SF algorithm has considered the mechanisms that remove dust particles from the surface and therefore provide a natural cleaning effect to the mirror. The first process that appears to reduce dust accumulation on PTCs is called "rebound", and it is described as the removal of dust particles that occurs due to adhesion forces between the particles and the mirror surface. Individual rainfall events can also affect the concentration of dust deposited on solar mirrors. The contribution of both Rebound and rain washout processes to the soiling estimation is determined by mapping the values to the existing meteorological conditions [1].

2.3 Reflectivity estimation

The level of dust accumulation on a PTC mirror's surface is estimated from the cleanliness ξ, defined as the fraction of soiled mirror's reflectivity in time *t* to the mirror's reflectivity in clean state. The soiling rate *(SR)* is expressed as the decrease of cleanliness with time *t:*

$$SR = \frac{d\xi}{dt} \tag{4}$$

In this study, the assumption is made that the *SR (%)* is the daily rate estimation of dust accumulation on the mirror's surface. To quantify the *SR*, a metric is used that is proportional to the *SR*, namely the rate of coverage *(CR)* calculated as:

$$CR=\sum_{d_p=0.03\mu m}^{d_{pMAX}} F_{mirr}(d_p) \cdot d_p^2 \cdot \frac{\pi}{4}=\sum_{d_p=0.03\mu m}^{d_{pMAX}} v_D(d_p) \cdot C(d_p) \cdot d_p^2 \cdot \frac{\pi}{4}, \tag{5}$$

where the respective categories of the d_p for each model make up the summation. Deposition flux F_{mirr} is defined by the concentration of the number of spherical particles $C(d_p)$ $(1/m^3)$ and the deposition velocity $v_D(d_p)$ (m/s). *SR* is approximated by *CR* and the proportionality coefficient ζ. This proportionality coefficient ζ was the primary goal of the training phase (RMSE minimization in the training dataset):

$$SR = CR \cdot \zeta \tag{6}$$

The predicted estimation of the mirror's reflectivity ρ is calculated as:

$$\rho(t{+}1day)=\rho(t) - \rho_{Clean} \cdot SR(t), \tag{7}$$

where $\rho_{Clean}$is the reflectivity of the clean mirror.

3. Validation of the soiling model

The meteorological data used for the training and validation of the model were taken from a weather station at the company KEAN Soft Drinks Ltd in Limassol, Cyprus (location of the PTC plant) while the particle concentrations were retrieved from the CAMS global atmospheric forecasts [5]. Furthermore, reflectivity measurement data from aforementioned PTC plant acquired between 2018-2019 [3] has been used.

To provide an efficient prediction of the soiling rate, two similar versions of the model were used. The first model includes particle concentration information from the Particulate Matter (PM) forecasts. Because of that, the first model is calibrated with PM2.5 and PM10 (kg/m^3) only (i.e., $d_{pMAX} = 10\ \mu m$). The second model uses a wider distribution of aerosols, including coarse particles. Specifically, dust aerosol mixing ratio in the bins 0.03-0.55 μm, 0.55-0.9 μm and 0.9-20 μm were used in the CR estimation for the impact of the fine, medium and coarse particles (i.e., $d_{pMAX} = 20\ \mu m$).

To verify the performance of the SF tool, the reflectivity predictions from model 1 and model 2 were compared with the available PTC mirror reflectivity measurements. These reflectivity measurements had been acquired during previous project campaign that occurred in June 2019 at KEAN factory and has been described in detail in [3]. The measurement validation campaign was carried out for the period from 3rd until 7th June 2019, with one missing entry on 6th June. During the first 3 days, there was a significant soiling event that increased gradually until 5th June 2019 and then recedes the days afterwards.

Figure 1 illustrates the predicted reflectivity estimations of model 1 (top graph) and model 2 (bottom graph) against the reference reflectometer measurements. Both models accurately captured the phasing and the magnitude of reflectivity during the calibration period. To assess the effect of each mechanism on the model outputs, additional analysis with hourly data is presented in the following figures.

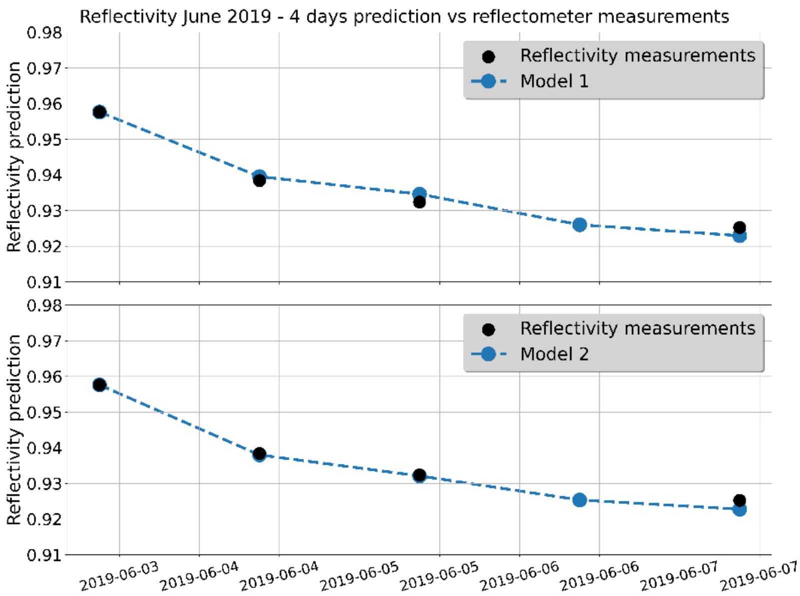

Figure 1. Daily reflectivity estimation and comparison with validation measurements.

Figure 2 shows the total aerosol optical depth (AOD), the dust AOD and some meteorological variables (e.g., air temperature). During the validation period, a dust event occurred, affecting the PTC system. The dust event can be verified from the values of dust AOD, shown in 1st and 2nd graph (from the top) of Figure 2. This is expected to be anticipated in the model's results, increasing the soiling rate and decreasing the estimated reflectivity. For that period no rain events happened. Relative humidity was mostly over 60%, resulting in no rebound effect.

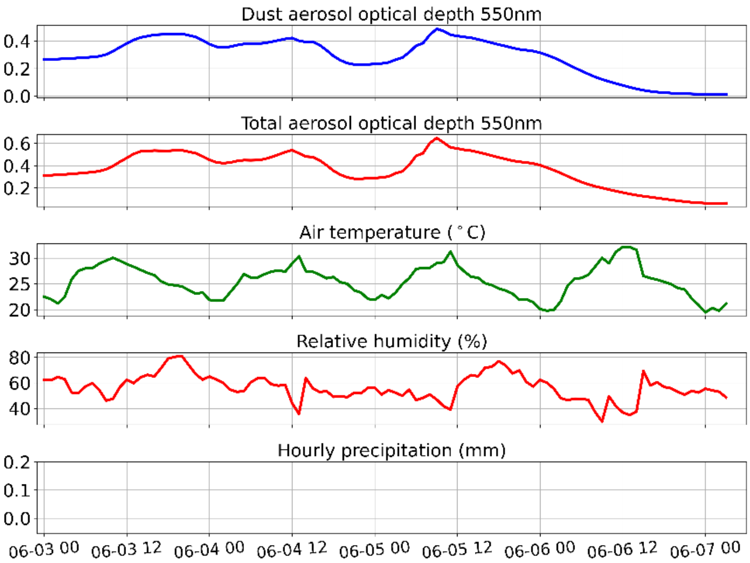

Figure 2. Hourly aerosol optical depth and meteorological conditions.

The outputs of model 1 are demonstrated in Figure 3 and Figure 4. Firstly, in Figure 3, the 1st and the 2nd graph from above show the hourly variability of the particulate matter (PM) concentration. PM patterns are not identical to AOD due to the occurred dust event that affected the PTC plant. Dust particles with diameters bigger than 10 μm are not included, resulting to different graph patterns of coarse particles (2nd graph in Figure 3). The deposition velocity, calculated with the equation for laminar flow, is presented in the 3rd graph of Figure 3. Zero deposition velocities are documented due to nighttime hours where the PTC plant is off. As presented in detail previously, the soiling rate is proportional to the deposition velocity. This is apparent by the 3rd and 4th graph in Figure 3. The hourly forecast reflectivity is presented in the 5th graph of Figure 3. As the soiling rate increases, the reflectivity decreases but if $SR = 0$ the estimated reflectivity does not change.

In Figure 4, the mechanisms of the 1st model are illustrated. As presented before, sedimentation velocity is proportional to sun's position, also known as "gravitational settling". According to previous session, at night there is no effect of sedimentation, justifying the missing values. The impaction (3rd graph in Figure 4) is a function of wind speed and wind direction. Values of zeroes appear at many times, even in daytime hours caused by the interaction of the wind's direction and the angle of the PTC mirror. Brownian motion (2nd graph in Figure 4) among the other parameters presents the lower impact to the total deposition velocity, whereas sedimentation provides the opposite behavior. The wind speed (Figure 4) does not exceed the threshold value of $6.8\ \mathrm{m/s}$, indicating the activation of laminar flow under the 4-day period.

For both models, deposition velocity is calculated based on fine and medium particles information and only for model 2, deposition velocity is calculated also for coarse particles. The outputs of model 2 are demonstrated in Figure 5 and Figure 6. Sedimentation, in Figure 6, has the same profile as model 1 but with different magnitudes due to use of different particle sizes. Larger particles result in higher values in Brownian motion. Impaction has the same values range because the wind is the dominant factor of this mechanism. Larger particles increase the "gravitational settling" resulting in the increase of deposition velocity and soiling rate. Like model 1, the sedimentation has the highest influence of models estimated deposition velocity.

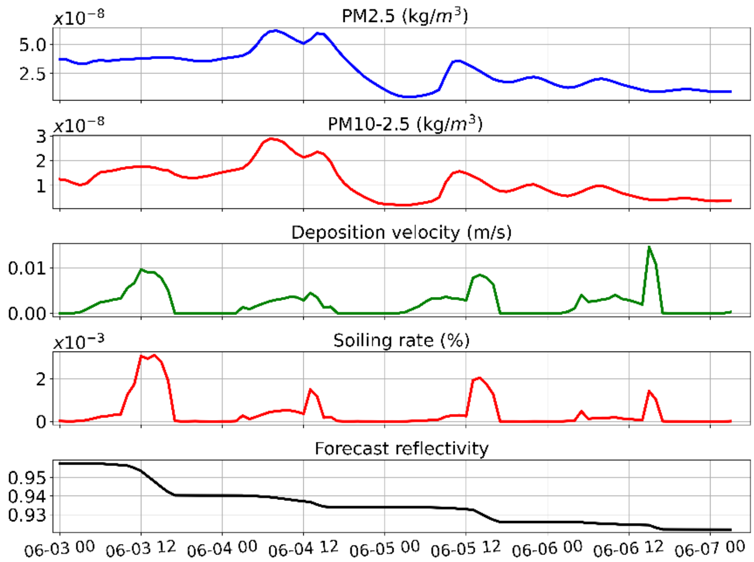

Figure 3. Hourly PM2.5 and PM10 concentration, deposition velocity, soiling rate and forecast reflectivity for model 1.

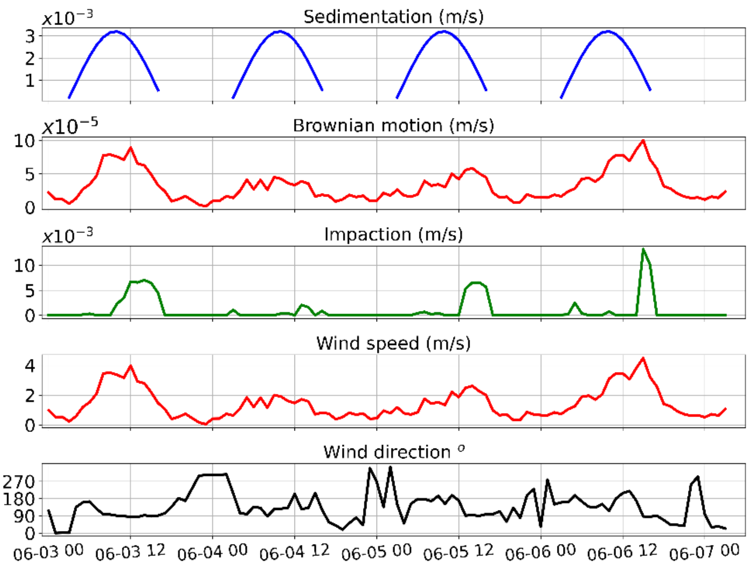

Figure 4. Hourly sedimentation, Brownian and impaction mechanisms, wind speed and wind direction for model 1.

The biggest drop of reflectivity estimation appears at the time of the highest soiling rate as shown in Figure 5. At that period, sedimentation, impaction and Brownian motion haves their highest values, the dust aerosol mixing ratio was high and the dust AOD was over 0.4, which describes the intense dust event. Furthermore, relative humidity was over 60% resulting in no rebound effect. This indicates that there was no mechanism that removed dust particles from the surface and "cleaned" the mirror. The timing of the favorable environmental conditions for dust accumulation is aligned with the period exhibiting the maximum reduction of the predicted reflectivity, demonstrating a correct replication of the underlying physical mechanisms.

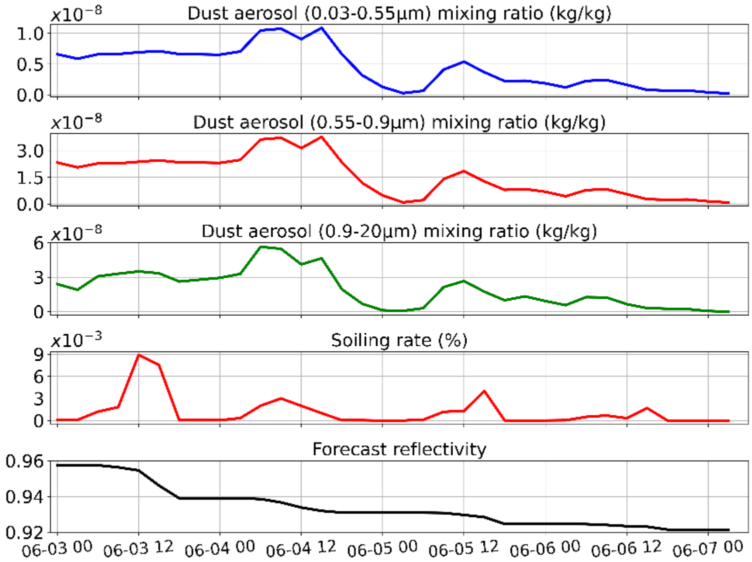

Figure 5. Hourly dust aerosol mixing ratio, soiling rate and forecast reflectivity for model 2.

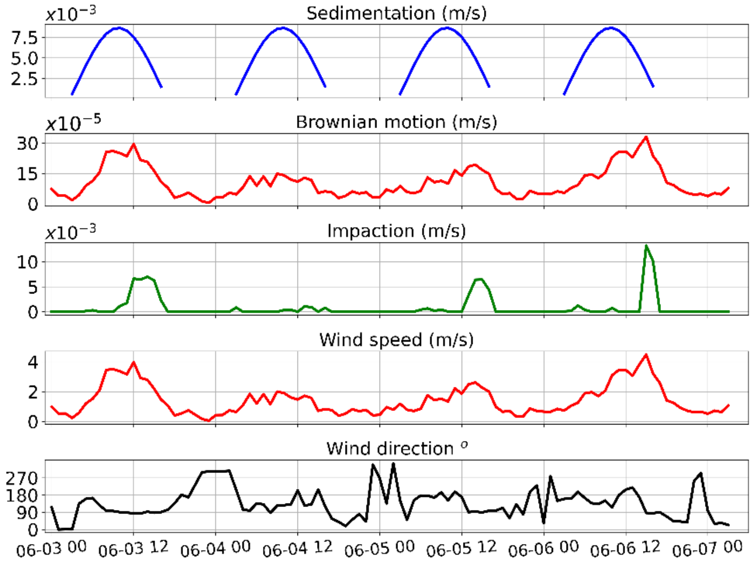

Figure 6. Hourly sedimentation, Brownian and impaction mechanisms, wind speed and wind direction for model 2.

4. Results and Discussion

During the calibration period, both models correctly estimated the reduction and the phasing of the reflectivity. The sedimentation mechanism had the highest influence of SF's estimated deposition velocity. The wind (speed and direction) had the biggest impact on the deposition velocity relative to other meteorological variables. In general, the model 2 is more efficient than model 1 because it uses a wider distribution of aerosols.

The next step will be further optimize the model by mean of implementing a wider range of atmospheric conditions (e.g. warm-humid, red-rain events) in view of its operational implementation in refl ectivity forecasts.

Author contributions

Conceptualization[1,2,3,4,5,6], Data curation[1,2,6], Formal Analysis[1,2,6], Funding acquisition[project consortium], Investigation[1,2,6], Methodology[1,2,6], Software[1,2,6], Supervision[6], Validation[1,2,6], Visualization[1,2,6], Writing – original draft[1,2,6], Writing – review & editing[1,2,3,4,5,6].

Competing interests

The authors declare no competing interests.

Data availability statement

The detailed and extensive amount of data supporting the results of this paper is only (and even only in parts) accessible to the consortium members of project S3 within legal restrictions bound by a cooperation agreement. For reasons of maintaining intellectual property, the information and data presented in this paper is limited.

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References

1. Water Saving for Solar Concentrated Power, “Deliverable 3.2: Soiling and condensation model applied to CSP solar field.” H2020-LCE-02-2015 Developing the next generation technologies of renewable electricity and heating/cooling, 2018
2. F. Wolfertstetter, S. Wilbert, N. Hanrieder, S. D. Rodriguez, P. Kuhn and B. Nouri, “Soiling in CSP: modeling and forecasting from weather inputs.”, p. 22
3. P. K. Ktistis, R. A. Agathokleous, and S. A. Kalogirou, “Experimental performance of a parabolic trough collector system for an industrial process heat application,” *Energy*, vol. 215, p. 119288, Jan. 2021, doi: 10.1016/j.energy.2020.119288.
4. F. Gensdarmes, “Methods of Detection and Characterization,” in *Nanoengineering*, Elsevier, 2015, pp. 55–84. doi: 10.1016/B978-0-444-62747-6.00003-8.
5. “CAMS global atmospheric composition forecasts” ads.atmosphere.copernicus.eu. https://ads.atmosphere.copernicus.eu/cdsapp#!/dataset/cams-global-atmospheric-composition-forecasts (accessed Aug. 3, 2022).
6. K. Peters and R. Eiden, “Modelling the dry deposition velocity of aerosol particles to a spruce forest,” *Atmospheric Environ. Part Gen. Top.*, vol. 26, no. 14, pp. 2555–2564, Oct. 1992, doi: 10.1016/0960-1686(92)90108-W.

7. A. Muyshondt, N. K. Anand, and A. R. McFarland, “Turbulent Deposition of Aerosol Particles in Large Transport Tubes,” *Aerosol Sci. Technol.*, vol. 24, no. 2, pp. 107–116, Jan. 1996, doi: 10.1080/02786829608965356