Why Natural Cleaning of Solar Collectors Cannot be Described Using Simple Rain Sum Thresholds

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Abstract

This study investigates parameters describing the modelling of natural cleaning by precipitation in soiling models for solar collectors. Approaches assuming that the solar collector is cleaned completely if a daily rain sum threshold is exceeded are investigated with the help of more than three years of soiling and natural cleaning data at CIEMAT's Plataforma Solar de Almería in Spain. It is found that the natural cleaning completeness by rain cannot be described well by using only a threshold of the daily rain sum. We discuss the dependence on further parameters, e.g. the existing soiling levels, the rain direction dependent on wind speed, the collector orientation, the kind of soiling, the collector surface properties and several more. Considering the rain/wind and collector orientation is especially important for the modelling of natural cleaning of tracked collectors as the effective rain sum hitting the collector and the runoff speed is expected to change drastically with the orientation of the collector.

Keywords: Soiling, Natural Cleaning, Photovoltaic, Solar Energy

1. Introduction

The accumulation of aerosol particles on photovoltaic (PV), concentrated solar power (CSP) or non-concentrating solar thermal collectors causes soiling losses and can vary dependent on the implementation site and also with time. Those losses have been studied at several sites around the world and different analytical soiling models have been implemented to describe soiling losses dependent on local aerosol deposition and rainfall pattern (Picotti et al., 2017, Wolfertstetter et al., 2019). If information of the local expected soiling rate and precipitation would be available for the site of interest, the soiling model results could be considered within PV or CSP performance models and a tradeoff between minimizing the soiling losses and the induced cleaning costs of the collectors could be predicted.

One key effect is the natural cleaning of the solar collectors by rain. It can be observed that light rain rather soils the collectors while heavy rain reduces the soiling levels or cleans the collectors completely. For simplification, in most PV soiling models which can be found in literature (e.g. Hamond et al., 1979; Kimber et al. 2006; Caron and Littman, 2013; Mejia et al., 2014; Coello and Boyle, 2019), a fixed threshold for the daily rain sum is defined assuming a completely cleaned collector if the threshold is exceeded. Due to the lack of detailed information on the site and time dependent particle removal mechanisms, this simplification can be used for a rough estimation of natural cleaning of collectors, but several natural cleaning events might be missed by this simplification.

In this work, soiling ratios measured with pairs of reference cells mounted at CIEMAT's Plataforma Solar de Almería (PSA) during more than 3 years (2018-2021) are analyzed. The soiling rates and natural cleaning events are compared with measured precipitation and thresholds found in literature are evaluated. Different important mechanisms influencing the natural cleaning process are discussed and further geometrical considerations are presented to enable an enhanced modelling of natural cleaning events of solar collectors.

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2. State of the Art: Threshold Approaches to model Natural Cleaning

In literature, several approaches to estimate the effect of natural cleaning by rain events have been found. Micheli and Muller (2017) and Micheli et al. (2018) investigated for example the correlation between the *SRatio* and rainy days while a rainy day has been defined with daily rain sums of more than 0.3 to 1 mm. In studies of Kimber et al. (2006), Hamond et al. (1979), Caron and Littman (2013), Mejia et al., (2014) and Coello and Boyle (2019), Micheli and Muller (2017) or Micheli et al. (2018) thresholds for the daily rain sum between 0.3 and 10 mm for a complete recovery of the efficiency of a solar collector have been assumed (see Table 1). But no clear evidence could be found that these thresholds hold to satisfactorily reproduce natural cleaning within PV soiling models (Picotti et al., 2018).

Table 1: Threshold for total recovery of reflectivity by rainfall found in literature

Reference	Precipitation threshold [mm per day]	Comment
Hamond et al., 1997	5	
Kimber et al., 2006	5-10	6 mm as default in pvlib
García et al., 2011	4-5	
Mejia et al. 2013	0.5>	No cleaning for less than 0.5mm
Caron and Littman, 2013	0.5-1	Dependent on soiling level and tilt
Micheli and Muller 2017	0.3	
Coello and Boyle, 2019	1	
Conceição et al. 2020	2.2	2.2 mm has 50% chance to reduce *SRatio*

3. Experimental Test of State-of-the-Art Models for Natural Cleaning

3.1 Measurement Setup

The here analyzed measurements of the soiling ratio (*SRatio*) have been performed at CIEMAT's PSA in Almería, Spain between December 1st 2018 and June 13th 2021. The daily *SRatio* is derived from a set of two PV reference cells (PVRC, Figure 1) of 50 x 50 mm^2 monocrystalline silicon covered with a smooth solar glass (Viel, 2017). Both cells are 45° inclined and oriented in South direction. While one cell is cleaned manually week-daily, the other cell has only been cleaned four times during the whole analyzed time period. The temperature corrected *SRatio* is determined according to the IEC 61724-1 standard ("short-circuit current reduction due to soiling", Standard IEC 61724-1:2017) through the measurement of the short-circuit current of the two PVRCs. As the power output of the PVRCs is proportional to the irradiance, the PVRCs *SRatio* is the ratio of the power output of the soiled and the cleaned PVRC. Brightening or dimming events which might have occurred during the investigated period therefore cancel out in the *SRatio* measurements. The *SRatio* is measured at CIEMAT's PSA with a 1-minute resolution.

Figure 1: Two pairs of PV reference cells (PVRC) mounted at CIEMAT's Plataforma Solar de Almería, Spain. The left pair uses textured glass, the right pair smooth glass. The upper row is cleaned and the lower row is soiled. The right pair is used in this study

To derive the daily *SRatio*, the 1-minute resolved measurements are averaged in a 1-hour window around solar noon. Dependencies of the *SRatio* measurements on the solar angle of incidence as discussed e.g. in Wolfertstetter et al. (2021) don't have to be considered in this analysis as only the change due to cleaning is investigated and not the average reduction of the energetic yield. Rain measurements at PSA have been conducted with a Vaisala's Present Weather Detector (PWD52, Vaisala, 2010). 1-minute resolved precipitation measurements are summed-up to daily sums.

3.2 Data analysis

Figure 2 shows the measured daily *SRatios* conducted with the PVRCs at CIEMAT's PSA in Almería, Spain. Further, the *SRatios* modeled with the Kimber model (Kimber et al., 2006) for two different assumed soiling loss rates (*SLR*, 0.0001/d and 0.0002/d) are displayed as an example for a state-of-the-art PV soiling model. Additionally, the daily precipitation sums and maximum daily wind speeds are displayed. The four manual cleaning events during the evaluated time period are marked as red dots. In light blue, the daily *SRatio* measurements which might have been affected by dew have been marked. It was assumed that dew might form if the dew point is surpassed by the ambient temperature by at least 3 K and this state has been present for at least 100-minute values per day.

The Kimber model has been applied using the default values of the Python code library PVlib (Holmgren et al., 2018)

- for the cleaning threshold (daily rainfall acquired to clean the panels, set here to 6 mm)
- the grace period (number of days after a rainfall event when it's assumed that the ground is damp and there is no soiling, set here to 14 days)
- the maximum soiling rate (maximum fraction of energy lost due to soiling, set here to 0.3).

The Kimber model is an empirical model in which the assumed cleaning mechanisms are limited to manual cleaning and cleaning by precipitation. It assumes a constant soiling loss rate (SLR, fraction of energy lost due to one day of soiling) which depends on the geographical region as well as the soiling environment type (Polo et al., 2021). Two different fixed SLR have been tested (0.0001/d and 0.0002/d). The default value for the SLR in PVlib is set to 0.0015, but for the usage of the model in this analysis, the SLR has been adapted. Two values for SLR have been tested to reproduce best the observed soiling events of the site. It can be seen that these fixed soiling loss rates sometimes captures the measured soiling loss well, but in many cases they over- or underestimates (especially during the winter months) the actual soiling losses.

The seasonal pattern of soiling which has been observed at several sites (Javed et al., 2021) is better reproduced by this approach during the summer months when less precipitation events occur. Further, it can be seen that the Kimber model does capture some rain induced natural cleaning events like e.g. in summer 2019 or autumn 2020, but misses several soiling rate recoveries which might be caused by light rain events or strong winds (e.g. beginning of 2019 and 2021) which removed deposited particles for the collector surface.

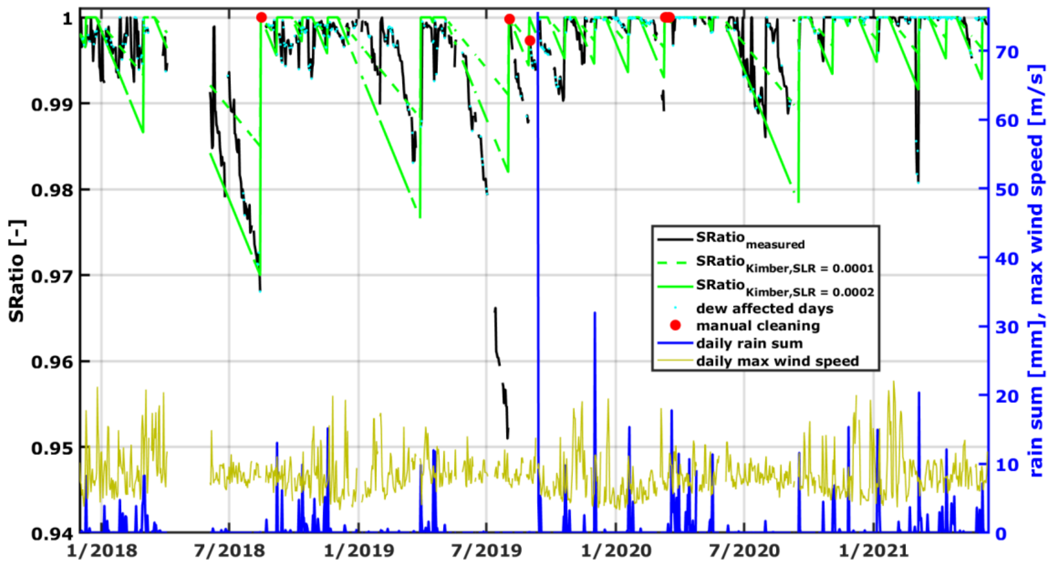

Figure 2: Measured daily *SRatios*, *SRatios* modeled with the Kimber model and two different assumed soiling loss rates, daily rain sums and maximum daily wind speeds at CIEMAT's PSA in Almería, Spain.

To analyze the effect of the natural cleaning, the new parameter "completeness of natural cleaning" is defined. It describes the effectiveness of natural cleaning in dependence of the prevailing soiling levels. It is calculated using the *SRatios* measured before and after the cleaning as:

$$completeness\ of\ natural\ cleaning = (SRatio_{after\ cl} - SRatio_{before\ cl}) / (1 - SRatio_{before\ cl}). \quad \text{(eq. 1)}$$

In other words, the completeness of natural cleaning is the decrease of the soiling loss due to the cleaning divided by the soiling loss before the cleaning. We use the soiling ratios determined the day before the cleaning event and the day after the cleaning for its calculation. Figure 3 displays the completeness of a natural cleaning event in comparison to daily rain sums measured at PSA as well as several thresholds from literature. It can be seen that no unique threshold for rain sums can be defined to describe a complete natural cleaning event. It demonstrates that the threshold-based models do not deliver an acceptable description of the natural cleaning.

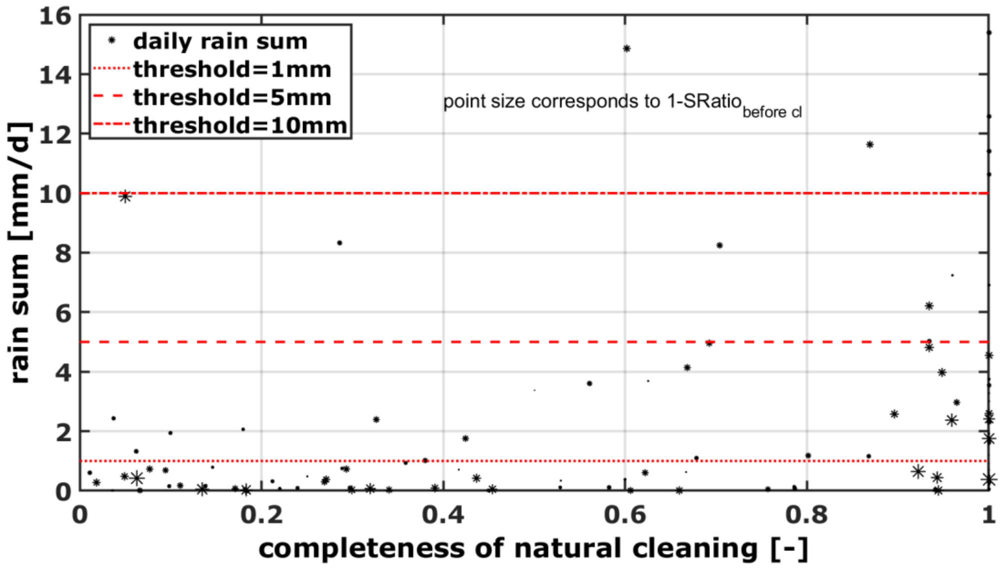

Figure 3:Completeness of natural cleaning dependent on the measured daily rain sum at PSA together with several thresholds for complete cleaning from literature. The point size is dependent on the soiling level of the day before the precipitation event (1-*$SRatio_{before\ cl}$*).

4. Discussion of Natural Cleaning Mechanisms

The strong deviation of the completeness of cleaning from the threshold assumption of most soiling models seems to be caused by a multitude of physical effects that influence the cleaning apart of the rain sum. The mechanisms for natural cleaning are rather complex and are influenced not only by meteorological parameters like precipitation, temperature, relative humidity, wind and aerosol particle concentration but also by the collector and installation specifications. Due to the complexity of the mechanisms (see also Ilse et al., 2018), simple precipitation threshold models aim to reproduce the natural cleaning behavior only considering the precipitation amount as data for this parameter is often available.

There are several reasons for the observed inaccurate modelling of the completeness of cleaning. It is influenced, for example, by the intensity of the rain, the contaminant properties, the soiling pattern or the collector surface properties. In the following, different effects concerning natural cleaning and the influence of precipitation will be discussed.

4.1 Removal by wind

The natural removal of particles from collector surfaces are mainly driven by precipitation and wind (Picotti et al., 2017). The resuspension of particles by wind is mainly dependent on wind speed and the particle diameter (Nicholson (1993), Ibrahim et al. (2003, 2004), Picotti et al., 2017). Wind can have an important cleaning contribution especially in semi-arid or arid regions where only few precipitations events occur during the course of the year and mainly dust particles contribute to soiling. Wind can cause deposited particles to roll off, slide off or lift off while it has been found that the dominant detachment mechanism for typical particle sizes of dust particles (larger 10 µm diameter) is rolling off (Roth and Anaya (1980), Ilse et al., 2018). It has been found that particles with smaller diameters are less likely to be removed by wind (Picotti et al., 2017).

4.2 Rain intensity

It can be observed that heavy rain can restore the cleanliness of solar collectors almost entirely, while light rain might even increase the soiling level of the collector. In this context, not only the daily precipitation sum influences the cleaning effect, but also the rain intensity which is the rate at which the rainfall falls and which is described with the unit mm/h. High precipitation values during a short time period have a stronger cleaning effect than the same amount of precipitation falling on the collector within larger time periods. This can be explained as it is assumed that the cleaning effect is mainly caused by running off rain drops. Is has been observed (e.g. in Blocken and Carmeliet, 2015) that rain drops typically run off after several smaller rain drops accumulated on the surface to a threshold diameter. This diameter is dependent on the tilt of the collector and the weight of the drop, the adhesion force of the collector, the drag force caused by wind and the shear force within the drop (Andre, 2019). Higher rain intensities favor the accumulation of larger rain drops on the surface and therefore also the runoff. Lower rain intensities might induce the remaining and evaporating of smaller rain drops on the surface which can increase the soiling levels of the surface.

4.3 Wet deposition and evaporation

If the force caused by the weight of the drop is exceeded by the other force components, the drop does not run off and is disposed to evaporation. If the rain drops on the collector are evaporating depends on the ambient temperature, the relative humidity, the barometric pressure, the wind speed and rain drop surface and therefore also the shape and the drop volume. While the liquid water component of the drop evaporates, the solid aerosol particles which have been dissolved within the drop remain on the surface and are disposed to mechanisms like cementation or caking. Light rain events which do not induce a drop runoff but only deposit additional particles on the collector surface, therefore further reduce the *SRatio*.

4.4 Dew and soiling pattern

It has been discussed already in several publications that dew is one main driving factor for persistent soiling of solar collectors (e.g. Figgis et al., 2018 or Ilse et al., 2019). Dew enhances **cementation, caking or capillary aging** processes of disposed particles, independent on the particle type (Ilse et al., 2018, Ilse et al., 2019). The resulting increased capillary forces acting on deposited particles therefore reduce e.g. the probability of particle removal by wind or rain. Especially in semi-arid or arid regions, where ambient temperatures drop significantly during nighttime or in coastal regions with high relative humidity, dew formation on solar collectors is an issue as the collector surfaces cool down below ambient temperature due to radiative cooling. It has been found that only one dew cycle increases strongly cementation, caking or aging processes (Ilse et al., 2018) which makes it an important parameter also in the frame of natural cleaning modeling. Further, in few cases dew can also contribute to partial removal of particles from the collector surface by the formation of dew drops running off the collector.

4.5 Particle types and size distribution

Modeling natural cleaning mechanisms, also the particle types and size distribution and therefore the induced different physical and microscopical mechanisms have to be considered. Dependent on the prevailing particle types deposited on the collector surface, the mechanisms of cementing, caking and capillary aging can be more or less progressed. Soluble particles can be taken up from the surface by the rain drops and be therefore washed off. Spherical particles might slide off easier than non-spherical particles. Smaller particles might not be lifted off by wind. Therefore, natural cleaning by impacting rain drops or wind is more or less affective dependent on the present particle types and size distributions.

4.6 Snow

In Cuddihy (1983) it has been stressed that snow can remove particles from collectors when it slides off from a tilted surface. On the contrary, when it melts on the surface, it can even increase soiling losses similar to the effect of dew described before. In the simple natural cleaning models from literature, the effect of snow on dust removal processes has not been considered so far to our knowledge.

4.7 Collector surface properties

The detachment of particles induced by precipitation is dependent on the surface properties of the collector. Particles deposited on smooth surfaces might be removed by lower precipitation amounts due to reduced adhesion forces in comparison to particles on textured surfaces. Several developments to mitigate or reduce soiling of solar collectors have been published (e.g. Guo et al, 2019). In Curtis et al (2019), the authors investigated the effectiveness of rain cleaning on anti-soiling coated collector surfaces in comparison to non-coated collectors. It has been found that the properties of anti-soiling coatings might be more favorable also in terms of collector cleaning by rain. Goossens (2019) showed in wind tunnel experiments, that anti-soiling coated surfaces are cleaned more effectively by lower wind speeds than non-coated or anti-reflective coated surfaces.

4.8 Geometrical considerations

One major influence on the effectiveness of natural cleaning by precipitation is the orientation of the collector and therefore several geometrical effects have to be considered.

One component is the actual precipitation sum which is hitting the collector. The orientation of the collector determines the amount of rain that is intercepted by the collector surface. From geometrical considerations it is clear that the effective rain amount which hits the solar collector is not only depending on the precipitation amount, but also on the wind speed and direction and the orientation of the solar collector. PV and CSP collector surfaces are usually not horizontally mounted and tracked collectors are moving throughout the day. A heavy rain event at times when the collector is facing e.g. down (stow position) or during strong side winds (respectively to the collector position) won't clean the collector the same way as if the rain drops hit the collector perpendicularly.

Additionally, the velocity with which the drops are running off the collector and also the shape of the water stream contribute to the effectiveness of cleaning. The orientation of the collector influences the runoff speed and hence the cleaning effect. Horizontally-oriented collectors have to collect more precipitation to be cleaned completely. The runoff velocity depends not only on the collector orientation, but also on the drop sizes accumulating on the surface and therefore the rain intensity, the adhesion force and the surface properties of the collector as well as the solution processes in which the drop takes up deposited particles.

Further, the force of the hitting drops which is transmitted to the surface has an impact on the removal of deposited particles. This force depends on the drop size distribution, the velocities of the falling drops and the hitting angle.

Some of those influences are discussed in the next subsections to illustrate the possibility to derive such complex parameters.

4.8.1 Effective precipitation intensity

For rain drops falling on the collector surface, the collector surface portion β_{or} (between 0 and 1) perpendicular to the wind direction can be calculated during the rain event according to Wolfertstetter et al. (2019):

$$\beta_{or} = \begin{cases} 0, & for\ \cos\Delta\theta \leq 0 \\ \cos\Delta\theta * \sin\gamma, & for\ \cos\Delta\theta > 0 \end{cases} \quad \text{(eq. 2)}$$

where γ is the collector's elevation angle and $\Delta\theta$ is the difference between the azimuth wind direction and the mirror azimuth orientation (the vertical wind component is here neglected).

The effective precipitation intensity p_r (in mm which corresponds to liter/m^2) can then be calculated with Eq. 3 dependent on the precipitation intensity p and the proportional surface ratio A/B which is hit by falling rain drops (see Figure 4). The surface ratio is dependent on the angle between the normal vector of the solar collector and the rain vector:

$$p_r = p * \beta_{or} * \frac{A}{B} = p * \beta_{or} * \cos(\alpha - (90° - \gamma)) \quad \text{(eq. 3)}$$

The collector's tilt is the difference between 90° and α is the distraction angle from a horizontal plane of the rain drop.

The angle α depends on the wind speed and direction. This correlation is also important for e.g. buildings and driving rain on facades. For example, the minimum runoff offset under windows to control the drop impact zone is defined in architecture standards (e.g. in Germany: DIN 18339 or DIN EN 1391-1) and depends on the height of the building (presumably due to assumed larger wind speeds in greater heights). Table 2 and Figure 5 display an experimental correlation between the angular direction of the rain drop and the wind speed according to Schulz (2020) which is inter- and extrapolated up to wind speeds of 25 m/s for this study. With the help of α and Eq. 3, the effective rain sum hitting the solar collector for the site of interest can be derived.

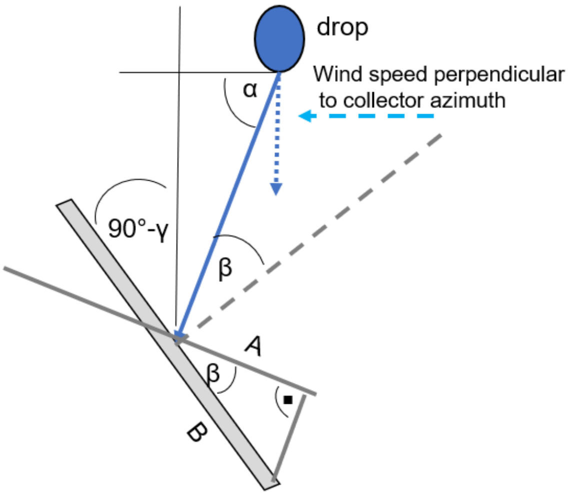

Figure 4: Sketch of rain drops falling on a solar collector.

Table 2: Angular drop falling direction distraction depended on wind speed according to Schulz (2020)

Wind speed [m/s]	Angle distraction from horizontal plane α [°]
3.4	69.30
5.5	58.57
8.0	48.37
17.2	27.62

4.8.2 Drop size distribution and mean drop falling velocity

It can be assumed that the cleaning effect of each rain drop is also dependent on the momentum of the drop transferred to the soiling particles on the collector surface among other influences. The force each drop is introducing on the collector's surface is dependent on the distinct falling velocity, the drop's weight and the angle with which the drop is falling on the surface. To estimate the falling velocity, the drop size distribution during the precipitation event has to be known. Rain drops typically have drop diameters between 0.1 and 6 mm (VDI, 2010). The rain drop size

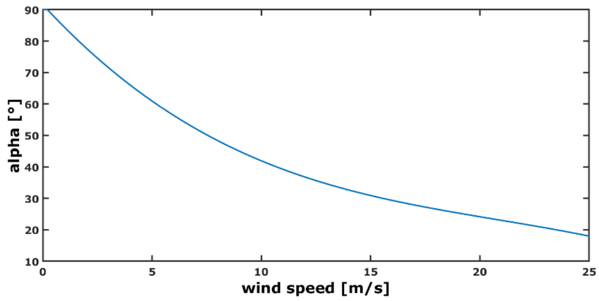

Figure 5: Inter- and extrapolated assumed distraction angle α dependent on wind speed according to Schulz (2020).

distribution *N(D)* during a rain event can be derived with the help of the Marshall-Palmer distribution (Marshall and Palmer, 1948). This distribution is dependent on the precipitation sum and the empirical derived constants N_0 which is the number density of rain drops with diameters converging to 0 (equal to 8*103 1/(m^3 mm)) and a and b (while a is equal to 4.1 and b is -0.21):

$$N(D) = N_0 \cdot e^{-D \cdot a \cdot R^b} \qquad \text{(eq. 4)}$$

R is here the rain rate in mm/h and *D* is the drop diameter.

The drop falling velocity v_{rd} (in m/s) dependent on the drop diameter D (in mm) can then be derived following the empirical approach of Atlas et al. (1973) using measurement data of Gunn and Kinzer (1949):

$$v_{rd}(D) = 9.65 - 10.3 \cdot \mathrm{e}^{-6 \cdot D} \qquad \text{(eq. 5)}$$

The according curve of the calculated rain drop falling velocity v_{rd} dependent on the drop diameter D can be seen in Figure 6.

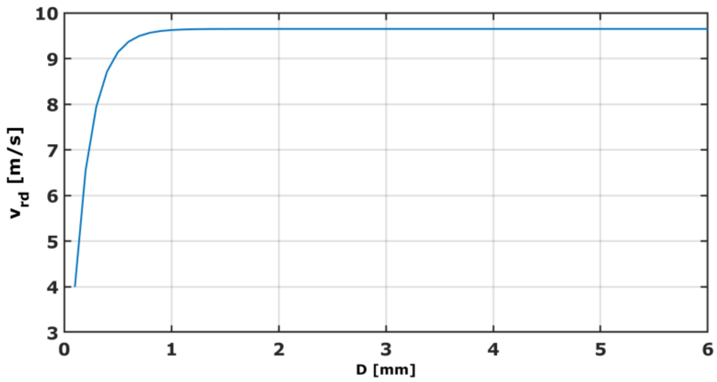

Figure 6: Rain drop falling velocity dependent on rain drop diameter according to Atlas et al. (1973).

The mean drop falling velocity $v_{rd,mean}$ (in m/s) for a precipitation event can then be calculated for the diameter size grid (i=1 to k) according to Eq. 6:

$$v_{rd,mean} = \frac{\sum_{i=1}^{k} \mathrm{N(D)}^{*}\, v_{rd}(D_i)}{\sum_{i=1}^{k} N(D_i)} \qquad \text{(eq. 6)}$$

Figure 7 shows the calculated $v_{rd,mean}$ for the measured precipitation events at CIEMAT's PSA and the assumed rain drop size range between 0.1 and 6 mm. According to literature, mean falling velocities of around 7 m/s have been observed typically for daily precipitation intensities of 2-3 mm (e.g. Marzuki et al. (2013) or Bringi et al. (2018)) which coincides well with the calculation results for CIEMAT's PSA.

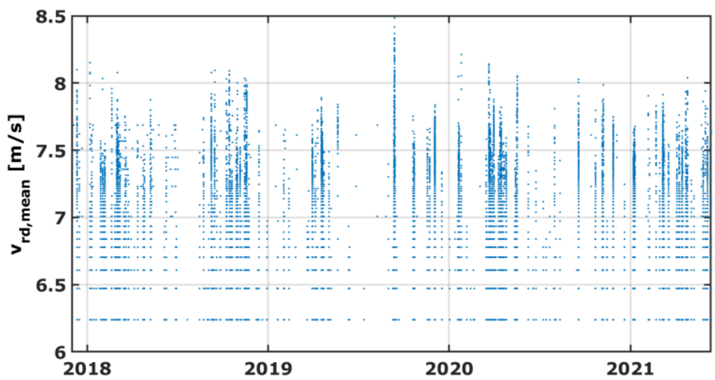

Figure 7: Calculated mean drop falling velocities for measured precipitation events at CIEMAT's PSA.

The force transferred to the collector's surface and the soiling particles located on it for every timestep can be calculated with the effective precipitation intensity p_r falling on the collector each timestep (in mm which corresponds to liter/m^2), the density of water (corresponding to 1 kg/liter), the mean drop falling velocity $v_{rd,mean}$ (in m/s) and the hitting angle of the drop. It can be assumed that drops hitting the surface in a steeper angle might remove deposited particles easier than drops hitting the surface perpendicularly as a steeper angle might increase the runoff velocity. To fully estimate particle removal by these effects, they have to be integrated in a complete natural cleaning model.

5. Conclusion and Outlook

This study investigates parameters describing the modelling of natural cleaning by precipitation in soiling models for solar collectors. It can be seen, that simplified approaches assuming that the collector is cleaned completely if certain thresholds for the daily rain sum are exceeded do not hold in many cases. The natural cleaning completeness by precipitation depends also on several other parameters like e.g. the intensity of the rain, the soiling levels, the kind of soiling, the collector surface properties, the rain impact direction dependent on the wind speed and the collector orientation. Additionally, it is assumed that the tilt of the solar collector influences the runoff velocity of rain drops and therefore also the cleaning effect. Horizontally-oriented collectors might require more precipitation to be cleaned completely. This geometrical consideration is especially important for the modelling of natural cleaning of tracked collectors as the effective rain sum hitting the collector might change drastically with the orientation of the collector.

In this paper, a detailed discussion of the effect of these parameters and some suggestions to improve the modelling of natural cleaning by rain have been presented. Further insights on the influence of the particle and soiling type on the natural cleaning phenomenon will be investigated with the help of digital cameras. Future work will be the implementation of a complete natural cleaning model which aims to estimate all described removal processes and which can be combined with a soiling model considering dynamic soiling rates.

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