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Numerical modeling of flow structures over various flat-topped stockpiles height: Implications on dust emissions

C. Turpin [a,b,*], J.-L. Harion [a,b]

[a] Univ Lille Nord de France, F-59000 Lille, France
[b] EMDouai, EI, F-59500 Douai, France

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ABSTRACT

Fugitive dust emissions from open stock yards for bulk materials, such as coal or ores, can represent a significant part of overall estimated atmospheric emission on industrial site, as example on steel plant sites. Stockpile topography is known to modify the near field uptake force of the wind through changes of the mean flow. Various studies have shown that aeolian erosion strongly occurs on the stockpile crest, so it appears relevant to carry out a study to analyze the effect on the dust emissions of the stockpile clipping. Three-dimensional numerical simulations were done with the aim of simulating wind flow over different flat-topped pile scenarios, corresponding to a constant material volume. Various wind flow directions were tested to determine its impact on particle emissions. Data obtained from Computational Fluid Dynamics simulations were then integrated in order to estimate the effect of the clipping on the stockpiles dust emission rates by using the EPA's emission factors method. Results provide evidence to suggest that clipping stockpiles does not reduce dust emissions. This study provides to industrial operators some informations on the best geometrical pile characteristics in order to limit particles emissions.

1. Introduction

First investigations about aeolian erosion started with Bagnold (1941) work which was largely concentrated on the physics associated with the movement of individual sand grains in the wind. Succeeding studies have largely discussed the surrounding wind flow implications on the aeolian particles transport in case of dunes erosion (Lancaster et al., 1996; McKenna Neuman et al., 1997; Wiggs et al., 1996; Parson et al., 2004). These researches have greatly improved the understanding of the relation between dune form and flow interactions (stoss flow acceleration, crestal separation, lee recirculation, reattachment) and have foregrounded that sediment transport phenomenas depend strongly on dune morphology and on secondary flow structures. Investigations assessing the transport of granular materials on sloped surfaces represent a relevant subject for various applications such as prevention of desert expansion, farmland erosion, bedforms in fluvial environments, quantification of dust emissions. The present study, within this latter framework, aims to improve the understanding of fugitive emissions from granular material stockpiles on industrial sites. The methodology mostly used by the industrial operators to quantify dust emission from their plants is based on the emission factor formulations proposed by the US EPA (United State Environmental Protection Agency) (EPA, 1988). These formulations allow to estimate the stockpile erosion potential considering the results of the velocity distribution over the stockpiles obtained from wind tunnel experimentation. Recent studies about industrial fugitive dust emissions on sites introduced new approach to map the degree of wind exposure over a stockpile using data from CFD simulations and suggested solutions to reduce emissions from stockpiles (Badr and Harion, 2007; Torano et al., 2006). Badr carried out three-dimensional numerical simulations, previously validated against wind tunnel measurements (Stunder and Arya, 1988; Badr and Harion, 2005), to simulate flow structure over different stockpile configurations. This work allowed to found the most favorable flat-topped pile configuration to limit aeolian erosion for the range of pile forms and wind conditions tested. The study presented in this paper aims to evaluate the influence of the flattening of the stockpile crests on dust emissions. Since it is well known that acting on the pile morphology induce a variation of the emission rate, and that stockpile crest is the area having the higher erosion potential, it appears relevant that flat-topped stockpile configurations could lead to a significant change of dust emission rate compared to crested ones. On industrial site, granular materials are delivered on the stock yards at fixed tonnage or volume, corresponding to the capacity of

* Corresponding author. Univ Lille Nord de France, F-59000 Lille, France. Tel.: +33 (3) 27 71 23 86; fax: +33 (3) 27 71 29 15.
E-mail address: cturpin@ensm-douai.fr (C. Turpin).

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a ship or a train. In order to suggest, to industrial operators, the best arrangement of the material during the storage to limit wind erosion (Badr and Harion, 2007), it seems more relevant to consider a quantity or a volume of this material. It is commonly known that slip faces of stockpiles stand at a certain angle of repose, which is constant for a single dry material (Allen, 1970; Carrigy, 1970). Based on this approach, this paper presents results of numerical simulations over flat-topped stockpiles with varying clipping heights for a constant volume of granular material and a fixed angle of repose. The wind properties near the piles surface were analyzed in order to understand the dust emission mechanisms over the various stockpile configurations. Emission factor formulations, proposed by the US EPA to quantify fugitive dust emissions from a stockpile, were used to check the particles emissions rate for each considered configuration. This allowed to assess the effect of pile configurations and wind conditions variations on dust emissions.

2. EPA emission factor

An emission factor is a representative value that attempts to relate the average emission rate of a given pollutant for a given source, relative to the intensity of a specific activity. US EPA proposes a methodology, based on the determination of an emission factor, to quantify fugitive dust emissions from granular materials subject to disturbances. The EPA emission factor EF for wind-generated particulate emissions is expressed in units of grams per year as follows (EPA, 1988):

$$\mathrm{EF} = k\sum_{i=1}^{N} P_i S_i \tag{1}$$

where k is a particle size multiplier, N is the number of disturbances per year, P_i is the erosion potential corresponding to the observed (or probable) fastest mile of wind for the ith period between disturbances in gm^{-2} and S_i the pile surface area in m^2.

The erosion potential function for a dry exposed surface is:

$$P = 58\left(u^* - u_t^*\right)^2 + 25\left(u^* - u_t^*\right) \quad \text{for } u^* > u_t^* \tag{2}$$

$$P = 0 \quad \text{for } u^* \le u_t^*$$

where u^*, the wind friction velocity, is given by:

$$u^* = 0.1 u_{10}^{+}(u_s/u_r) \tag{3}$$

u_t^* is the threshold friction velocity (ms^{-1}), u_{10}^{+} is the fastest mile value collected on an anemometer reference height of 10 m, u_s is the wind speed measured at 25 cm from the pile's surface and u_r is the wind speed reference measured at a height of 10 m.

The use of the ratio u_s/u_r in this formulation allows to take into account the influence of the pile geometry and the wind direction on the velocity distribution over the piles. In fact, the wind erosion process depends strongly on the local wind flow characteristics. It is considerably affected by flow field changes that are caused by changes in the geometry of the field. To represent the different degrees of wind exposure over the pile, the pile area is divided into subareas of constant u^* or u_s/u_r intervals considered as separate sources. For large disturbances of wind, such as example on large storage piles, the emission factor is estimated by the sum of local erosion potentials corresponding to a same value of u_s. The emission factor in then given by:

$$\mathrm{EF} = k\sum_{i=1}^{N}\sum_{j=1}^{M}\left(P_j S_j\right)_i \tag{4}$$

where M is the number of area parts, S_j is the corresponding surface area.

EPA report provides subareas distributions of normalized velocity values for a flow over two representative pile shapes and for three incident flow angles. These data were derived from wind tunnel studies. However, the stockpiles investigated do not cover the wide variety of pile forms and dimensions that can be found on industrial sites. This is also true for wind conditions. In this context, a new approach which consists of retrieving normalized velocity values from numerical simulations was developed by several authors (Badr and Harion, 2005, 2007; Torano et al., 2006). The agreement between modeled and measured values of u_s/u_r over the piles was generally good, the correlation coefficients averaged $r = 0.9$ (Badr and Harion, 2005). The advantage of using numerical method to determine the ratio u_s/u_r, in comparison with the experimental method, is the possibility to test various pile configurations more quickly and with less technical equipment. Moreover, this technique provides more detailed data because of the fine spatial resolution necessary to carry out the numerical simulations.

3. Numerical simulations

3.1. Geometry, mesh and turbulence model definitions

The commercial Computational Fluid Dynamics (CFD) software FLUENT (FLUENT, 2006) was employed to simulate the wind flow over various pile configurations. FLUENT uses a finite volume method to solve the three-dimensional Reynolds averaged Navier–Stokes equations.

In a previous study, Badr and Harion (2007) have carried out similar numerical simulations applied to wind tunnel experimental configurations that are used as references for the different u_s/u_r distributions proposed by the EPA. Two shapes of piles were studied, one conical and the second one oblong with flattop with a 37° side slope angle. An irregular grid which followed the shape and orientation of the geometries was applied. A particular attention was given to the wall regions. A study of sensitivity to the mesh was performed to ensure that numerical results are independent of the grid (Badr, 2007). Profiles of velocity u, turbulent kinetic energy k and specific dissipation rate ω were used to define the entry of calculation domain. u and k profiles come from the experimental study (Stunder and Arya, 1988). The specific dissipation rate ω profile was calculated from the k experimental values using a relation proposed by FLUENT (FLUENT, 2006) which reads,

$$\omega = \frac{k^{1/2}}{C_\mu^{1/4} l}$$

C_μ is an empirical constant specified in the turbulence model (0.09) and l is the turbulence length scale ($l = 0.07h$, h is the pile height). Outflow conditions were those corresponding to well developed flow, i.e. zero normal gradient for all flow variables except pressure. Symmetry boundary conditions were used for the lateral sides and the upper limits of the domain. The lower boundary surface as well as the pile was considered as rough walls. In accordance with the experimental study, the roughness length on the pile surface was fixed to $z_0 = 0.012$ mm, and on the wall $z_0 = 0.4$ mm. Turbulence closure was achieved through application of the two-equation k–ω SST model developed by Menter (1994). This choice is based on a comparative study between experimental and numerical results for different closure models. Second order discretization scheme was used for the numerical solution (pressure terms and all other variables) to increase the accuracy and reduce numerical diffusion. The SimpleC algorithm was used for pressure–velocity coupling.

To ensure the validity of the simulations, numerical results were compared to experimental results (Stunder and Arya, 1988). Full verification and validation of numerical simulations to the