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NUMERICAL MODELLING OF FLOW STRUCTURES OVER AN INDUSTRIAL SITE: EFFECT OF THE SURROUNDING BUILDINGS ON DUST EMISSIONS

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ABSTRACT

In this paper, three-dimensional numerical simulations are used to simulate the wind flow structure over coal stockpiles of a real configuration of a power plant. Two configurations are tested for various wind directions: the first one without representing the buildings and the second one with the surrounding buildings in the calculation domain. The wind flow properties over the full site and near the stockpile surfaces are analyzed in order to understand the dust emission mechanisms over the various tested configurations. The emission factor formulation, proposed by the EPA to quantify fugitive dust emissions from a stockpile, is used to check the particle emission rate for each considered configuration using the velocity fields given by the simulations.

The analysis of the results from the two tested configurations shows by evidence that the topography of the industrial site exerts large perturbations on the flow structure over the site. This work shows that previous studies carried out without taking into consideration the topography of the site probably lead to an inaccurate estimation of the fugitive dust emissions. This study highlights the necessity to take into account the presence of surrounding buildings to estimate and quantify the particle emission rate on stockpiles.

The study reported in this paper improves the understanding of fugitive dust emissions on industrial sites and in mining zones. These results will allow a more accurate and relevant evaluation of fugitive dust emissions from open storage systems on industrial sites and a better evaluation of its environmental impacts.

KEYWORDS: Computational Fluid Dynamics (CFD), Emission factors, Wind erosion, Buildings, Industrial site.

1. INTRODUCTION

On industrial sites, fugitive dust emissions from open storage systems for bulk materials, such as coals or irons, represent a significant part of overall estimated particle emissions and can lead to environmental and health risks. The aeolian erosion process, generating atmospheric pollution, depends strongly on the turbulent flow structure over the stockpiles and is conditioned by the topography of the site, the wind direction and the shape of the stockpiles.
The quantification of the emissions is usually obtained from standardized emission factor formulations for wind erosion such as those proposed in the US EPA's AP 42 report for air pollution control (EPA, 1988). These formulations allow to estimate the stockpile erosion potential by the consideration of the wind velocity distribution over the stockpile.

Till now, an extensive amount of experimental and numerical studies have been carried out to cartography the wind exposure over a wide variety of pile geometries and dimensions that can be found on industrial sites (Stunder and Arya, 1988; Torano *et al*., 2006; Badr and Harion, 2007). But, in these previous studies, the wind flow structure over stockpiles was only analyzed for isolated pile configurations without considering their environment. However, structures created by the neighbouring buildings or stockpiles can interfere with the stockpiles under consideration, and lead to a strong re-organisation of the flow pattern. Thus, it appears relevant that the real exposure of the granular material pile can be accurately known only if the surrounding buildings are taken into consideration. In the present study, the effect of the buildings on dust emissions is analyzed by comparing the wind velocities over isolated stockpiles with those over a fully industrial site.

2. METHODOLOGY

2.1. EPA Emission factor

An emission factor *EF* is a representative value that links the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. The EPA emission factor *EF* (g yr^{-1}) for wind-generated particle emissions from granular materials subject to disturbance is expressed as follows (EPA, 1988):

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

where *k* is a particle size multiplier, *N* the number of disturbances per year, P_i an erosion potential corresponding to the observed (or probable) maximum wind speed for the i^{th} period between disturbances (g m^{-2}) and S_i the pile surface area (m^2).

The erosion potential function for a dry exposed surface is:

$$P = 58(u^* - u_t^*)^2 + 25(u^* - u_t^*) \qquad for \qquad u^* > u_t^*$$

$$P = 0 \qquad for \qquad u^* \le u_t^*$$

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

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

u_t^* is the threshold friction velocity (m s^{-1}), this parameter allows to take into account the characteristics of the piled material such as density, granulation of particles and moisture.

u_{10}^+ is the maximum wind speed measured by an anemometer reference height of 10 m (m s^{-1}). u_s is the wind speed measured at 25 cm from the pile's surface and u_r 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. To represent the different degrees of wind exposure over the pile, its area is divided into subareas of constant u^* or u_s/u_r intervals considered as separate sources. For wind variations 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:

$$EF = k\sum_{i=1}^{N}\sum_{j=1}^{M}(P_j S_j)_i$$

where *M* is the number of subareas, S_j is the surface of each subarea (m²).

The EPA emission factor considers only the take off of the particles and not the secondary production of particles by the mechanism of saltation and bombardment.

2.2. Numerical simulations descriptions

Knowledge of the turbulent flow characteristics over stockpiles is required to assess the erosion potential over stockpiles. In this study, the FLUENT (FLUENT, 2006) code is employed for the numerical simulations of the wind flow over the industrial site. The characteristics of the numerical simulations are similar to those used by Badr and Harion

(2007) to simulate the wind flow over different isolated piles, with different heights. Full verification and evaluation of these numerical simulations to experimental results obtained by Stunder and Arya (1988) is demonstrated and discussed by Badr and Harion (2005).

The calculation domain is materialized by a box of variable dimensions (function of the geometric characteristics of the industrial site and the wind angle incidence). Profiles of velocity, turbulent kinetic energy and specific dissipation rate, which are specific of an atmospheric boundary layer, are used to define the calculation domain entry. Symmetric boundary conditions are used for the lateral sides and the upper limit of the domain. The lower boundary is considered as a wall. An irregular mesh is applied to follow the site topography. Turbulence closure model is achieved through application of the two-equation *k-ω SST* model developed by Menter (1994).

2.3. Tested configurations

The previously validated three-dimensional numerical simulations are used to simulate the wind flow structure over coal stockpiles of a power plant in real conditions for various wind flow directions: θ=270°, 315°, 45° and 90° (see Figure 1). In order to evaluate the effect of the site topography on dust emissions from stockpiles, two simulations are performed for each wind flow direction (see Table 1). In a first step, the calculation domain represents only the stockpiles submitted to aeolian erosion. Then the real topography of the site, including different buildings, is integrated. Domain dimensions are keeping constant between the two tests.

The whole simulations are carried out for only one wind speed, u_r=5 m s^{-1}, because the normalized wind speed u_s/u_r is independent of the wind speed flow [4]. This is also a hypothesis on which the method proposed by the EPA is based. For each configuration, data of normalized velocity values for u_s/u_r range and their corresponding areas are computed at 25 cm from the pile surfaces. Results are then integrated in the EPA emission factor formulations to determine the dust emission rates. The erosion potential for each configuration is estimated for three wind speeds by varying u_{10}^+ in the formulation of u^*. The erosion conditions are reached when $u^*>u_t^*$, what corresponds to u_s/u_r>0.7 for u_{10}^+=5 m s^{-1}, u_s/u_r >0.3 for u_{10}^+=10 m s^{-1} and u_s/u_r>0.2 for u_{10}^+=15 m s^{-1}. The same coal material is taken as reference for the simulations, its threshold friction velocity, measured from a wind tunnel experiment, is u_t^*=0.35 m s^{-1}. It is assumed that there is only one pile disturbance per year (N=1).

Figure 1. Top view of the industrial site

Table 1. Test names for the wind flow simulations over the industrial site

Angle θ (°)	Complete site (real conditions)	Site with only the stockpiles (surroundings excluded)
270	Test 1A	Test 1B
315	Test 2A	Test 2B
45	Test 3A	Test 3B
90	Test 4A	Test 4B

3. RESULTS AND DISCUSSION

Figure 2 shows the contours of the normalized velocity u_s/u_r over the stockpiles for the tests 1A, 2A, 3A and 4A obtained by the three dimensional numerical simulations previously validated. In a general manner, this figure shows that buildings behave as huge obstacles for the wind flow and perturb largely the dynamic flow structure over stockpiles. The turbulent flow around isolated obstacles has been extensively studied notably by Martinuzzi and Tropea (1993). From their experimental investigations, they described in detail the flow past a cubical obstacle set in a developed channel flow. When approaching the cube, the flow decelerates and separates on the upstream corners of the obstacle creating separation vortexes. The main vortex wraps as a horseshoe vortex around the cube. A broad recirculation zone develops downstream of the obstacle. In presence of several obstacles, wakes of the upstream obstacles interfere with the downstream ones. When the obstacles are adjacent, the wakes interfere and tend to become similar to the wake of a single body.
The numerical simulations carried out in this study allow to analyse the effect of the surrounding buildings on the wind speed around the stockpiles. In the tests 1A and 2A, where the wind first comes across the stockpiles, the buildings do not significantly disturb the flow structure over the stockpiles. However, the low velocity region generated by the flow deceleration upstream the buildings (black circle in Figure 2) interacts with the stockpiles and protects the stockpiles from the wind erosion.

When the flow circulates first of all around the buildings before reaches the stockpiles, the flow structure over the stockpiles is strongly modified.

In the test 3A, only the buildings adjacent to the stockpiles modify the flow structure over the stockpiles (Figure 2). The stockpile 1 is protected by the drag zone generated downstream the buildings while the stockpile 2 is subjected to the flow acceleration from the lateral sides of the buildings.

In the test 4A, the wind flow first comes across the higher buildings which are adjacent. Figure 2 shows that the flow behaves like if this group of buildings formed only one large obstacle (right side of the picture). Indeed, the flow accelerates from the lateral sides of this large obstacle and creates downstream a large wake zone. These results are consistent with those obtained in the literature for adjacent obstacles (Martinuzzi and Tropea, 1993). Zones of low velocity inside the wake region and of high velocity on both sides of the wake region extend downstream. Over the stockpiles 1 and 2 the wind speed is very high because these stockpiles are located downstream the vortexes generated by the buildings. The stockpile 3 is, as for it, located in the wake of the buildings, so it is protected from the wind erosion.

Table 2 sums up the differences between the results of the global erosion potential of the three stockpiles obtained by the simulations of the flow over the industrial site in real condition (configuration A) and excluding the buildings (configuration B) for different wind speeds u_{10}^+.

The results presented in this table show that the differences observed between the erosion potential calculated for the configuration A and B are lesser for higher wind speed. Indeed, for high wind velocities, even considering the stockpiles as isolated, almost the entire stockpile surface is submitted to the wind erosion. Therefore the flow disorganization generated by the buildings does not increase or decrease significantly the erosion potential of the stockpiles. This explains why the differences between the erosion potential calculated for the configurations A and B tend to decrease for the highest wind speed.

For the tests 1A-1B and 2A-2B, whatever the wind speed, the analysis of the results obtained by the numerical simulations shows that the presence of the buildings downstream the stockpiles leads to a decrease of the erosion potential.

For the tests 3A-3B and 4A-4B, the disorganization of the flow structure over the stockpiles, implying by the presence of the buildings, leads to an increase of the aeolian erosion. On average for the test 4A, the erosion potential of the three stockpiles, calculated by the EPA method, dramatically increases by taking into account the presence of the buildings, until 90.8% for u_{10}^+=5 m s^{-1}. In this configuration, the wind which comes first across the buildings largely perturbs the dynamic structure loading on the stockpiles. The consideration of the topography in this critical test is therefore crucial to accurately assess the dust emission rates on industrial sites.

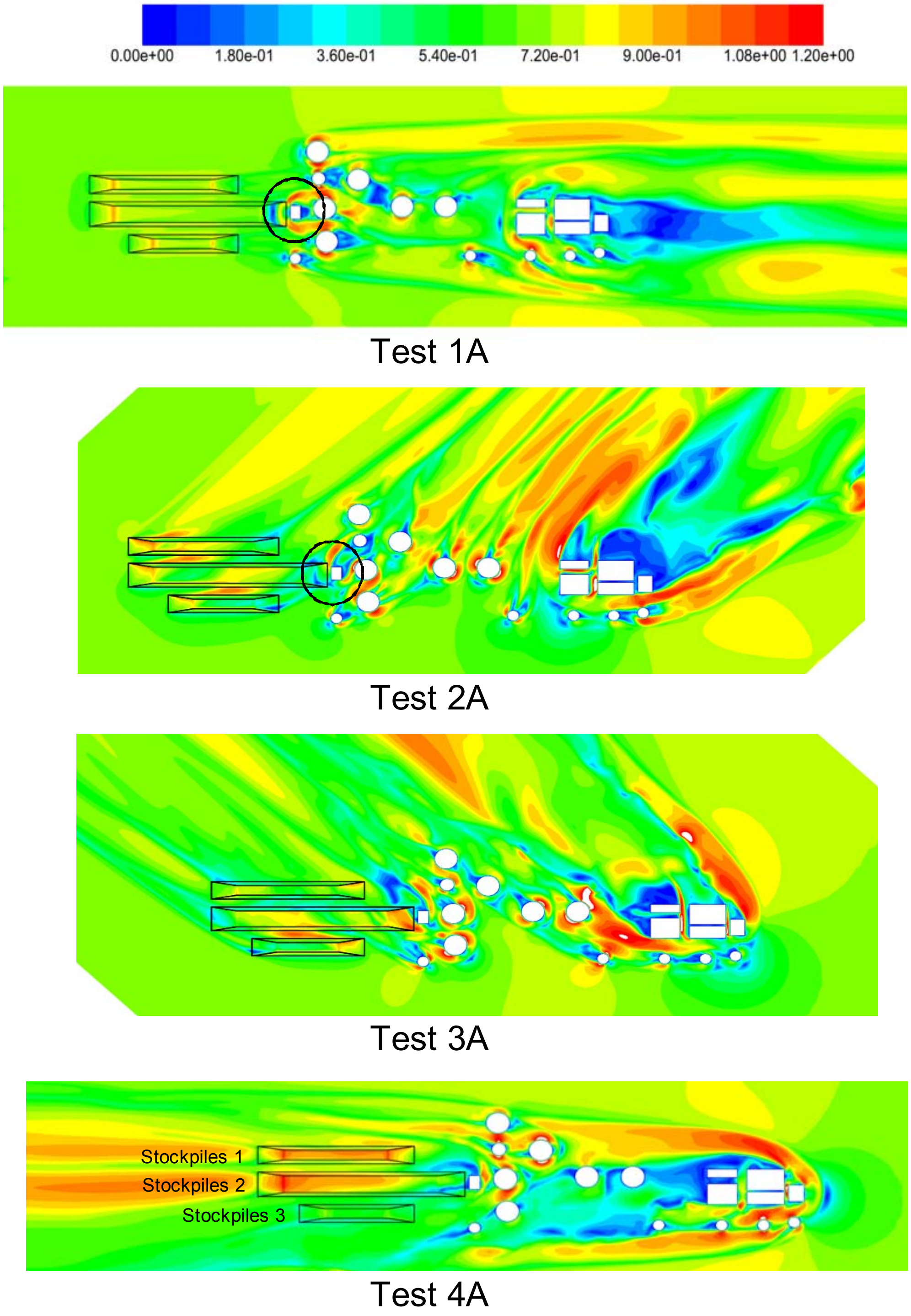

Figure 2. Top view of the normalized velocity contours u_s/u_r at 25 cm from the pile surface for the tests 1A, 2A, 3A and 4A

Table 2. Differences observed between the erosion potential calculated for a full site configuration (configuration A) and for isolated stockpiles (configuration B)

	Test 1 θ=270°	Test 2 θ=315°	Test 3 θ=45°	Test 4 θ=90°
u_{10}^{+}=5 m s^{-1}	-14.3 %	- 2.5 %	+ 21 %	+ 90.8 %
u_{10}^{+}=10 m s^{-1}	- 9.4 %	- 4 %	+ 2 %	+ 10.8 %
u_{10}^{+}=15 m s^{-1}	- 8%	- 3.6 %	+ 0.8 %	+ 8 %

For this real configuration of a power plant, when the flow comes first on the buildings adjacent to the stockpiles the erosion processes are stronger mainly because of the flow acceleration from the lateral sides of the buildings. However, if the wind comes from the storage area to the buildings, erosion process is slightly attenuated by the flow stagnation upstream the buildings. Furthermore, the results presented in Table 2 show that when the wind speed increases, the erosion phenomena are less sensitive to the flow perturbations generated by the neighbouring buildings.

It must be noticed that these results are only available for this real configuration of power plant. Due to the different arrangement, shape, size of the buildings and of the stockpiles on other industrial sites, each stockpile has its own particular cartography representing its wind exposure.

4. CONCLUSIONS

In this paper are presented the numerical modelling results of flow structure over coal stockpiles of a real power plant configuration. The emission factor formulation, proposed by the EPA to quantify fugitive dust emissions from a stockpile, is used to check the particle emission rates for each considered configuration using the velocity fields from simulations.

The sensitivity analysis of the wind flow on surrounding buildings shows by evidence that large buildings on industrial site, and more generally the site topography exert large perturbations on the flow structure over the stockpiles. The arrangement of the buildings around the stockpiles and the wind flow direction affect the wind exposure of the stockpiles and therefore their erosion potentials. Moreover, the numerical simulations show critical wind flow directions and wind speeds for which the intensity of the erosion processes can be strongly increased.

The results of these simulations emphasize the necessity to take into consideration the topography of an industrial site, at least the main buildings and all the significant stockpiles, to enhance the accuracy of the dust emission estimation.

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