EFFECTIVENESS OF USING SCREENS TO REDUCE PM10 EMISSIONS IN PORT AREAS

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ABSTRACT

Maritime solid bulk cargo handling can lead to increased diffuse emissions of particulate matter (PM10) in ports and surrounding areas if appropriate preventive and corrective measures are not taken. Given the difficulty of completely confining some of the operations, one of the proposed measures to mitigate such emissions is to install perimeter fencing or screens at solid bulk terminals. In this regard and as part of its commitment to the environmentally sustainable growth of PortCastelló, the Castellón Port Authority has fitted three screens on the Outer Transverse pier and the Ceramics pier in the Northern dock, and a fourth screen in the Southern dock, to reduce impact on air quality.

This corrective measure is included in the "Guidelines of good practices in the handling and storage of solid bulk in port areas", which recommend the installation of porous screens to minimise PM emissions from wind draughting over stockpiles or over spots where the solid bulk is handled. These guidelines classify screens into two types, depending on the intended purpose: wind screens, to reduce wind erosion on the goods (upwind screens); and dust-trap screens, to capture airborne dust (downwind screens).

Although the use of screens in port areas is spreading, available data on the influence played by the different variables (weather, materials, screens, etc.) on their effectiveness is fundamentally of a qualitative type. In this sense, the study outlined in this paper is considered of great interest, given that it describes a quantitative assessment made of the effectiveness of dust-trap screens installed in PortCastelló in capturing PM10.

For this purpose, a 2D fluid dynamics model was designed to determine the range of wind speeds altered by the dust-trap screen. The model predicts how diffuse emissions of PM 10 evolve, thus providing quantitative assessment of the efficiency of perimeter screens. The modelling consists of solving Navier-Stokes equations applied to the fluid and the advection-diffusion equation in a turbulence regime applied to PM10 emission. All simulations were carried out in 2D and, in all cases, the corresponding wind component was taken to be in the direction of the screen.

The input physical parameters for this new model, which were determined experimentally, were as follows:

- Wind speed, which was calculated for different weather scenarios using a 3D sonic anemometer and applying the theory of the atmospheric boundary layer.
- Screen effect, for which a PM10 deposition rate was calculated with a membrane system facing the four cardinal points (N, S, E, and W), which in turn made collecting samples of deposited particles easier.

The model developed and the experiments carried out have enabled objective assessment of the effect of dust-trap screens. The study of emissions in different scenarios shows that screen effectiveness in capturing PM10 is significant when emission occurred at most at a distance of 50m from the screen and close to the ground (<3m high). Furthermore, both studies indicate that screens had a remarkable effect even at long distances (>200m), especially on PM10 concentration.

1. INTRODUCTION

In the Spanish Port Network's Sustainability Reports published by the Spanish State Ports and Port Authorities [1], outdoor handling and storage of solid bulk goods is identified as a major cause of atmospheric emissions of particles in port areas. The importance of these emissions has risen in recent years due to the significant increase in solid bulk traffic through Spanish ports, which reached the figure of 102 million tonnes in 2018, accounting for 19% of all goods handled [2].

In the specific case of PortCastelló, solid bulk handling grew by 15% in 2018, which made it the port with the highest increase tonnage-wise of solid bulk handling in Spain and number four in terms of volumes of this type of freight, with 7,425,415 tonnes of solid bulk handled [3].

To cope with this growing business, while also meeting increasingly demanding environmental requirements, the Spanish port network needs to encourage environmental initiatives that minimise the impact of operations associated with the handling of solid bulk in ports. In addition, improving the environmental sustainability of ports also makes for enhanced competitiveness, business generation, and public image, from which the main returns include improvements in institutional reputation and Port–City integration, business opportunities, operational safety and reliability, and lower operating costs [4].

The main environmental impacts associated with solid bulk handling are diffuse particle emissions and spillage onto the quay and into dock waters. These impacts occur during tasks related with quayside solid bulk handling operations: loading and unloading of ships, horizontal transport and storage. Ship loading/unloading is usually performed by mobile grab cranes, belt conveyors, pneumatic systems, etc. Transport by trucks and shovels is discontinuous but can flow continuously when conveyors are used. Finally, storage may be in outdoor, semi-covered or indoor bulk yards, vertical silos, domes, etc.

To prevent and control these emissions, one of the recommendations contained in the "Guidelines of good practices in the handling and storage of solid bulk in port areas" [4] consists of installing mobile porous screens near work areas in order to reduce particle emissions. The operating principle behind such screens varies according to their position: wind screens upwind of the stockpiles reduce wind erosion on stockpiles of bulk goods by reducing the speed at which the wind hits the material; dust screens downwind of the stockpiles trap dust that is already airborne due to various mechanisms, of which diffusion, interception and impact are the most prominent [5].

Figure 1 illustrates the two porous screen operating modes.

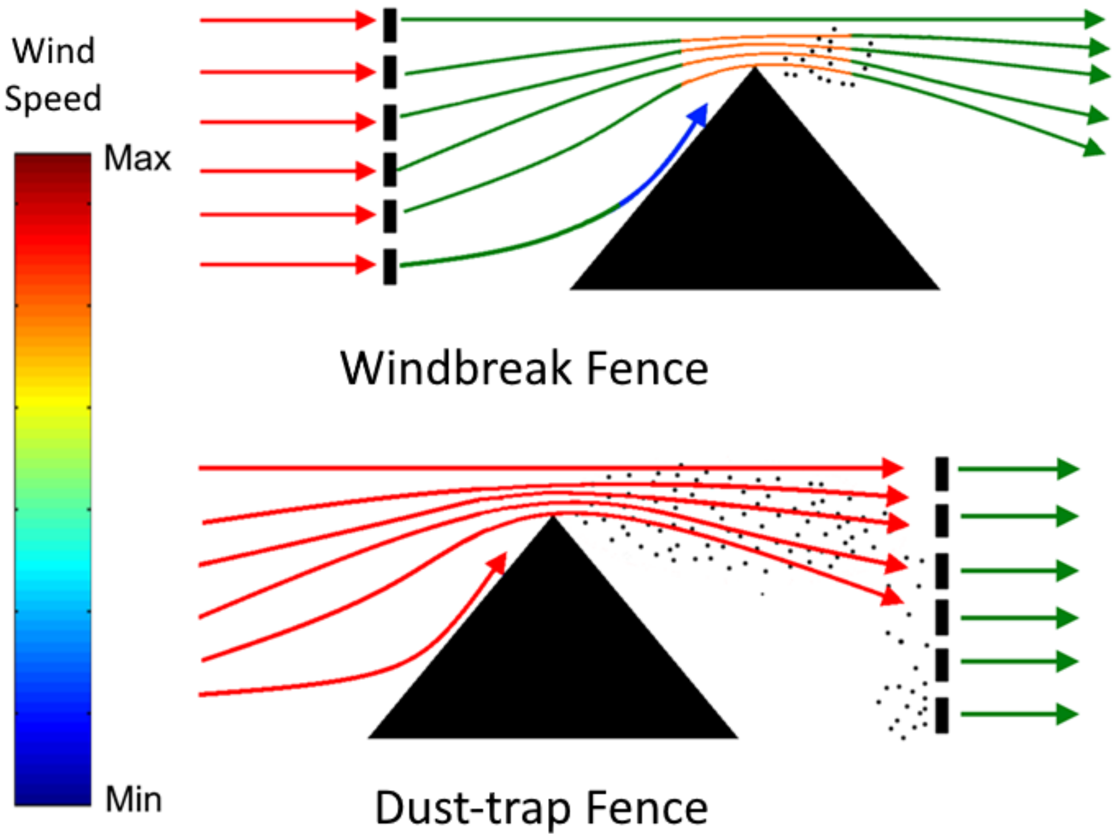


Figure 1. *Effect of a porous screen on a stockpile of bulk material.*
Top: Windbreak screen. Bottom: Dust-trap screen.

Following the recommendations in the guidelines and the Port Authority's commitment to furthering environmentally sustainable growth in PortCastelló, the Castellón Port Authority has fitted three dust-trap screens on the Outer Transverse pier and Ceramics pier in its Northern dock and a fourth screen in its Southern dock, thus improving air quality in the port and nearby urban areas. In addition, it has made significant improvements in environmental protection, such as expanding enclosed and semi-enclosed storage areas and installing wheel-wash stations in the Northern Dock, etc.

However, although the port community generally acknowledges the positive impact of installing porous perimeter screens, no studies are available that assess or quantify their operating efficiency, though some advances have been made at lab scale [6]. This may be due to the fact that they were only recently installed, to the difficulty of carrying out repetitive series of experiments, or to a lack of earlier studies in the sector. Nevertheless, it should be noted that other similar studies are currently attempting to quantify the effect of plant screens in cities and farming areas to reduce air pollution and mitigate particulate emissions [7]-[10].

This study arises from an interest in providing quantitative assessment of the real effect of porous dust-trap screens on mitigating and preventing PM10 emissions during port operations and is based on developing and applying a fluid dynamics 2D model. The model is fed with input parameters obtained experimentally at the Transverse pier in the port of Castellón and is able to estimate and quantify the effectiveness of the screens in mitigating PM10 emissions in various scenarios.

The paper's layout is as follows: section 2 briefly describes the proposed mathematical model. The experiment procedure carried out during port operations is then presented (section 3). Finally, the model is used to assess screen effectiveness in different scenarios (section 4), followed by a summary of the operating approaches and conclusions (section 5).

2. BRIEF DESCRIPTION OF THE FLUID DYNAMICS MODEL

The proposed 2D fluid dynamics model, first, required establishing the wind fields that formed around the screen, largely due to the screen's fluid dynamics characteristics and prevailing weather conditions (Figure 2).

For a stationary scenario with an incompressible Newtonian fluid (air at ambient temperature may be assumed a fluid with such characteristics), the Reynolds-averaged Navier–Stokes (RANS) equations can be written in Einstein notation as follows:

$$\bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + v \frac{\partial^2 \bar{u}_i}{\partial x_j x_j} - \frac{\partial \tau_{ij}}{\partial x_j} \quad (1)$$

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \quad (2)$$

where $\bar{u}_i$ is the average velocity of the fluid, $\bar{p}$ is the average pressure (divided by the density of the fluid), v is the kinematic molecular viscosity of the fluid, and τ_{ij} is the convective term of the equation or Reynolds stress tensor (divided by the density of the fluid). Likewise, t is time and xi is each of the Cartesian coordinates. These equations enable turbulent flows to be modelled, although they call for the use of a turbulence model, which acts as closure to the RANS equations. The closure is necessary in order to obtain a formula that defines the Reynolds stress tensor.

Therefore, in this study, the wind was modelled by solving the RANS equations and by a turbulence model k-ε, in which the initial wind profile and turbulence estimates were based on the Monin-Obukhov theory. Simulations were performed using the OpenFOAM® framework and a C++ library to develop continuous mechanics problems, including Computational Fluid Dynamics (CFD).

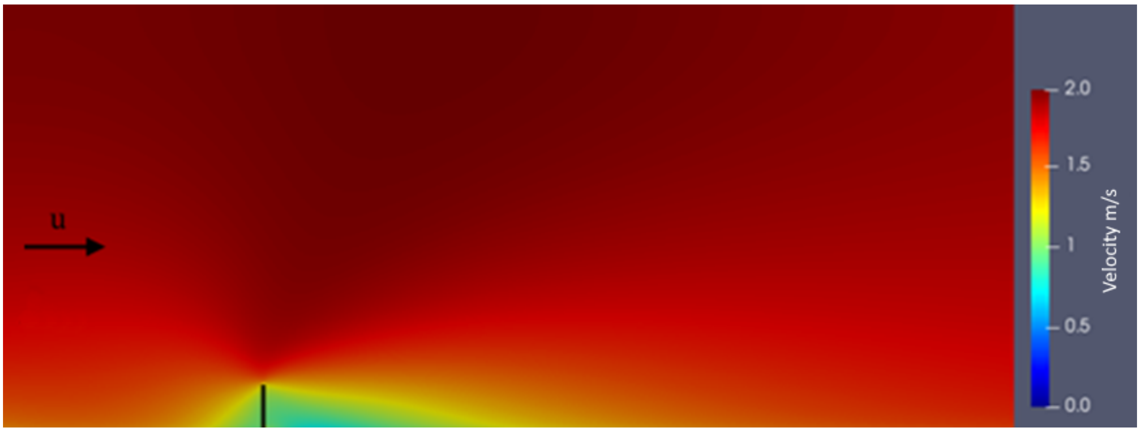


Figure 2. *Wind profile in a scenario with a 12m high porous perimeter screen.*

Once the speed profile was known, it was possible to predict the evolution of possible dust dispersion in any area surrounding the perimeter screen, after first characterising the emissions to be studied (Figure 3). This approach allowed the environmental impact of the screen to be assessed under operating conditions, and at the same time, situations to be identified in which emission mitigation maximised.

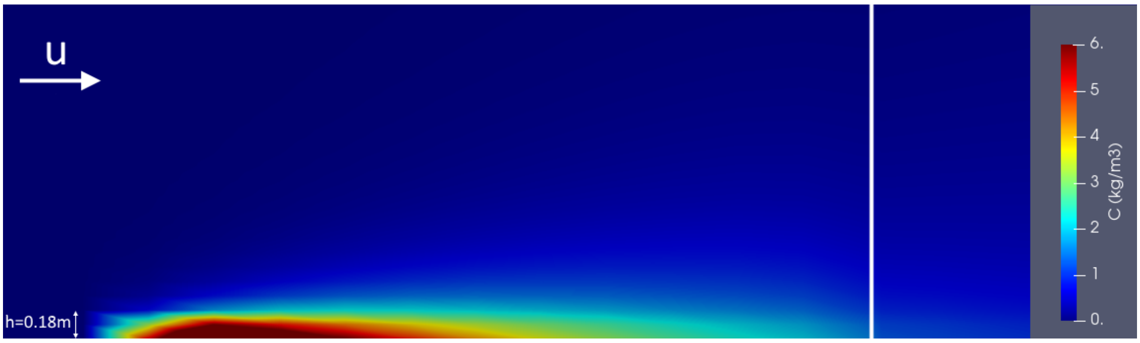


Figure 3. *Concentration profile in a scenario with a 12m high porous perimeter screen. Emission source: 0m high, 5m away from the screen.*

A similar fluid dynamics model had already been used to model diffuse pollutant emissions in earlier studies conducted by ITC [9, 10]. In short, the presence of a screen in the medium had a twofold effect: on the one hand, it altered the wind field in a given scenario; on the other, it acted as an obstacle, blocking particles and preventing them from going further (dust-trap effect) by various mechanisms: diffusion, interception, and impact [5].

3. EXPERIMENTAL PROCEDURE

3.1. SCREEN CHARACTERISATION

The porous screen at issue was made of high-tenacity synthetic polyester, 12m high and 150m long, fitted at an angle of 112°, so that it was practically perpendicular to the prevailing winds.

The main technical characteristics of the membrane were: 15.8% porosity and air permeability at 200 Pa of 2.70 m/s.

3.2. EXPERIMENT CAMPAIGNS

After developing the model, the next step was to determine the model input physical parameters, which were experimentally determined on the Transverse pier. In this sense, modelling the wind field required a wind speed profile and initial turbulence profile to be included, as well as parameters to be set for the screen's fluid dynamics properties. Furthermore, modelling the diffuse emissions required an emission source and PM10 deposition rate on the screen to be determined.

Figure 4 shows the final set-up of the equipment in the experiment campaigns: a 3D sonic anemometer, a high-volume gravimetric sampler, and a membrane system for particle deposition on the dust-trapping fabrics.

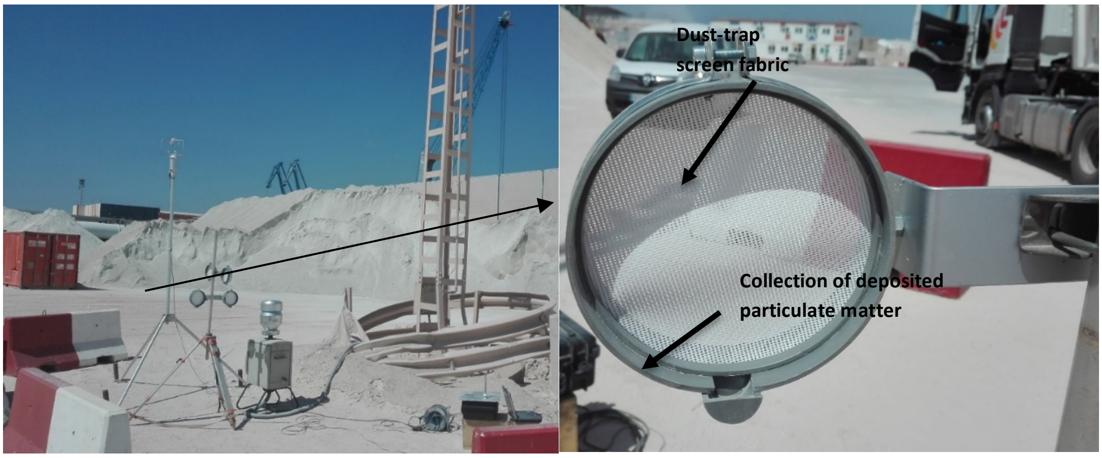


Figure 4. *Experiment set-up on the Transversal pier at the Port of Castellón.*

The initial speed profile was determined by using a 3D anemometer and the atmospheric boundary layer theory [12-13]. The anemometer was in service during the months of May, June, and July 2018, as a means of identifying weather conditions similar to the most common weather scenarios in the area throughout the year. Determining speed profiles required a large amount of data in a short space of time, since this profile was greatly influenced by continuous fluctuations in wind speed and temperature. Data from the anemometer was grouped into one-hour intervals, analysed and allocated to a standard scenario. The time intervals defining a scenario to be entered into the model were chosen according to NEPM (National Environment Protection (Ambient Air Quality) Measure, Australia) recommendations [15].

Finally, the most representative set of data from each typical scenario was chosen (Table 1).

Scenario	Average speed (m/s)	Prevailing direction (º)	Relative frequency (%)	Representative data selected
1	1.7	101.2	21.66%	24/06/18 – 06:00–07:00
2	8.2	171	1.10%	05/06/18 – 15:00–16:00
3	3.8	126	19.86%	23/06/18 – 11:00–12:00
4	1.7	148.9	36.83%	02/07/18 – 09:00–10:00

Table 1. *Data obtained from the 3D anemometer representative of each scenario.*

Furthermore, determining the deposition rate entailed ascertaining the mass of PM10 deposited on the membrane, for which a system of membranes oriented towards the four cardinal points (N, S, E, and W) (Figure 4) was used, which in turn facilitated collecting particles deposited by the wind [16] and obtaining the PM10 concentration from the gravimetric sampler. Once the value of these parameters was known, the deposition rate (v_d) could be experimentally obtained from the following formula [16]:

$$v_d = \frac{M_{dep}}{\bar{c} \cdot A \cdot t} \qquad (9)$$

where Mdep is the mass deposited on a given surface, $\bar{c}$ is the average ambient air concentration of the pollutant whose deposition rate is to be measured (i.e. PM10), A is the surface area, and t the length of time over which the pollutant is collected on the relevant surface.

This parameter depends on a number of variables, such as particle size, wind speed, and particle geometry [17]. After four data collection campaigns over varying lengths of time and under different weather conditions, a relatively constant average deposition rate of 0.27 m/s regardless of wind speed was obtained. This value was within the range deemed acceptable according to the literature [16].

4. BEHAVIOUR OF THE SCREENS AS DUST TRAPS

4.1. SCREEN EFFECTIVENESS IN WEATHER SCENARIO 1

Figure 5 shows the screen efficiency map, which directly assesses its dust-trapping capabilities in scenario 1 as a function of the emission point. It shows how, naturally, the closer to the ground and to the screen the emission occurred, the greater the amount of pollutant dust captured by the screen. At less than 4m in height, the screen was capable of trapping more than 20% pollutant over the first 50m. In fact, at a height of just 2 metres and at a distance of less than 20m from the screen, efficiency rates between 40% and 50% were achieved. At heights above 10m, the screen was less effective, yielding efficiency rates of less than 10%. Finally, when emission took place over 75–80m away, particle collection was less than 20% in all cases.

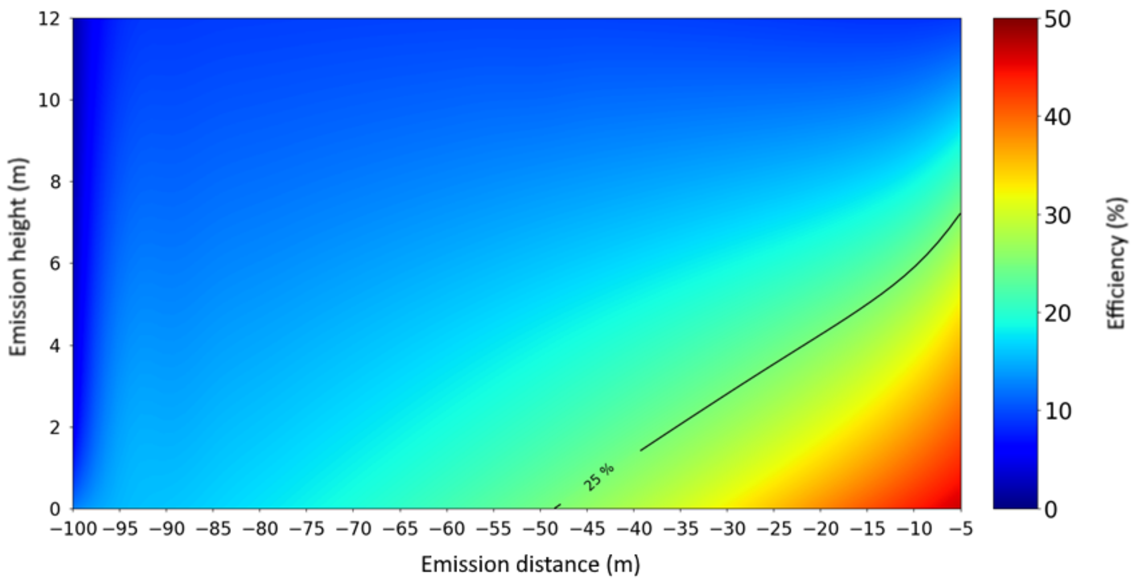


Figure 5. *Screen efficiency map in scenario 1, according to emission point position.*

4.2. SCREEN EFFECTIVENESS IN WEATHER SCENARIO 4

Figure 6 shows the efficiency map of the screen as a function of the emission point considered for a type 4 scenario. Screen efficiency in this scenario was again high, even when the emission point lay at a considerable distance from the screen.

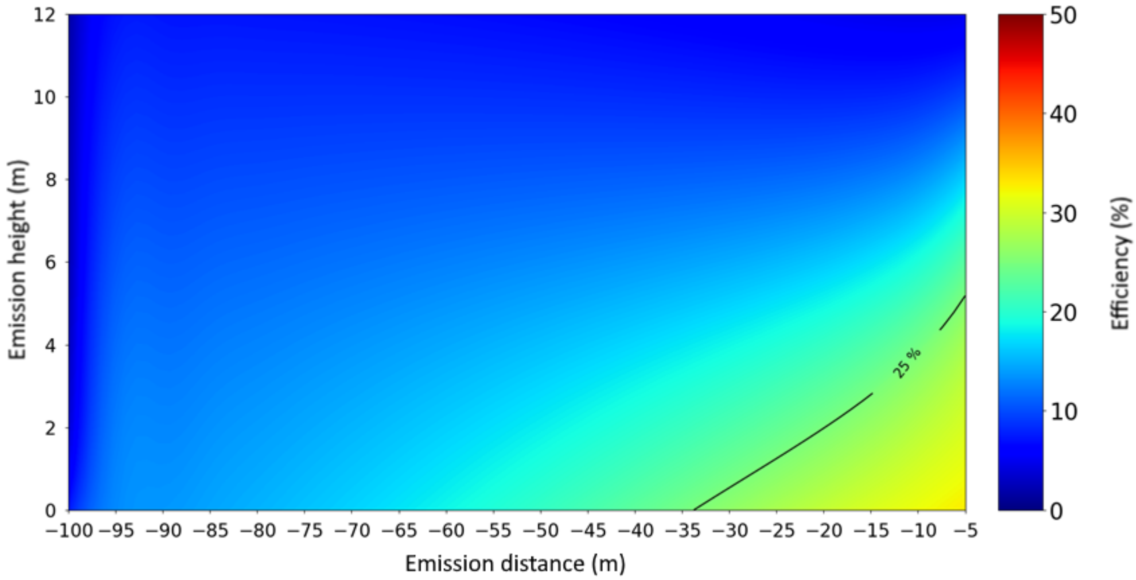


Figure 6. *Screen efficiency map in scenario 4, according to emission point position.*

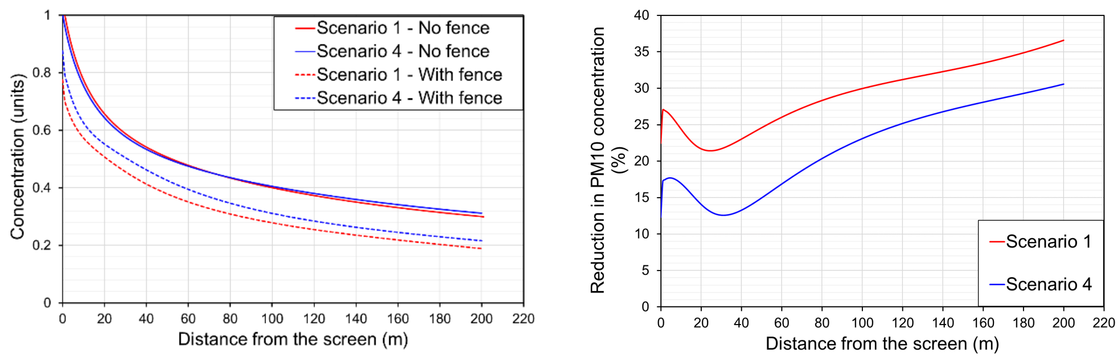
In this scenario, even though emissions that occurred at a height of over 5–6 metres would not be mitigated by more than 25% at most, an efficiency rate of 25% could be achieved at a distance of 33–34m if emission height were at ground level. At the same time, when the emission point was less than 15m away, screen efficiency exceeded 30% in all cases in which emission height was below 2m. Beyond a distance of 60m from the screen, efficiency was less than 20% in all cases. For example, it can be seen that, at distances of 90m from the screen and over a range between 0 and 6m in height, efficiency remained at around 10%.

4.3. ASSESSMENT OF PM10 CONCENTRATION DOWNWIND FROM THE SCREEN

Finally, the reduction in ambient air PM10 concentration was assessed by comparing concentration levels obtained in scenarios 1 and 4 with and without a screen.

To do so, the emission point was assumed to be 10 metres away at a height of 5 metres upwind from the screen. With this configuration, Figure 7A shows PM10 concentration in relative units (taking the unit value to be concentration level with no screen), obtained at a height of 5m and at varying distances downwind of the screen. Figure 7B includes the reduction (in %) of PM10 concentration in the scenario with a screen compared to the same scenario with no screen.

The results show how the presence of the screen significantly altered PM10 concentrations even at a distance of 200m from the screen, three clearly differentiated sections being noted (Figure 7B): i) an initial section in the immediate area leading up to the screen, in which PM10 concentration decreased between 15% and 25%; ii) a second section (20 to 40 metres), in which the relative PM10 concentration increased, due to the reduction in wind speed caused by the screen; and iii) a third section, at distances of 40m and over, in which concentration diminished more sharply than in the scenario with no screen, as a result of the increased turbulence caused by the screen [18] which, in turn, led to increased volume in the mixing area (plume) [19]. The differences observed between scenarios 1 and 4 may be attributed, among other factors, to the different angle at which the prevailing wind impinged upon the screen.



(A) **(B)**

Figure 7. (A): *Variation in PM10 concentration at a height of 5m downwind from the screen in scenarios 1 and 4 with and without a screen.* ***(B):*** *Reduction in PM10 concentration in the same scenarios when the screen was present.*

5. CONCLUSIONS

A model was developed that can assess the fluid dynamics and dust-trapping effect of perimeter screens installed in the port of Castellón. Furthermore, an experimental methodology was defined in the field to determine the typical environmental conditions in the area and deposition rates on the screens.

Operation	Emission point (m,m)	Efficiency (%)	
		Scenario 1	Scenario 4
Stockpiles unloaded on the pier	(-65,3)	17	15
Stockpiles unloaded in hopper	(-88,3)	14	13
Position of temporary stockpiles	(-4,3)	38	29

Table 2. *Screen efficiency at usual emission points*

From this emissions study, it may be concluded that screen effectiveness to capture particles was significant when emission took place no further than 50m from the screen and close to the ground (heights of <3m). Consequently, the closer to the screen and to the ground that emission took place, the greater was screen effectiveness. Table 2 shows the efficiency rates of the screens for conventional emission points. The table reveals how, in the two most relevant scenarios, the screens acted as significantly efficient means for trapping dust in all operations. Similarly, emissions caused by temporary stockpiles were the ones best controlled by the screens in both cases.

In addition, the study also shows that the screens had a remarkable effect even at long distances (>100m), since they reduced ambient air PM10 concentration, even in areas far removed from the emission point. Nevertheless, efforts need to focus in particular on reducing and/or collecting PM10 emissions to prevent release into the atmosphere.

In conclusion, the recommendation is to form stockpiles as close as possible to the screens and at the lowest possible height. In the current situation, the results indicate that the installation of screens as a means of mitigating PM10 emissions needs to be accompanied by additional measures. Such measures could involve wetting stockpiles, moving them into closed warehouses, or cleaning road surfaces in areas with heavy traffic more often, to reduce airborne emissions of particulate matter deposited on the road.

For future work, the model could be refined using more accurate turbulence models, 3D simulations, and taking into account dust deposition due to gravity. This last change would increase screen efficiency rates in all cases. Alternatively, it would be of great interest to assess PM10 tendency to be released into the atmosphere as a function of different, typical weather conditions. For that purpose, the development of a complementary model [6] would need to be considered.

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