Wind Environment and Loading Mitigation Effects on Coastal Enclosed Coal Yards with Porous Gables

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Abstract. In order to prevent dust emission, coastal coal yards are enclosed by coal sheds. The dust suppression rate increases as the closure of the coal shed by sacrificing the ventilation rate. Adopting porous gables may provide a balance between natural ventilation and dust suppression as well as mitigate the aerodynamic loading effect. Through wind tunnel tests and numerical simulation, the present research take an practical coastal power plant coal yard as an example to illustrate the natural ventilation, dust suppression and aerodynamic loading mitigation effect quantitatively. The results have shown that, with a favourable gable porosity of 30%, the natural ventilation rate can be enhanced from 0.7 to over 2.0 times/hour compared with solid gables. The dust suppression could be increased from 56% up to 80% compared with open gables. The unfavorable extremum aerodynamic suction coefficients on the central area and edges of roof are reduced by 20% and 70% respectively. The results provide a supportive evident that adopting prorous windbreak gables is a environmental friendly and economic construction scheme for coastal enclosed coal yards.

1. Introduction

As a result of increasing restriction of dust emission in coastal area, the coal yards in coastal power plants, bulk ports have faced great environmental pressure and challenges. The emission can be effectively supressed by enclosed coal sheds. Some conventional coal sheds are constructed with gables covered by colored steel plates to effectively suppress dust emission. Other coal sheds are constructed with open gables to enhance transportation efficiency with dust suppression rate sacrificed. In order to balance the dilemma between dust suppression and natural ventilation, coal shed with gables covered by porous windbreak plates emerged recently. In this way, the dust suppression as well as natural ventilation requirement can be satisfied [1]. Moreover, the ventilation may also reduce the extreme wind load on the structure, which might lead to an environmental friendly and economic construction scheme for coastal enclosed coal yards [2]. However, the key parameters for the construction decisions require qualitative investigation.

In the present research, wind tunnel tests and computational fluid dynamics (CFD) numerical simulation are applied to qualitatively investigate the detailed wind environment and wind load of an enclosed coal yard to be constructed in a coastal power plant. The effects of porous gables on the dust suppression rate, ventilation rate and extreme wind pressure of the enclosed coal yard covered by closed, porous (porosity \( \varphi = 10\%, 30\% \) and 60\%) and open gables are comparatively studied and the favorable gable porosity is recommended.
2. Wind tunnel test

2.1. Test model and cases

The test model was a power plant enclosed coal yard with layout demonstrated in Figure 1. There are 4 coal piles covered by 2 coal sheds in the site location. The dimension of each coal pile is $244 \text{ m} \times 63 \text{ m} \times 16.5 \text{ m}$, and the dimension of the coal shed is $264 \text{ m} \times 138 \text{ m} \times 45 \text{ m}$ with spacing of 10 m.

The geometric scale of the test is taken as 1:250 with a blockage rate of 3.9%. The models for wind tunnel tests are made of ABS plates. The coal shed gables are manufactured by a laser engraving machine to achieve a refined porosity of $\varphi = 10\%$, 30% and 60%. Moreover, the cases of closed and open gables are also tested marked as $\varphi = 0\%$ and 100%. A baseline case without coal shed is also tested for the estimation of basic dust emission condition. For each case, 16 azimuths shown in Figure 1 are tested.

2.2. Wind environment test

The wind environment test is carried out to achieve the wind velocity on the surface of the coal piles and around the ventilators such as skylights, doors and windows. 16 Irwin probes with a probe height of 4 mm (corresponding to 1 m height above the coal pile) are arranged on the surfaces of each coal pile to measure the wind velocity near the coal pile surface, shown in Figure 2a. And Cobra probes are adopted to measure the wind velocity around the ventilators, 10 locations around the skylights are arranged around the skylights shown in Figure 2b.

2.3. Wind pressure test

In order to test the wind pressure on the enclosed coal yard, there are 208 and 180 measuring taps on the outer and inner surfaces of the coal shed roof, respectively. And, 47 and 17 measuring taps were arranged on the outer and inner surfaces of each gable, respectively. A 1.5-m length PVC tube was installed on each measuring tap from the interlayer of the model. The PVC tube was connected to the electronic pressure scanners to measure the fluctuating wind pressure on both surfaces of the coal shed, shown in Figure 3.
2.4. Test setups and processing

In the wind environment test, the wind pressures \( p_0 \) and \( p_1 \) measured from Irwin probes are converted to wind velocity through Equation (1).

\[
V = a_0 \sqrt{p_1 - p_0} + b_0
\]  

(1)

where \( a_0 \) and \( b_0 \) are calibration coefficients determined as 1.785 and 0.148 by calibration tests. And the dimensionless wind velocity ratio \( R \) is determined by the ratio between \( V \) and \( U_0 \).

In the pressure measurement test, the wind pressure coefficient is determined as,

\[
C_{pj}(t_k) = \frac{P_{oj}(t_k) - P_{ij}(t_k)}{0.5 \rho U_0^2}
\]  

(2)

where \( t_k = k/f_s \) \((k = 1, 2, \ldots, N)\) is the time series, \( N = f_s T_s = 330\text{Hz} \times 60\text{s} = 19800\) is the sample length; \( P_{oj}(t_k) \) and \( P_{ij}(t_k) \) are the wind pressure at time \( t_k \) on point \( j \) of outer and inner surfaces, respectively; \( C_{pj}(t_k) \) is the dimensionless net wind pressure coefficient at time \( t_k \) on the point \( j \). \( \rho \) is the air density \((\text{kg/m}^3)\), \( U \) is the reference wind velocity \((\text{m/s})\). Through extremum analysis, the positive and negative extremum around all azimuths \((C_{pj}^+ \text{ and } C_{pj}^-)\) wind pressure coefficients are obtained for the design of coal shed claddings and components.

3. CFD numerical simulation

In order to fulfil the data for wind environment estimation, computational fluid dynamic (CFD) numerical simulations are applied for more detailed information. The numerical simulation simulates the same condition of wind tunnel tests, the wind velocity ratio results are compared to validate the simulation parameters demonstrated in this section.

3.1. Geometric model and meshes

The geometric model is built in full scale delicately. And the ventilators are built considering different opening cases for the flux results. A cylindrical computational domain is established to simulate the flow around the coal yard. The computational domain is divided into inner and outer layers, shown in Figure 4. The inner layer adopts tetrahedral unstructured meshes to adapt to complex architectural shapes. In the outer layer, hexahedral structured mesh is used to save the number of meshes and improve the mesh quality. Through grid dependence check, balancing the computational accuracy and costs, the total number of meshes was determined as 5.4 million.

3.2. Boundary conditions

The boundary of the computational domain is divided into 16 parts according to 16 azimuths. In each calculation case, 8 parts are set as flow inlets and the other 8 parts are set as flow outlets. The wind profile was employed for the flow inlets. The outflow boundary condition was selected as outflow for the fully developed turbulence. Free-slip boundary condition was employed on the top boundary of the computational domain.

For building surfaces covered with solid materials, non-slip wall boundary was applied. The porous gables are simulated with homogeneous and isotropic porous-jump model, governed by a momentum sink (pressure loss) \( \Delta p \), expressed as follows.
\[ \Delta p = \frac{1}{2} k_r \rho U^2 = 0.52 \frac{1 - \varphi^2}{\varphi^2} \rho U^2 \]  

(3)

where \( k_r \) is the pressure loss coefficient, \( \varphi \) is the porosity rate, and \( t \) is the thickness of the porous windbreak plate.

Figure 4. Meshes of computational domain

(a) inner layer with unstructured pyramid meshes     (b) outer layer with structured hexahedron meshes

3.3. Solution setups and validations

The wind environment of the coal yard can be obtained by solving governing equations of three-dimensional incompressible fluid. Steady RANS method with Re-Normalization Group (RNG) \( k-\varepsilon \) turbulent model was employed. Pressure velocity decoupling of the discretized equations is implemented by the semi-implicit method for pressure-linked equations (SIMPLE) algorithm, and second order upwind scheme and central differencing scheme are used for discretization of the convective and diffusive terms respectively. Non-equilibrium wall functions are employed to simulate the complex flows and pressure gradients near the walls. Solution convergence is obtained when the iterative residual errors of all variances in the governing equations are less than \( 1 \times 10^{-4} \).

The wind velocity results obtained from the numerical simulation are processed as wind velocity ratio and compared with the wind tunnel data. The numerical results agree well with experimental results, which validate the feasibility of the simulation.

4. Result analysis

4.1. Ventilation effect analysis

Wind-driven natural ventilation is quantified by ventilation rate \( N \) (h\(^{-1}\)) defined as,

\[ N = 3600 \times \sum_i Q_i / V_a \]  

(4)

where \( Q_i \) denotes the volume flux (m\(^3\)/s) at vent \( i \), \( V_a \) is the total air volume (m\(^3\)) in the coal shed. The ventilation rate denotes the times of air exchange per hour at a space.

Figure 5. Annually averaged wind-driven natural ventilation rate

As the wind-driven natural ventilation rate was directly in proportion with approaching wind velocity, the averaged ventilation rate can be obtained directly by through the ventilation rate at averaged wind velocity. The ventilation rates under different azimuths were further averaged weighted by the azimuth frequency. The annually averaged wind-driven natural ventilation rate with gable...
porosity is shown in Figure 5. The annually averaged ventilation rate of coal sheds with closed gables is about 0.7 times/hour, which is far from green industrial buildings requirements [3]. With porous windbreaks ($\phi \geq 30\%$), the wind-driven natural ventilation rate can be significantly improved above 2.0 times/hour, which is beneficial to energy saving.

4.2. Dust suppression effect analysis

As the increment of gable porosity, the wind velocities on the coal pile surfaces become larger, causing dust emission. The wind-erosion dust emission can be estimated by the AP-24 guideline recommended by US Environmental Protection Agency [4]. In the recommendation, the wind-erosion potential function at a single disturbance for a dry exposed surface is expressed as,

$$ P_{wj} = \begin{cases} 
58(u_j^* - u_j)^2 + 25(u_j^* - u_i^*) & u_j^* > u_i^* \\
0 & u_j^* \leq u_i^* 
\end{cases} $$

(5)

where $P_{wj}$ is the wind-erosion potential (g/m²) at location $j$, $u_j^*$ is the friction velocity (m/s) at location $j$, $V_j$ is the velocity measured at height $h$ above location $j$, $z_0$ is the roughness height, $\kappa_0$ is the von Karman constant taken as 0.4, and $u_t^*$ is the threshold friction velocity (m/s).

The emission quantity a single disturbance is summed up by area weights. And the emission quantity is statistically estimated with wind velocity and azimuth frequencies, denoted as $E_1$ and $E_0$ for annual emission with and without coal sheds. Then, the dust suppression rate $\eta$ is defined as follows.

$$ \eta = [1 - (1 - \zeta) E_1 / E_0] \times 100\% $$

(7)

where $\zeta$ is the empirical dust suppression rate of other dust control measures. The dust emission factor and dust suppression rate of different porosities are shown in Figure 6.

![Figure 6. Emission factor and dust suppression rate](image)

![Figure 7. Ventilation and dust suppression rates](image)

It is revealed from Figure 6 that, the dust suppression rate of coal sheds without gables is about 56%. The dust suppression rate increases up to 80% as the gables are covered with windbreaks. When the coal shed gables are totally closed, it can be up to 95%. If regular spray is carried out, emission can be further suppressed. The ventilation and dust suppression rates are shown in Figure 7. The contradictory of ventilation and dust suppression is revealed in the figure. It is also indicated that to balance the ventilation and dust suppression effects, the favorable gable porosity should be around 30%.

4.3. Wind load mitigation effect analysis

The wind load on the coal shed was divided into zones. The envelope of peak wind pressure coefficients of each zone over all the wind directions is obtained as the zone values of peak wind pressure coefficients. The results of typical zones (roof edges, central zone, top ventilator, and gable walls) are plotted with gable type, demonstrated in Figure 8.
It can be found in Figure 8 that the absolute values of negative peak wind pressure coefficients are generally reduced by the gable ventilation. Particularly, the zone values of peak suction on for gables reduce over 70% from solid to porous. The zone values of the central area of roof and top ventilators reduce about 20%. However, the peak suctions on roof edges are less sensitive to the gable porosities when $\phi \leq 30\%$.

![Figure 8. Zone values of peak wind pressure coefficient](image)

5. Concluding remarks
The present research takes a coal yard in coastal power plant as an example, the wind environment and wind load of enclosed coal yard with gables of different porosities are investigated through wind tunnel tests and numerical simulations. The following concluding remarks are drawn.

- The increment of gable porosity is helpful for natural ventilation as well as retaining considerable dust suppression rate. The favorable gable porosity is around 30%.
- With a favourable gable porosity of 30%, the natural ventilation rate can be enhanced from 0.7 to over 2.0 times/hour compared with solid gables.
- The dust suppression could be increased from 56% up to 80% compared with open gables.
- The unfavorable extremum aerodynamic suction coefficients on the central area and edges of roof are reduced by 20% and 70% respectively.
- The results provide a supportive evident that adopting porous windbreak gables is a environmental friendly and economic construction scheme for coastal enclosed coal yards.

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References
[1] Su N, Peng S, Hong N, Zhang J. (2020). Experimental and Numerical Evaluation of Wind-driven Natural Ventilation and Dust Suppression Effects of Coal Sheds with Porous Gables. Building and Environment, 177: 1068555.
[2] Su N, Peng S, Hong N, Hu T. (2020). Wind Tunnel Investigation on the Wind Load of Large-span Coal Sheds With Porous Gables: Influence of Gable Ventilation. Journal of Wind Engineering and Industrial Aerodynamics, 204: 104242.
[3] US EPA. (2009). AP-42: Compilation of Air Emissions Factors, Section 13.2.5, https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-compilation-air-emissions-factors
[4] GB/T50378-2014. (2014), Assessment standard for green building, China Architecture and Building Press. Beijing, 2014 (in Chinese).