Effect of wind turbulence on gas transport in porous media:
Experimental method and preliminary results.

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Running title: Wind-induced gas transport in porous media
We demonstrate a novel experimental arrangement for measuring wind turbulence-induced gas transport in dry porous media under controlled conditions. This equipment was applied to assess the effect of wind turbulence on gas transport (quantified as a dispersion coefficient) as a function of distance to the surface of the porous medium exposed to wind. Two different strategies for the measurement of wind-induced gas transport were compared. Experiments were carried out with O₂ and CO₂ as tracer gases with average vertical wind speeds of 0.02 to 1.06 m s⁻¹. Oxygen breakthrough curves as a function of distance to the wind-exposed surface of the porous medium were analysed numerically with a finite-difference based model to assess gas transport. We showed that wind turbulence-induced gas transport is an important transport mechanism that can be 20 to 70 times larger than molecular diffusion-induced transport. Wind conditions and properties of the porous medium had strong controlling effects on this relation. Importantly, we show that even though wind-induced gas transport is greatest near to the wind-exposed surface, it can have marked effects on the variation in gas concentration at much larger depths.

Keywords: Wind speed, porous media soil, soil–air boundary, turbulent flow, molecular diffusion, gas dispersion, breakthrough time.
Highlights

- We explored the effect of atmospheric wind turbulence on gas transport in porous media.
- We measured the depth relation of wind-induced dispersion in porous media for real wind conditions.
- Wind-induced gas dispersion coefficients were 20 to 70 times larger than molecular diffusion.
- Wind turbulence can potentially have a considerable effect on gas transport in porous media.

Introduction

Greenhouse gases play an important role in global warming. Soil is a source of some greenhouse gases such as methane (CH₄), carbon dioxide (CO₂) and nitrous oxide (N₂O). Various soil properties affect soil gas emissions, such as humidity, temperature, air pressure and vegetation (Oertel et al., 2016). Furthermore, the emission of methane, which is an important greenhouse gas, can result from land management such as from rice paddy soil and landfill sites that receive organic matter (Topp & Pattey, 1997). Radon (Rn) is a radioactive gas that can move from soil to the atmosphere with the potential to affect human health. Advective flow controlled by wind and the difference between indoor and outdoor temperatures are the main factors in the transport process of radon from soil to air and buildings (Nazaroff, 1992). Oliver & Khayrat (2001) found that in addition to lithology,
factors such as elevation, soil depth and particle size can affect the spatial variation
in radon in the soil atmosphere.

Wind action (high-frequency velocity or pressure fluctuations caused by wind
turbulence) has been shown in several cases to play an important role in the transport
of gaseous compounds in soil and other porous media, and the exchange of these
compounds with the atmosphere. Examples include: radon (Rn) transport into
buildings (Riley et al., 1999; Wang & Ward, 2002), landfill gas emissions (Poulsen
et al., 2001; Poulsen & Moldrup, 2006), water evaporation from soil (Hanks &
Woodruff, 1958; Acharya & Prihar, 1969; Ishihara et al., 1992; Novak et al.,
2000a, 200b) and exchange of natural soil gases with the atmosphere (Takle et al.,
2004; Massman & Frank, 2006; Maier et al., 2012). In particular, Poulsen &
Moldrup (2006) identified that wind-induced turbulence was responsible for 40% of
total landfill gas emissions at a Danish landfill site during a 7-day period. Hanks &
Woodruff (1958) found that the rate of water evaporation increased two to six times
for soil mulches and 10 to 15 times for gravel and straw when wind speed increased
from 0 to 40 km hour⁻¹.

Wind turbulence (gustiness) affects gas transport in porous media by inducing
high-frequency, multi-directional fluctuations in gas velocity with durations of up to
one minute within the pore system of the porous medium (Takle et al., 2003;
Poulsen & Moldrup, 2006; Maier et al., 2012). These fluctuations, in turn, result in
gas transport by advection and dispersion in addition to the molecular diffusion
which is always present (Maier et al., 2012).
Several studies have modelled the effect of the gustiness of wind on gas transport in porous media in one, two and three dimensions (Farrell et al., 1966; Scotter & Raats, 1969; Kimball & Lemon, 1970; Colbeck, 1981). These studies have generally represented wind action as sinusoidal pressure or velocity waves (including superimposed waves) to simplify computation. However, Poulsen & Moldrup (2006) used stochastic modelling to generate random fluctuations with specific statistical properties. A comparison of the modelling results from these two approaches showed that wind-induced gas transport in porous media is a multi-dimensional process, and that the use of sinusoidal functions to represent one-dimensional wind action generally underestimates gas transport. The above studies show further that wind-induced gas transport decreases with increasing distance from the surface exposed to wind action.

In general, modelling of wind-induced gas transport has been done by simulating the velocities of advective pore gas as functions of location (depth) and time within the porous medium. For real (random) wind velocity or pressure fluctuations, this is computationally intensive because very small time steps are required to resolve the fluctuations (Saffman, 1960; Poulsen & Sharma, 2011). The gustiness of wind at the surface of the porous medium generates velocities of pore gas that fluctuate rapidly in magnitude and direction (Maier et al. 2012). The velocities also vary spatially within the porous medium because of differences in pore size. This results in mixing of the gas within the porous medium, but does not usually generate net advective gas fluxes. This means that wind turbulence-induced gas movement in porous media behaves like a dispersive process (Poulsen & Moldrup, 2006). Computationally
intensive simulations can be avoided, therefore, by modelling wind turbulence-induced gas transport as a purely dispersive process with a cumulative location-dependent dispersion coefficient, $D_{\text{tot}}$, that represents the sum of molecular diffusion, $D_m$, and wind-induced mixing, $D_w$ (Poulsen et al., 2001; Poulsen & Sharma, 2011).

This approach, however, requires knowledge about the relation between $D_w$ and distance from the surface exposed to wind. Experimental investigations of $D_w$ are limited at present, however. The authors are aware of four earlier studies only that focus on this property. Scotter & Raats (1968, 1969) and Poulsen & Sharma (2011) measured $D_w$ in columns of porous media under fluctuations in sinusoidal pressure induced by an oscillating piston (one-dimensional gas transport). Maier et al. (2012) carried out similar experiments, but used a fan combined with a chopper wheel, which is a wheel-shape frame with shutters inside to generate more realistic conditions of wind turbulence. These four studies measured gas concentrations as a function of time at both ends of the columns. None of these studies, however, assessed the variation in $D_w$ with position inside the columns of the porous medium, but measured average $D_w$ values only across the entire columns. Therefore, to the best of the authors’ knowledge there is no experimental assessment in the scientific literature at present of the relation between $D_w$ and distance to the surface of the porous medium exposed to the wind or the effect of column length on the dispersion coefficient. To provide such knowledge would require measurements of gas concentration at different positions within the porous medium.

This research had two main objectives, therefore. First, to measure the variation in gas concentration of the porous medium in response to wind turbulence at
different distances from the surface exposed to wind, and second to use these
measurements to determine $D_w$ as a function of distance to the surface exposed to
wind. Measurements were made by two different methods: (i) gas concentrations
were measured at both ends of a porous medium column, following the approach
used in previous research. To assess the effect of distance, columns of different
length were used with one end exposed to wind turbulence, and (ii) gas
concentrations were measured at several distances from the surface exposed to wind
simultaneously within the same column. The results are used to compare the two
methods of measurement and to assess the relation between the wind-induced
dispersion coefficient $D_w$ and distance below the surface exposed to wind.

Theory

Gas transport in porous media is traditionally described by the advection–dispersion
equation (ADE). For three-dimensional transport of a non-sorbing gas in a porous
medium with no liquid phase, the ADE is given as:

$$\frac{\partial c}{\partial t} = \nabla^2 (DC) - \nabla (vC),$$

(1)

where $C$ is the pore gas concentration, $t$ is time, $D$ is the diffusion–dispersion
coefficient (representing the sum of molecular diffusion and mechanical dispersion)
and $v$ is the gas velocity (Darcy velocity). In a porous medium where $v$ is controlled
solely by wind turbulence, Equation (1), there is no systematic movement of gas, but
random fluctuations in velocity only. As discussed in the introduction, gas phase
movement can then be expressed as a dispersive process with a cumulative
diffusion–dispersion coefficient, $D_{tot}$, which represents the sum of molecular
diffusion $D_m$ and wind-induced mixing $D_w$ (Poulsen et al., 2001; Poulsen & Sharma, 2011). In this case Equation (1) reduces to

$$\frac{\partial c}{\partial t} = \nabla^2 (D_{\text{tot}} C).$$

(2)

For a porous medium where gas concentration and wind conditions in the atmosphere at its surface exposed to wind are uniform, net gas transport in the porous medium is one-dimensional (Poulsen et al., 2001) and Equation (2) becomes:

$$\frac{\partial c}{\partial t} = \frac{\partial^2 (D_{\text{tot}} C)}{\partial z^2} = \frac{\partial^2 ((D_m + D_w) C)}{\partial z^2},$$

(3)

where $z$ is the distance from the surface exposed to wind.

The coefficient of molecular diffusion in the porous medium ($D_m$) can be estimated from the molecular diffusion coefficient in free air ($D_0$) with for instance the Penman (1940) model,

$$\frac{D_m}{D_0} = 0.66 \varepsilon,$$

(4)

or the Millington & Quirk (1961) model

$$\frac{D_m}{D_0} = \frac{\varepsilon^{10/3}}{\phi^2},$$

(5)

where $\varepsilon$ is gas-filled porosity and $\phi$ is total porosity (assumed to be equal in media with no liquid phase)

**Materials and methods**

**Material characteristics**

The dry porous medium used in this study was a crushed and polished, sub-rounded marble rock with particle sizes that ranged between 6.3 and 14 mm. This material was selected because it was very permeable to gas, which allowed the effects of
wind turbulence to penetrate deep into the medium. This also made it easier to
calculate the methods to measure $D_w$ and to assess the relation between $D_w$ and
distance to the surface exposed to wind.

Gas permeability in a porous medium, $k$, was determined by measurement of the
drop in pressure $\Delta P$ across a sample of the medium with length $L$ and cross-sectional
area $A_s$ exposed to a gas flow $Q$, followed by the application of Darcy’s law
(Kirkham, 1947),

$$k = \frac{Q \eta L}{A_s \Delta P},$$

(6)

where $\eta$ is the dynamic viscosity of the gas. Darcy’s law was chosen because
relations between $Q$ and $\Delta P$ were approximately linear. Particle shape of the medium
was characterized by particle roundness, $\rho$, given as (Russ, 2007)

$$\rho = \frac{4 A_p}{\pi R^2},$$

(7)

where $A_p$ is the area of a two dimensional image of the particle and $R$ is the major
axis of the best fitting ellipse to the area, $A_p$ of the particle image. The roundness
was determined by analysing images of 459 randomly selected particles with ImageJ
(National Institutes of Health, Bethesda, MA, USA). An overview of the physical
characteristics of the porous medium is given in Table 1.

Experimental set-up

We developed our experimental set-up based on those used by Scotter & Raats
(1968), (1969); Poulsen et al. (2008); Poulsen & Sharma (2011) and Maier et al.
(2012). It was designed to enable measurements of gas (oxygen) concentration on
samples of variable thickness at several locations within each sample. A schematic
diagram of the set-up is shown in Figure 1. It consists of a 56-cm high, 25-cm inner
diameter PVC column divided into two separate chambers by a perforated metal
plate with 1-mm holes that cover 30% of the surface of the plate. The upper chamber
was used to hold a porous medium sample of the desired depth. Samples with depths
less than the depth of the chamber were supported by an additional perforated metal
plate. This plate was adjustable to any elevation within the chamber so that surface
of the sample was level with the top of the column. A 1.5 m × 1.5 m wooden board
with a hole the same diameter as the column was installed horizontally, and level
with the top edge of the column to minimize unwanted patterns of standing wind
turbulence around the column. The lower chamber was connected to a pressurized
source of CO₂ through a precision ball flow meter, Model LZM-15ZT (Yuyao
Kingtai Instrument Co., Ltd, Yuyao, China). A differential pressure sensor (AB
Micatron, Solna, Sweden) was connected to the lower chamber to facilitate
measurements of pressure gradient across the sample. The column was fitted further
with several KE-50 galvanic oxygen electrodes (Yuasa Power Supply Ltd, Kyoto,
Japan) connected to a Campbell Scientific CR 1000 data logger (Campbell
Scientific, Logan, UT, USA). To reduce the effects of preferential gas transport,
oxygen sensors were not installed directly above one another but at different
positions along the inner wall of the column (Figure 1 right). The column was further
fitted with a Gill Wind master ultrasonic anemometer (Gill Instruments Ltd.
Lymington, UK) for three-dimensional wind speed measurements at one second
intervals. The main axis of the anemometer was placed 10 cm above the surface of
the sample. A fan was used to create the desired wind conditions by adjusting the fan speed and inclination, and also distance between the fan and column.

**Experimental procedure**

The dry porous medium was packed into the upper chamber of the column in 5-cm increments to ensure a homogeneous medium. During each experiment, the column was saturated initially with CO₂. Carbon dioxide was used rather than N₂ because it is heavier than air, which avoids the effects of buoyancy-driven flow that occurs when N₂ is used, which is lighter than air. During the saturation process, the top of the column was closed with a non-air tight lid. The level of CO₂ saturation (replacing the atmospheric air) was monitored by an oxygen sensor placed on top of the porous medium (at saturation the sensor would read zero O₂). At saturation, the CO₂ supply was switched off, the fan was turned on and the lid was removed by sliding it horizontally to minimize disturbance to the gas phase inside the column during its removal. Atmospheric air would then re-enter the column by molecular diffusion and wind-induced mixing, and the progress of air entry was recorded by oxygen electrodes at one-second intervals. Experiments were continued until oxygen concentrations had reached 21% throughout the column. Room temperature was recorded during all experiments. Oxygen was used as an indicator of the amount of air that has entered the column.

Two sets of experiments (A and B) were carried out. In set A, six different sample thicknesses (5, 10, 15, 20, 25 and 30 cm) were considered. These experiments were carried out with one oxygen sensor at the bottom of the sample and another placed in the lower chamber at 46-cm depth (to ensure full oxygen
penetration). This approach is equivalent to that used in earlier research (Scotter & Raats, 1968, 1969; Maier et al., 2012; Poulsen & Sharma, 2011). The experiments were carried out in triplicate for four different wind conditions (0, 3, 10 and 11 in Table 2) to give a total of 72 experiments and 144 oxygen breakthrough curves.

In all set B experiments, a sample thickness of 35.5 cm (corresponding to the height of the upper chamber) was used. In all experiments, five oxygen sensors were placed inside the sample at depths of 5.5, 13, 20.5, 28 and 35.5 cm and one sensor was placed in the lower chamber at a depth of 46 cm. This number of sensors was chosen as a ‘trade-off’ between accuracy in the estimates of the $D_w$-depth relations and the amount of computation time required to determine $D_w$. Set B experiments were carried out in triplicate for 13 different wind conditions (Table 2) to give a total of 39 experiments and 234 oxygen breakthrough experiments. An example of wind speed measurements for wind condition 9 is shown in Figure 2. Wind conditions were chosen based on the possible settings of the fan and to cover a reasonable range of near-surface wind speeds and turbulence intensities (represented by the standard deviation in wind speed).

**Data analyses**

A one-dimensional numerical model used to solve Equation (3) with an explicit forward time, central space finite difference method that was implemented in Microsoft Excel with the following initial and boundary conditions:

\[ C(z, t) = 0 \quad \text{for } z \geq 0 \text{ and } t = 0, \quad (8a) \]

\[ C(z, t) = 0.21 \quad \text{for } z = 0 \text{ and } t > 0. \quad (8b) \]
One-dimensional modelling was chosen because one measurement only was available for each depth. This is equivalent to assuming that vertical concentration gradients only existed in the column. The model was fitted to the measured oxygen concentration data to determine values of $D_w$ as a function of sample depth for different wind conditions. For experiment A, the model fitting procedure was carried out as follows: for each wind condition, the model was fitted to the oxygen breakthrough curves for the oxygen sensors placed at the bottom of the 5-cm sample and in the lower chamber simultaneously by optimizing the values of $D_{tot}$ in the porous medium and in the free air phase below. The model was then applied to the 10-cm depth sample assuming that $D_{tot}$ for the top 5 cm of that sample is equal to that fitted to the 5-cm sample while optimizing the values of $D_{tot}$ for the bottom 5 cm of the 10-cm sample and the free air phase below. This procedure was applied to samples of consecutively increasing thickness to give a $D_{tot}$ value for each 5-cm depth increment. The approach assumes that the value of $D_{tot}$ for a given depth is independent of the thickness of the sample. For experiment B, the model was fitted to the six oxygen concentration datasets from the oxygen sensors inside the porous medium and in the lower chamber simultaneously by optimizing $D_{tot}$ values for each of the five depth increments represented by the sensors. Breakthrough was very rapid for shallow depths, and the corresponding values of $D_w$ were not always physically meaningful. Therefore, the model was fitted so that $D_w$ could not increase with depth (see Fukuda, 1955). For both sets of experiments, model fitting was done by minimizing the root-mean-square error (RMSE) between measured and fitted oxygen concentrations.
\[
\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=0}^{n} (C_{\text{measured}}^n - C_{\text{fitted}}^n)^2}, \quad (9)
\]

where \( n \) is the number of measurements of concentration. The model fitting procedure was done with Microsoft Excel. For wind condition 0, the fitted values of \( D_{\text{tot}} \) for the porous medium and the free air space correspond to the molecular diffusion coefficients \( D_m \) and \( D_0 \), respectively. For wind conditions 1–12, the fitted \( D_{\text{tot}} \) values for the porous medium correspond to \( D_m + D_w \). Values of \( D_w \) are obtained by subtracting \( D_m \) from \( D_{\text{tot}} \). Prior to the determination of \( D_w \), all values of \( D_m \) were standardized to a temperature of 20°C based on data from Denny (1993).

Results and discussion

The observed values of \( D_m \) and \( D_0 \) were independent of depth of the porous medium, as expected, and relatively constant in their agreement with theory. Average values of \( D_m \) and \( D_0 \) at 20°C across all experiments at wind condition 0 were 0.0485 cm\(^2\) s\(^{-1}\) with a standard deviation of 0.013 and 0.12 cm\(^2\) s\(^{-1}\) with a standard deviation of 0.009, respectively. By comparison, values in the literature for \( D_0 \) as the binary diffusion coefficient of CO\(_2\) and air at 20°C are about 0.16 cm\(^2\)s\(^{-1}\) according to Denny (1993). The deviation between these values might be explained partly by differences in experimental set-up and the sensors used. Estimates of \( D_m \) by Equations (4) and (5) did not compare well with the measured values, probably because these equations were developed for soil, which is much finer grained than the medium used here.
Figure 3 shows the six oxygen breakthrough curves for experiment B at wind condition 3, which corresponds to the six oxygen sensors installed inside and below the sample. Figure 3 shows the curves that represent the fitted numerical model. These show that it is possible to obtain models that fit well to the measured concentration data. This was also the case for the remaining experiments, indicating that Equation (3) can be used to describe wind-induced gas transport.

Comparison of experimental approaches for measuring wind-induced gas transport

Values of $D_w$ for wind conditions 3, 10 and 11 for both experiments A and B are shown in Figure 4 where the $D_w$–z relations follow similar patterns for both types of experiments. There is a large $D_w$ zone near the wind-exposed surface below which $D_w$ decreases quite rapidly with depth to approximately zero. Maximum values of $D_w$ are of the same order of magnitude in both types of experiments, however, the range of observed values is 3.5 times larger for experiment B than experiment A. For experiment A, the zone of large $D_w$ values extends about 30% deeper on average than in experiment B.

These observations indicate that there is a difference between the two methods of measurement to represent wind-induced gas exchange. This is probably because the assumption that both the wind-induced gas transport and the value of $D_w$ for a given depth are independent of sample thickness is not completely correct, especially for samples that are less than approximately 10-cm thick for the material used in this study. A possible explanation is that for thin samples the effects of wind turbulence can penetrate through the sample and into the gas-filled space below. This means that the gas breakthrough curves measured at different depths during experiment A
do not represent the transport conditions that would exist inside a continuous porous medium, and fitted $D_w$ values based on such data would therefore be incorrect. When $D_w$ is measured close to the surface exposed to wind, we recommend that the samples used should be of sufficient thickness. The sensor should be installed at the desired location inside the sample (such as in experiment B) rather than use thinner samples with the sensor located at the bottom (such as in experiment A). Wind turbulence penetration is likely to be proportional to air permeability of the porous medium, $k$ (Fukuda 1955), therefore values of $D_w$ in porous materials with values of $k$ smaller than those used here can probably be measured with thinner samples than we used without any loss of accuracy.

Relation between wind-induced gas transport and distance to the surface exposed to wind

Values of $D_w$ as a function of depth measured during experiment B for wind conditions 1–12 are shown in Figure 5. The average coefficient of variation (standard deviation divided by mean of the three replicates) across all data points in Figure 5 is 1.24.

The $D_w$–$z$ relations for all 12 wind conditions show similar patterns; $D_w$ is almost constant for $z$ less than approximately 10–15 cm. For $15 < z < 25$ cm. values of $D_w$ decrease relatively rapidly to near zero where they remain at larger depths. This is different from the results of earlier theoretical modelling studies (Fukuda 1955; Massmann et al. 1997; Poulsen et al. 2001; Poulsen et al., 2011) that assumed an exponentially decreasing $D_w$–$z$ relation. The results in Figure 5 suggest, therefore,
that assuming an exponential $D_{w-z}$ relation when modelling wind-induced gas
transport in porous media is possibly not completely correct. This is probably
because earlier studies have assumed that wind velocities within the porous medium
are one-dimensional and occur perpendicular to the surface exposed to wind only.
Although net dispersive gas flux might still be represented as being one-dimensional,
wind velocities are in reality likely to be multi-dimensional resulting in more
complex $D_{w-z}$ relations. Observed values of $D_w$ in the upper 10−15 cm of the sample
are between approximately 20 (for wind conditions 1–4) and 70 (for wind condition
12) times larger than $D_m$, which indicates that wind turbulence-induced gas transport
in porous media under certain conditions can be more important than molecular
diffusion.

Figure 5 further indicates that there is a tendency for $D_w$ to increase with
increasing values of vertical, horizontal and total wind velocity together with wind
turbulence (standard deviations in Table 2 are an indicator of the intensity of wind
turbulence) although the tendency is not fully consistent.

Figure 6a shows the breakthrough time ($t_b$) as a function of depth for the 13
wind conditions. In this case breakthrough time is taken as the amount of time that
elapsed before the oxygen concentration at a given depth reaches 50% of its final
value (10.5 relative to 21% oxygen). As expected, $t_b$ increases with $z$ (Figure 6a).
Although $t_b$ increases almost linearly with $z$ for wind condition 0, the $t_b-z$ relation is
strongly non-linear for the remaining 12 wind conditions. Under windy conditions, $t_b$
is very small for $z$ less than about 15−20 cm and only increases for $z > 20$ cm. This
corresponds well with the depth of penetration for the wind turbulence observed in
Figure 4. Oxygen breakthrough times are less for windy conditions than for the no wind condition for all depths investigated. Figure 6(a) also indicates a strong inverse relation between $t_b$ and wind speed. The largest effect of wind turbulence on $t_b$ occurs at shallow depths ($z < 20$ cm, Figure 6b). At these depths $t_b$ under windy conditions is 2–9% only of the corresponding $t_b$ values under calm conditions (molecular diffusion only). At larger depths the relative effect of wind on $t_b$ decreases, however, at $z = 30–35$ cm wind effect still reduces $t_b$ to between 23 and 55% of that observed under calm conditions. Note that breakthrough times at 2.5 cm were very small (Figure 6a), therefore, the values of relative breakthrough time at this depth were variable and not always physically meaningful. They were excluded therefore from Figure 6(b). The results in Figure 6 indicate that even though wind turbulence penetrates to a limited depth only, it can have a potentially large effect on gas transport at much larger depths.

**Modelling $D_w$ as a function of distance to the surface exposed to wind**

Figure 5 indicates that the relations between $D_w$ and $z$ follow the same general pattern regardless of wind condition. To model relations with this pattern, Poulsen et al. (2006) suggested an expression based on the van Genuchten (1980) expression for soil-water retention. With the $D_w$–$z$ relation this model takes the form:

$$\frac{D_w}{D_{w0}} = \frac{1}{(1 + (\alpha z)^{\beta_0})^{(1 - \beta_0)/\beta}},$$

(10)

where $D_{w0}$ is the value of $D_w$ at the surface of the porous medium and $\alpha$ and $\beta$ are empirical constants. Best fitting curves for Equation (10) to the $D_w$–$z$ and the $D_w/D_0$–$z$ relations using the fitting approach described above with $D_{w0}$, $\alpha$ and $\beta$ as fitting parameters are shown in Figure 5 and Figure 7(a), respectively. Measured
values plotted against fitted values of $D_w$ (with Equation (10)) are shown in Figure 7(b). Resulting values of $D_{w0}$, $\alpha$ and $\beta$ are given in Table 2.

Figure 7(a,b) shows that Equation (10) can fit the experimental $D_w$ values closely, which indicates that it could potentially be used to represent the $D_w-z$ relation for modelling wind-induced gas transport in porous media. The amount of experimental data used here is relatively small and is based on a single porous medium; therefore, more data from a larger set of porous media with a wider range of physical properties are needed to verify the applicability of Equation (10).

Figure 8 shows the relations between $\alpha$ and $V_z$ (Figure 8a) and also $\alpha$ and $\beta$ (Figure 8b). $V_z$ is average near-surface vertical wind speed. There is a weak inverse relation between $\alpha$ and $V_z$, which indicates that, $\alpha$ depends to some degree on wind conditions. Relations between $\alpha$ and other wind characteristics did not show any strong trends. There is a relatively strong inverse relation between $\alpha$ and $\beta$, which suggests further that $\beta$ also depends on wind conditions. A direct correlation between $\beta$ and wind characteristics, however, did not reveal any strong trends, which suggests that this relation is possibly more complex. Furthermore, it is likely that the relations in Figure 8 are specific to the type of porous material used, therefore, more data are required to assess if this is the case.

Conclusions

The results show that wind turbulence can potentially have a considerable effect on gas dispersion in the porous medium and on gas exchange between the medium and
the atmosphere. For the wind conditions considered in this study, gas dispersion was 20–70 times greater than for calm conditions (molecular diffusion only) near the surface of the porous medium exposed to wind. In addition, we observed that although wind turbulence affects gas dispersion close to the surface exposed to wind only (in this case 20 cm into the medium), it can have effects on the variation in gas concentration at much greater depths. An increase in average wind speed and fluctuations in wind speed and direction seemed to increase wind-induced transport although the relation was not simple. To establish this relation, further experiments with a wider range of wind conditions and properties of the porous medium than considered here are needed. The results indicate further that measurements with deeper samples and with multiple gas sensors placed inside the sample are more reliable than for a series of thinner samples with the gas sensor placed at the bottom. Measurements with deeper samples equipped with multiple gas sensors are also much more rapid to carry out, therefore, we suggest that this approach should be adopted for the measurement of wind turbulence-induced gas transport.
References


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Table 1. Physical properties of the porous medium used in this study: $d_{10}$ and $d_{50}$ are the particle diameters for which 10% and 50% of the particles (by mass) are smaller, respectively. $\phi$ is total porosity, $k$ is air permeability and $\rho$ is particle roundness.

Table 2. Wind conditions used in the experiments in this study. $V_z$, $V_x$ and $V$ are near-surface vertical, horizontal and total wind speeds, respectively (average wind speed out and standard deviations in parentheses). The fitted values of $D_{w0}$, $\alpha$ and $\beta$ from Equation (10) are also given.
Table 1

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<th>$d_{10}$/ mm</th>
<th>$d_{50}$/ mm</th>
<th>$\phi$</th>
<th>$k$/ mm$^2$</th>
<th>$\rho$</th>
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<td>Average $V_x$ /m s$^{-1}$</td>
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<td>$D_{w0}$ /m$^2$ s$^{-1}$</td>
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<td>W2</td>
<td>0.12 (0.46)</td>
<td>1.80 (0.36)</td>
<td>1.86 (0.36)</td>
<td>1.10 (0.05)</td>
</tr>
<tr>
<td>W3</td>
<td>0.13 (0.46)</td>
<td>1.92 (0.32)</td>
<td>1.98 (0.32)</td>
<td>1.07 (0.01)</td>
</tr>
<tr>
<td>W4</td>
<td>0.15 (0.61)</td>
<td>1.98 (0.39)</td>
<td>2.08 (0.40)</td>
<td>1.04 (0.02)</td>
</tr>
<tr>
<td>W5</td>
<td>0.30 (0.75)</td>
<td>2.40 (0.50)</td>
<td>2.53 (0.52)</td>
<td>1.42 (0.03)</td>
</tr>
<tr>
<td>W6</td>
<td>0.31 (0.61)</td>
<td>2.33 (0.46)</td>
<td>2.43 (0.46)</td>
<td>2.51 (0.04)</td>
</tr>
<tr>
<td>W7</td>
<td>0.36 (0.60)</td>
<td>0.97 (0.49)</td>
<td>1.19 (0.50)</td>
<td>1.55 (0.01)</td>
</tr>
<tr>
<td>W8</td>
<td>0.52 (0.58)</td>
<td>2.74 (0.42)</td>
<td>2.85 (0.43)</td>
<td>1.58 (0.07)</td>
</tr>
<tr>
<td>W9</td>
<td>0.66 (0.60)</td>
<td>3.06 (0.45)</td>
<td>3.19 (0.47)</td>
<td>2.57 (0.06)</td>
</tr>
<tr>
<td>W10</td>
<td>0.67 (0.69)</td>
<td>3.27 (0.54)</td>
<td>3.41 (0.51)</td>
<td>2.80 (0.07)</td>
</tr>
<tr>
<td>W11</td>
<td>0.83 (0.59)</td>
<td>2.64 (0.42)</td>
<td>2.83 (0.42)</td>
<td>3.12 (0.12)</td>
</tr>
<tr>
<td>W12</td>
<td>1.06 (0.67)</td>
<td>1.55 (0.63)</td>
<td>1.98 (0.67)</td>
<td>3.43 (0.03)</td>
</tr>
</tbody>
</table>
526  **FIGURE CAPTIONS:**

527  Figure 1. Schematic diagram of the experimental set-up. Cross-section of the  
528  equipment (left) and top view of the column (right). Schematic diagram is for set B  
529  experiments.

530  Figure 2. Variation in vertical ($V_Z$) and total ($V$) near surface wind speed as a  
531  function of time for wind condition W9 (Table 2).

532  Figure 3. Relative oxygen concentration ($C/C_{atm}$) as a function of time and depth for  
533  experiment B, under wind condition W3 where $C_{atm}$ is the atmospheric oxygen  
534  concentration. Note that not all individual measurements (taken at 1s intervals) are  
535  shown.

536  Figure 4. Wind-induced dispersion coefficients ($D_w$) as a function of depth at wind  
537  conditions W3, W10 and W11 for: (a) Experiments type A and (b) Experiments type  
538  B.

539  Figure 5. Wind-induced dispersion coefficient, $D_w$, as a function of depth for wind  
540  conditions W1–W12. Symbols indicate $D_w$ values measured during experiment B  
541  and curves are those that fitted best from Equation (10) to the measured data.

542  Figure 6. (a) Breakthrough time, $t_b$ (time to reach 10.5% O$_2$), as a function of depth  
543  below the column surface for wind conditions W0–W12 and (b) relative  
544  breakthrough time (compared to wind condition 0) for wind conditions W1–W12.  
545  Note that the y-axis is reversed to represent measurement location better.
Figure 7. (a) $D_w/D_{w0}$ as a function of depth for wind conditions 1–12. Symbols indicate experimental values and curves are fitted by Equation (10) to the data and (b) experimental values plotted against fitted values of $D_w$ for wind conditions 1–12.

Figure 8. (a) Relation between vertical component of wind ($V_z$) and empirical constant $\alpha$ and (b) relation between empirical constants $\alpha$ and $\beta$. 
Figure 1.
Figure 2.
Figure 3.
Figure 4.
Figure 5.
Figure 6.
Figure 7.
Figure 8.