Optimizing landfill aeration strategy with a 3-D multiphase model

van Turnhout, André G.; Oonk, Hans; Scharff, Heijo; Heimovaara, Timo J.

DOI
10.1016/j.wasman.2019.10.051

Publication date
2020

Document Version
Final published version

Published in
Waste Management

Citation (APA)
van Turnhout, A. G., Oonk, H., Scharff, H., & Heimovaara, T. J. (2020). Optimizing landfill aeration strategy with a 3-D multiphase model. *Waste Management*, *102*, 499-509. https://doi.org/10.1016/j.wasman.2019.10.051

Waste Management 102 (2020) 499–509

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Optimizing landfill aeration strategy with a 3-D multiphase model

André G. van Turnhout [a,*], Hans Oonk [b], Heijo Scharff [c], Timo J. Heimovaara [a]

[a] Geoscience & Engineering Department, Faculty of CiTG, Delft University of Technology, Stevinweg 1, 2628CN Delft, Netherlands
[b] Oonkay!, Fabianusstraat 12, 7333 BD Apeldoorn, Netherlands
[c] NV Afvalzorg Holding, PO Box 2, 1566 PB Assendelft, Netherlands

ARTICLE INFO

Article history:
Received 30 April 2019
Revised 23 October 2019
Accepted 28 October 2019
Available online 21 November 2019

Keywords:
Landfills
Waste treatment
Aeration
Design criteria
3-D multiphase model
Field scale

ABSTRACT

In order to reduce the environmental and financial burden for future generations, approaches are needed to shorten aftercare of landfills. Aeration of the waste-body is a promising approach, however, the poor understanding of transport of gas and water through a waste-body makes it difficult to design an effective aeration strategy. The aim of this study is to develop a tool to determine the optimal aeration strategy for landfills. This study presents a comparison of aeration strategies based on the air distribution they generate with a 3-D multiphase model. The implemented theory is based on parameter values obtained from (laboratory) experiments performed under conditions which are similar to those in a full scale landfill. Calibration with field scale gas extraction data from the Dutch pilot site Wieringermeer shows that the model gives a good description of the average gas flow under extraction. Scenario analyses for the case study landfill indicate that injection strategies reach a larger volume fraction of waste with a higher air flow compared with extraction strategies, especially at the bottom of the landfill. Extraction, however, supplies oxygen more homogeneously through-out the waste. An import design criterion is also the distance between the wells. Too large distances lead to ineffective treatment because too large volumes of waste/leachate remain untreated. In addition to the comparison of aeration strategies, an optimal aeration strategy for the pilot site is presented. A combination of (alternating) injection and extraction wells which are maximum 20 m apart seems to be the optimal strategy.

1. Introduction

Dutch operators and regulators seek approaches to shorten and reduce the aftercare of landfills in order to reduce the environmental and financial burden for future generations. Essential to such an approach is a fast removal of compounds from the waste-body too such extent that the concentrations in remaining emissions are and remain acceptable (Laner et al., 2012; Scharff et al., 2011). The main challenge in developing these approaches is to accelerate the removal mechanisms in a waste-body which are severely inhibited and/or mass transport limited due to heterogeneity (Kjeldsen et al., 2002; Laner et al., 2011; Meima et al., 2008).

Aeration is an approach that showed promising results in lysimeter scale experiments. Injection of air into the waste led to accelerated release of carbon and nitrogen to the leachate and gas phases (Erses et al., 2008; Brandstätter et al., 2015a; Brandstätter et al., 2015b). In general, aeration can lead to oxidation of many problematic compounds which are non-reactive under anaerobic conditions such as NH_4^+ (Bolyard and Reinhart, 2016) and oxidation can lead to immobilization of compounds that co-precipitate with oxidized dissolved organic matter (DOM). Aeration has also been tested on a field scale (Ritzkowski and Stegmann, 2012), however, it has yet to be proven successful for reducing long-term emissions through leachate (Benson et al., 2007; Hrad et al., 2013).

A key factor influencing the effectiveness of aeration on a lysimeter scale is the amount of biodegradable carbon reached by the electron acceptor or main reactant (van Turnhout et al., 2018). Apparently, the most important factor for optimal aeration on a field scale is the distribution of air throughout the waste-body. As a consequence, knowing which aeration strategy yields the optimal distribution of air given the available energy resources and infrastructure is crucial for designing full-scale aeration projects.

Air flow through a waste-body at the field scale is not well understood. Field scale measurements and experiments are very scarce which limits the development of validated conceptual models (Hrad et al., 2013; Ritzkowski et al., 2006; Ritzkowski and Stegmann, 2012). Also, extensive numerical models (Fytanidis and Voudrias, 2014) are over-parametrized which results in poor calibration and therefore prediction. Although such models are

* Corresponding author.
E-mail address: a.g.vanturnhout@tudelft.nl (A.G. van Turnhout).

https://doi.org/10.1016/j.wasman.2019.10.051
0956-053X/

interesting for fundamental insights, it is questionable if they give very realistic simulations of field scale conditions. As a result, a thorough quantitative comparison of different aeration strategies is currently missing in literature.

The aim of this paper is to quantitatively compare different aeration strategies for the distribution of air they generate within a full scale waste-body. In addition, the optimal aeration strategy for the Dutch pilot site Wieringermeer is evaluated for illustrative purposes. A description of this landfill can be found in Scharff and Jacobs (2006). A 3-D model is used for the comparison which is based on fundamental principles from multiphase flow theory in porous media. Liquid and gas phase pressures are coupled. Because the objective is to compare distributions of air, biochemical processes are not included. In general, implemented theory is kept as simple as possible to limit over-parametrization. Material properties are obtained from literature data of lab scale experiments performed under conditions similar to those found in full scale landfills (Powrie and Beaven, 1999; Stoltz et al., 2010b; Stoltz et al., 2010a; Stoltz et al., 2012). Data obtained from gas extraction measurements at the Wieringermeer are used for calibration.

Four common extraction/injection strategies are compared with each other: S1) extraction near the bottom with short filters; S2) injection with long filters; S3) combined extraction (short filters) and injection (long filters); and S4) combined extraction near the bottom and injection near the surface with short filters (Hupe et al., 2003; Ritzkowski and Stegmann, 2012). Details on the wells in these scenarios can be found in Table 2 and Figs. 2, 3. In addition to the above four scenarios, we also present a comparison of four different well distances and an optimal strategy for Wieringermeer. The criterion to assess aeration effectiveness is the minimum air flow rate achieved in a certain volume percentage of the waste-body.

2. Material & methods

2.1. Model implementation

2.1.1. Governing equations

The implemented theory is based on Darcy's law for two-phase flow coupled in a 3-dimensional porous media which gives the flux for a phase α:

$$q_\alpha = -\nabla \frac{\kappa k_{r\alpha}}{\mu_\alpha}(\nabla p_\alpha + \rho_\alpha g \nabla z), \tag{1}$$

where α denotes the phase (w for water and g for the gas phase), q is the flux [m/s], κ is the permeability of the porous medium [m^2], $k_{r\alpha}$ is the relative permeability, μ_α is the viscosity [Pa s], p_α is the pressure [Pa], ρ the density, g the gravitational constant and z the vertical spatial coordinate. The mass balance equations for both phases are given by:

$$\frac{\partial \theta_\alpha \rho_\alpha}{\partial t} + \nabla \cdot \rho_\alpha \boldsymbol{q}_\alpha + R_\alpha = 0, \tag{2}$$

where θ_α is the volumetric fraction of phase α [–], t the time [s] and R_α is the local production term of phase α [$\frac{kg}{m^3 s}$]. The mass balance equations for both phases can be coupled using the capillary pressure which is defined as the difference between the non-wetting and the wetting phase:

$$p_c = p_g - p_w. \tag{3}$$

The phase saturation is defined as the ratio of the volumetric fraction of phase α to the porosity (ϕ [-]):

$$S_\alpha = \frac{\theta_\alpha}{\phi}, \tag{4}$$

which relates the two phase saturations with:

$$S_w + S_g = 1. \tag{5}$$

The van Genuchten equation (van Genuchten, 1980) is used to calculate the effective water saturation (S_e) from the capillary pressure:

$$S_e = \left(1 + (\alpha p_c)^{\frac{1}{1-m}}\right)^{-m} \quad \text{for} \quad p_c > 0, \quad S_e = 1 \quad \text{for} \quad p_c =< 0, \tag{6}$$

where

$$S_e = \frac{S_w - S_{wr}}{1 - S_{wr}}. \tag{7}$$

Combining all above leads to two equations which describe the coupled rate of change in the pressures in both the water and the gas phase:

$$\phi \rho_w (S_w \beta_w - C_p) \frac{\partial p_w}{\partial t} + \nabla \cdot \rho_w \boldsymbol{q}_w = -\phi \rho_w C_p \frac{\partial p_g}{\partial t} - R_w \tag{8}$$

and

$$\phi \rho_g (S_g \beta_g - C_p) \frac{\partial p_g}{\partial t} + \nabla \cdot \rho_g \boldsymbol{q}_g = -\phi \rho_g C_p \frac{\partial p_w}{\partial t} - R_g, \tag{9}$$

where β_α is the compressibility for phase α and C_p is the specific moisture capacity which is defined as:

$$C_p(p_c) = \frac{\partial S_w(p_c)}{\partial p_c} = (1 - S_w) \frac{\partial S_e(p_c)}{\partial p_c} \tag{10}$$

2.1.2. Material properties

The properties of landfilled waste are obtained from either data from lab scale experiments performed under conditions similar to landfilled conditions found in the literature or measurements performed at the field site under investigation (of which details are given in the section: Site characteristics and criteria for optimization). Porosity in the waste body decreases with depth:

$$\phi = \mathrm{a} + \frac{z}{\mathrm{b} - \mathrm{c}z}, \tag{11}$$

where the range is taken from Stoltz et al. (2010a) and the curvature is taken from White et al. (2014) which leads to a = 0.6125, b = 133.84 and c = 5.258. Intrinsic permeability is derived from the porosity with a power law fitted by Stoltz et al. (2010b) on measured data:

$$\kappa = 3.82 \times 10^{-8} \cdot n^{18.13}. \tag{12}$$

Because permeability of the waste body is anisotropic (Powrie and Beaven, 1999) and its value is derived from an averaged measured porosity (Eq. (12)), permeability is set 2x higher than its averaged value in the horizontal direction and 2x lower in the vertical direction. Profiles of porosity and intrinsic permeability along the height (z) are presented in the supplementary information in Fig. 1.

The van Genuchten parameters in Eq. (6) are obtained from measurements performed by Stoltz et al. (2010a), Stoltz et al. (2012). The associated water retention curve is shown in the supplementary information in Fig. 2 for a porosity of 0.7. The relative permeabilities for the water and gas phase are calculated with:

$$k_{rw} = S_e^{L_w}\left(1 - \left(1 - S_e^{\frac{1}{G_w}}\right)^{G_w}\right)^2 \tag{13}$$

and

$$k_{rg} = (1 - S_e)^{L_g}\left(1 - S_e^{\frac{1}{G_g}}\right)^{2G_g}, \tag{14}$$

where L_w and G_w are taken from White et al. (2014) and L_g and G_g are taken from Stoltz et al. (2010b). The relative permeability of the water and gas phase are also shown in the supplementary information in Fig. 2.

The density and compressibility of the gas phase are calculated from the ideal gas law as:

$$\rho_g = \frac{p_g M_g}{RT} \tag{15}$$

and

$$\beta_g = \frac{1}{\rho_g}\frac{\partial \rho_g}{\partial p_g} = \frac{M_g}{RT\rho_g} \tag{16}$$

where M_g is the molar mass of the gas phase, R is the universal gas constant and T is the ambient temperature [K]. All parameters related to material properties are listed in Table 1. The gas generation rate (R_g) was modeled for the site under investigation. The modeled results were checked for plausibility by means of gas extraction tests. The water production rate within the waste body is set to zero because it is expected to be very low or zero at the site under investigation.

2.1.3. Geometry, boundary and initial conditions

The waste-body is modeled as a block with periodic, continuous boundary conditions at its sides. The size of the block and the placing of the wells depend on the type of aeration strategy under investigation. In the supplementary information in Fig. 3, two geometries for air extraction with different well spacing and filter lengths are shown together with the mesh.

The boundary conditions at the top are Neumann for the water phase (F_w^{top} = 1 mm d^{-1}) and Dirichlet for the gas phase:

$$p_g^{top} = p_{atm} e^{\frac{M_g g\left(z^{wt} - z_{top}\right)}{RT}} \tag{17}$$

where p_{atm} is the atmospheric pressure, z^{wt} is the height of the water table and z_{top} is the height of the waste-body. The boundary conditions at the bottom are Neumann for the water phase given by:

$$F_w^{bot} = \rho_w \frac{\kappa k_{rw}}{\mu_w}\left(\frac{p_{atm} + \left(z^{wt} - z^{bot}\right)\rho_w g}{K_{res}}\right) \tag{18}$$

where z^{bot} is the height of the bottom of the landfill and K_{res} is the resistance in the drainage layer. For the gas phase the boundary conditions at the bottom are Dirichlet:

$$p_n^{bottom} = p_{atm} e^{\frac{M_g g\left(z^{wt} - z^{bot}\right)}{R \cdot T}}. \tag{19}$$

The boundary conditions at the filters for the gas phase are Dirichlet which impose pressure differences in relation to the atmosphere. The wells are impermeable with respect to the water phase.

The initial water and gas pressures in the modeled domain follow the hydrostatic conditions

$$p_w^{ini} = p_{atm} + \rho_w g \cdot \left(z^{wt} - z\right) \tag{20}$$

and

$$p_g^{ini} = p_{atm} e^{\frac{M_g g\left(z^{wt} - z\right)}{RT}}. \tag{21}$$

2.1.4. Model resolution

The model is implemented in COMSOL 5.2 using two Coefficient Form PDE modules that are coupled. The mesh size is automatically generated with the option size fine. An example of the mesh size is given in the supplementary information in Fig. 3. Equations are solved with the stationary solver (standard settings). A parametric sweep is used to investigate the steady state distribution of water and gas pressures for a series of gas pressures applied at the well boundaries.

2.2. Modeled scenarios

2.2.1. Scenarios for comparing aeration strategies

Modeled scenarios of aeration strategies are compared in two steps. In the first step, four injection/extraction strategies are compared based on the air distributions they generate. These strategies are: S1) air extraction with short, deep filters; S2) air injection with long filters; S3) a combination of air injection with long filters and air extraction with short, deep filters and S4) a combination of air injection with short, shallow filters and air extraction with short, deep filters. In the second step, effectiveness of the best injection/extraction strategy from step 1 is further evaluated with four well distances. In addition, an optimal aeration strategy is found for the Dutch pilot site Wieringermeer (of which details are given below). Details of all scenarios are listed in Table 2.

2.2.2. Site characteristics and criteria for optimization used in the scenarios

To illustrate the comparison of aeration strategies with realistic waste-body properties, the characteristics of the Dutch pilot site Wieringermeer are used of which a description can be found at Scharff and Jacobs (2006). At this pilot site, full-scale aeration will be carried out at one landfill cell to demonstrate the effectiveness of a sustainable approach towards landfill management. This pilot site represents an ideal case for our model scenarios. The cell has a height of 12 m and an area of 2.6 ha. In the period 1992–1996 this compartment received mainly industrial waste, with smaller amounts of demolition waste, contaminated soils and composting waste. The total amount of waste deposited is 280.000 tons. The waste-body has an estimated wet density of 1.28 $\frac{\text{ton}}{\text{m}^3}$ and approximately 19 kg biodegradable carbon left per m^3 of waste (van Vossen and Heyer, 2009). This amount of biodegradable carbon was estimated with a model based on waste composition (Afvalzorg, 2009).

To find the optimal aeration strategy for this site, the following criteria are important. The landfill operator aims to convert 80% of

Table 1
Values of model parameters implemented in the model. All values that are related to material properties are retrieved from (laboratory) measurements under landfilled conditions. Environmental conditions are set to standard average values. The van Genuchten parameter m was used to fit measured data. The value for gas production [R_g] is the average gas extraction measured during an extraction experiment at the pilot site.

T	298	K	R	8.31	$\frac{\text{J}}{\text{mol}\cdot\text{K}}$	p_{atm}	1	bar	ρ_w	1000	$\frac{\text{kg}}{\text{m}^3}$
z^{top}	12	m	z^{bot}	0	m	μ_w	0.001	Pa · s	μ_g	1.81×10^{-5}	Pa · s
β_w	4.55×10^{-10}	$\frac{1}{\text{Pa}}$	M_g	28.97	$\frac{\text{g}}{\text{mol}}$	z^{wt}	0.5	m	S_{wr}	0.4	–
m	0.26	–	α	0.0025	$\frac{1}{\text{Pa}}$	L_w	0.5	–	G_w	0.7	–
L_g	5.2	–	G_g	0.3	–	R_g	0.292	$\frac{\text{g}}{\text{m}^3\cdot\text{h}}$	K_{res}	0.01	m
F_w^{top}	0.001	$\frac{m}{d}$									

Table 2
Specifications of the modeled aeration scenarios and specifications of the gas extraction experiments used for calibration and validation.

	R_{well} [m]	L_s [m]	z_{well}^{bottom} [m]	type1)	D_{space} [m]
Calibration	0.5	7	−10	extraction	60
Validation	0.0315	0.9	−10	extraction	10
$S1_{D10}$	0.0315	0.9	−10	extraction	10
$S2_{D10}$	0.0315	5	−10	injection	10
$S3_{D10}$	0.0315	$[2 \times 0.9\ 2 \times 6.4]^{2)}$	−10	extraction-injection	10
$S4_{D10}$	0.0315	0.9	$[2 \times -10\ 2 \times -2.9]^{3)}$	extraction-injection	10
$S3_{D16.5}$	0.0315	$[2 \times 0.9\ 2 \times 6.4]^{2)}$	−10	extraction-injection	16.5
$S3_{D20}$	0.0315	$[2 \times 0.9\ 2 \times 6.4]^{2)}$	−10	extraction-injection	20
$S3_{D30}$	0.0315	$[2 \times 0.9\ 2 \times 6.4]^{2)}$	−10	extraction-injection	30

R_{well}: radius of the well, L_s: filter screen length, z_{well}^{bottom}: bottom of well screen, D_{space}: well spacing. 1) for each type, a pressure difference is applied between either the extraction/injection well and the environment or between the extraction and injection wells. 2) the long filters are used for injection, the short filters for extraction. 3) the injection wells are shallow and the extraction wells deep.

the remaining carbon via aeration. This target value is in agreement with Emission Target Values set by the Dutch authorities (Brand et al., 2016). To achieve this within 8 years, approximately 21.5 $\frac{m^3_{air}}{m^3_{waste} \cdot y}$ is required assuming an oxygen consumption of 80% and a conversion of 2.67 kg O_2 per kg C. Even more, this 21.5 $\frac{m^3_{air}}{m^3_{waste} \cdot y}$ has to be achieved in at least 85% $\frac{v}{v}$ of the waste-body considering the inevitable heterogeneous distribution of air throughout the waste-body. Also, sufficient air must be especially received by the lower part of the waste-body, assuming that the quality of leachate that infiltrates the sub-surface is mainly determined here. An important operational restriction (reduction of power consumption) is that pressure differences at the injection or extraction wells should not exceed 50 mbar which is considered to be sufficient as the height of the landfill is 12 m.

2.2.3. Data for calibration and validation

The model used for the scenario analyses is calibrated using measured flow rates during a gas extraction experiment carried out at the pilot site. In this experiment, gas flow was measured through each individual gas well during low pressure extraction on a set of gas wells. The vacuum on the gas wells was stepwise increased (in 14 steps) from about 1 to 28 mbar. After each step, gas collection was allowed to stabilize for 2–3 days and subsequently the amount of landfill gas recovered was measured for each individual well. Data measured during this experiment are presented in Fig. 1 and further details of this experiment are listed in Table 2. To fit the modeled data to the measured data, only a value for the parameter m of the water retention curve was selected within the range measured in the experiments performed by Stoltz et al. (2012).

The calibrated model was validated by simulating a very different type of extraction experiment that was also performed at the pilot site. In this experiment, suction was applied at single wells and well distances, the well radius and the length of the well screens were smaller compared with the experiment used for calibration (Table 2). Simulated and measured data are compared that correspond to the gas flow through individual wells and the gas pressures in the wells surrounding the gas well on which suction was applied. Measured data is presented in Fig. 1.

3. Results & discussion

The aim of this study is to compare aeration strategies based on the air distributions they generate throughout the waste-body. In addition, it is evaluated which aeration strategy is optimal for the Dutch pilot site Wieringermeer. Optimization criteria are a minimum flow rate of 21.5 m^3 air per m^3 waste per year in at least 85%(v/v) of the waste-body, gas pressure differences in the injection and/or extraction filters that are less than 50 mbar (to reduce

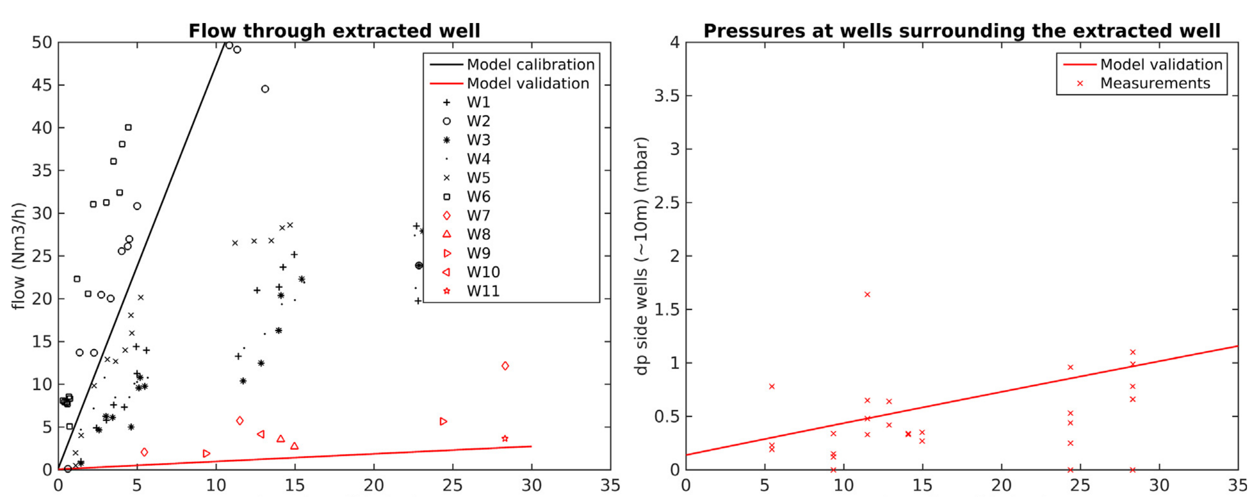

Fig. 1. Modeled and measured data for calibration are presented in black. To fit the measured flow rates through single extraction wells (W1-W6), the van Genuchten parameter m was set to 0.26. Modeled and measured data for validation are presented in red. The left graph shows data on extraction flows through single wells (W7-W11) and the right graph shows the pressure drops in wells surrounding the extraction well. The calibration and validation experiments differ in well dimensions, well distances and types of filters. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

energy consumption) and good aeration in the lower parts of the waste body.

3.1. Calibration & validation

Before the model is used for comparison and optimization, it was first calibrated and validated. Fig. 1 presents in black the fitted model results and the measured flow rates through single wells during extraction (W1-W6) used for calibration. These results show that the average behavior of gas extraction at field scale is reproduced with this model using only parameter values which are retrieved from (laboratory) measurements under landfilled conditions. The van Genuchten parameter was used to fit the measured data. Its calibrated value ($m = 0.26$) falls in the range measured by Stoltz et al. (2012). The wide spread in measured flows per well indicates that heterogeneity has a significant impact on the gas extraction. The model does not include heterogeneity yet and it can therefore only be used to estimate average flow behavior at field scale. As heterogeneity cannot yet be sufficiently quantified, it can also not be included in the modeling other than a sensitivity analysis. The averaged comparison therefore is an appropriate approach to determine the effectiveness of aeration strategies.

Furthermore, for the sake of objective comparison of the aeration strategies, the distribution of water throughout the landfills was simulated as steady state (constant inflow and outflow of water at the boundaries). This to solely compare the impact of different aeration strategies on the distribution of air throughout the waste-body. However, since (steady state) water distribution is accounted for in the modeled scenarios, the van Genuchten parameter has a significant influence on gas flow due to the coupling of both phases. The van Genuchten parameter influences the effective saturation and thereby influences the relative permeability of the gas phase. This explains the impact of a change in the value of the van Genuchten parameter on the modeled gas flow in Fig. 1. A different value for the van Genuchten parameter would increase or decrease the averaged gas flux through the wells.

In order to validate our model, we applied the calibrated model to simulate a second type of field scale experiment in which completely different types of filters were used. Fig. 1 presents the modeled and measured data for this extraction experiment (in red) in which well dimensions and distances were smaller compared with the experiment used for calibration. In the left graph, extraction flow through single wells (W7-W11)) is presented. In the right graph, the pressure drop in filters nearby the extraction well are presented. The agreement between the modelled and measured pressure drops in nearby wells increases our confidence in the correctness of the modeled gas permeability throughout the waste-body.

3.2. Comparison of aeration strategies (step 1)

Four different aeration scenarios were compared with each other using the calibrated model. Figs. 2 and 3 present the air distribution generated by these four strategies through-out the block of waste at a pressure difference of 50 mbar. Volumes with high flow rates are red and volumes with low flow rates are blue. Clearly, the injection strategy S2 generates the highest flow rates in the largest volume of the waste block. It therefore produces the most optimal air distribution at a set pressure difference compared with the other strategies. Even more, the S2 strategy also produces the highest flow rates near the bottom of the landfill where most oxygen is needed because leachate accumulates here. However, strategies that are based on only injection are not accepted by the Dutch authorities because the emission and treatment of off-gas cannot be controlled.

A strategy that combines gas injection with gas extraction may be more beneficial than applying only injection anyway. With injection only, most of the oxygen is depleted near the filters due to degradation. The waste that is positioned further away from the filters is therefore poorly treated as it receives little oxygen even at reasonable air flows. When adding extraction, air converges as it flows from injection to extraction filter which leads to concentration of the remaining oxygen in the air, thereby countering the oxygen depletion. In addition, extraction may also induce inward airflow via the surface of the waste-body thereby supplying more oxygen near the surface (this however is only true for landfills without an impermeable cover layer, as at the pilot site). An aeration strategy that combines injection and extraction can therefore generate a more optimal and homogeneous distribution of oxygen throughout the waste-body compared with applying only injection.

How injection and extraction are combined, however, is also important. This is indicated by the air distributions generated with strategy S3 and S4 (Fig. 3). While S3 still generates a reasonable air distribution, S4 leads to a very poor treatment near the bottom of the waste. To further investigate oxygen distributions generated by the aeration strategies discussed, we recommend to add transport of gases by convection in the gas phase to the implemented theory in the model.

3.3. Comparison of aeration strategies (step 2)

Another important aspect that influences the air distribution generated by an aeration strategy is the spacing between the filters. This aspect was investigated for aeration strategy S3 with well spacings of 10 m, 16.5 m, 20 m and 30 m. The generated air flow distributions are presented in Figs. 4 and 5. They show that when well distances become larger, the volume of the waste that is treated with a significant flow of air becomes smaller. This means that the effectiveness of aeration treatment is highly dependent on the well distance applied. A too large distance may result in large volumes of untreated waste which after treatment still significantly contribute to the emitted concentrations via leachate.

3.4. Optimal aeration strategy for the Dutch pilot site Wieringermeer

Aeration strategy S3 was also used to advise on an optimal strategy for the Dutch pilot site Wieringermeer. S3 was chosen in this study because it combines injection with extraction (which should distribute oxygen more homogeneously) and it produces a good air flow distribution near the bottom of the waste where leachate accumulates. An optimal aeration is achieved when a minimum of 85 % of the total waste volume is affected by a minimum air flow of $21.5 \frac{m^3_{air}}{m^3_w \cdot y}$. It was therefore investigated which fraction of the total waste volume is reached by an air flow larger than $21.5 \frac{m^3_{air}}{m^3_w \cdot y}$ for different well spacings (10 m, 16.5 m, 20 m and 30 m) under different applied gas pressures. Results are presented in Fig. 6 in which the dashed horizontal line indicates the criterion of 85% of the total waste volume affected by the desired minimum flow rate. Results show that this criterion can be met with a well spacing of 20 m and an applied pressure difference of at least 35 mbar. Smaller well spacing could also be interesting because lower pressure difference are required, thereby reducing operational costs. However, smaller well spacing also increases investment costs. An optimal balance should be found between both.

An interesting fact that is also indicated in Fig. 6 is that even when no pressure difference is applied air flow is generated. This

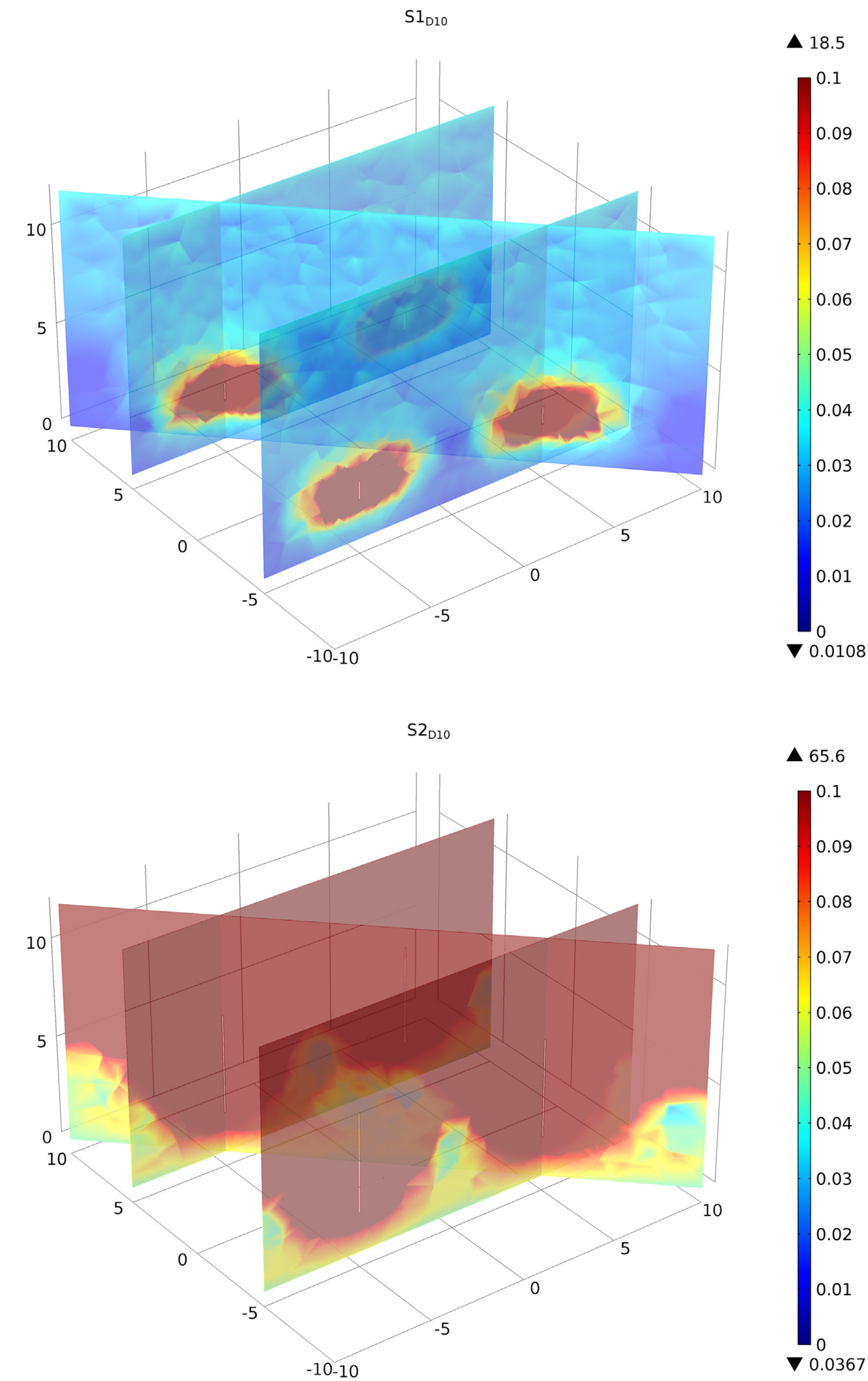

Fig. 2. The distribution of airflow ($\frac{m}{h}$) through-out the model domains for air extraction with short, deep filters ($S1_{D10}$ and air injection with long filters ($S2_{D10}$)) for a well spacing of 10 m and a pressure difference of 50 mbar. The rainbow color scale indicates the magnitude of the airflow rates. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

can be explained by natural convection which is stimulated due to perforation of the waste. The natural convection logically increases with smaller well distances. Perforation of the waste without active injection or extraction afterwards might therefore also be an option for treatment.

As a final note, we like to point out that care must be taken with estimating optimal values for well distances with this homogeneous modeling approach. Although on average a well distance may be optimal, in practice, heterogeneity has a significant impact on gas permeability. For further model development, the addition

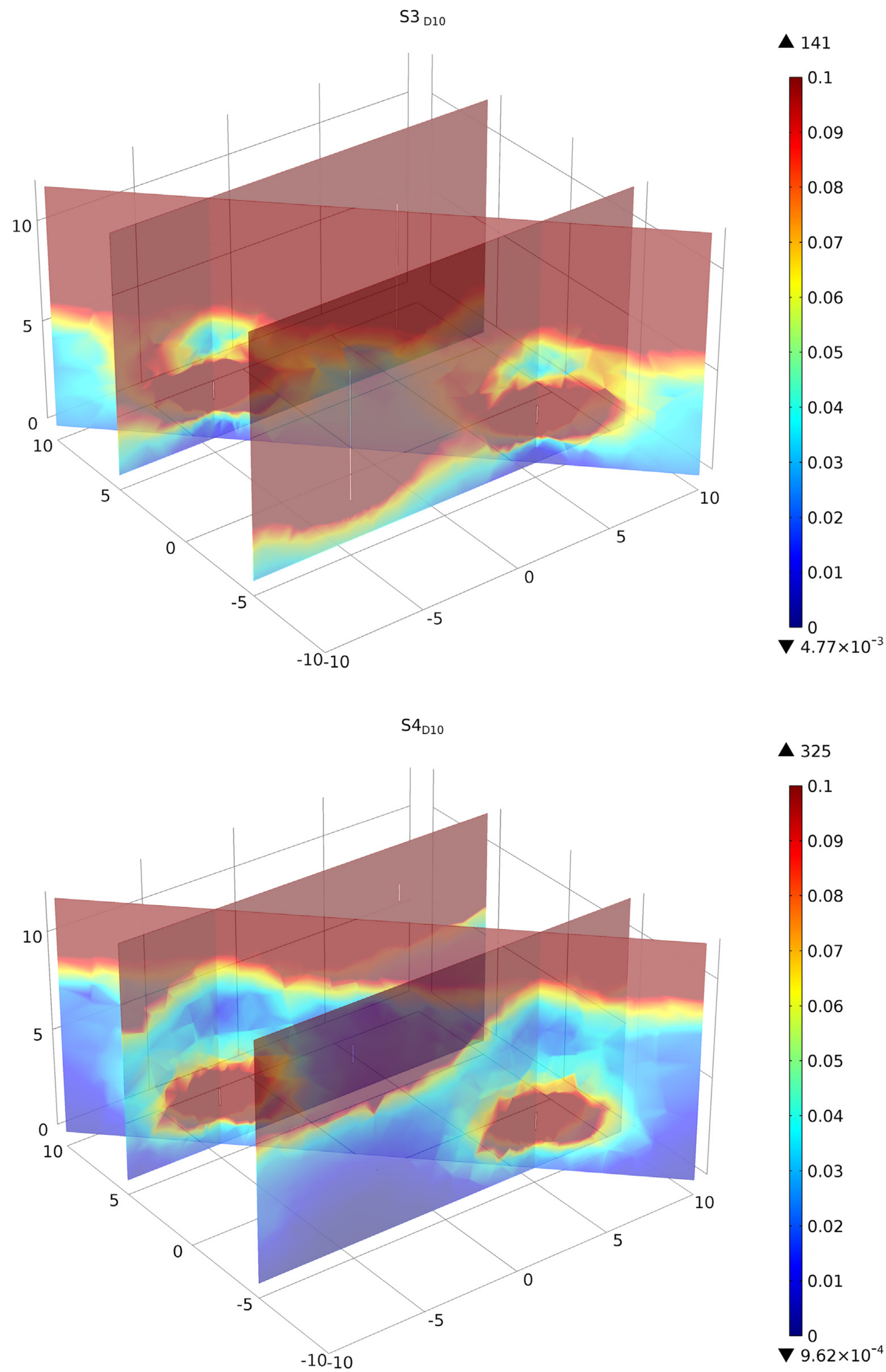

Fig. 3. The distribution of airflow $(\frac{m}{h})$ through-out the model domains for a combination of air injection with long filters and air extraction with short, deep filters ($S3_{D10}$) and a combination of air injection with short, shallow filters and air extraction with short, deep filters ($S4_{D10}$)) for a well spacing of 10 m and a pressure difference of 50 mbar. The rainbow color scale indicates the magnitude of the airflow rates. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of a simplistic mechanism for heterogeneity in permeability may already significantly improve prediction accuracy. Also, extending the model with biochemical processes and heat transport may improve model predictions by considering their impact on treatment effectiveness.

4. Conclusions

A 3-D multiphase model was developed to compare the effectiveness of different aeration strategies at the field scale and to find an optimal aeration strategy for the Dutch pilot site Wieringer-

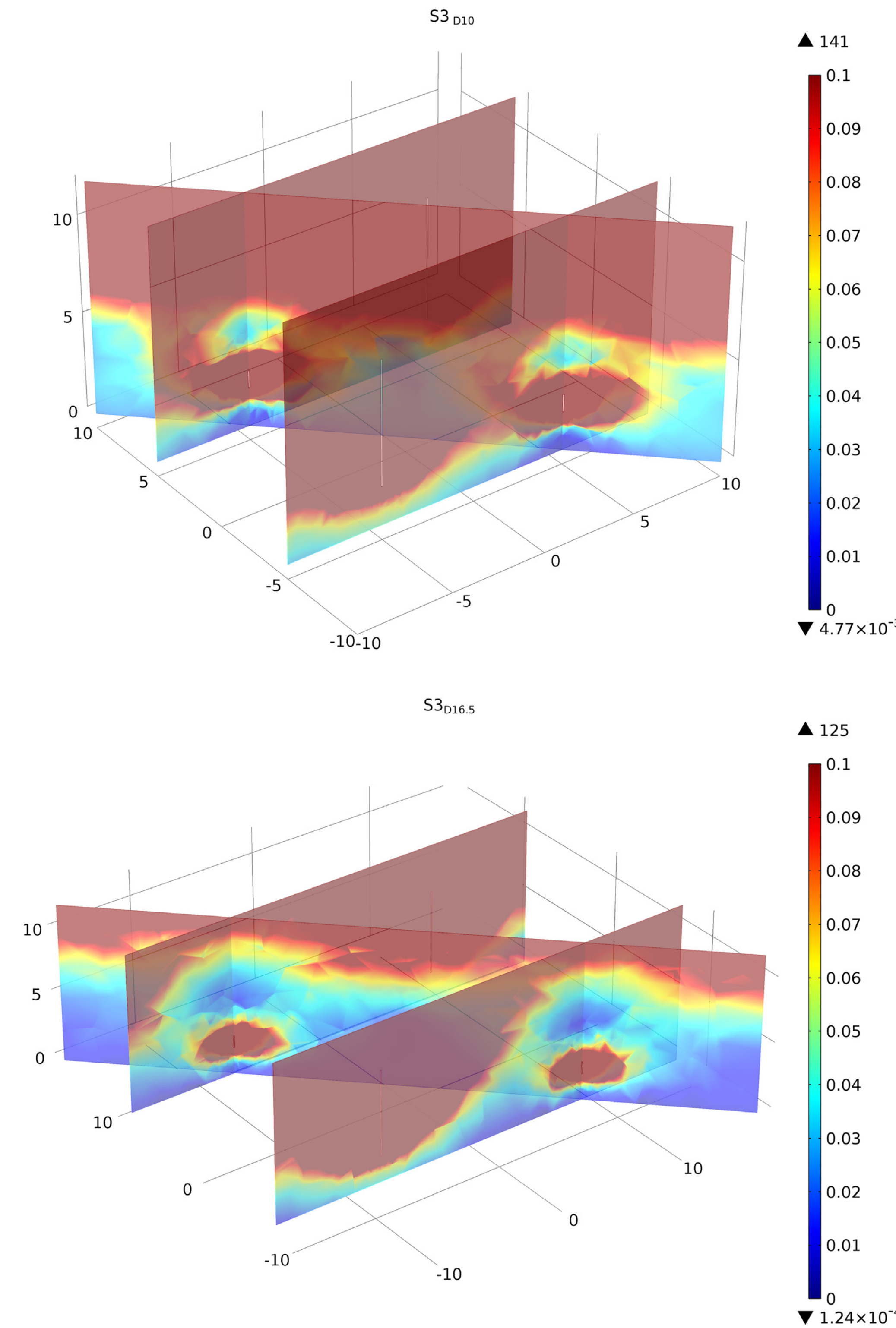

Fig. 4. A further investigation of the air flow distribution generated by strategy S3 (air injection with long filters combined with air extraction with short, deep filters) for well spacings of 10 m and 16.5 m. The rainbow color scale indicates the magnitude of the airflow rates ($\frac{m}{h}$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

meer. Model calibration and validation resulted in good agreement between modeled and measured field scale extraction data. In addition, confidence in the plausibility of the modeled scenarios is increased by the fundamental nature of the model which is based on material properties obtained from laboratory experiment under landfilled conditions.

Four aeration strategies were compared based on the distribution of air they generate through-out the waste-body. Injection generates the highest air flow in the largest volume of the waste-body. It also distributes most air towards the bottom of the waste-body. Extraction, however, can provide a more homogeneous distribution of oxygen throughout the waste because oxygen

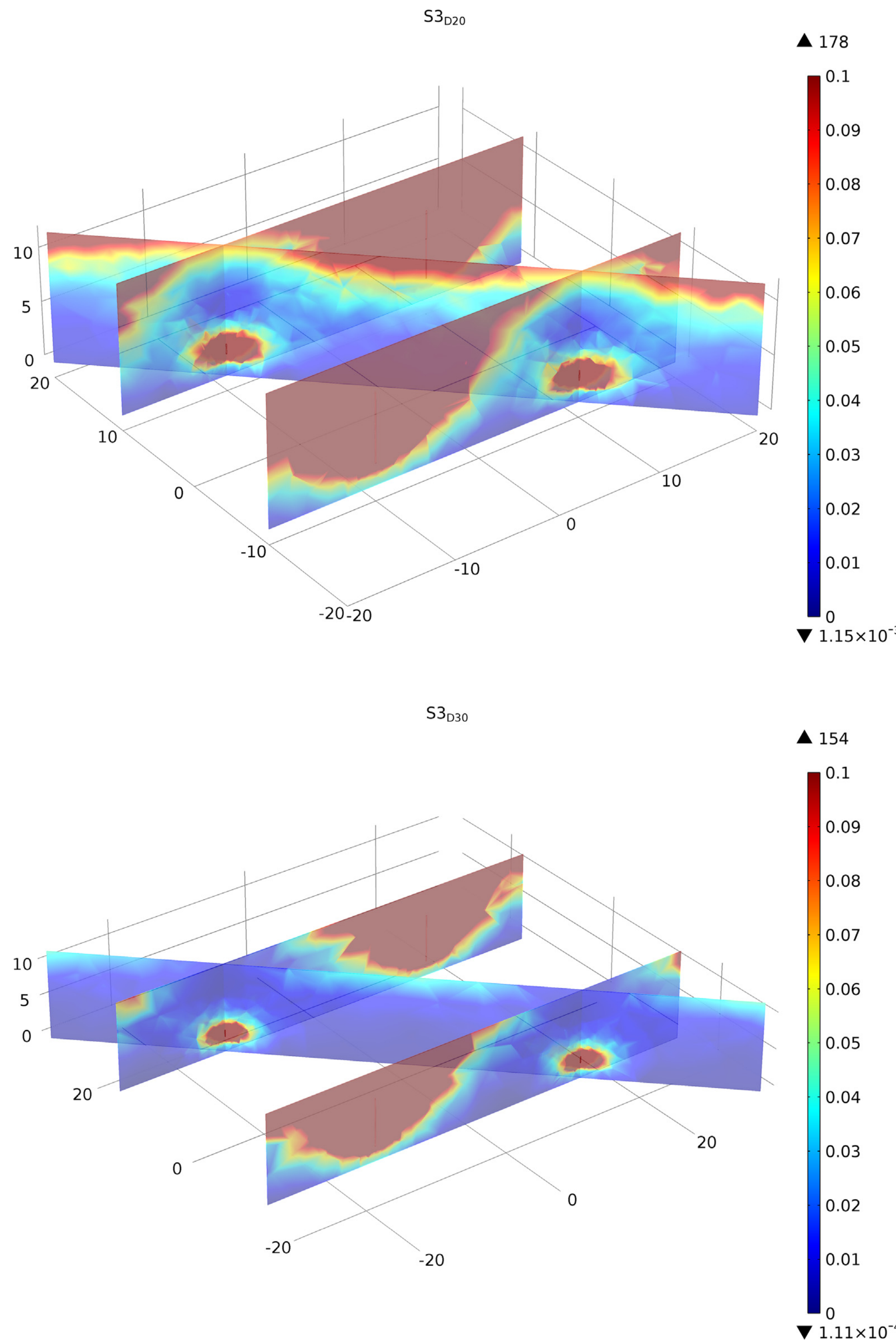

Fig. 5. A further investigation of the air flow distribution generated by strategy S3 (air injection with long filters combined with air extraction with short, deep filters) for well spacings of 20 m and 30 m. The rainbow color scale indicates the magnitude of the airflow rates ($\frac{m}{h}$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

depletion in the transported air is balanced by convergence of flow from injection to extraction wells. A combination of (alternating) injection and extraction wells may therefore be most efficient.

A comparison of scenarios with different well spacings indicates that the distance between injection/extraction wells must be small enough for effective treatment. The risk of using a too large well distance is that a large volume of the waste-body and leachate will remain untreated. Interestingly, small well distances lead to significant natural convection through-out the waste-body due to perforation which might be an alternative option for treatment.

The optimal aeration strategy for the Dutch pilot site Wieringermeer is a combination of injection and extraction with a well dis-

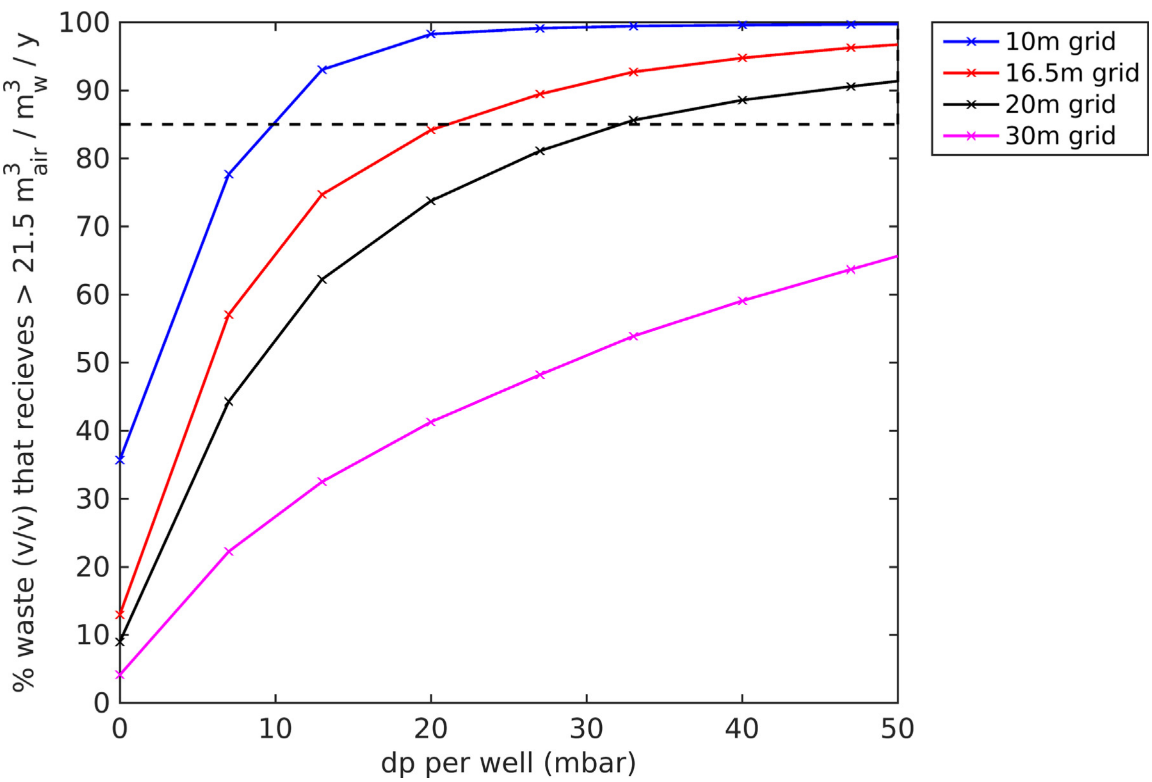

Fig. 6. The results of an optimization to find the best aeration strategy for the Dutch pilot site Wieringermeer based on strategy S3 (air injection with long filters combined with air extraction with short, deep filters). This figure presents the percentage of the total volume of the waste that receives an air flow rate larger than $21.5\,\frac{m^3_{air}}{m^3_w \cdot y}$ for well spacings of 10 m, 16.5 m, 20 m and 30 m and pressure differences between 0 and 50 mbar. The aim of the landfill operators is to treat at least 85 % of the waste-body (indicated by the dashed line in the figure) with an air flow larger than $21.5\,\frac{m^3_{air}}{m^3_w \cdot y}$.

tance of 20 m and applied pressure differences of at least 35 mbar. However, these design criteria must be interpreted with care because heterogeneity of the waste-body is not included in the model. Most likely, the model overestimates the effectiveness of all aeration strategies.

Declaration of Competing Interest

None.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.wasman.2019.10.051.

References

Afvalzorg (2009). Simple landfill gas generation and emission model. https://www.afvalzorg.nl/publicaties/rapporten/simple-landfill-gas-generation-and-emission-model/.

Benson, C.H., Barlaz, M.A., Lane, D.T., Rawe, J.M., 2007. Practice review of five bioreactor/recirculation landfills. Waste Manage. (New York, N.Y.) 27 (1), 13–29.

Bolyard, S.C., Reinhart, D.R., 2016. Application of landfill treatment approaches for stabilization of municipal solid waste. Waste Manage. 55, 22–30.

Brand, E., de Nijs, T., Dijkstra, J., Comans, R., 2016. A novel approach in calculating site-specific aftercare completion criteria for landfills in The Netherlands: Policy developments. Waste Manage. 56, 255–261.

Brandstätter, C., Laner, D., Fellner, J., 2015a. Carbon pools and flows during lab-scale degradation of old landfilled waste under different oxygen and water regimes. Waste Manage. 40, 100–111.

Brandstätter, C., Laner, D., Fellner, J., 2015b. Nitrogen pools and flows during lab-scale degradation of old landfilled waste under different oxygen and water regimes. Biodegradation 26 (5), 399–414.

Erses, A.S., Onay, T.T., Yenigun, O., 2008. Comparison of aerobic and anaerobic degradation of municipal solid waste in bioreactor landfills. Bioresource Technol. 99 (13), 5418–5426.

Fytanidis, D.K., Voudrias, E.A., 2014. Numerical simulation of landfill aeration using computational fluid dynamics. Waste Manage. 34 (4), 804–816.

Hrad, M., Gamperling, O., Huber-Humer, M., 2013. Comparison between lab- and full-scale applications of in situ aeration of an old landfill and assessment of long-term emission development after completion. Waste Manage. 33 (10), 2061–2073.

Hupe, K., Koop, A., Ritzkowski, M., 2003. The low pressure aeration of landfills: experience, operation and costs. In: Proceedings Sardinia 2003, Ninth International Waste Management and Landfill Symposium, number 9. CISA, Environmental Sanitary Engineering Centre.

Kjeldsen, P., Barlaz, M., Rooker, A.P., Ledin, A., Christensen, T.H., 2002. Present and Long-Term Composition of MSW Landfill Leachate: A Review. Crit. Rev. Environ. Sci. Technol. 32 (4), 297–336.

Laner, D., Crest, M., Scharff, H., Morris, J.W.F., Barlaz, M.A., 2012. A review of approaches for the long-term management of municipal solid waste landfills. Waste Manage. (New York, N.Y.) 32 (3), 498–512.

Laner, D., Fellner, J., Brunner, P.H., 2011. Future landfill emissions and the effect of final cover installation–a case study. Waste Manage. (New York, N.Y.) 31 (7), 1522–1531.

Meima, J.A., Naranjo, N.M., Haarstrick, A., 2008. Sensitivity analysis and literature review of parameters controlling local biodegradation processes in municipal solid waste landfills. Waste Manage. (New York, N.Y.) 28 (5), 904–918.

Powrie, W., Beaven, R., 1999. Hydraulic properties of household waste and implications for landfills. Proceedings of the ICE - Geotech. Eng. 137 (4), 235–247.

Ritzkowski, M., Heyer, K.-U., Stegmann, R., 2006. Fundamental processes and implications during in situ aeration of old landfills. Waste Manage. (New York, N.Y.) 26 (4), 356–372.

Ritzkowski, M., Stegmann, R., 2012. Landfill aeration worldwide: concepts, indications and findings. Waste Manage. (New York, N.Y.) 32 (7), 1411–1419.

Scharff, H., Jacobs, J., 2006. Applying guidance for methane emission estimation for landfills. Waste Manage. (New York, N.Y.) 26 (4), 417–429.

Scharff, H., van Zomeren, A., van der Sloot, H.A., 2011. Landfill sustainability and aftercare completion criteria. Waste Manage. Res.: J. Int. Solid Wastes Public Cleans. Assoc., ISWA 29 (1), 30–40.

Stoltz, G., Gourc, J.P., Oxarango, L., 2010a. Characterisation of the physico-mechanical parameters of MSW. Waste Manage. 30 (8–9), 1439–1449.

Stoltz, G., Gourc, J.P., Oxarango, L., 2010b. Liquid and gas permeabilities of unsaturated municipal solid waste under compression. J. Contam. Hydrol. 118 (1–2), 27–42.

Stoltz, G., Tinet, A., Staub, M.J., Oxarango, L., Gourc, J., 2012. Moisture Retention Properties of Municipal Solid Waste in Relation to Compression. J. Geotechn. Geoenviron. Eng. 138 (April), 535–543.
van Genuchten, M.T., 1980. A Closed-form equation for predicting the hydraulic conductivity of unsaturated soils1. Soil Sci. Soc. Am. J. 44 (5), 892.
van Turnhout, A.G., Brandstaetter, C., Kleerebezem, R., Fellner, J., Heimovaara, T.J., 2018. Theoretical analysis of municipal solid waste treatment by leachate recirculation under anaerobic and aerobic conditions. Waste Manage. 71, 246–254.
van Vossen, W., Heyer, K., 2009. Feasibility study sustainable emission reduction at the existing landfills Kragge and Wieringermeer in the Netherlands. Technical Report March, Royal Haskoning.
White, J.K., Nayagum, D., Beaven, R.P., 2014. A multi-component two-phase flow algorithm for use in landfill processes modelling. Waste Manage. 34 (9), 1644–1656.