Simulation of aeration process in landfill with preferential flow and immobile zone

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ABSTRACT

Evaluation of oxygen distribution during aeration in landfill is significantly important to determine the design parameters of an injection well. A coupling model, linked the effect of advection–diffusion and oxidation reaction and mass exchange between the fracture and the matrix system, describing gas preferential transport in a landfill, was developed. The quantitative simulation of the variation in gas distribution during vertical well aeration in short term was presented, combined with the typical cases in field site. The parameter sensitivity in the coupling model to gas transport was addressed. Simulation result of the oxygen and methane concentrations by using the dual advective–diffusive (DAD) model, which considered the immobile zone effect, was closer to the monitoring data than that by using SAD model. When using the single advective–diffusive (SAD) model, the gas curve was obviously delayed. The residual concentration of the oxygen and methane was contributed by the immobile zone fraction. This study provided reference for the design of the gas injection well distribution in aerobic landfill.

Keywords: preferential flow; modeling; oxygen transport; landfill

1 INTRODUCTION

Aeration is one of the most effective methods for in situ repair in old landfill. The achievement of abundant oxygen in waste layer by adjusting the operation of the air injection well is the general aim, which needs understanding the gas transport behavior in landfill body (Liu et al.,2016a).

A mathematical model is the foundation for the quantified evaluation of oxygen transport behavior. Cossu et al. (2005) predicted the aeration radius (AR) of an injection well using the continuity equation with gas pressure. With oxygen flow at the pressure gradients, the mass will be consumed, consequently decreasing its concentration. The models from Yuan et al. (2009) and Fytanidis and Voudrias (2014), provided reference for further studying the oxygen transport behavior in landfill. However, the modeling of oxygen transport in landfill, especially under the preferential flow effect, has not been reported. The major factors contributing to the variation in aeration rate have not been determined. These two issues are necessary to determine the gas well distribution and operation plan in aeration projects.

Nevertheless, several researchers have found, based on the lab and field site tests, that the obvious preferential flow effect occurs in landfill body with the heterogeneity in the pore structure (Liu et al., 2016b; Yazdani et al., 2015; Liu et al.,2016c). Given that gas concentration diffusion was contributed by pressure gradient, the distribution of oxygen concentration in landfill would also be affected by preferential pathways.

The aims of this paper were: 1) to develop an oxygen transport model which considered the preferential flow effect and chemical reaction between the oxygen and methane; 2) to predict the variation of the oxygen during injection process in immobile zone and mobile zone.

2 OXYGEN TRANSPORT MODEL

The transport behavior of oxygen in landfill was influenced by the effect of advection–diffusion and biodegradation reaction and temperature (Cossu and Cestaro, 2005; Fytanidis and Voudrias, 2014; Liu et al., 2014). The consumption of oxygen and methane was determined by the biodegradation reaction. Given the short-term effect in this study, the temperature and water content were assumed to be constant, which insignificantly contributed to biodegradation and gas flow. The effect of the temperature on the aerobic reaction and gas transport was ignored.

We assumed that: The pore media of the waste body was consistent with the mobile zone and the immobile zone. The mobile zone in landfill could be divided into two regions, the matrix region (less mobile areas) and fracture region (fast mobile areas).

The gas transport in the waste body could be described by two coupled advective–diffusive equations, namely,

$$\frac{\partial}{\partial t}(n_f C_{if}) = \nabla(n_f D_{if} \nabla C_{if}) - \nabla(V_{if} C_{if}) - n_f R_{if} - \frac{\Gamma_{is}}{w_f} + Q_f \tag{1}$$

$$\frac{\partial}{\partial t}(n_m C_{im}) = \nabla(n_m D_{im} \nabla C_{im}) - \nabla(V_{im} C_{im}) - n_m R_{im} + \frac{\Gamma_{is}}{w_m} + Q_m \tag{2}$$

$$n \cdot C_i = n_f \cdot w_f \cdot C_{if} + n_m \cdot (1 - w_f) \cdot C_{im} \tag{3}$$

$$V_i = -\frac{k}{\mu} \nabla P_i \tag{4}$$

where C_i is the total gas concentration i (mol/m^3); i refers to any of the gases (i.e., CH_4 and O_2); P_i is the pressure of gas i; R_i is the reaction rate of the gas i (mol/m^3/s); n is the sum porosity in both pore systems; V_i is the average gas velocity of the gas i (m/s); D is the effective diffusion coefficient of gas (m^2/s); Q is the methane generation rate (mol/m^3/s); f and m represent the fracture and matrix system in the pore media, respectively; k is the gas permeability (m^2); w_f is the relative volumetric proportion of the fracture pore system; μ is the coefficient of viscosity (ML^{-1}T^{-1}); Γ_{is} is the solute mass transfer term of gas i (ML^{-3}T^{-1}), including the contribution from the advective and diffusive effects.

$$\Gamma_{is} = \pm\Gamma_{ig} C_{if} + \alpha_{is}(1 - w_f) n_m (C_{if} - C_{im}) \tag{5}$$

where α_{is} is the first-order transfer coefficient (T^{-1}), Γ_{ig} is the transfer term of gas i induced by the pressure gradient between the two pore systems.

The preferential flow in waste body could be also described by Darcy's law. Liu et al,(2016b) have presented the assessment method of the preferential flow in lab to predict the quantifiability of gas flow in fracture and matrix domain.

The oxidation rate of methane could be estimated using Monod kinetics theory, could be written as

$$R_{CH_4} = -V_{\max} \cdot \frac{1}{\left(1 + \frac{k_{m,m}}{C_{CH_4}}\right) \cdot \left(1 + \frac{k_{m,o}}{C_{0_2}}\right)} \tag{6}$$

$$R_{0_2} = 1.73 R_{CH_4} \tag{7}$$

where $V_{\max}$ is the maximum oxidation rate of methane (mol/m^3/s); C_{CH_4} and C_{0_2} are the methane and oxygen concentrations, respectively (m^3/m^{-3}); and $k_{m,m}$ and $k_{m,o}$ are the half-saturation constants of methane and oxygen, respectively (m^3/m^{-3}).

When the preferential flow effect (i.e., Γ_{is} =0, $V_f = V_m$, and $D_f = D_m$) was not considered, Equation (1) could be defined as

$$\frac{\partial}{\partial t}(nC_i) = \nabla(n\ D_i \nabla C_i) - \nabla(V_i C_i) - n\ R_i \qquad (15)$$

This equation could be called single advective–diffusive (SAD) model, which had single permeability and single dispersion coefficient.

In order to achieving the quantitative prediction of gases transport in those two zones, the assumption should be considered as follow: (1) without seepage and diffusion in immobile zone; (2) mass transfer between the mobile and immobile zone. The mass equilibrium between those zones could be described by

$$\frac{\partial}{\partial t}(n_{\mathrm{im}} C_{i,\mathrm{im}}) = n_{\mathrm{m}} \alpha_{\mathrm{m,im}}(C_i - C_{i,\mathrm{im}}) - n_{\mathrm{im}} R_i + Q_{\mathrm{im}} \qquad (8)$$

where $C_{i,\mathrm{im}}$ is the gas i concentration in immobile zone; $\alpha_{\mathrm{m,im}}$ is the first-order mass transfer rate coefficient between the mobile and immobile zone; n_{m} and n_{im} is the porosity in mobile and immobile zone, respectively. Q_{im} is the methane generation rate in immobile zone.

3 SIMULATION RESULTS AND DISCUSSION

The field test was conducted in landfill Legnago in Province of Verona, Italy. The methane concentration was more than 50%. Two monitoring wells and one injection well were set up. The detail information presented by Cossu and Cestaro (2005).

The measurement and simulation results of the oxygen concentration from M1 are shown in Fig.1. The distance between the M1 to injection well was 6 m. The simulation result by using the DAD model was represented the measurement result in principle. The oxygen concentration increased rapidly in the initial phase of air injection. The simulation curve of oxygen from SAD model was obviously behind the curve from DAD and measurement curve, because SAD model could not predict the preferential flow effect. As the immobile effect was not considered, the oxygen concentration up to 21% in the stable phase achieved by two models was higher than the monitoring value of 13% (Fig.1 (b)). The methane concentration received from SAD model was obviously lagged behind the measurement and DAD model data. Because the simulation result from SAD model could not represents the preferential flow. The simulation result from DAD model considered the immobile effect was closer to the measurement data. This was because the methane continuously generated in immobile zone and mobile zone in landfill. Due to without considered the immobile zone effect, the simulation results of methane concentration from SAD model come to 0 in the stable phase. This is because the methane occurred in pore media was all depleted by the oxygen which was continuously injected from aeration system.

With the fraction of the immobile zone increasing, the simulation curve was closer to the measurement results, especially in the stable phase (see Figure 2). It was indicated that the residual methane was determined on the immobile zone, where the methane emission from waste matrix degradation and almost non-flow. Similarly, the oxygen concentration in stable state was decreased with the immobile zone increasing.

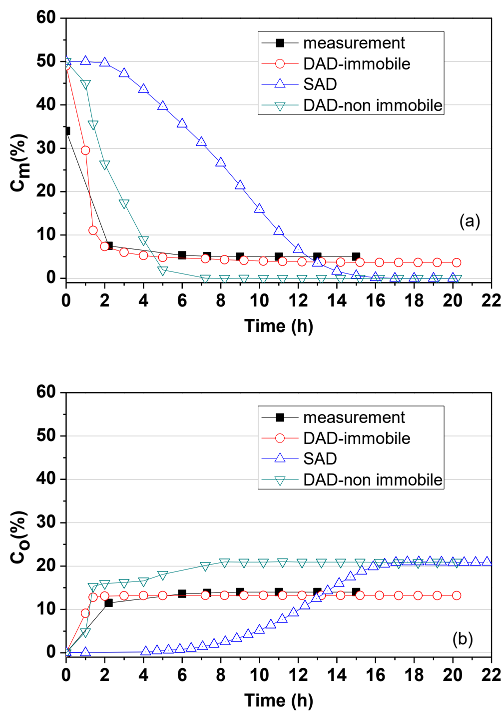

Fig. 1. Measurement and simulation result of the concentration from M1 well (a) Methane; (b) Oxygen.

4 CONCLUSION

In order to address the oxygen transport in the aeration process in landfill, a coupling model was developed, based on the solute transport theory. This model considered the gas preferential flow effect and the chemical reaction between oxygen and methane and immobile effect. The simulation prediction of the aeration process was conducted using a vertical injection well in typical cases. The conclusions were as follows.

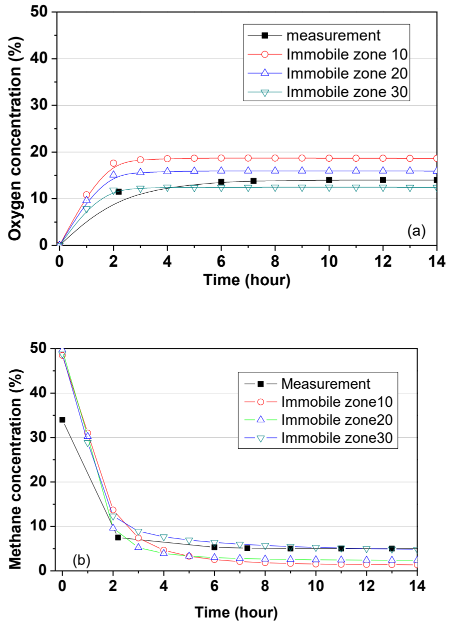

Fig. 2. The variation of the gas concentration with different fraction of the immobile zone

1) Preferential flow obviously occurred in landfill during the aeration process. This behavior could be represented by the DAD model, which has a good correlation coefficient by the comparison between the simulation result and measurement result of the oxygen and methane concentration. The parameters sensitivity analysis provided an evidence for this claim.

2) The variation in oxygen and methane concentrations was delayed using conventional SAD model. Because this model could not consider the preferential flow effect, which was generally occurred in waste pore media.

3) The immobile zone determined the residual concentration of the oxygen and methane in the aeration process in landfill.

ACKNOWLEDGMENTS

This research was supported by the Youth Innovation Promotion Association CAS (2017376); Hubei Outstanding Young key talents Program. Thank you Roberto Raga and Silvia Cestaro work at Department of Industrial Engineering in University of Padua in Italy, for the field-site information in landfill A.

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