*Jurnal Rekayasa Kimia dan Lingkungan*
Vol. 10, No. 3, Hlm. 112 - 120, Juni 2015
ISSN 1412-5064, e-ISSN 2356-1661
DOI: https://doi.org/10.23955/rkl.v10i3.3065

# Effectiveness of the Vertical Gas Ventilation Pipes for Promoting Waste Stabilization in Post-Closure Phase

## Keefektifan Pipa Ventilasi Vertikal untuk Meningkatkan Stabilisasi Limbah pada Phase Penutupan Akhir

**Yasumasa Tojo*, Natsuki Kishizawa, Toshihiko Matsuto, Takayuki Matsuo**
Graduate School of Engineering, Hokkaido University, Kita 13, Nishi 8, Kita-ku, Sapporo, Japan
*E-mail: tojo@eng.hokudai.ac.jp

**Abstract**

To make inside of the municipal solid waste (MSW) landfill aerobic as much as possible is thought to be preferable for promoting waste stabilization, reducing pollutant's load in leachate, minimizing greenhouse gas emission and shortening post-closure-care period. In Japan, installation of semi-aerobic landfill structure has widely spread in order to promote waste stabilization in MSW landfill from 1980s. In semi-aerobic landfill structure, outlet of main leachate collection pipe is opened to atmosphere. Heat generated by aerobic degradation of waste causes natural convection and natural aeration arises from the outlet of leachate collection pipe to the gas vents. It is so-called stack effect. This air flow is thought to be effective for purifying leachate flowing through drainage layer and leachate collection pipes. And it is also thought to be contributing to expanding aerobic region in waste layer in landfill. Recently, measures attempting the promotion of waste stabilization are taken at several landfills at where stabilization of waste delays, in which many vertical gas vents are newly installed and close structure to semi-aerobic landfill is created. However, in many cases, these gas vents are not connected to leachate collection pipes. Many vertical gas vents are just installed without scientific proof regarding whether they can contribute for waste stabilization. In this study, how such installation of gas vents is effective for waste stabilization and aerobization of waste layer was discussed by numerical analysis. In numerical analysis, heat transfer, gas movement by pressure, gas diffusion, biological degradation of organic matter, and heat generation by biodegradation were taken into account. Simulations were carried out by using the general purpose simulator of finite element method. Three types of landfill structure were assumed. As the results, the following information were obtained. In dig-down type landfill, installation of gas vents has no effect for changing air flow. On the other hand, in pile-up type landfill, installation of vertical gas vents can accelerate air invasion and significantly promote waste stabilization, if it has high permeable horizontal layer.

Keywords: gas ventilation pipe, natural convection, semi-aerobic landfill, waste stabilization

**Abstrak**

Pembuatan kondisi yang sangat aerobik dalam sistem penimbunan limbah padat domestik dilakukan dengan menciptakan stabilisasi limbah, mengurangi beban pencemaran lindi, mengurangi emisi gas rumah kaca, dan memperpendek periode penutupan akhir. Di Jepang, pemasangan struktur penimbunan semi-aerobik sudah secara luas untuk memperkenalkan stabilisasi limbah pada proses penimbunan sejak tahun 1980-an. Pada struktur tersebut, keluaran pipa pengumpul lindi terbuka ke atmosfer. Panas yang dibangkitkan dari degradasi limbah menyebabkan konveksi alami dan aerasi alami timbul dari keluaran pipa pengumpul lindi menuju cerobong gas. Ini disebut pengaruh cerobong asap. Aliran udara dianggap efektif untuk memurnikan lindi yang mengalir melalui lapisan drainase dan pipa pengumpul lindi. Dan aliran ini juga memperluas kawasan aerobik dalam lapisan limbah pada landfill. Akhir-akhir ini, upaya memperkenalkan stabilisasi limbah dilakukan pada beberapa bangunan *landfill* yang stabilisasi limbahnya terlambat, dimana banyak cerobong gas vertikal baru dipasang dan struktur penutup mengarah ke *semi-aerobic landfill* diciptakan. Namun, dalam banyak kasus ventilasi gas ini tidak terhubung ke pipa pengumpul lindi. Banyak ventilasi gas vertical dipasang tanpa bukti ilmiah apakah berkontribusi pada stabilisasi limbah. Kajian ini membahas instalasi cerobong gas efektif untuk stabilisasi limbah dan aerobisasi lapisan limbah dengan analisis numerik. Analisis mempertimbangkan perpindahan panas, gerakan gas karena tekanan, difusi gas, degradasi biologis zat organik, dan pembangkitan panas karena biodegradasi. Simulasi menggunakan simulator tujuan umum dengan metode elemen tak-terbatas. Tiga tipe struktur *landfill* diasumsikan. Hasilnya diperoleh bahwa pada *landfill* tipe *dig-down*, instalasi cerobong gas vertikal tidak berpengaruh terhadap perubahan laju alir udara. Pada *landfill* tipe *pile-up*, pemasangan cerobong gas vertikal mempercepat invasi udara dan secara signifikan menaikkan stabilisasi limbah jika cerobong memiliki lapisan horizontal yang sangat permeabel.

Kata kunci: pipa ventilasi gas, konveksi alami, penimbunan semiaerobik, stabilisasi limbah

## 1. Introduction

In Japan, installation of semi-aerobic landfill structure, which is generally called "FUKUOKA Method" (Hanashima, 1999, Matsufuji, 2004), has widely spread in order to promote waste stabilization in MSW landfill from 1980s because land reclamation is in particular important. In semi-aerobic landfill structure, outlet of main leachate collection pipe is opened to the atmosphere. This leachate collection pipe is designed to have relatively large diameter compared to ordinary system installed in anaerobic landfill and it is connected to vertical gas vents.

Almost a half of cross section of the leachate collection pipe is used for leachate to flow and the other half is used for air to flow. Air introduced from the outlet of leachate collection pipe flows towards the exits of each gas vents due to the heat generated by aerobic degradation of waste adjacent to the pipes. Driving force of this air flow is considered to be the natural convection caused by the difference between the temperature of the waste mass and the ambient temperature outside the landfill (Matsuto et al, 2015). It is so-called stack effect or buoyancy effect. This air flow is thought to be effective for purifying leachate flowing through drainage layer and leachate collection pipes. And it is also thought to be contributing to expand aerobic region in waste layer in landfill (Ishimori et al., 2011). Advantages of this system are low installation cost and low operational cost compared to the forced aeration (Hrad et al, 2013; Ritzkowski et al, 2006; Ritzkowski and Stegmann, 2012; Raga and Cossu, 2014) because it doesn't require additional energy for aeration.

Figure 1 shows typical semi-aerobic landfill structure. Semi-aerobic structure requires temperature rise generated by aerobic reaction for introducing air inside. It is known that temperature of waste mass rises up to 70-80°C under aerobic degradation. Therefore, if the waste mass is dry, landfill fire is likely to be caused. So, this structure may not be suitable for arid or semi-arid region. However, it is especially suitable for the areas in tropical climate and actually installation of this structure to several landfills in Southeast Asian country showed success (Chong et al., 2005; Matsufuji and Tachifji, 2007). In the survey conducted by Kim *et al*. (2010), they identified upward gas velocity in many vents. However, they also identified existence of oxygen and nitrogen in deep part of the vents. So, they concluded that "Inflow of air into the gas vents can occur at a wide range of depths, even 10–20 m below ground level. Air is induced not from the surface of the landfill, but horizontally along the waste layer" and "passive gas vents can help to aerate landfilled waste as well as collect and release LFG".

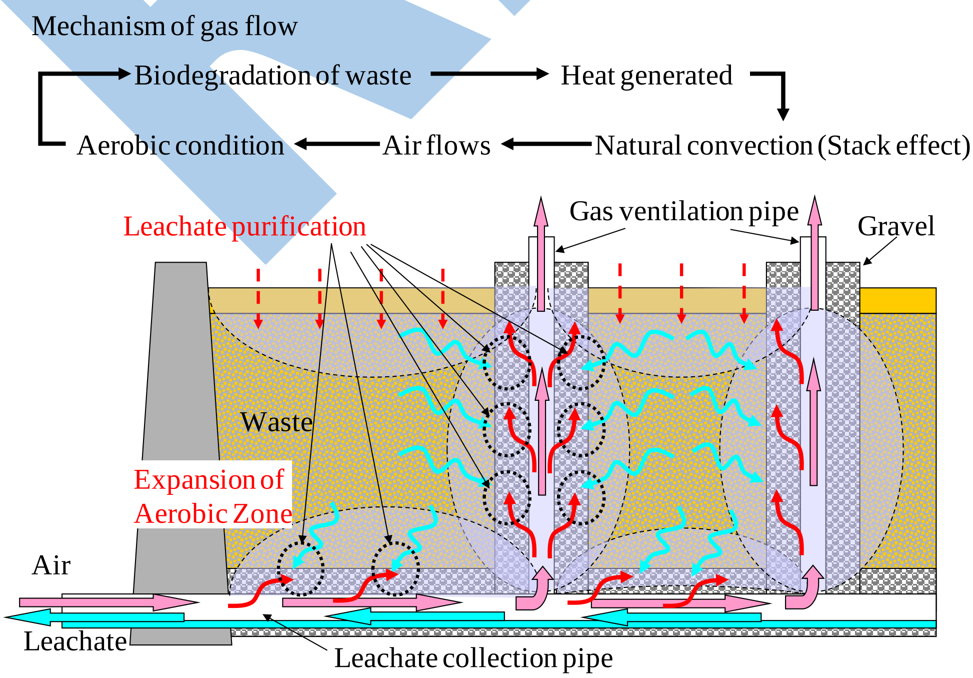


**Figure 1**. Schematic diagram of semi-aerobic landfill structure

In addition, from similar study, Yoshida (2010) reported that temperature of vents increased to 60°C even in winter and concluded that aerobic degradation of waste occurred around vents caused temperature increase and the aerobic condition was created by installation of vents. If just installing vertical gas vents simply can promote aeration, such methodology is regarded to be effective for landfill in which stabilization is delayed because the method is low-cost and low energy. But both studies mentioned above did not confirm practically two facts; from where did air enter? By what route did air flow? It is not clear whether simple installation of vertical gas vents contributes air induction or not. Furthermore, what air flow occur is not clear. So, in this study, how such installation of gas vents is effective for waste stabilization and aerobization of waste layer was discussed by numerical analysis.

First, as for natural convection in porous media caused by temperature increase, validity of theoretical formula was confirmed by conducting small scale experiment. Next, coupled model in which heat transfer, gas movement by pressure, gas diffusion, biological degradation of organic matter, and heat generation were taken into account was developed. Then, by using the model, how installation of vertical gas vents affect on the stabilization of waste in landfill was examined assuming three different landfill structures. So, temperature field with heat generation was created experimentally in order to confirm gas flow caused by natural convection. Then, numerical model that can simulate natural convection was developed and results of both experiment and numerical simulation were compared.

## 2. Methodology

### 2.1. Confirmation of natural convection by small-scale lab test

Experimental apparatus is indicated in Figure 2. Size of the rectangular parallelepiped that is made of acrylic is 30 cm of height, 30 cm of width, and 5 cm of depth. At the side of the box, many thermocouples were equipped at intervals of 5 cm to measure temperature. To exert the effect of natural convection more efficiently, steel shot and sand were used for filling material. In Table.1, specific weight, porosity, and intrinsic permeability of both materials are indicated. Steel shot was filled with 5 cm height at the bottom then sand was filled over the steel shot.

At the right side of the box, steel shot was again filled vertically to imitate gas ventilation pipe. Ribbon heater (10 cm long and 4 cm wide) was placed directly above bottom steel shot layer. After filling of material was completed, temperature of heater was raised to 110°C and it was maintained until steady state was achieved. After temperature and gas flow reached at steady state, temperature of each thermocouple was measured and gas flux at the exit was measured.

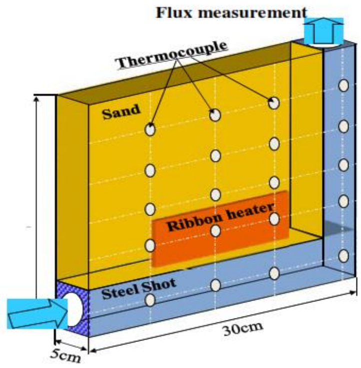


**Figure 2**. Experimental apparatus

**Table 1.** Basic characteristics of filling

| Material | Intrinsic Permeability [m²] | True density [Kg/m³] | Void ratio [-] |
|---|---|---|---|
| Sand | 4.47E-10 | 2604 | 0.4236 |
| Steel shot | 8.15E-09 | 7401 | 0.402 |

### 2.2. Modelling of Natural Convection

Mass balance equation under advection of gas can be expressed by equation (1).

$$\theta \frac{\partial \rho_g}{\partial t} + \nabla \cdot \left[ \rho_g \cdot \left\{ -\frac{\kappa}{\eta} \left( \nabla p + \rho_g g \nabla D \right) \right\} \right] = R \quad (1)$$

where; $\rho_g$ is density of gas (kg·m$^{-3}$), $\theta$ is porosity (-), $\kappa$ is intrinsic permeability (m$^2$),$\eta$ is viscosity (kg·m$^{-1}$·s$^{-1}$), $p$ is pressure (Pa=kg·m$^{-1}$·s$^{-2}$), $g$ is gravitational constant (m·s$^{-2}$), $D$ is height (m), $R$ is source-sink term (kg·m$^{-3}$·s$^{-1}$). Terms within brace indicate Darcy's velocity ($u$(m·s$^{-1}$)).

In above equation, density of gas ($\rho_g$) is calculated by equation of state. So, the equation (1) is depending on temperature. Then, heat balance equation is as follows.

$$C_{eq}\frac{\partial T}{\partial t}=\nabla\cdot(K_{eq}\nabla T-C_g\mathbf{u}T)+Q \qquad (2)$$

Here; $T$ is temperature (K), $t$ is time (s), $C_{eq}$ ($J\cdot m^{-3}\cdot K^{-1}$) is effective specific heat, $K_{eq}$ is effective thermal conductivity ($J\cdot m^{-1}\cdot K^{-1}$), $Q$ is heat generation rate ($J\cdot m^{-3}\cdot s^{-1}$=W). $C_{eq}$ can be calculated from equation (3).

$$C_{eq}=\theta C_g+(1-\theta)C_P\cdot\rho_p \qquad (3)$$

Here; $C_g$ ($J\cdot m^{-3}\cdot K^{-1}$) is specific heat of gas and $C_P$ ($J\cdot kg^{-1}\cdot K^{-1}$) is that of porous media, $\rho_P$ is true density of porous media ($kg\cdot m^{-3}$). Also, $K_{eq}$ is calculated by using thermal conductivity of gas ($K_g$) and porous media ($K_P$).

$$K_{eq}=K_g{}^{\theta}K_P{}^{1-\theta} \qquad (4)$$

By substituting temperature calculated by equation (2) for equation (5), density of gas ($\rho_g$) is calculated.

$$\rho_g=\frac{p\cdot M_{mix}}{T\cdot R_g} \qquad (5)$$

Here, $M_{mix}$ is molar weight of gas ($g\cdot mol^{-1}$) and $R_g$ is gas constant ($Pa\cdot m^{-3}\cdot K^{-1}\cdot mol^{-1}$). By coupling equation (1), (2) and (5), change of temperature produces change of gas density and this change creates driving force of gas movement. By this way, natural convection was modelled.

## 3. Results and Discussion

### 3.1. Temperature Distribution and Flow Vector

Calculated temperature distribution and flow vector are showed in Figure 3. In Figure 3, right side part is steel shot layer with high permeability which was set to imitate vertical gas vent. As indicated in the figure, strong air flow occurred in layer with high permeability if heat is generated in adjacent region. Therefore, if aerobic degradation that is generally exothermic reaction occurs in adjacent zone of pipe, it induces natural convection and air flow is produced. In figure 4, temperature distributions obtained by experiment and simulation respectively are indicated. Both temperature distributions show similar pattern. And gas flux at right upper edge was 0.62 L/hour in experiment. Meanwhile, the flux calculated from the model was 0.79 L/hour. They were slightly different but we evaluated that developed model is able to express air flow caused by natural convection.

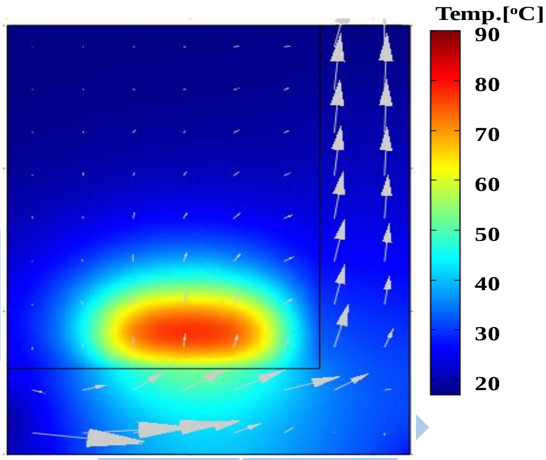


**Figure 3**.Calculated temperature distribution and flow vector

Experimental Result (temp. °C)

| | | | | |
|---|---|---|---|---|
| 20.8 | 21.6 | 23.0 | | 19.7 |
| 22.5 | 24.3 | 28.5 | | 21.8 |
| 23.9 | 32.8 | 44.5 | | 26.9 |
| 28.5 | 62.9 | 91.2 | | 35.0 |
| 26.8 | 46.4 | 66.0 | | 33.0 |

Flow rate at exit = 0.62 L/hour

Calculation Result (temp. °C)

| | | | | |
|---|---|---|---|---|
| 17.6 | 17.9 | 18.2 | | 19.0 |
| 19.0 | 20.3 | 20.7 | | 21.3 |
| 23.2 | 29.5 | 30.3 | | 24.7 |
| 30.2 | 63.1 | 66.6 | | 29.0 |
| 27.7 | 45.2 | 49.1 | | 32.1 |

Flow rate at exit = 0.79 L/hour

**Figure 4**. Comparison of temperature distribution between experiment and calculation

It was confirmed that natural convection created by heat generation can be expressed by the developed model. However, the model is simplifying the phenomena by setting constant heat generation. In actual condition, microorganisms degrade organic matter then heat is generated. Furthermore, activity of microorganisms generates gas (such as $CO_2$ and $CH_4$) and also consumption of oxygen occurs under aerobic condition. These formation and consumption of gas create concentration gradient and it results in diffusion of gas. So, in order to express heat generation and consumption/generation of gas, advection-diffusion equation and biodegradation model for organic carbon were added.

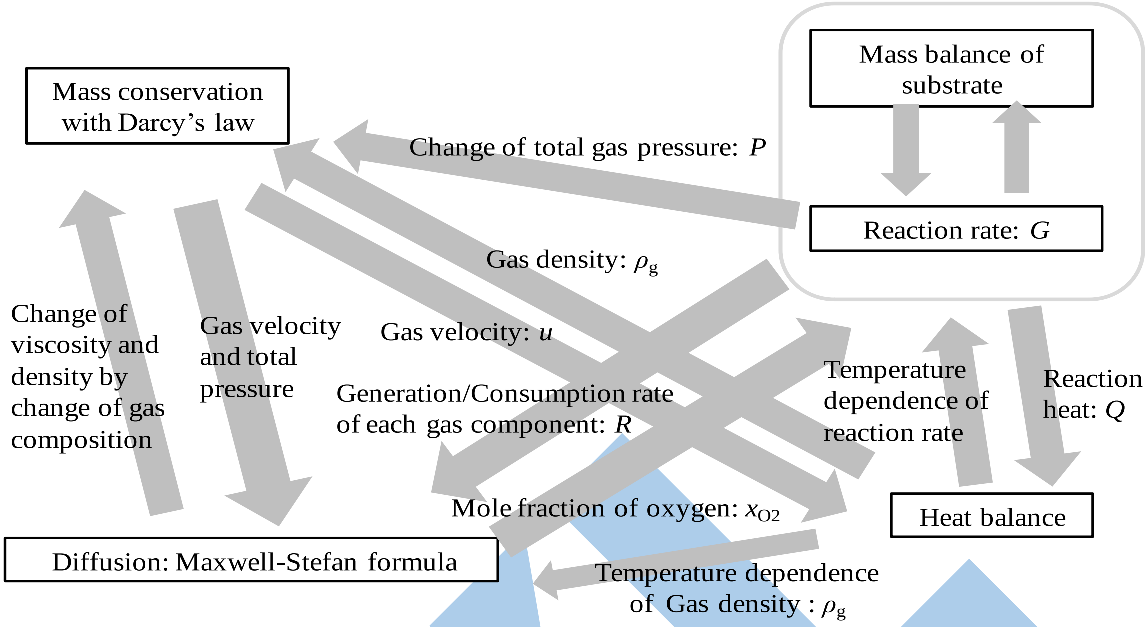


**Figure 5.** Interrelation among each equation

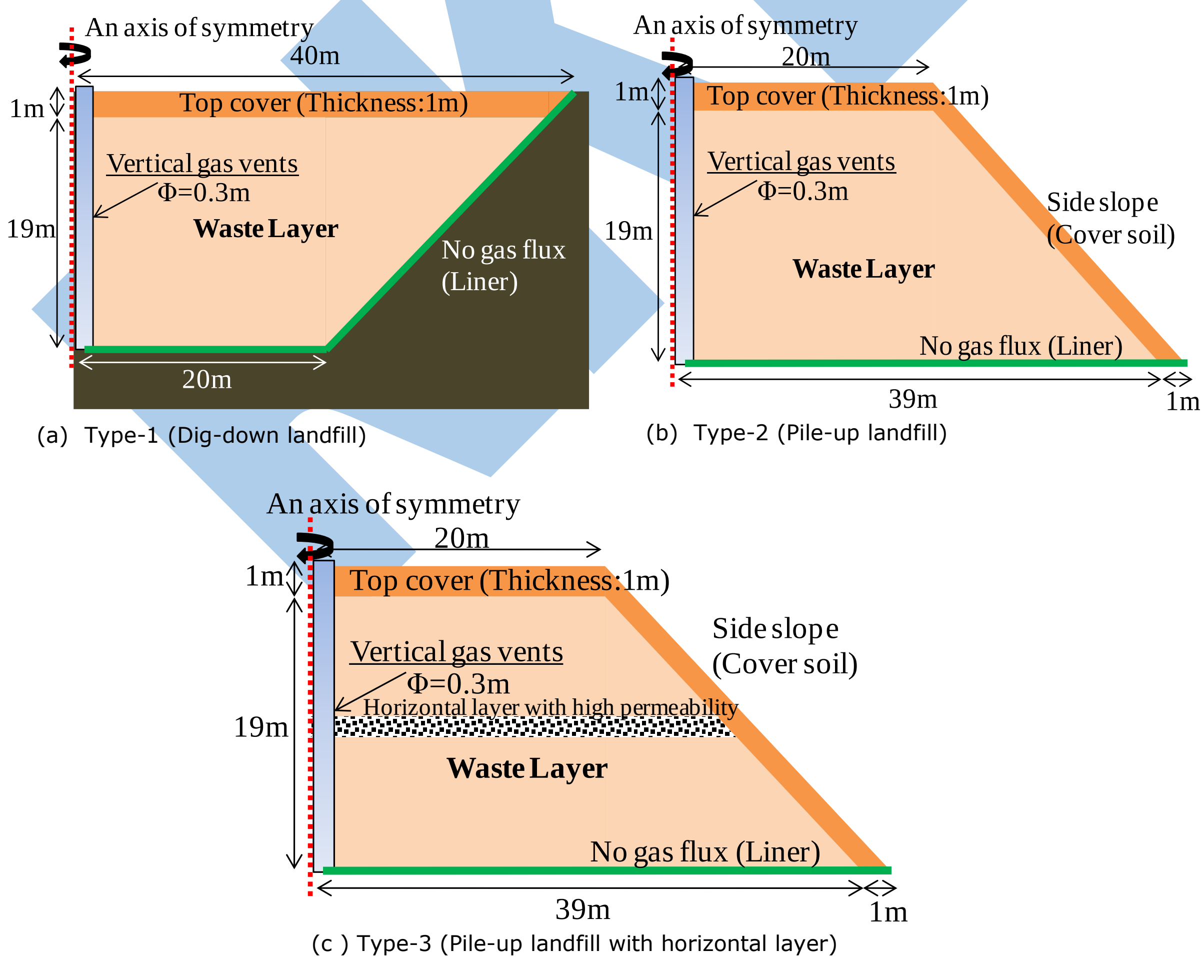


**Figure 6** Simulated landfill structure

### 3.2. Development of Coupled Simulation Model

*Advection-diffusion equation*

In this study, advection-diffusion equation by Maxwell-Stefan is used because multi-component gas diffusion has to be considered. As for gas component, oxygen, carbon dioxide, and methane are taken into account. In addition, nitrogen was used as a balancing component. So, in total, four components are considered. For each gas component ($i$), the following Maxwell-Stefan equation can be formulated.

$$\theta \frac{\partial}{\partial t} \rho_g x_i = \nabla \left[ \rho_g x_i \sum_{j=1}^{4} D_{ij} \frac{\theta}{\xi} \nabla x_j - \mathbf{u} \rho_g x_i \right] + R_i \qquad (6)$$

Here, $x_i$ is mole fraction of gas $i$ ($kg \cdot kg^{-1}$), $D_{ij}$ is molecular diffusion coefficient for component $i$ and $j$ ($m^2 \cdot s^{-1}$), $\theta$ is porosity (-), $\xi$ is tortuosity factor (-), $R_i$ is source and sink term for component $i$ ($kg \cdot m^{-3} \cdot s^{-1}$).

*Formulation of biodegradation*

Only two organic substrates were set such as easily-degradable organic matter and organic acid in the model. And four reactions are taken into account; aerobic biodegradation of easily-degradable organic matter (*AeOm*), aerobic degradation of organic acid that is formed under anaerobic condition (*AeOa*), acidogenesis of easily-degradable organic matter (*AnOm*), and methanogenesis of organic acid (*AnMt*). Mass balance equations of each organic substrate are as follows. To simplify the model, these organic substrates increase or decrease by only biodegradation and their transport by liquid was not incorporated.

$$\frac{dS_1}{dt} = \left( G_{S_1\_AeOm} + G_{S_1\_AnOm} \right) \qquad (7)$$

$$\frac{dS_2}{dt} = \left( G_{S_2\_AeOa} + G_{S_2\_AnOm} + G_{S_2\_AnMt} \right) \qquad (8)$$

Here, $S_1$ is content of easily-biodegradable organic matter ($kg \cdot m^{-3}$), $S_2$ is content of organic acid ($kg \cdot m^{-3}$), $G_{S1\_x}$ is consumption rate of $S_1$ by reaction $x$ ($kg \cdot m^{-3} \cdot s^{-1}$), $G_{S2\_x}$ is formation/consumption rate of $S_2$ by reaction $x$ ($kg \cdot m^{-3} \cdot s^{-1}$). Then, the following three reaction rates are substituted for source-sink term ($Ri$) in Maxwell-Stefan equation.

$$R_{CH_4} = G_{CH_4\_AnMt} \qquad (9)$$

$$R_{O_2} = G_{O_2\_AeOm} + G_{O_2\_AeOa} \qquad (10)$$

$$R_{CO_2} = G_{CO_2\_AeOm} + G_{CO_2\_AeOa} + G_{CO_2\_AnMt} \qquad (11)$$

In addition, by substituting sum of these three reaction rates for $R$ in equation (1), coupling with advection is achieved.

### 3.3. Coupled Simulation Model

The model is created based on the following assumption; installation of vertical gas vent creates air flow and the induced air flow changes anaerobic condition in landfill to aerobic then aerobic degradation occurs. As the result, temperature distribution changes by reaction heat then air flow is further promoted. In order to simulate this scheme, equations for heat transfer, gas movement by pressure, gas diffusion, biological degradation of organic matter, and heat generation were coupled. Their inter-relations are indicated in Figure 5.

In the model, output of each equation is utilized by others mutually. Calculation was done by using The COMSOL Multiphysics engineering simulation software environment (COMSOL, Inc.) which is multi-purpose finite element model solver. These structures are indicated in Figure 6. The depth and width of landfill were set to 20 m and 40 m respectively. For each structure, two cases were considered; namely with or without installation of vent. In the case with gas vent, vent whose diameter is 30 cm was assumed to be installed at the left side of landfill. Since the simulated landfill structure is designed to be symmetrical about an axis of left edge, the vent is in actual located at the center of the landfill. As for Type-3 landfill, horizontal layer was set to have high permeability that was two orders of magnitude higher than waste layer.

### 3.4. Simulated Landfill Structure

Changes of gas flow and temperature and degradation of organic matter in landfill for 50 years after installation of vertical gas vent were simulated by using the developed coupled model. Simulated landfill was assumed to be a closed landfill in which much organic matter still remained. Three structures were assumed; dig-down landfill (Type-1), pile-up landfill (Type-2), and pile-up landfill with horizontal layer (Type-3). Figure 7 indicates transition of organic carbon in Type-1 landfill after 10, 30 and 50 years. Initial content of organic carbon was set to 7.8 $kg\text{-}C \cdot m^{-3}$. Left column shows landfill without gas vents and right column shows that with vents. Any significant difference cannot be found. Air gets in from only top surface, so organic carbon disappears gradually from top towards bottom in both cases. However, organic carbon still exists even after 50 years. Hence, even if vertical gas vent is installed, no specific flow change arises in the dig-down type landfill and it can be concluded that installation of gas vent does not have effect for acceleration of waste stabilization.

Figure 8 shows temperature distribution at 10, 30, 50 years in Type-2 landfill. Initially, temperature of entire landfill was set to 15°C. In pile-up landfill, air can get in from both top and side slope. Induced air creates aerobic zone and the zone expands gradually into inside. So, temperature rise by aerobic reaction occur from side slope. Temperature reaches to approximately 50°C at area in which aerobic reaction is most active. Effect of air invasion is more prominent in the case with vent. And its high temperature area spreads wider than the case without vent. At 50 years, temperature of most of landfill body becomes steady (15°C) but its distribution is not so different in both cases with or without vent. In Type-3 which has high permeable horizontal layer, organic carbon disappears from not only top and side but also along with the horizontal layer.

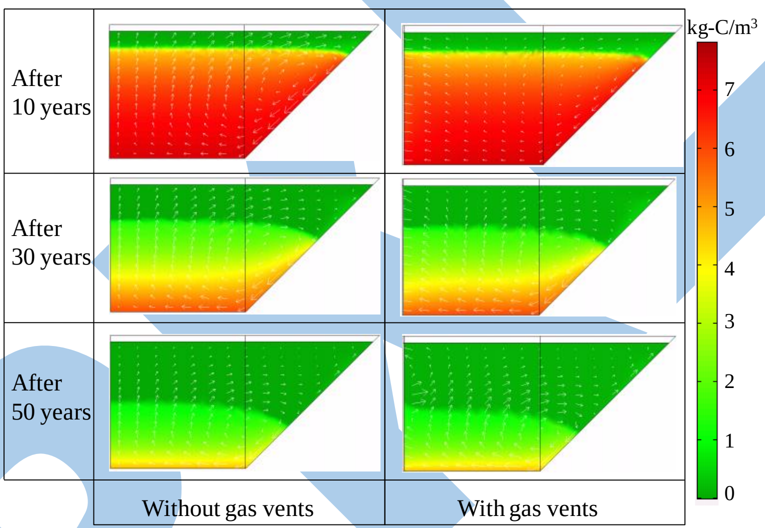


**Figure 7.**Transition of organic matter in Type-1 (Dig-down landfill)

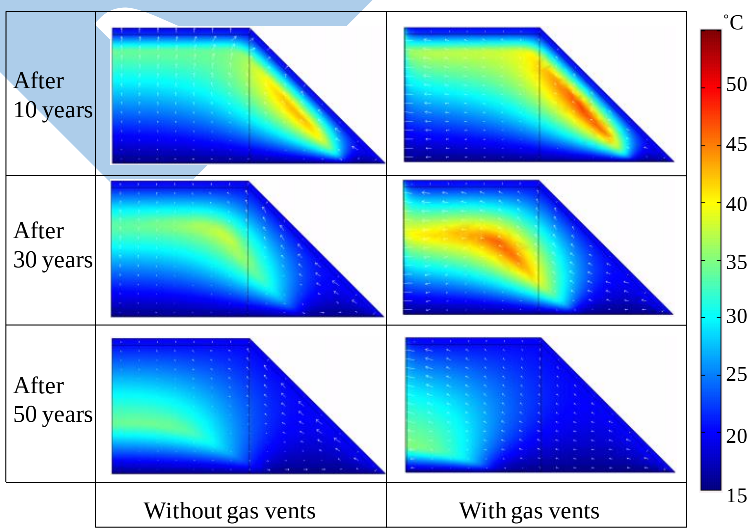


**Figure 8.** Change of temperature in Type-2 (Pile-up landfill)

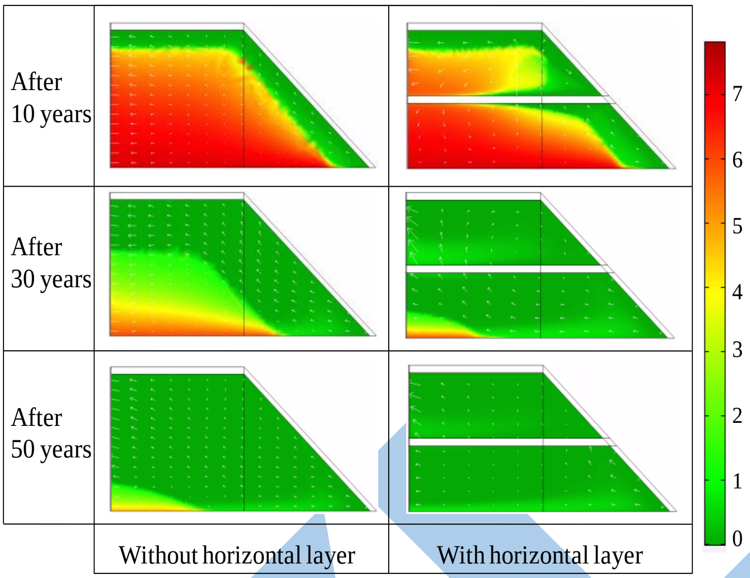


**Figure 9.** Change of organic matter in Type-2 and Type-3 with gas vents

Installation of gas vent leads to more drastic promotion of air induction if horizontal layer exists. This is because stack effect is produced more effectively with horizontal layer. The difference of organic carbon content is evident at 30 years when only a little organic carbon remains at the bottom central region in Type-3. And it is vanished completely at 50 years. From these results, it can be concluded that installation of gas vent becomes particularly effective when there is high permeable horizontal layer. So, creating such horizontal layer with coarse material before installation of gas vents is recommended when remediation counter-measure to promote stabilization of waste in landfill of high organic matter content is taken.

## 4. Conclusion

In this paper, waste stabilization in landfill construction was discussed. Heat transfer, gas movement by pressure, gas diffusion, biological degradation of organic matter, and heat generation by biodegradation were calculated by using coupled model for three landfill structures. The effect of gas vent was various depending on landfill structure. In dig-down landfill, installation of vertical vent has no effect. On the other hand, the effect was obvious in pile-up landfill. Especially, in pile-up landfill with high permeable horizontal layer, installation of gas vent changes gas flow drastically and induction of air is promoted. The induced air makes circumstance of landfill aerobic from anaerobic and aerobic degradation of waste readily stabilizes organic carbon remaining in landfill. Therefore, it can be concluded that creating high permeable horizontal layer with coarse material before installation of vertical gas vents is recommended when remediation countermeasure to promote stabilization of waste in landfill of high organic matter content is taken. This measure is thought to be especially effective for landfills/open dumps under tropical climate at which remediation is required because rainy climates is favorable to maintain water content and to control excessive rise in heat.

## References

Chong, T. L., Matsufuji, Y., Hassan, Moh. N. (2005) Implementation of the semi-aerobic landfill system (Fukuoka method) in developing countries: A Malaysia cost analysis, *Waste Management*, 25, 702-711.

Hanashima, M. (1999) Pollution control and stabilization process by semi-aerobic landfill type: the Fukuoka Method, *Proceedings of SARDINIA, 7th International Waste Management and Landfill Symposium*, 1, 313–326.

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 Management*, 33, 2061–2073.

Ishimori, H., Endo, K., Ishigaki, T., Sakanakura, H., Yamada, M. (2011) Coupled fluid flow and thermal and reactive transport in porous media for simulating waste stabilization phenomena in semi-aerobic landfill, *Proceedings of COMSOL Conference Worldwide*, Boston, USA.

Kim, H., Yoshida, H., Matsuto, T., Tojo, Y., Matsuo, T. (2010) Air and landfill gas movement through passive gas vents installed in closed landfills, *Waste Management*, 30, 465–472.

Matsufuji, Y. (2004) A Road to semi-aerobic landfill experience of semi-aerobic landfills in Japan and Malaysia, *The 3rd Intercontinental Landfill Research Symposium*, Hokkaido, Japan.

Matsufuji, Y., Tachifuji, A. (2007) The history and status of semi-aerobic landfills in Japan and Malaysia. In: Stegmann, Ritzkowski (Eds.), Landfill aeration, IWWG Monograph, CISA Publisher.

Matsuto, T., Zhang, X., Matsuo, T., Yamada, S. (2015) Onsite survey on the mechanism of passive aeration and air flow path in a semi-aerobic landfill, *Waste Management*, 36, 204-212.

Raga, R., Cossu, R. (2014) Landfill aeration in the framework of a reclamation project in Northern Italy, *Waste Management*, 34, 683-691.

Ritzkowski, M., Heyer, K. U. (2006) Stegmann, R., Fundamental processes and implications during in situ aeration of old landfills, *Waste Management*, 26, 356–372.

Ritzkowski, M., Stegmann, R. (2012) Landfill aeration worldwide: concepts, indications and findings, *Waste Management*, 32, 1411-1419.

Yoshida, H. (2010) Analysis of landfill gas temperatures and components in new passive gas extraction wells of a closed landfill, *Proceedings of the 5th Intercontinental Landfill Research Symposium*, Colorado, USA.