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NUMERICAL SIMULATION OF GAS EMISSION IN A SANITARY LANDFILL EQUIPPED WITH A PASSIVE VENTING SYSTEM

Keywords: Gas emission, numerical modeling, sanitary landfill

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ABSTRACT

The gas emission in a sanitary landfill equipped with a passive venting system was investigated numerically. The Darcy's law was employed to simulate the gas flow in the landfill. We used the first order biodegradation rate in modeling the waste biodegradability. The results show that more than 43.3% gases produced from the waste will emit from the landfill surface for R = 30 m, where R is the half of the well spacing. These indicate that the influence radii (between 30 to 50 m) were overestimated in the designing of the gas collection systems in the Sanjuku and the Taichung City sanitary landfills in Taiwan. This might pose a potential of air pollution and raise chances of fires under such designing.

INTRODUCTION

Sanitary landfilling is a common method for the disposal of solid waste. However, concerns about the air pollution and fire risk problems have arisen with

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the growing use of such a disposal. Two major pollution issues associated with the landfill are the leachate and gases. The gases produced in the landfills are mainly the methane and carbon dioxide. Methane in volumetric concentration of 5 % to 15 % is explosive. After the closure of the landfilling, the gas production can last for more than twenty years. In order to control the air pollution and fire hazard from the gases, gas collection system is installed in the landfill. There are two kinds of gas collection systems, the passive venting system and the active gas pumping system (O'Leary and Walsh, 1991). The passive venting system is a system in which perforated venting pipes are installed within the landfill or the soil surrounding it. The well depth ranges from 50% to 90% of the landfill depth. The wells collect gas by the natural pressure difference and convection inside the landfill. In general, these wells are equipped with flares to burn off the gas. The advantages of the passive venting systems are simple to install, less expensive to operate, and easy to maintain, but its drawback is not effective in extracting the landfill gas that may emit from landfill surface or from the underground soil surrounding the landfill. The other system is the active gas pumping system, which collects gas by using the vacuum pumps. A pipe network, which is built to connect the wells and the blower equipment, directs the collected gas to an energy recovery system. This system extracts the landfill gas effectively, but the installation and maintenance fees of such a system are pretty high.

In the modeling of the gas flow in the landfill, Esmaili (1975) proposed a single well model to analyze the gas extraction from the well in a landfill for the active gas pumping system, where the well is located at the surrounding soil outside the landfill limits. Lu and Kunz (1981) developed a one-dimensional radial-flow model which calculates the landfill's methane production rate and gas-flow permeability by measuring the landfill gas pressures and pressure changes caused by the withdrawal of gas. Findikakis and Leckie (1979) developed one-dimensional numerical model to simulate the gas pressure and concentration profiles in a landfill. Arigala *et al.* (1995) developed a model to describe the gas generation, transport, and extraction in a landfill. The wells are assumed to be one-dimensional line sinks with uniform gas extraction rates.

Most of the wells in the passive venting system are installed within the landfill to prevent the gas emission from the landfill surface. The well influence radius is generally used to determine the spacing and the number of the wells in the gas collection system design. The influence radius of 45 to 50 m was estimated for the planning and designing of the gas collection system in the Sanjuku landfill in Taipei City (Chung-Hsing Engrg. Consulting Corp., 1992). The influence radius of 30 to 35 m was estimated for the planning and designing of the gas collection system for the Taichung City sanitary landfill (Hwan-Chi Engrg. Consulting Corp., 1994). Since there had been several fires caused by the excessive gas discharge in the landfills in Taiwan during the past few years, thus the study of the gas flow in the landfill was motivated. In this paper, two-dimensional model was employed to simulate the gas flow in a landfill.

GAS FLOW MODEL

The sanitary landfill is composed of the solid waste layer and the final soil cover. The biodegradation of the solid waste is based on the approach by Findikakis and Leckie (1979), which assumed the refuse to be classified into three categories: readily biodegradable, moderately biodegradable and slowly biodegradable. Since the time scale of the gas-flow dynamics within the landfill can be neglected, the gas flow can be approximated as a qusi-steady-state, once the gas landfill is sufficiently mature. The landfill gas is assumed to be an equimolar mixture of CH_4 and CO_2. The variation of the gas flow in the azimuthal direction is also neglected. A schematic of the landfill geometry and coordinate system is given in Figure 1. The governing equation of the mass conservation in the landfill can be written as

$$\frac{1}{r}\frac{\partial}{\partial r}(r\rho u_r)+\frac{\partial}{\partial z}(\rho u_z)=\alpha \qquad (1)$$

where ρ = density of gas mixture; r = radial distance from the center of the well; z = vertical distance measured from top of the landfill; u_r and u_z = gas velocity in the r and z directions, respectively; α = overall gas production rate for the

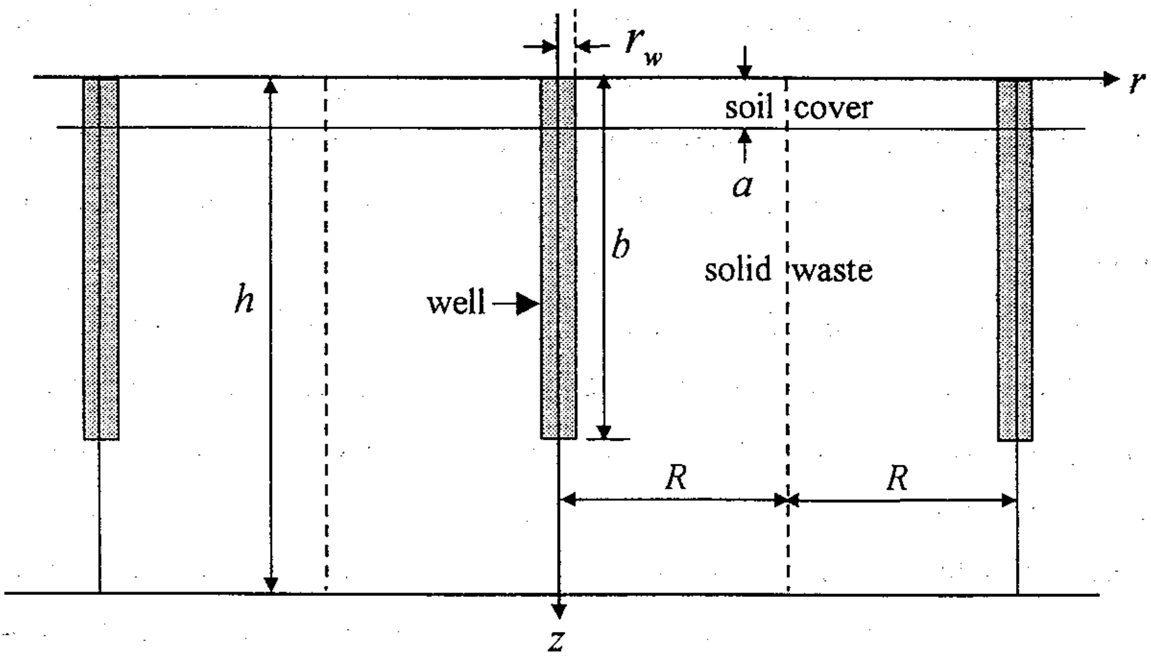

FIGURE 1
The schematic of the landfill geometry and coordinate system.

solid waste layers. The gas production rate for all of the three components is assumed as follows (Findikakis and Leckie, 1979 ; Arigala *et al.*, 1995):

$$\alpha = C \cdot \sum_{i=1}^{3} A_i \lambda_i e^{-\lambda_i t}, \qquad t = t_0 + \frac{z}{h} t_f \tag{2}$$

where C = mass of total gas produced per volume of waste; A_i and λ_i = fraction and reaction-rate constant for the waste component i, respectively; t = time; t_0 = time elapsed after the closure of the landfill; t_f = total time to fill the landfill; h = total landfill depth. The Dracy's law is employed for the gas flow through the landfill. An ideal gas model is assumed for the gas mixtures.

$$u_r = -\frac{K_r}{\mu}\frac{\partial P}{\partial r}, \qquad u_z = -\frac{K_z}{\mu}\left(\frac{\partial P}{\partial z} - \rho g\right), \qquad \rho = \frac{PM}{R_u T} \tag{3}$$

where P = gas pressure; μ = viscosity of gas mixture; g = acceleration of gravity; K_r and K_z =horizontal and vertical permeabilities of waste or soil layers, respectively; T = gas absolute temperature; M = mean molecular weight of gas mixture; R_u = universal gas constant; In the waste layer, different horizontal and vertical permeabilities are used (Arigala *et al.*, 1995). In the final soil cover, the horizontal and vertical permeabilities are assumed to be the same. A new function can be defined as;

$$\phi = P - \rho g z - P_{atm} \tag{4}$$

where P_{atm} = atmosphere pressure. By substituting equations (3) and (4) to equation (1), it yields

$$\frac{1}{\mu}\frac{1}{r}\frac{\partial}{\partial r}(r\rho K_r \frac{\partial \phi}{\partial r}) + \frac{1}{\mu}\frac{\partial}{\partial z}(\rho K_z \frac{\partial \phi}{\partial z}) = -\alpha \tag{5}$$

The associated boundary conditions are

$$\phi = 0 \qquad \text{at } z = 0, \quad r_w \le r \le R \tag{6a}$$

$$\frac{\partial \phi}{\partial z} = 0 \qquad \text{at } z = h, \quad 0 \le r \le R \tag{6b}$$

$$\frac{\partial \phi}{\partial r} = 0 \qquad \text{at } r = 0, \quad b \le z \le h \tag{6c}$$

$$\frac{\partial \phi}{\partial r} = 0 \qquad \text{at } r = R, \quad 0 \le z \le h \tag{6d}$$

where r_w, R, and b = well radius, half of the well spacing, and the well depth, respectively. It is assumed that the bottom surface of the landfill is impermeable. Boundary conditions (6c) and (6d) stand for the symmetric condition of the gas flow. The one-dimensional Bernoulli equation is assumed for the gas flow to obtain the pressure distribution inside the well, that is

$$\phi_w + \frac{1}{2}\rho u_w^2 = const, \qquad \text{for } r \le r_w, \quad 0 \le z \le b \tag{7a}$$

where the subscript w refers to the quantity within the well. The gas velocity distribution inside the well is obtained by using the mass conservation as shown in the following:

$$\frac{du_w}{dz} = 2\pi r_w u_r\big]_{r=r_w} \tag{7b}$$

where $u_r\big]_{r=r_w}$ is the gas velocity at the well boundary and is calculated from the equation (3). The governing equation (5) and associated boundary conditions are solved by the finite-difference method. The numerical details can be found in Pantankar [8]. The solution procedure is as follows:

a. guess the pressure fields in the landfill and inside the well.
b. calculate the new pressures in the landfill from the equation (5).
c. obtain the gas velocity at the boundaries between the well and the landfill from the equation (3).
d. compute the distribution of u_w inside the well. The computation begins from the bottom point by using the equation (7b).
e. obtain the pressure distribution ϕ_w inside the well from the equation (7a) and then repeat the process from step b.

In this study, the grid points in the r and z directions for R = 30 m are 38 and 39, respectively. The criterion used for the iteration convergence is

$$Max\left|\phi^{n+1} - \phi^{n}\right| \leq 0.01 \qquad (8)$$

where ϕ^n is the values at the iteration number n.

RESULTS AND DISCUSSION

In this study, the final soil cover thickness $a = 1.2$ m, the total landfill depth $h = 40$ m, the well radius $r_w = 0.15$ m, and the gas temperature of 310 K were chosen for sample calculations. The values of the parameters $t_f = 7$ years and $t_0 = 4$ years in equation (2) were used. Some other typical values of parameters for the soil and refuse properties used by Findikakis and Leckie (1979) and Arigala et al. (1995) were also adopted in this paper. They are listed in Table 1. Figure 2 shows the variation of the gas extraction rate from the well, Q_w (m^3/hr), with the well depth, b, for R = 30 m, where R is the half of the well spacing. The well depth ranges from 50% to 90% of the total landfill depth. The gas extraction increases with the increasing well depth, while the increase rate slightly decreases with the increasing well depth. The Q_w for the $b = 38$ m is 43.07 m^3/hr, which

TABLE 1
Typical Values of Parameters

Landfill data	Value
Permeability of final soil cover (m^2)	1.0×10^{-13}
Horizontal permeability of refuse (m^2)	3.0×10^{-12}
Vertical permeability of refuse (m^2)	1.0×10^{-12}
Viscosity of gas mixture ($Pa\cdot s$)	1.54×10^{-5}
Refuse density (kg/m^3)	800
Methane gas generation potential (m^3/kg)	0.178
Refuse composition:	
readily biodegradable (%)	15
moderately biodegradable (%)	55
slowly biodegradable (%)	30
Reaction rate constant of refuse:	
readily biodegradable (yr^{-1})	0.1386
moderately biodegradable (yr^{-1})	0.0231
slowly biodegradable (yr^{-1})	0.017328

is 1.53 times of that (28.08 m^3/hr) for the $b = 20$ m. This indicates that the well depth has an important effect on the gas extraction rate, Q_w.

Figure 3 plots the variation of $Q_s/(Q_s+Q_w)$ with the well depth, where Q_s (m^3/hr) is the gas emission rate from the landfill surface within the radius $r \le R$. The well is located within the landfill, and it is assumed that the gases produced in the solid waste in this configuration are either extracted by the well or emitted from the landfill surface. Thus the value of $Q_s/(Q_s+Q_w)$ represents the ratio of the gas emission from the landfill surface to the total gas production. Figure 3 shows that the gas emission from the landfill surface increases with

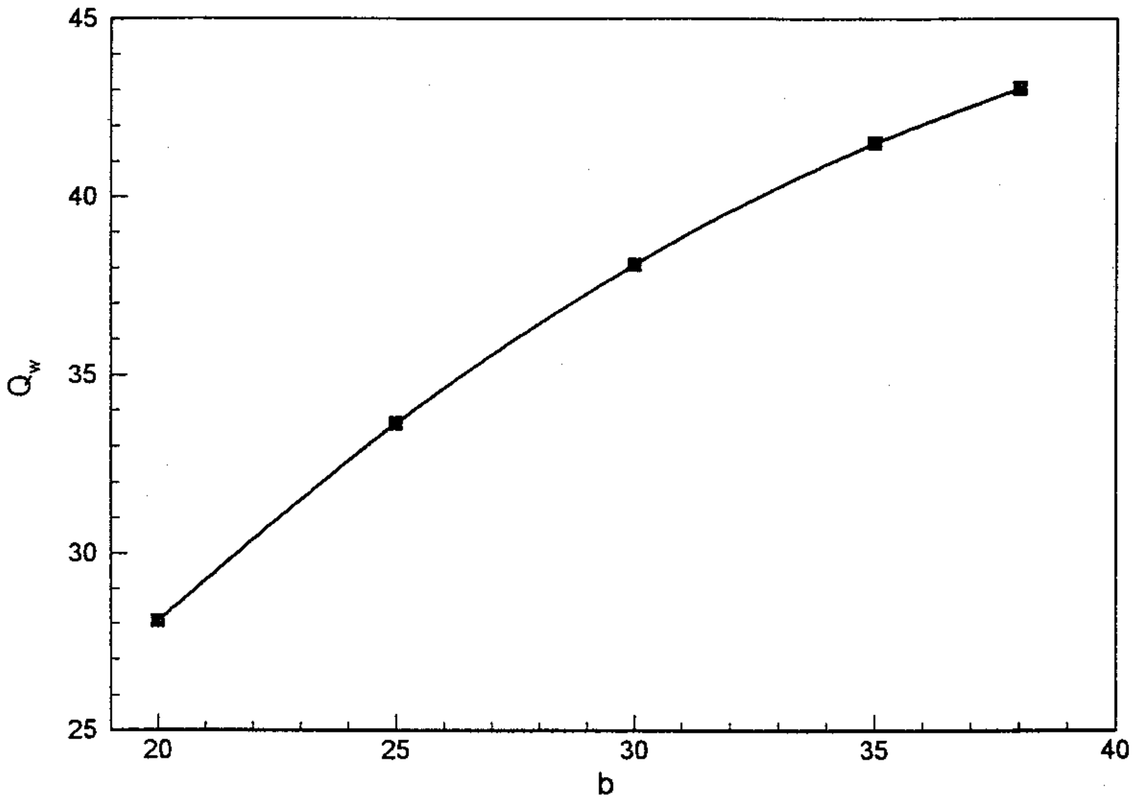

FIGURE 2
The variation of gas extraction rate, Q_w (m^3/hr), with the well depth, b (m).

decreasing well depth. The percentage of gas emission from the landfill surface increases from 43.3% to 62.6%, when the well depth decreases from 90% to 50% of the landfill depth. This implies that a high proportion of the gases will emit from the landfill surface. In the designing of the gas collection system, the well venting influence radii for the Sanjuku and the Taichung City landfills in Taiwan were estimated to be 45 to 50 m and 30 to 35 m, respectively. These indicate that the influence radii were overestimated in the designing of the gas collection system in both sanitary landfills. Thus this might pose a potential of air pollution and fire risk caused by the methane gas under such designing, especially when the temperature in summer is pretty high in Taiwan.

Figure 4 plots the pressure contour ϕ $(= P - \rho g z - P_{atm})$ for the well depth $b = 20$ m (50% of landfill depth). The results show that the constant pressure lines

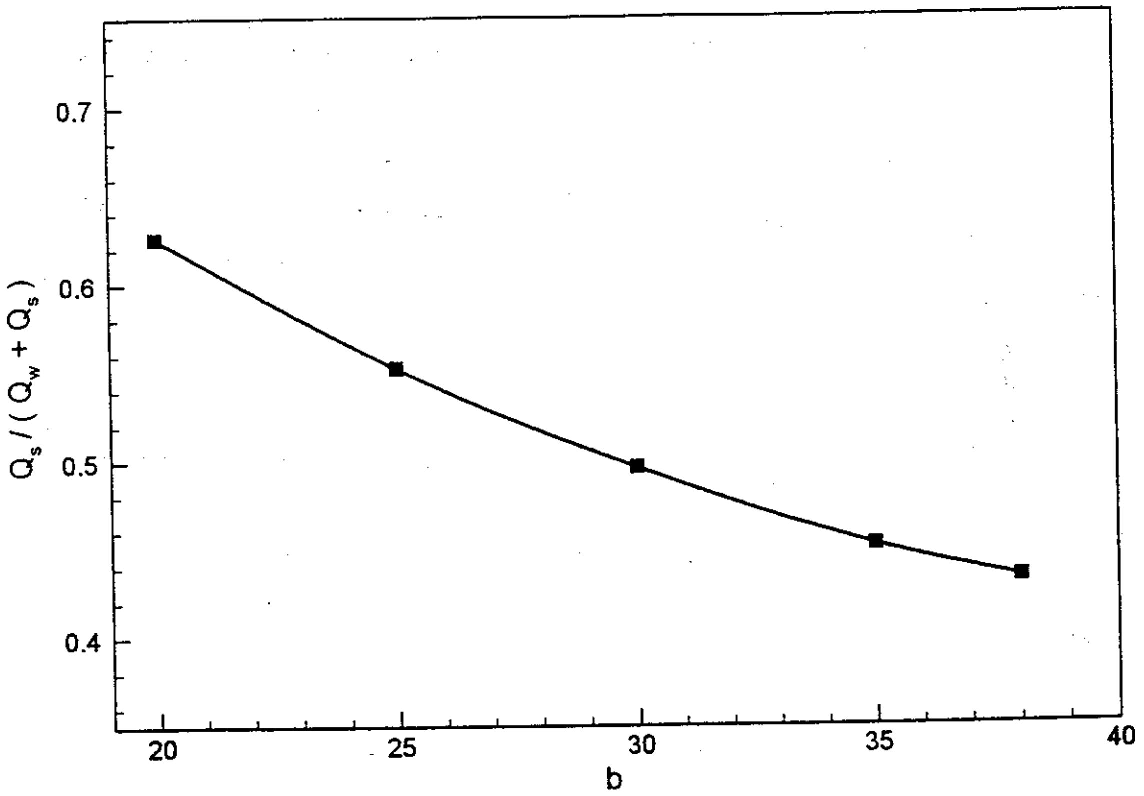

FIGURE 3
The variation of the ratio $Q_s/(Q_s+Q_w)$ with the well depth, b (m).

near the well are close to each other and the curves stand almost vertically. This indicates that the gas in that area moves almost horizontally and will be collected by the well. But as the radial distance from the well increases, the interval between any two curves increases quickly and the slope of the curve declines quickly. This implies that the well's ability in capturing gases decays quickly with the increase of the radial distance from the well in the passive venting system. The curves for the radius $r \geq 15\,\mathrm{m}$ are almost horizontal, that is, the gases move almost vertically. It is also seen that most of pressure curves are almost horizontal in the near surface region. Thus a high percentage of the landfill gases, which are produced from the region of $r \geq 15\,\mathrm{m}$ and the near surface region, can't be extracted by the well and will emit directly from the landfill surface. It also shows that the pressure curves for the depth $z \geq 22\,\mathrm{m}$ are almost horizontal. This indicates that the well almost doesn't have any effect on the gases for the depth

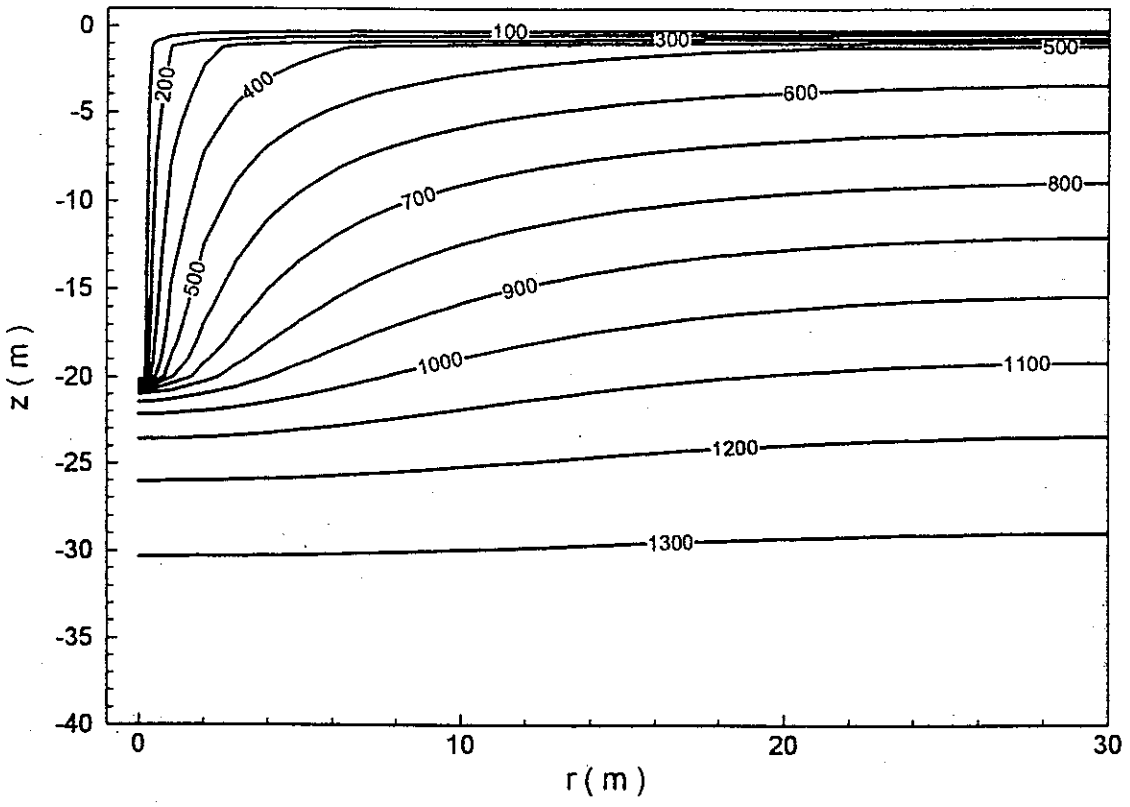

FIGURE 4
The pressure contour (ϕ) for the well depth $b = 20$ m.

$z \geq 22$ m. Those results explain why the ratio of $Q_s/(Q_s + Q_w)$ is as high as 62.6% for the case of $b = 20$ m.

Figure 5 plots the pressure contour ϕ for the well depth $b = 38$ m (90% of landfill depth). It is seen that the gas velocity in the radial (r) direction is significantly higher than that for the well depth $b = 20$ m in most regions, especially in the region of $r \geq 15$ m and in the deeper region of the landfill. More gases move towards the well and are easily extracted by the well. This indicates that the ability of the well in capturing the gases for $b = 38$ m is much better than that for $b = 20$ m. The percentage of the gas emission from the landfill surface for $b = 38$ m is 43.3%, which is 19.3% less than that for $b = 20$ m. Thus the well depth should be as deep as it can be. The effects of the well spacings on the gas emission are currently under investigation.

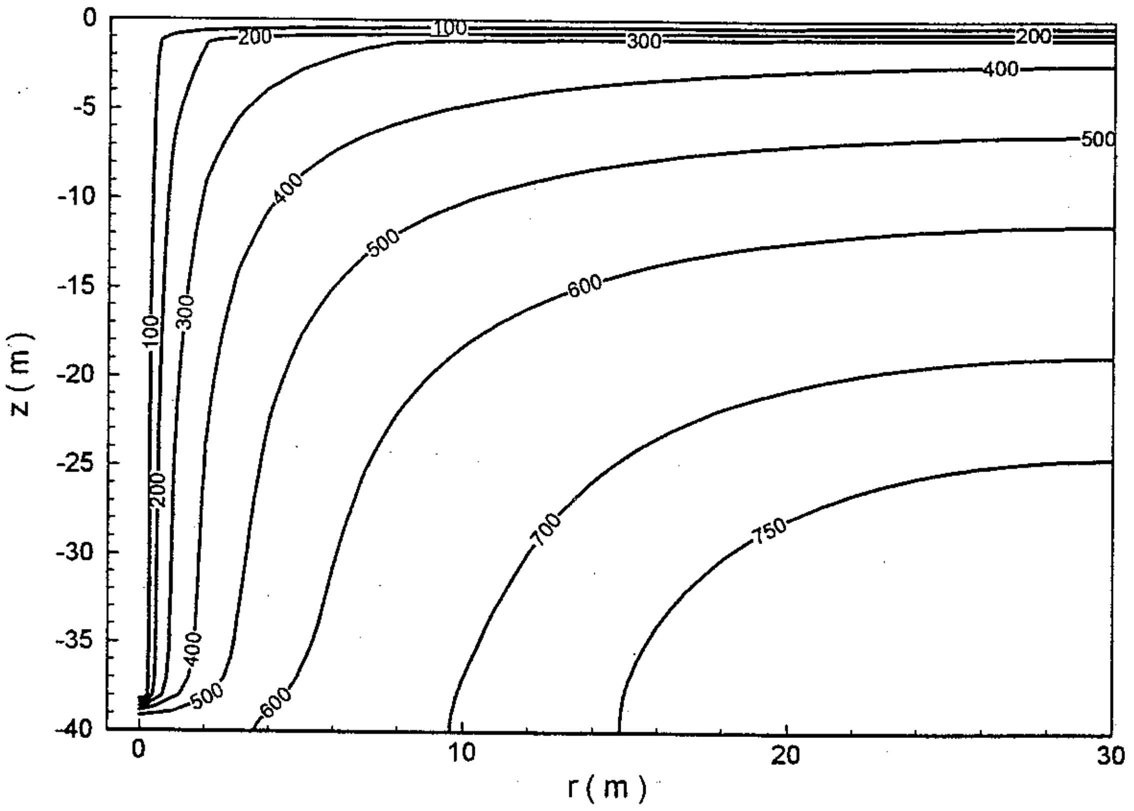

FIGURE 5
The pressure contour (ϕ) for the well depth $b = 38\,\text{m}$.

CONCLUSION

The gas emission from the landfill surface in a sanitary landfill equipped with a passive venting system was investigated numerically. The Darcy's law was employed for the modeling of two-dimensional gas flow in the landfill. The one-dimensional Bernoulli equation was assumed for the gas flow within the well. The results show that at least 43.3% gases produced from the solid waste will emit from the landfill surface for R = 30 m, where R is the half of the well spacing. The percentage of the gas emission from the landfill surface increases with decreasing well depth. It increases from 43.3% to 62.6% as the well depth decreases from 90% to 50% of the landfill depth. These indicate that the influence radii estimated in the designing and planning of the gas collection system in the Sanjuku landfill (influence radius = 45 to 50 m) in Taipei City and the Taichung

City sanitary landfill (influence radius = 30 to 35 m) in Taiwan were too large. This might pose a potential of air pollution and raise chances of fires under such designing.

The results from the pressure contours show that the well's ability in extracting the landfill gases declines quickly, when the radial distance from the well increases in the passive venting system. The gas velocity in the radial (r) direction in the region of $20 \text{ m} \leq r \leq 30 \text{ m}$ is very small. Thus most of gases produced in that region are difficult to be extracted by the well and will emit from the landfill surface. It also shows that the gas velocity in the radial direction increases with increasing well depth, especially in the deeper region of the landfill. Thus the gases are easily extracted by the well when the well depth is deeper.

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