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Рекомендовано до публікації д-р техн. наук, професор Міхайленко В. М.
Дата надходження рукопису 10.07.2018

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УДК 504.3.504:51-74
DOI: 10.15587/2313-8416.2018.143412

MATHEMATICAL MODELING OF BIOGAS LIFTING FROM THE MUNICIPAL SOLID WASTE POLYGON

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Розроблено математичну модель, яка описує динаміку конвекційного підйому нагрітих газоутворень (біогазу) в атмосферному повітрі. Встановлені висотні та часові залежності швидкості переміщення, характерного розміру, надлишкової відносної температури, плавучості цих газоутворень. Виконані числові оцінки зміни основних параметрів газоутворень для характерних ситуацій на полігоні твердих побутових відходів

Ключові слова: *біогаз, математична модель, полігон твердих побутових відходів, нагріті газоутворення*

1. Introduction

Municipal solid waste (MSW) polygons are located in the settlements vicinity. Decomposition products of municipal solid waste are danger not only for the environment, but also to public health [1, 2].

There is a chemical pollution of atmospheric air over the territory of municipal solid waste polygons due to biogas formation. The biogas composition includes flammable, toxic substances, which create a threat of fires and explosions [3]. Biogas raises upward, carries by the wind for a sufficiently long distance, including to the populated areas direction. This can lead to massive people poisoning [3].

Reported data of the fires occurrence and other emergencies in the waste disposal places [4, 5] indicates the imperfection of modern measures to prevent and minimize the impact of technogenic and ecological hazards sources on the environment and public health.

2. Literature review

The calculating biogas emissions models are mainly based on the Mono equation solution, first order decay, such as TNO, LandGEM, Gassim, Afvalzorg, EPER, IPCC, LFGEEN. These models take into account the carbon content, moisture, age of the waste, their ability to decompose and meteorological conditions. Meteorological conditions significantly affect to the composition and flux of landfill gas regeneration. Depending on the initial data, the techniques of Tabasaran-Rettenberger, Weber B., LandGEM, and AM Shaimova [6, 7] are of practical interest.

Estimating models for the biogas components distribution in atmospheric air are in most cases constructed using the Gaussian distribution function [8], the OND-86 technique [9] and the turbulent diffusion equation.

The temperature treatment in the polygon body based on numerical simulation [10] shows a temperature in the range of 20–50 °C. This confirms the biogas ability to buoyancy, when its temperature is warmer than atmospheric air.

The estimation of the maximum height and speed of the heated gas formations (biogas) rise, their size, buoyancy, excessive temperature as a function of altitude and rise time, especially in emergency situations, is necessary to ensure the environmental safety of municipal solid waste polygons.

3. Aim and objectives

The aim has been to treat the biogas spreading in convective rising to the atmosphere from the municipal solid waste polygon.

For achieving the set aim the following tasks have been put forward:

– to specify the main biogas parameters, such as height and time dependence of the center movement speed, proper size (radius), excess relative temperature, and buoyancy of heated gas formations (biogas);

– to estimate the main parameters changes of heated gas formations from the municipal solid waste polygon for proper situations.

4. Materials and methods

It has been assumed that the biogas takes the sphere form with a gradually increasing radius. At the same time, the rate of cold air intake is proportional to both the area of the emerging formation and the velocity of its center of mass rise. The coefficient of proportionality is considered constant. Since the formation radius is much smaller than the homogeneous atmosphere height and the troposphere thickness, the stratification of the atmosphere could be neglected.

As initial data, let's choose the equations for the velocity of the center of heated volume air V, weight m, radius R, density ρ and absolute temperature T, the increase rate of the mass of the involved cold air with density ρ0, temperature T_0 and the total buoyancy integral.

$$\frac{4\pi}{3}F=\frac{4\pi}{3}g\vartheta R^3, \qquad (1)$$

where g – acceleration of gravity, $\vartheta=(\rho_0-\rho)/\rho_0$ – buoyancy.

The biogas buoyancy conduced by the fact that its density is less than air $\rho < \rho_0$. Thus, this gas is lighter. The used model is suitable if the volumes of heated formation are raise. As a result of biochemical processes of waste decomposition, the heat is released, which causes a temperature difference. The buoyancy is caused by $T > T_0$. In this case $\vartheta=(T_0-T)/T_0$. In the conditions of the MSW polygon, the both cases are take place simultaneously.

The initial equations, taking into account air resistance, include the ratios for the lift speed, the mass of the cold air to be attracted and the total buoyancy integral of the heated formation:

$$m\frac{d\upsilon}{dt}=F_A-mg-C\rho_0\upsilon^2 S/2, \qquad (2)$$

$$\frac{dm}{dt}=\alpha S_1\upsilon\rho_0, \qquad (3)$$

$$\frac{dF}{dt}=-N^2\upsilon R^3, \qquad (4)$$

where t – time, $F_A=\rho_0 Vg$ – Archimedean force, mg – gravity, $C\rho_0\upsilon^2 S/2$ – air resistance force.

For spherical gassing $S=\pi R^2$ – cross sectional area, $S_1=4\pi R^2$ – sphere surface area, α – coefficient of cold air intake, $N\approx 10^{-2}$ c^{-1} – Brunt-Vaisala coefficient [11], $C=C_D+8\alpha$ – effective coefficient of resistance, C_D – coefficient of resistance (for a sphere at moderate speeds $C_D\approx 0{,}5$, а $\alpha\approx 0{,}1$ и $C\approx 1{,}3$ [11]). Because the $m=\rho V=4\pi R^3\rho/3$, $\rho=\rho_0 T_0/T$, equations (2) – (4) with considering (1) will take the form:

$$\frac{d\upsilon}{dt}=\vartheta g-\beta(1+\vartheta)\frac{\upsilon^2}{R},\ \beta=3C/8\approx 0{,}5,$$

$$\frac{dR}{dt}-\frac{R}{3(1+\vartheta)}\frac{d\vartheta}{dt}=\alpha\upsilon(1+\vartheta), \qquad (5)$$

$$\frac{d\vartheta}{dt}+3\vartheta\left(\frac{1}{R}\frac{dR}{dt}\right)=-\frac{N^2\upsilon}{g}. \qquad (6)$$

The final solution has the form:

$$\vartheta(R)=\vartheta_0(R_0/R)^3 \text{ или } \vartheta R^3=\vartheta_0 R_0^3. \qquad (7)$$

Relation (7) reflects the fact of total buoyancy integral conservation, that is $dF/dt=0$, and $F=F_0$.

5. Results and discussion

The calculations results of the main parameters describing the convective rise of heated formations in the atmosphere (biogas), for the values of ϑ_0 equal to 10^{-3}, $3\cdot 10^{-3}$, 10^{-2}, $3\cdot 10^{-2}$, 10^{-1}, and also for R_0, equal to 10, 100 and 1000 m (Tables 1–3) has been presented in the paper. The maximum value of R_0 has been determined not by the size of the emergency source, which could be ~1–10 km, but by the value of the external turbulence scale L_t in the atmosphere.

Table 1

The main parameters value of heated gas formation (R_0=10 m)

Parameters	ϑ_0				
	10^{-3}	$3\cdot 10^{-3}$	10^{-2}	$3\cdot 10^{-2}$	10^{-1}
z_1, m	900	900	900	900	900
z_{max}, m	1000	1000	1000	1000	1000
υ_{ch}, m/s	0,50	0,86	1,57	2,71	5,00
υ_{max}, m/s	0,36	0,63	1,14	1,98	3,61
t_0, s	111	64,6	35,4	20,5	11,1
t_υ, s	55,6	31,75	17,54	10,10	5,54
t_ϑ, s	94,3	52,9	29,2	16,8	9,2
t_R, s	383	158,75	87,7	50,50	27,7
t_{max}, s	$1{,}1\cdot 10^4$	$6{,}5\cdot 10^3$	$3{,}5\cdot 10^3$	$2{,}1\cdot 10^3$	$1{,}1\cdot 10^3$

Table 2

The main parameters value of heated gas formation (R_0=100 m)

Parameters	ϑ_0				
	10^{-3}	$3\cdot10^{-3}$	10^{-2}	$3\cdot10^{-2}$	10^{-1}
z_1, km	9	9	9	9	9
$z_{\max}$, km	10	10	10	10	10
υ_{ch}, m/s	1,50	2,71	5,00	8,57	15,00
$\upsilon_{\max}$, m/s	1,10	1,98	3,61	6,26	11,00
t_0, s	370,3	205	111,1	64,8	37,0
t_υ, s	181,8	101,0	55,4	31,9	18,2
t_ϑ, s	302,2	168,3	92	53,2	30,2
t_R, s	906,5	505	277	159,5	90,7
$t_{\max}$, s	$3{,}7\cdot10^4$	$2{,}05\cdot10^4$	$1{,}1\cdot10^4$	$6{,}5\cdot10^3$	$3{,}7\cdot10^3$

Table 3

The main parameters value of heated gas formation (R_0=1000 m)

Parameters	ϑ_0				
	10^{-3}	$3\cdot10^{-3}$	10^{-2}	$3\cdot10^{-2}$	10^{-1}
z_1, km	90	90	90	90	90
$z_{\max}$, km	100	100	100	100	100
υ_{ch}, m/s	5,00	8,57	15,00	27,11	50,00
$\upsilon_{\max}$, m/s	3,61	6,26	11,00	19,80	36,1
t_0, s	1111	648,2	370,3	204,9	111,1
t_υ, s	554	319,5	181,8	101	55,4
t_ϑ, s	923	532,5	303	168,3	92,3
t_R, s	2770	1597,5	909	505	277
$t_{\max}$, s	$1{,}1\cdot10^5$	$6.5\cdot10^4$	$3{,}7\cdot10^4$	$2\cdot10^4$	$1{,}1\cdot10^4$

Tables 1–3 show that with ϑ_0 increasing the spatial and temporal scales of the velocity changing, radius and relative formation heating (buoyancy) are decrease. The velocities values $\upsilon_{\max}$ and $\upsilon(L_\upsilon)$, and also height and rise time of the heated formations, on the contrary, are growth with ϑ_0 increasing.

6. Conclusions

1. The mathematical model depicted altitude and time dependence of the heated gasses main parameters during their convective ascent in the atmospheric air has been developed in the paper. Numerical calculations for different biogas buoyancy ($\vartheta_0 \approx 10^{-3} - 10^{-1}$) and different sizes of the danger source (with radius R_0 10, 100 and 1000m) have been carried out. It has been established that with increasing radius, the maximum height of biogas rise proportionally grows, reaching 1-10 km. The maximum rate of biogas rise varies from 0,36-3,6 m/s at $\vartheta_0 = 10^{-3}$ up to 3,6–36,1 m/s at $\vartheta_0 = 10^{-1}$. The biogas rise time decreases from 3-24 hours at $\vartheta_0 = 10^{-3}$ to 0,3–3 hours at $\vartheta_0 = 10^{-1}$.

2. It has been shown that during the biogas rise due to the cold air addition the radius of the heated volume increases, the excess temperature in it and buoyancy decrease, and the ascent rate firstly increases and then gradually decreases. The treatment outcomes are of practical importance in the state assessing of atmospheric air in the area affected by the MSW polygons, for efficient monitoring of hazard factors (concentrations, temperatures), making management decisions for conducting emergency rescue operations, and for predicting the consequences of emergency situations exposure on the environment and population.

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Дата надходження рукопису 02.08.2018

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