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PLUME RISE IN PARTICULAR METEOROLOGICAL CONDITIONS

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ABSTRACT

The problem of air pollution in calm weather conditions is discussed in the paper. The plume rise of exhausted gases, containing a gas pollutant is investigated when the wind velocity is equal or close to zero. The main goal is to offer a relationship for predicting of the effective stack height in such a case. The factors that influence the plume behavior have been defined. A numerical experiment based on a PHOENICS software package simulation has been performed for data collection. A simple mathematical model characterized with a very good accuracy has been worked out for plume rise calculation.

Keywords: air pollution, gas pollutant, calm weather, mathematical modeling, computer simulation, plume rise, effective height.

INTRODUCTION

The effective stack height is a very important characteristic of all exhausting units. It defines to a great extent the air pollution at the ground level. The effective height is defined as a sum of the geometric height of the stack and the plume rise caused by the initial gas velocity and the gravitational force.

The importance of the effective stack height makes its calculation one of the most important points in all mathematical models or software products intended for the air pollution assessment caused by existing or future sources of pollutants. The wind velocity has a strong influence on the plume rise. This is the reason, the wind velocity to be taken in account in all the published and used relationships for calculation of the effective height [1 - 3]. Unfortunately, in those relationships the wind velocity appears in the denominator and so, they cannot be applied at zero wind velocity. If non zero, but quite small value is accepted, the same relationships give unrealistic results [4].

The present work is dedicated to the investigation and the mathematical description of the plume rise in calm weather conditions.

Mathematical modeling of plume rise in calm weather conditions

The PHOENICS software package [5] is used for mathematical modeling end computer simulation of gas pollutant dissipation in calm weather conditions (wind velocity equals 0). A cylindrical-polar grid is used for the purpose. In such a case, the pollutant dissipation in radial and vertical direction is described [6] by a system of partial differential equations (1).

In a case of high initial vertical speed of exhausted gases, the flow turbulence is taken in account by use of LVEL turbulence model [7].

$$\frac{\partial(\rho P)}{\partial \tau} + div[\rho VP - Kgrad(P)] = S_p$$

$$\frac{\partial(\rho v)}{\partial \tau} + div[\rho Vv - Kgrad(v)] = S_v$$

$$\frac{\partial(\rho w)}{\partial\tau} + div[\rho V w - K grad(w)] = S_w$$

$$\frac{\partial(\rho T)}{\partial\tau} + div[\rho V T - K grad(T)] = S_T$$

$$\frac{\partial(\rho C)}{\partial\tau} + div[\rho V C - K grad(C)] = S_C \qquad (1)$$

In (1) ρ is density, $kg\ m^{-3}$; τ – time, s; V – velocity vector, $m\ s^{-1}$; K – exchange coefficient, $kg\ m^{-2}s^{-1}$; P – dynamic pressure, Pa; v and w – fluid velocity in radial and vertical direction, $m\ s^{-1}$; T – temperature, K; C – pollutant concentration, $mg\ m^{-3}$; r_s – inside stack radius, m; S - source.

The presented mathematical model has been used for simulation of a gas pollutant SO_2 in the atmosphere [6]. The results obtained give reason to accept that in calm weather conditions the exhausted gases are transported to a certain height above the stack and then the pollutant dissipates mainly in radial direction, as shown on Fig. 1. Isolines for concentration values between 0.0 and 1.0 $mg\ m^{-3}$ are shown on the figure. Each one of them can be approximated by two semi-ellipses with:

- equal semi-major axes a;
- different semi-minor axes b_1 and b_2;
- common center O.

Table 1. Factors and levels

No	Coded factor	Real factor	Low level	Mid point	High level
1	x_1	$\partial T/\partial h$	-0.009	-0.0075	-0.006
2	x_2	T_0	283	293	303
3	x_3	T_s	353	403	453
4	x_4	w_s	5	10	15

Obviously, the distance between the center O and the ground surface represents the effective height of the stack H_{ef}. Considering the geometric stack height H_s, the plume rise is

$$\Delta h = H_{ef} - H_s \qquad (2)$$

EXPERIMENTAL

The factors which the plume rise depends on are:
- the initial vertical velocity of the stack gases;
- the stack gases temperature;
- the air temperature at the ground surface;
- the temperature gradient of the atmosphere.

A numerical experiment based on the mathematical model (1) has been performed to establish a relationship describing Δh as a function of the factors men-

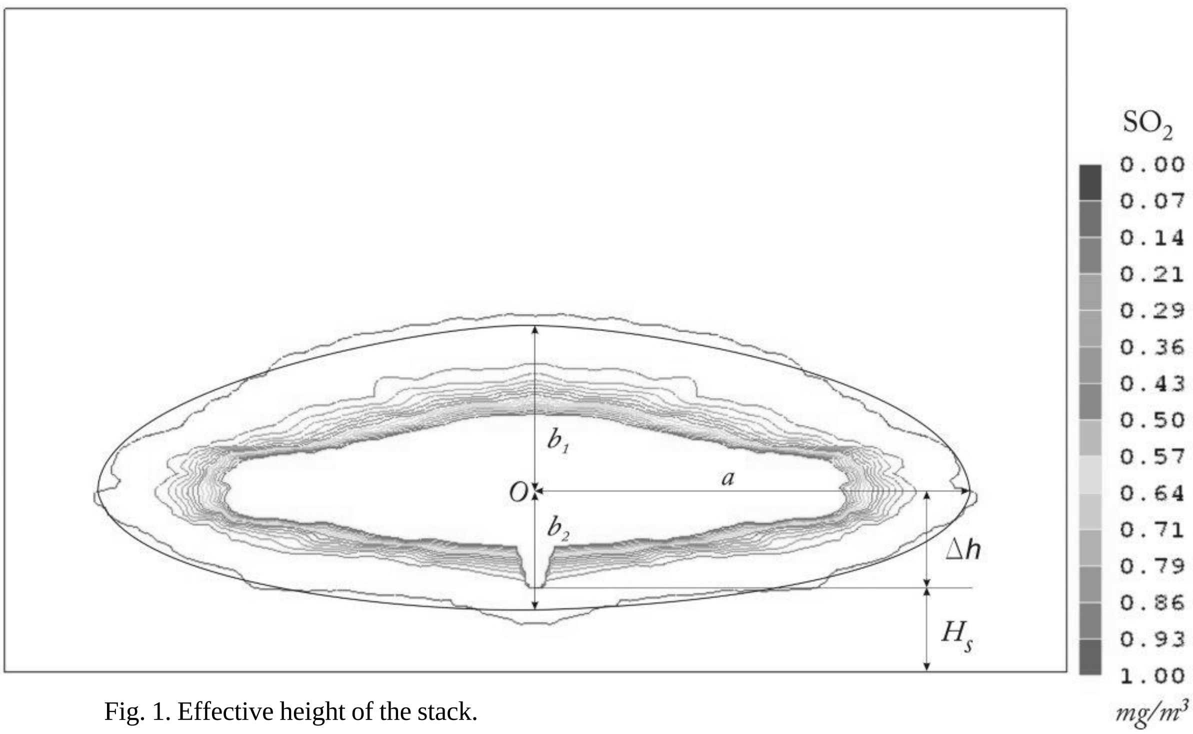

Fig. 1. Effective height of the stack.

Table 2. Experiment design and values of Δh.

No	x_1	x_2	x_3	x_4	Δh
	-	-	-	-	*m*
1	+1	-1	-1	-1	379
2	-1	-1	-1	-1	710
3	+1	+1	-1	-1	328
4	-1	+1	-1	-1	667
5	+1	-1	+1	-1	430
6	-1	-1	+1	-1	820
7	+1	+1	+1	-1	379
8	-1	+1	+1	-1	834
9	+1	-1	-1	+1	496
10	-1	-1	-1	+1	945
11	+1	+1	-1	+1	430
12	-1	+1	-1	+1	779
13	+1	-1	+1	+1	562
14	-1	-1	+1	+1	1001
15	+1	+1	+1	+1	536
16	-1	+1	+1	+1	917
17	+1	0	0	0	456
18	-1	0	0	0	890
19	0	-1	0	0	643
20	0	+1	0	0	589
21	0	0	-1	0	562
22	0	0	+1	0	643
23	0	0	0	-1	509
24	0	0	0	+1	670

Table 3. Model accuracy.

No	Δh_{exp}	Δh_{calc}	Error
	m	*m*	%
1	379	350.86	-7.43
2	710	682.37	-3.89
3	328	331.73	1.14
4	667	645.74	-3.19
5	430	407.64	-5.20
6	820	791.72	-3.45
7	379	399.05	5.29
8	834	775.14	-7.06
9	496	433.46	-12.61
10	945	843.02	-10.79
11	430	409.83	-4.69
12	779	797.77	2.41
13	562	503.62	-10.39
14	1001	978.13	-2.28
15	536	493.01	-8.02
16	917	957.65	4.43
17	456	432.63	-5.12
18	890	840.70	-5.54
19	643	632.77	-1.59
20	589	613.63	4.18
21	562	563.50	0.27
22	643	664.33	3.32
23	509	545.68	7.21
24	670	674.16	0.62

tioned above. Their levels are given in Table 1 and the experiment design is shown in Table 2.

RESULTS AND DISCUSSION

The „measured" values of Δh are given in the last column of Table 2. The air temperature at ground level T_0, the exhausted gasses temperature T_s and the temperature gradient of the atmosphere $\partial T/\partial h$ define the difference between the stack gases temperature and the ambient air temperature at level H_s.

$$\Delta T = T_s - \left(T_0 + H_s \frac{\partial T}{\partial h}\right) \quad (3)$$

Then the number of factors can be reduced to 3, namely: $X \equiv -(\partial T / \partial h) / \Gamma$; $X_2 \equiv \Delta T$ and $X_3 \equiv w_s$. Here w_s is the initial vertical velocity of exhausted gases, and $\Gamma = 0.00976$ *deg* m^{-1}, represents the adiabatic lapse rate [8].

On the base of the collected data for Δh (Table 2), the following mathematical model for calculation of plume rise has been deduced

$$\Delta h = A\left(-\frac{1}{\Gamma}\frac{\partial T}{\partial h}\right)^{\alpha}\left(T_s - T_0 - H_s\frac{\partial T}{\partial h}\right)^{\beta}(w_s)^{\gamma}, \quad (4)$$

$$\text{or } ln\Delta h = lnA + \alpha lnX_1 + \beta lnX_2 + \gamma lnX_3 \quad (5)$$

The following values of A, α, β, and γ have been found:
A=273.0022; $\alpha = 1.63475$; $\beta = 0.17223$, and $\gamma = 0.19245$.

The model accuracy is illustrated in Table 3, where Δh_{exp} is the plume rise estimated during the numerical experiment by use of PHOENICS software package and Δh_{calc} is calculated applying formula (4).The maximum and the average error are 12.61 and 5.0 %, correspondingly. The model is valid for the following conditions:

$283 \leqq T_0 \leqq 303;$

$353 \leqq T_s \leqq 453);$

$-0.009 \leqq \partial T/\partial h \leqq -0.006;$

$5 \leqq w_s \leqq 15$

CONCLUSIONS

The problem of air pollution with gas pollutants in particular meteorological conditions (zero wind velocity) is discussed in the paper. The PHOENICS software package has been used for simulation of sulfur dioxide dispersion in calm weather conditions.

A numerical experiment has been realized to investigate the influence of four factors which the plume rise depends on – the air temperature at the ground level, the temperature gradient of the atmosphere, the stack gasses temperature and the initial stack gases vertical velocity. A good accuracy mathematical model has been deduced for plume rise and the effective height calculation.

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