Point Pollution Sources Dimensioning

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ABSTRACT
In this paper a method for determining the main physical characteristics of the point pollution sources is presented. It can be used to find the main physical characteristics of them. The main physical characteristics of these sources are top inside source diameter and physical height. The top inside source diameter is calculated from gas flow-rate. For reckoning the physical height of the source one takes into account the relation given by the proportionality factor, defined as ratio between the plume rise and physical height of the source. The plume rise depends on the gas exit velocity and gas temperature. That relation is necessary for diminishing the environmental pollution when the production capacity of the plant varies, in comparison with the nominal one.

KEYWORDS: *point pollution source, source diameter, physical height, proportionality factor.*

JEL Classification: O14, Q53

Introduction

There are many types of pollution sources: point, linear, of surface and volume, as form; low, mean and high, as height; continuous, intermittent and instantaneous, as time of emission.

The point sources have a large use in industry for evacuating the gases resulting from the technological processes. They are of stack type and are met in power plants, metallurgy, chemical industry, paper industry, petrochemistry etc. Their main physical characteristics are the top inside diameter of the source, d, and the physical height of the source, h. These characteristics must be determined so that to assure a minimum impact on environment, even when the production capacity of plant varies.

1. Theoretical Base

The data necessary for calculating the two source characteristics mentioned above are:

- gas flow rate, V_g, evacuated from the source, computed from the production capacity of the plant;
- stack gas exit velocity, v, and stack gas temperature, T_g, chosen in such way that buoyancy flux to assure an appropriate plume rise.

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The top inside diameter of the stack, *d*, is determined from the gas flow rate and is equal to:

$$d = \sqrt{\frac{4 \cdot V_g}{\pi \cdot v}} \quad (1)$$

where V_g is in [m^3/s] and v in [m/s].

The physical height of the stack, *h*, is calculated by using the proportionality factor, *R*, given by the following formula (Cuculeanu, 2010):

$$R = \frac{\Delta H}{h} \quad (2)$$

where ΔH is the plume rise.

In the industrial activity there are periods of time when, for different reasons, the plants function at a smaller production capacity than the nominal one. For decreasing the environmental pollution in these periods, the proportionality factor must fulfil the condition (Cuculeanu, 2010):

$$O < R < 1 / \left[\left(\frac{p+q}{q} m - 1 \right) k \right] \quad (3)$$

where: *p*, *q* are dispersion parameters, depending on the atmospheric stability class and the dispersion scheme.

$m \in \left\{ \frac{1}{4}, \frac{1}{3}, \frac{3}{5}, \frac{2}{3}, \frac{3}{4}, 1 \right\}$ according to the atmospheric stability

$k \approx 1$ (Cuculeanu, 2010)

The plume rise is calculated with the general formula:

$$\Delta H = C \frac{F^m}{u_h^n} \quad (4)$$

where: *F* is buoyancy flux, m^4/s^3

u_h – wind speed at the source height, m/s.

The coefficient *C* and exponents *m* and *n* depend on stability class, being (Turner, 1994):

- ✓ for unstable and neutral conditions:
  - C = 21,425, m = 3/4, n = 1, when F < 55;
  - C = 38,71, m = 3/5, n = 1, when F > 55;
- ✓ for stable conditions:
  - C = 2,6/s$^{1/3}$, $m = n$ = 1/3;
- ✓ for calm conditions:
  - C = 4/s$^{3/8}$, m = 1/4, n = 0.

In the formulae of the *C*, *s* represents the stability parameter (Turner, 1994) and is given by:

$$s = \frac{1}{T}\left(g\frac{dT}{dz} + \Gamma\right) \tag{5}$$

where: *T* is air temperature, ^{0}K
g – acceleration of gravity, 9,8 m/s2
Γ – adiabatic lapse rate, 0,0098 ^{0}K/m.

The buoyancy flux is calculated using either the formula (Turner, 1994):

$$F = 9{,}8 d^2 \nu \frac{\Delta T}{4T_g} \tag{6}$$

where: ΔT is stack gas temperature minus ambient air temperature, ^{0}K

or the formula depending on the gas volume evacuated from the source:

$$F = 9{,}8 \frac{V_g}{\pi} \frac{\Delta T}{T_g} \tag{7}$$

The wind speed at the physical height of the source, u_h, is computed with the formula (Romanof, 1983; Turner, 1994):

$$u_h = u_a \left(\frac{h}{h_a}\right)^r \tag{8}$$

when: u_a is the wind speed at anemometer height, m/s
h_a – anemometer height above ground, m
r – exponent dependent on atmospheric stability and surrounding area.

Taking into account the relations (2) and (8), ΔH given by (4) can be written as:

$$\Delta H = \left[C \frac{F^m (R\, h_a)^{nr}}{u_a^n} \right]^{1/(1+nr)} \tag{9}$$

where *R* fulfil the condition (3).

It is recommended that the *R* value to be chosen round the average of the interval defined above. The values near the maximum limit of the interval results in low physical height of the stack, what does not assure an appropriate dispersion. The values of *R* near the minimum limit of the interval determine great values of the stack height, difficult to be built.

The physical height of the stack, *h*, is calculated by means of the relation (2). The effective height of the plume, *H*, is obtained by adding the physical height and plume rise.

The maximum ground level concentration is equal to (Arya, 1999):

$$C_{max} = \frac{Q}{\pi a b u_h}\left[\frac{b^2 (p+q)}{q H^2}\right]^{(p+q)/2q} \tag{10}$$

where: Q is pollutant emission rate, g/s
a, b – dispersion parameters depending on the atmospheric stability class.

The environmental protection is assured when the maximum ground level concentration is equal or less than the admissible maximum concentration (CMA); the pollutant emission rate is determined under this condition.

The difference between the pollutant quantity per unit time, occurring from the technological process and the pollutant emission rate will be retained in gas cleaning equipment before the gas evacuation in the atmosphere.

When the production capacity of plant varies up to a percentage l, the effective height of the plume will be calculated with the formula (Cuculeanu, 2010):

$$H_l = h + k \cdot l^m \Delta H \tag{11}$$

In the same condition the maximum ground level concentration will be (Cuculeanu, 2010):

$$(C_{max})_l = l\left(\frac{H}{H_l}\right)^{(p+q)/q} C_{max} \tag{12}$$

where C_{max} is the maximum ground level concentration, when plant works with whole production capacity and equal with CMA.

In order to calculate the physical characteristics of the stack one may use this method, which supposes the following steps to be achieved.
1. Calculation of the top inside diameter, d, of the stack.
This is done by means of the formula (1), for any atmospheric stability class.

2. Calculation of the physical height, h, of the source.
The physical height of the source is computed following the procedure:

- establishing the atmospheric stability classes for the annual mean wind speed (Turner, 1994) of the area where the plant will be built;
- choosing the dispersion scheme, that is necessary for the values of the dispersion parameters, a, b, p, and q;
- choosing the value of r, depending on the atmospheric stability class and area where plant will be built (Romanof, 1983; Turner, 1994);
- calculating the buoyancy flux;
- establishing the variation interval of R, from the condition (3) and choosing its value that is to used;
- calculating the plume rise for chosen R;
- calculating the physical height of the source.

3. Calculation of the pollutant emission rate.
The pollutant emission rate is calculated from the formula (10) using the effective height of the plume, *H*, which has been previously computed. This calculation supposes that the maximum ground level concentration in equal to CMA.

In order to take into account the wind variability during the year, the maximum ground level concentration is verified for different wind speeds.

For each considered wind speed one calculates:

- the plume rise;
- the effective height of plume, by keeping the same value of the physical height of the stack previously calculated;
- the maximum ground level concentration;
- the pollutant emission rate for the wind speed which determines the greatest value of the maximum ground level concentration, under the condition that this concentration to be equal to CMA.

The dispersion parameters used in the verification are those of the atmospheric stability class corresponding to the wind speed interval in which the considered wind speed belongs to (Turner, 1994). The verification has resulted in the fact that the pollutant emission rate, when plant works at the nominal production capacity, has the smallest value.

When the wind speed has smaller value than the annual mean one, the maximum ground level concentration is smaller than CMA, because the plume rise increases.

2. Numerical Application

Let's suppose that a plant emitting sulphur dioxide in the atmosphere is to be built in one of two urban areas: first, where the annual mean wind speed at the anemometer height (h_a = 10 m) is 2 m/s; second, where the annual mean wind speed at the same height is 4 m/s. One has to calculate the physical height and top inside diameter of the stack using the following data:

- stack gas flow rate, V_g = 350 m^3/s;
- stack gas exist velocity, v = 15 m/s;
- stack gas temperature, T_s = 383^0K.

The maximum ground level concentration, when the production capacity of the plant will decrease till 70% of the nominal one, is to be determined.

1. The top inside diameter of the stack, for any atmospheric stability class is calculated with the formula (1) and the result is 5,46 m.

2. According to the Pasquill atmospheric stability, the possible classes are:

- A, B, C, E and F, when the wind speed is 2,5 m/s;
- B, C and D, when the wind speed is 4 m/s.

The dispersion scheme used in these calculations is that given in ASME (Seinfeld, 1986), which has not dispersion parameters for the classes C and E.

In table 1 the dispersion parameters used in the present calculation are given:

Table 1. Dispersion parameters (after Seinfeld, 1986)

Atmospheric stability class	a	p	b	q
A	0,4	0,91	0,4	0,91
B	0,36	0,86	0,33	0,86
D	0,32	0,78	0,22	0,78
F	0,31	0,71	0,06	0,71

The values of the r for the four atmospheric stability classes are (Romanof, 1983): r = 0,15 for classes A and B; r = 0,25 for class D: r = 0,6, for class F.

The buoyancy flux, computed with the formula (7), is 256,69 m^4/s^3, for all atmospheric stability classes.

According to the condition (3) the factor R is in the interval (0,5), because m = 3/5 and $k \approx 1$ (Turner, 1994; Cuculeanu, 2010). In accordance with what was previous mentioned, the value of R has been considered 2,35.

For the annual mean wind speed of 2,5 m/s the values of the physical height of the stack and plume rise for the class A are equal with the corresponding values for the class B. These values are h = 125,8 m and ΔH = 295,6 m.

In case of SO_2 for the same value of the wind speed and maximum ground level concentration equal with CMA ($25 \cdot 10^{-6}$ g/m^3) the pollutant emission rate is 69,04 g/s, for the class A, and 75,32 g/s, for the class B.

For the class A the wind speed ranges in the interval (0,3) and the class B the wind speed in interval (0,5) depending of insolation (Turner, 1994). Therefore, the verification of the maximum ground level concentration was performed for more values of the wind speed. On the base of the results presented in table 2, the following conclusions can be drawn:

- the maximum ground level concentration has the same value for the both atmospheric stability classes though the pollutant emission rate is different.
- the maximum ground level concentration is smaller than CMA when the wind speed is smaller than its annual mean value and greater than CMA when the wind speed rises above its annual mean value (2,5 m/s).

When the wind speed rises above its annual mean value the environmental pollution increases. Consequently, the pollutant emission rate must have the value corresponding to the class A for the maximum wind speed used for verifications. From the table 2 one can notice that this speed is 4 m/s. The corresponding pollutant emission rate is 58 g/s.

Table 2. Physical and emission characteristics for the classes A and B when u_a = 2,5 m/s

Wind speed m/s	ΔH m	h m	H m	Q, g/s		C_{max} g/m^3	$(C_{max})_{70}$ g/m^3
				A	B		
1	738,72	125,8	864,52			$14,85 \cdot 10^{-6}$	$14,9 \cdot 10^{-6}$
2	369,4	125,8	495,2			$22,63 \cdot 10^{-6}$	$20,73 \cdot 10^{-6}$
2,5	**295,6**	**125,8**	**421,4**	**69,04**	**75,32**	$\mathbf{25 \cdot 10^{-6}}$	$\mathbf{23,41 \cdot 10^{-6}}$
3	246,24	125,8	372			$26,74 \cdot 10^{-6}$	$24,59 \cdot 10^{-6}$
4	184,64	125,8	310,44			$28,78 \cdot 10^{-6}$	$25,71 \cdot 10^{-6}$

Concerning the class E, only verifications have been made for some wind speeds, because its probability of occurrence is very small. The results of the verifications find in the table 3; they show that at the ground level the pollution is very small, even for the greatest pollutant emission rate (75,32 g/s).

Table 3. Physical and emission characteristics for the class F when u_a = 2,5 m/s

Wind speed m/s	ΔH m	h m	H m	Q g/s	C_{max} g/m^3	$(C_{max})_{70}$ g/m^3
1	236,38	125,8	362,2		$5,72 \cdot 10^{-6}$	
2	118,2	125,8	244		$6,3 \cdot 10^{-6}$	
2,5	**94,56**	**125,8**	**220,36**	**75,36**	**$6,178 \cdot 10^{-6}$**	
3	78,8	125,8	204,6		$5,97 \cdot 10^{-6}$	
4						

When the annual mean wind speed is 4 m/s and class is B, the physical height of the source and the plume rise are 83,6 m and 196,4 m respectively. For the same wind speed, but the class D, the two characteristics are 70,51 m and 145,7 m respectively. The pollutant emission rate is 50,036 g/s for the class B and 56,28 g/s, for the class D. For these atmospheric stability classes the verifications were made for more values of the wind speeds and their results are given in the table 4. The analysis of the table 4 shows that the same conclusions can be drawn, as in the case of the wind speed of 2,5 m/s.

For protection the environment, the pollutant emission rate must be smaller than the value resulted from the annual mean wind speed.

Thus, for the class B it must be 44 g/s and for class the D it must be 49 g/s, values corresponding to the wind speed of 6 m/s.

Taking into account that the difference between the classes B and D consists in the insolation degree and day time (Turner, 1994) the dispersion parameters of one class were verified on the physical height of the other class. The results are presented in the tables 5 and 6.

Table 4. Physical and emission characteristics for the classes B and D when u_a = 4 m/s

Wind speed m/s	ΔH m	h m	H m	Q g/s	C_{max} g/m^3	$(C_{max})_{70}$ g/m^3
class B						
2	392,74	83,6	476,34		$17,28 \cdot 10^{-6}$	$17,1 \cdot 10^{-6}$
3	261,82	83,6	345,42		$21,91 \cdot 10^{-6}$	$21,04 \cdot 10^{-6}$
4	**196,4**	**83,6**	**280**	**50,036**	**$25 \cdot 10^{-6}$**	**$23,41 \cdot 10^{-6}$**
5	157,1	83,6	240,7		$27,065 \cdot 10^{-6}$	$24,8 \cdot 10^{-6}$
6	131	83,6	214,6		$28,37 \cdot 10^{-6}$	$25,52 \cdot 10^{-6}$
class D						
2	331,29	70,51	401,8		$17,28 \cdot 10^{-6}$	$17,1 \cdot 10^{-6}$
3	220,86	70,51	291,37		$21,9 \cdot 10^{-6}$	$21,04 \cdot 10^{-6}$

Wind speed m/s	**ΔH m**	**h m**	**H m**	**Q g/s**	**C_{max} g/m^3**	**$(C_{max})_{70}$ g/m^3**
4	**165,7**	**70,51**	**236,21**	**56,28**	**$25 \cdot 10^{-6}$**	**$23{,}41 \cdot 10^{-6}$**
5	132,52	70,51	203		$27{,}08 \cdot 10^{-6}$	$24{,}8 \cdot 10^{-6}$
6	110,44	70,51	181		$28{,}39 \cdot 10^{-6}$	$25{,}55 \cdot 10^{-6}$

The verification of the stack physical height for the class B with the dispersion parameters of the class D shows that pollution decreases for the pollutant emission rate of 56,28 g/s, even for the wind speed more than 4 m/s (table 5).

Table 5. Verification of the class B dimensions for u_a = 4 m/s, with the class D dispersion parameters

Wind speed m/s	**ΔH m**	**h m**	**H m**	**Q g/s**	**$C_{max} \cdot$ g/m^3**	**$(C_{max})_{70}$ g/m^3**
2	317,65	83,6	401,25		$16{,}62 \cdot 10^{-6}$	$16{,}2 \cdot 10^{-6}$
3	211,77	83,6	295,37		$20{,}44 \cdot 10^{-6}$	$19{,}28 \cdot 10^{-6}$
4	158,83	83,6	242,43	56,25	$22{,}76 \cdot 10^{-6}$	$20{,}88 \cdot 10^{-6}$
5	129,34	83,6	213		$23{,}45 \cdot 10^{-6}$	$21{,}76 \cdot 10^{-6}$
6	106	83,6	189,6		$24{,}8 \cdot 10^{-6}$	$21{,}79 \cdot 10^{-6}$
7	90,76	83,6	174,36		$25{,}14 \cdot 10^{-6}$	$21{,}75 \cdot 10^{-6}$

The verification of the stack physical height for the class B with the dispersion parameters of the class B shows that pollution increases even from the wind speed of 4 m/s for the pollutant emission rate smaller than in the precedent case (table 6).

From the results one infers that the physical height corresponding to the instable conditions determines a smaller pollution at the ground level.

Table 6. Verification of the class D dimensions for u_a = 4 m/s, with the class B dispersion parameters

Wind speed m/s	**ΔH m**	**h m**	**H m**	**Q g/s**	**C_{max} g/m^3**	**$(C_{max})_{70}$ g/m^3**
2	403	70,51	473,51		$17{,}95 \cdot 10^{-6}$	$17{,}99 \cdot 10^{-6}$
3	268,7	70,51	339,21		$23{,}31 \cdot 10^{-6}$	$22{,}74 \cdot 10^{-6}$
4	201,5	70,51	272	50,036	$27{,}185 \cdot 10^{-6}$	$25{,}91 \cdot 10^{-6}$
5	161,2	70,51	231,71		$29{,}97 \cdot 10^{-6}$	$27{,}99 \cdot 10^{-6}$
6	134,33	70,51	204,84		$31{,}41 \cdot 10^{-6}$	$28{,}82 \cdot 10^{-6}$
7	115,14	70,51	185,65		$33{,}35 \cdot 10^{-6}$	$30{,}13 \cdot 10^{-6}$

Conclusions

The method presented in this paper for determining the physical height of the point pollution source, at their designing, has the following advantages:

- it makes a connection between the physical height of the source and functional characteristics of the plant by means of the proportionality factor;
- it is assuring the ground level concentration under the admissible maximum limit;
- it is assuring a precise determination of the pollutant quantity that has to be retained by purification equipment;
- it is leading to the reducing of the environmental pollution where the production capacity of plant was decreased.

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