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Estimation of Downwash Effects

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INTRODUCTION

This is a simplified approach to the calculation of ground-level concentrations of effluents from small industrial and fuel-burning installations. It is intended to serve as a first approximation to a very complex process. Because each stack, building, and terrain configuration is different, actual ground concentration may frequently differ from the values calculated here by a factor of two.[1]

The procedures given here were designed especially for source heights of less than 100 m; some of the simplifications made are not valid for large emissions. It is important to note that all *lengths are in meters* (m) and *velocities are in meters per second* (m/sec) in these formulas; this avoids needless reiteration of the formulas for different units. Table 6.1 provides all necessary conversion factors.

This chapter gives a method for predicting the occurrence of downwash. This is a common occurrence with small emissions, and greatly increases ground concentrations in the immediate vicinity downwind of the source.

ELEVATED SOURCE OR GROUND SOURCE?

The answer to this question can mean either a zero concentration or a very high concentration of effluent at the ground in the neighborhood of an emission. Does the plume keep its distance from the ground, and if so, what is its effective height, or is the plume brought to the ground very near the source? The latter can happen if the

Table 6.1. Conversion Factors.

1 m = 3.28 ft	1 cal/sec = 4.185 watt
10^{3}m = 0.621 mi	1 cal/g-°C = 1.00 Btu/lb-°F
1 sec = min/60 = hr/3600	1 watt = 1 joule/sec = 1 kg-m^{2}/sec^{3}
= day/86,400 = 30 days/259	1 ft = 0.305 m
10^{6} = yr/3.14 • 10^{7}	1 mi = 1.61 • 10^{3}m
1 kg = 10^{3} g = 10^{6} mg = 10^{9} μg	1 lb = 0.454 kg
1 kg = 2.2 lb	1°R = 0.555 °K
1 °K = 1.8°R	°R = °F + 460
°K = °C + 273	1 Btu = 252 cal
1 cal = 1 g-cal = 10^{-3} kg-cal	1 ft/sec = 0.305 m/sec
1 cal = 0.00397 Btu	1 mph = 0.447 m/sec
1 m/sec = 3.28 ft/sec	1 ton/hr = 0.252 kg/sec
1 m/sec = 2.24 mph	1 ppm = 10^{-6}(m_o/24)kg/m^{3}
	= (m_o/24)mg/m^{3}
1 kg/sec = 3.96 ton/hr	1 lb/hr = 0.126 g/sec
1 kg/m^{3} = 10^{6}(24/m_o)ppm	1 ton/mi^{2} = 0.35 g/m^{2}
1 g/sec = 7.93 lb/hr	1 watt = 0.239 cal/sec
1 g/m^{2}= 2.85 ton/mi^{2}	1 Btu/lb-°F = 1.00 cal/g-°C

efflux velocity is too low, the stack is too short, or the emission is denser than air. Downwash of the plume due to terrain is also possible, particularly if there is an escarpment upwind of the source, but this case is relatively rare.

The answer to the above question can depend on the wind speed. It also can depend on the location of the stack relative to buildings and the wind direction. The great variety of possible building geometries gives ample reason for not expecting great accuracy from the following "rules-of-thumb."

Stack Aerodynamic Effect

An effluent emitted vertically from a stack can rise due to its momentum or can be brought downward by the low pressure in the wake of the stack. Which occurs depends on the ratio of the efflux velocity, v_s, to the crosswind velocity, u. Make the following computation, where D is the inside stack diameter and h_s is the source height above the ground:

$$h' = h_s + 2(v_s/u - 1.5)D \qquad (1)$$

It is suggested that this be done for the following values of u: 1, 2.5, 4.5, 7, and 10 m/sec. The efflux velocity can be determined from direct measurement, from the amount of forced draft, from the rate of the process and relative proportions of its gaseous product (thermal expansion should be taken into account), or from visual or cinematographic estimates (if there are visible tracers in the effluent.) Building and stack measurements can be made directly, taken from drawings, or scaled from photographs.

If the effluent is emitted from a nonvertical stack or vent, set $h' = h_s$.

Equation (1) is based partly on wind tunnel observations of Sherlock and Stalker[2] who showed that downwash (negative rise) occurs when v_s/u is less than about 1.5 and that the plume downwashes about one stack diameter at $v_s/u = 1$. For high values of v_s/u, it is a conservative form of Equation (5.2) recommended by Briggs[3] for momentum rise; $2(v_s/u)D$ approximates the plume rise at the point where it is equal to 1.7 times the downwind distance, so essentially represents the very close-in plume rise. Buoyancy is neglected in this stage, since it does not cause a doubling of the plume rise until a distance $x = 10\ u\ v_s/(-g\ \Delta)$.

Building Effect

If the effluent is emitted from a stack or vent on or near a building, it may be brought downward by the flow of air over and around the building. Let l_b equal the lesser of the building height, h_b, or the building width perpendicular to the wind direction, w_b. If h' is less than $(h_b + 1.5\ l_b)$ and the point of emission is on the roof, anywhere within $l_b/4$ of the building, or within $3l_b$ directly downwind of the building, the plume can be considered to be within the regional of building influence. If the plume is within the region of building influence, there are several possibilities:

A. If h' in Equation (1) is less than $(h_b + 0.5l_b)$, part or all of the effluent is likely to circulate within the aerodynamic "cavity" that forms in the lee of the building. This cavity usually begins at the upwind edge of a flat roof or at the crest of a pitched roof (unless the crest is parallel to the wind). It grows to a height of about $(h_b + 0.5\ l_b)$ and a width a little greater than w_b, and extends over all lee sides of the building and downwind 2 to 3.5 l_b. Thus, effluents in the cavity region may affect persons on the ground and in the building. One must especially consider the placement of intake vents providing ventilation within the building. Following are some rough guidelines for estimating the concentration (χ) experienced in the cavity region. Let $\chi = KQ/(u\ l_b^2)$, where Q is source strength. If $H' > 0.35$, K is generally 1 or less throughout the cavity. If $H' < 0.35$, K is typically 1.5 and at most is 3.0, except on the side of the building where the effluent is emitted (for instance, the roof). Here, K can range up to 100 $(H' = (h' - b_b)/l_b)$, The concentration along the axis of the plume can be roughly approximated by $\chi = 4Q/(us^2)$, where s is the distance from the source measured along the axis. The airflow near buildings is complicated, and it is difficult to predict the trajectory of the plume axis. For example, in the cavity within $l_b/4$ of the roof, the flow is usually upwind.

B. If $h' > h_b$, compute $h'' = 2\,h' - (h_b + 1.5\,l_b)$ (2)
If $h' < h_b$, compute $h'' = h' - 1.5\,l_b$ (3)

C. If h'' is greater than $l_b/2$, the plume remains an elevated source. If h'' is less than $l_b/2$, treat the plume as a ground source with an initial cross-sectional area $A = l_b^2$.

The above rules reduce to a simpler form in the case of a squat building, *i.e.*, when $h_b < w_b$: If $h' \geqslant 2.5\,h_b$, the plume escapes the region of building influence and $h'' = h'$; if $h' \leqslant 1.5\,h_b$, the plume downwashes into the building cavity [see (1) above] and also becomes a ground source with $A = h_b^2$ [see (3) above]; for in-between values of h', the plume remains elevated and $h'' = 2\,h' - 2.5 h_b$ [see (2) above].

The method suggested here for accounting for the building effect is an interpolation of several rules-of-thumb respecting air flow around buildings. It is generally accepted that a building has very little effect on the airflow at 2½ building heights above the ground and above. On the other hand, the aerodynamic cavity downwind of a sharp-edged building develops to roughly 1½ building heights. It develops higher over a very wide (*i.e.*, squat) building, but the plume also has more distance in which to rise out of the cavity in this case. This method does allow some close-in plume rise to be considered with respect to escaping the cavity; however, it should be conservative since it does not allow for the lower wind speed near the building, which promotes greater rise. The cavity height may be less than 1½ building heights in the case of pitched or rounded roofs.

For a squat building, this method assumes that if $h' < 1.5\,h_b$, the plume behaves as if it were a ground source of initial area $A = h_b^2$. This gives concentrations in approximate agreement with those measured by Yang and Meroney[4] near the end of the cavity. The values of χ within the cavity adjacent to the building were estimated from measurements around cubes and rectangles by Halitsky.[5] Equation (2) is a linear interpolation formula giving $h'' = h'$ when $h' = 2.5\,h_b$ and $h'' = 0.5\,h_b$ when $h' = 1.5\,h_b$, thus giving a χ of the same order as that given for a ground source ($h' < 1.5\,h_b$, $A = h_b^2$).

For tall buildings, w_b replaces h_b as the characteristic cavity width and height above h_b. It is assumed that a roof level plume is not pulled all the way down to the ground within the cavity if $h_b > 2\,w_b$; hence, h'' is no more than $1.5\,w_b$ below h'.

Yang and Meroney[4] found that atmospheric stability had only a slight effect on concentrations immediately downwind of a building, so this effect is neglected here.

SUMMARY OF EQUATIONS AND WORKED EXAMPLE

Summary of Equations

Stack aerodynamic effect:

$$h' = h_s + 2D(v_s/u - 1.5). \quad (1)$$

Building effect: applies only if stack is on or near building or is within 3 l_b downwind and $h' < h_b = 1.5\, l_b$, where l_b = lesser of h_b or w_b; if not, $h'' = h'$.

If $h' < h_b + 0.5\, l_b$, high concentrations may occur in building "cavity;"

If $h' > h_b$, compute $h'' = 2h' - (h_b + 1.5\, l_b)$ (2)

If $h' < h_b$, compute $h'' = h' - 1.5\, l_b$ (3)

If $h'' < l_b/2$, treat plume as ground source with $A = l_b^2$

Worked Example

Suppose we have a plant with a stack located on the roof of a long, flat building with the following specifications:

$h_b = l_b$ = 66 ft = 20 m
h_s = 99 ft = 30 m
r = 1.64 ft = 0.5 m
V_s = 16 ft/sec = 5 m/sec
Q (SO_2) = 0.035 lb/sec = 0.016 kg/sec
Effluent temperature = 290 °F = 416 °K
Ambient temperature = 70 °F = 294 °K
Distance to nearest property line = 330 ft = 100 m

Solution

Stack aerodynamic effect: $h' = h_s + 4\,(V_s/u - 1.5)\,r$

u = 1 m/sec: h' = 30 + 4 (5/1 − 1.5) (0.5) = 37 m
u = 2.5 m/sec: h' = 30 + 4 (5/2.5 − 1.5) (0.5) = 31 m
u = 5 m/sec: h' = 30 + 4 (5/5 − 1.5) (0.5) = 29 m
u = 10 m/sec: h' = 30 + 4 (5/10 − 1.5) (0.5) = 28 m

Building effect: $h'' = 2h' - (h_b + 1.5\, l_b)$ if 30 m < h' < 50 m
$h'' = h_b - l_b = 0$ if h' < 30 m (downwash)

u = 1 m/sec: h'' = 2 (37) − 50 = 24 m
u = 2.5 m/sec: h'' = 2 (31) − 50 = 12 m
u = 5 m/sec: h'' = 0
u = 10 m/sec: h'' = 0
(plume becomes ground source when h' = 30 m, $h' = h_s + 4\,(V_s/u - 1.5)r$
Solving for u, 30 = 30 + 4 (5/u − 1.5) (0.5), u = 3.33 m/sec

SYMBOLS AND DEFINITIONS

Symbol	*Definition*	*Units*
A	Initial cross-sectional area of a ground plume	m^2
D	Inside stack diameter	m
h	Effective source height (after stack aerodynamic, building, and buoyancy effects have been accounted for)	m
h′	Plume height after stack aerodynamic effect is accounted for	m
h″	Plume height after building effect is accounted for	m
h_b	Building height	m
h_s	Source height above the ground	m
K	Dimensionless concentration coefficient in cavity region	—
l_b	The lesser of h_b or w_b	m
Q	Source strength of a component of the effluent	kg/sec
u	Wind speed at source height or at an open location	m/sec
v_s	Average efflux velocity (volume flow rate ÷ area)	m/sec
w_b	Building width perpendicular to the wind direction	m
x	Distance downwind of the source	m
χ	Concentration of a component of the effluent	kg/m^3

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