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Short communication

Sheltering as a protective measure against airborne virus spread

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Abstract

The dispersion of airborne viruses can play an important role in the spread of a disease. Especially for short or moderate emission periods — such as emissions from farms or accidental releases from laboratories or industrial plants — indoor concentrations can be significantly lower than outdoor concentrations. The relationships between these two concentrations are analysed for continuous, temporary and instantaneous releases. The efficiency of sheltering as a protective measure for persons or animals is discussed. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Contagious diseases can spread over moderate or long distances by different mechanisms: movement of carrier persons or animals, vehicles, infected food, water, etc. However, there is another mechanism which, in some cases, can play an important role and which is very difficult to control in practice: the dispersion of airborne infectious particles. The release of these agents from an infected farm or — as has happened sometimes — from a vaccine plant or a military facility, gives rise to a plume which, depending on the meteorological conditions, can move to other farms or urban zones. If the virus concentration in the plume is high enough, there is a significant probability of infection of persons or animals located downwind from the source. Depending on the

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release duration and wind direction, the dose received by persons or animals will vary; this, in turn, influences the probability of infection.

In such cases, and especially for relatively short periods, sheltering in buildings can be a useful measure for reducing the dose, thus decreasing the probability of infection. Therefore, the prediction of outdoor and indoor virus concentrations to which persons and animals will be exposed in the event of an atmospheric virus dispersion seems very interesting. Such information could be helpful in real-time emergency management for deciding whether a herd should be slaughtered immediately, or for estimating the relative effect of a virus plume on the population.

However, although several authors have studied the atmospheric dispersion of viruses, practically no attention has been devoted to protection by sheltering in these situations. In fact, this subject is similar to that related to the protection of people following a toxic gas release from a chemical plant [1]. In this paper, a specific solution for the variation of indoor concentration of virus with time for the instantaneous release case is presented.

2. Indoor–outdoor concentration

A closed building, with a given ventilation rate, can give rise to different indoor and outdoor concentrations of a pollutant. If this is not ‘‘stationary’’, but appears in the outdoor atmosphere only for a given period of time, as in the case of a virus plume, obviously, the indoor concentration will be a function of the evolution of the outdoor concentration and of the ventilation rate. The evolution of outdoor concentration will depend, as stated above, on meteorological conditions and on the release features (flow rate, concentration and duration). Therefore, at least for the first steps of the event, the indoor concentration will be clearly lower than outdoor concentration.

In the case of virus releases, the plume may cover certain areas for long periods. Taking this into account, it is interesting to analyse different cases: continuous emission, temporary release and instantaneous release. The first two are typical of infected farms, while instantaneous release can be found only in very special and unusual cases, such as accidental releases from laboratories or industrial plants. Infected farms release virus for several days and the exposure of other farms depends mainly on the time during which wind has a given direction. Obviously, longer times will allow indoor concentrations similar to those of the stationary state.

2.1. Continuous source

If the outdoor concentration c_o is constant, the indoor concentration will increase continuously up to a certain value due to the air which enters the building by ventilation. For a building of a given volume and with a constant ventilation rate, the virus balance is (Fig. 1):

$$\vartheta c_o = \vartheta c_i + \frac{dM_{virus}}{dt} + m_{ads} c_i \tag{1}$$

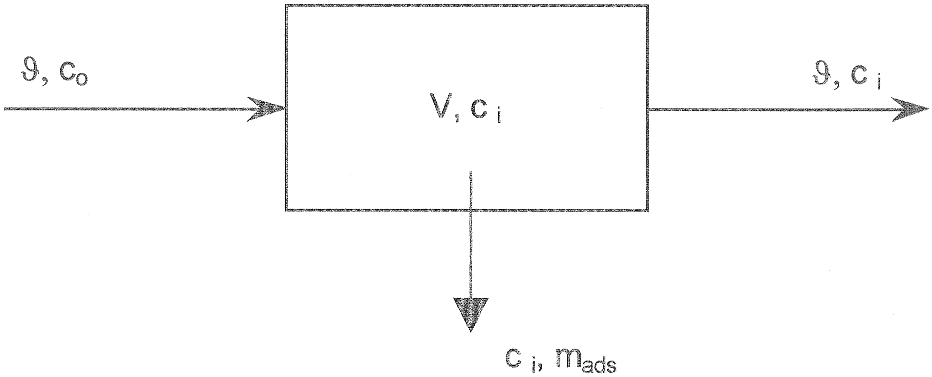

Fig. 1. Virus mass balance.

By integrating with the limiting condition $c_i = 0$ as $t = 0$, the following expression relating indoor and outdoor concentrations is obtained:

$$c_i(t) = c_o \frac{\vartheta}{\vartheta + m_{ads}} \left[1 - e^{\frac{-(\vartheta + m_{ads})t}{V}} \right]. \tag{2}$$

In these equations, m_{ads} has been introduced to take into account the rate at which viruses are eliminated inside the building by various mechanisms: adsorption on the walls, respiration, etc. If this rate is unknown or is taken to be negligible, Eq. (2) can be slightly simplified and, for sufficiently high times, indoor concentrations can be equal to outdoor concentrations (Fig. 2).

2.2. Temporary source

A ‘‘temporary source’’ is usually defined as a constant-rate emission, which lasts for a given period of time, which is higher than the time required for the plume to move from the source to the building. For temporary releases, the outdoor virus concentration changes as follows:

$$\begin{array}{llll} c_o & = & 0 & \text{for} \quad t < 0 \\ c_o & = & c_o(x) & \text{for} \quad 0 \le t \le t_\lambda. \\ c_o & = & 0 & \text{for} \quad t > t_\lambda \end{array}$$

Therefore, two different situations must be taken into account: $0 \le t \le t_\lambda$ and $t > t_\lambda$.

(a) $0 \le t \le t_\lambda$. In this case, the solution of the virus balance is the same as for an external continuous source; the relationship between indoor and outdoor concentrations is given by Eq. (2).

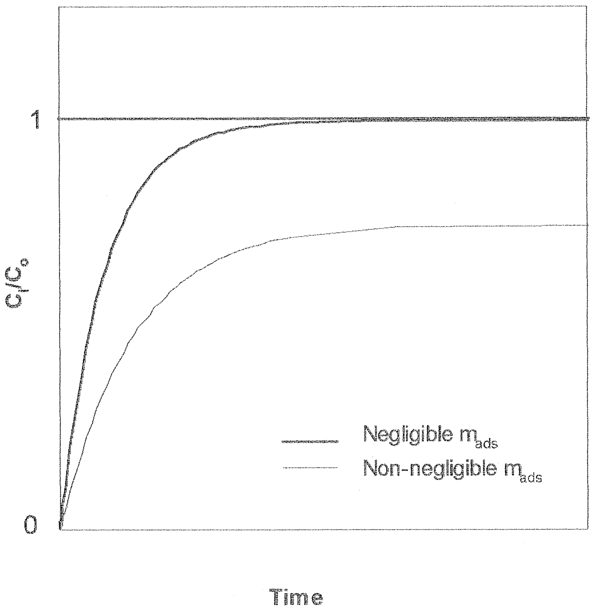

Fig. 2. Continuous source. Evolution of the c_i/c_o ratio as a function of time for two different situations.

(b) $t > t_\lambda$. From the instant $t = t_\lambda$, the indoor concentration will start to decrease due to ventilation, which will start to introduce virus-free air into the building. The virus balance for this situation can be written as in Eq. (1) and integration with the limiting condition $c_i(t) = c_{imax}$ as $t = t_\lambda$ gives the following expression relating indoor and outdoor concentrations:

$$c_i(t) = c_o \frac{\vartheta}{\vartheta + m_{ads}} \left(e^{\left(\frac{\vartheta + m_{ads}}{V}\right)t_\lambda} - 1 \right) e^{\frac{-(\vartheta + m_{ads})t}{V}} \tag{3}$$

The variation of c_o and c_i as a function of time according to this equation can be seen in Fig. 3 for a given case. The outdoor concentration can be considered to be approximately constant during a time t_λ, while the indoor concentration will increase from zero to a maximum value (at $t = t_\lambda$) and will then decrease gradually to zero.

2.3. Instantaneous source

This case is considerably more complicated than the previous ones, because the value of c_o changes continuously as a function of time, while the ''puff'' of released viruses passes over the building. The following relationship applies:

$$c_o(x,y,z,t) = mF_x(x,t)F_y(y,t)F_z(z,t) \tag{4}$$

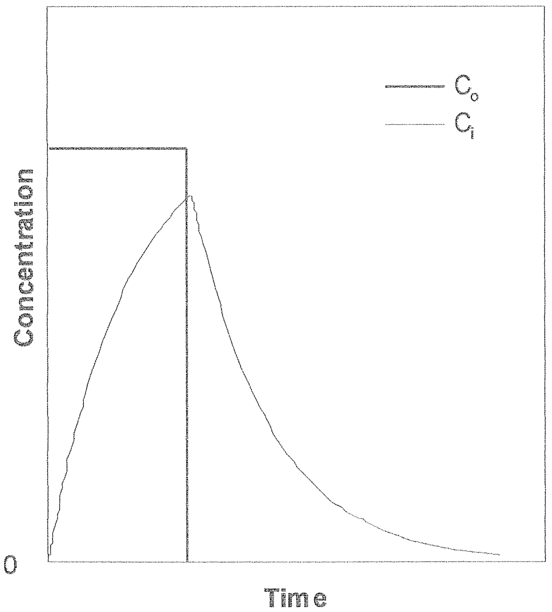

Fig. 3. Temporary source. Evolution of the c_o and c_i ratio as a function of time.

where [1]:

$$F_x(x,t) = \frac{1}{\sqrt{2\pi\sigma_x^2(ut)}} \exp\left(-\frac{(x-ut)^2}{2\sigma_x^2(ut)} \right)$$

$$F_y(y,t) = \frac{1}{\sqrt{2\pi\sigma_y^2(ut)}} \exp\left(-\frac{y^2}{2\sigma_y^2(ut)} \right)$$

$$F_z(z,t) = \frac{1}{\sqrt{2\pi\sigma_z^2(ut)}} \left[\exp\left(\frac{-(z-h)^2}{2\sigma_z^2(ut)} \right) + \exp\left(\frac{-(z+h)^2}{2\sigma_z^2(ut)} \right) \right].$$

The differential equation which represents the virus balance is also in this case the same as Eq. (1), which must fulfil the condition $c_i = 0$ at $t = 0$. This equation can be integrated with considerable manipulation, using the Laplace transform, and finally obtaining the following expression:

$$c_i(t) = \frac{\frac{\vartheta}{V} m F_z F_y}{2u} L^{-1} \left(\frac{Q(p)}{p + \frac{\vartheta + m_{ads}}{V}} \right) \tag{5}$$

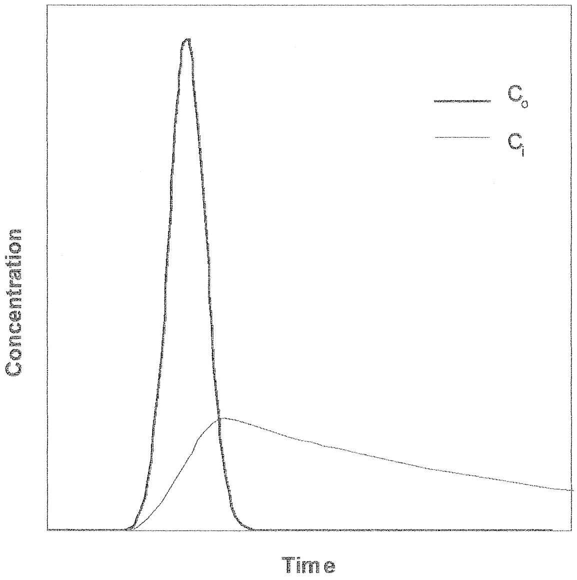

Fig. 4. Instantaneous source. Evolution of outdoors and indoors virus concentration as a function of time.

where:

$$Q(p) = e^{\frac{\sigma_x^2}{2u2}\left(p-\frac{xu}{\sigma_x^2}\right)^2} \mathrm{ERF_c}\left[\frac{\sigma_x}{u\sqrt{2}}\left(p-\frac{xu}{\sigma_x^2}\right)\right]$$

The final equation for $c_i(t)$ which results from the resolution of the inverse Laplace transform is:

$$c_i(t) = \frac{\frac{\vartheta}{V} mF_yF_z}{2u} e^{\frac{K^2}{2}-\frac{x2}{2\sigma_x^2}} e^{-\frac{\vartheta+m_{\mathrm{ads}}}{V}t}\left[\mathrm{ERF}\left(\frac{K}{\sqrt{2}}\right)+\mathrm{ERF}\left(\frac{ut}{\sigma_x\sqrt{2}}-\frac{K}{\sqrt{2}}\right)\right] \quad (6)$$

Where:

$$K = \frac{\left(\frac{\vartheta+m_{\mathrm{ads}}}{V}\right)\sigma_x^2+ux}{u\sigma_x}.$$

A typical variation of the values of c_o and c_i for the case of instantaneous source can be seen in Fig. 4. These results are similar to those obtained from analytical solution of classical equations for the protection of people following a toxic gas release.

3. Discussion

In the case of airborne viruses, the outdoor concentration is not constant but exists only for given periods of time, typically longer than those corresponding to accidental releases of toxic gases. This adds complexity to the phenomenon but simultaneously increases its interest, as the possibility that sheltering gives a significant protection — for relatively short exposure times — becomes higher. Knowledge concerning the protective effect of housing can be particularly useful in ruminants because these species are often kept outdoors. Swine are another species that has been involved in viral airborne transmission between farms, but pigs are usually housed. In this case, the mathematical model can help determine the risk of infection for animals in a particular situation.

In fact, whether sheltering of animals is a useful protective measure is a question that has been discussed many times, although very few references are found in the literature. During the 1967–1968 epidemic of foot-and-mouth disease in England, farmers were advised to house their stock. Nevertheless, there is no evidence that housing animals reduces the risk of infection [2,3]. In certain cases, it has been reported that sheltering of animals involves a delay of only 1 to 2 days in the infection [4]. This may be a consequence of a lower virus dose, which produces a prolongation in incubation period. However, this type of information should be considered with caution, as usually there is no certainty that infection was not caused by other mechanisms than airborne virus (for example, movement of persons or animals between farms). In the face of this uncertainty and the lack of data, the predictions made by means of the mathematical model described in the previous paragraphs may offer interesting help to determine whether sheltering is useful as a protective measure in the event of an atmospheric virus dispersion.

However, the application of the mathematical model involves a certain difficulty, as it requires knowledge of the ventilation rate of the building. In farms with mechanical ventilation, this rate can be ascertained quite accurately, but with natural ventilation, an approximation can be made. There are some recommended values [5,6], for example, 75 m^3/h (winter)–350 m^3/h (summer) for each lactating sow, or 15 m^3/h (winter)–125 m^3/h (summer) for each finishing pig (100 kg).

Figs. 2–4 show that for limited periods, the indoor concentration will be significantly lower than the outdoor concentration. Figs. 5 and 6 show, for a given case, the evolution of indoor virus concentration and of the average dose received by each animal as a function of time. The data were calculated for a farm with 500 pigs, exposed to a certain outdoors concentration of virus (0.05 ID_{50}/m^3) emitted from another farm. Two cases are presented: continuous source and temporary (30 min) source. (in the event of an epidemic outbreak, the reduction of the ventilation rate would be an elementary measure to be adopted [7]). In both examples, m_{ads} was supposed to be equal to the respiration rate; i.e., it was assumed that all the viruses inspired by the pigs were retained in their respiratory tracts. No adsorption on the walls was assumed.

In the case of a continuous source (Fig. 5), a stationary value of c_i was reached after 1 h when the ventilation rate was 15 $m^3/(h \cdot pig)$; this stationary value was $c_o = 0.047$ ID_{50}/m^3 (i.e., 95% of the outdoor concentration). However, it can be observed that, as the ventilation rate is reduced, the time required to reach a steady value of c_i increases and this steady value decreases. Thus, for a ventilation rate of 3 $m^3/(h \cdot pig)$, the stationary state is reached after 3 h and the constant c_i value is 0.037 ID_{50}/m^3 (75% of c_o).

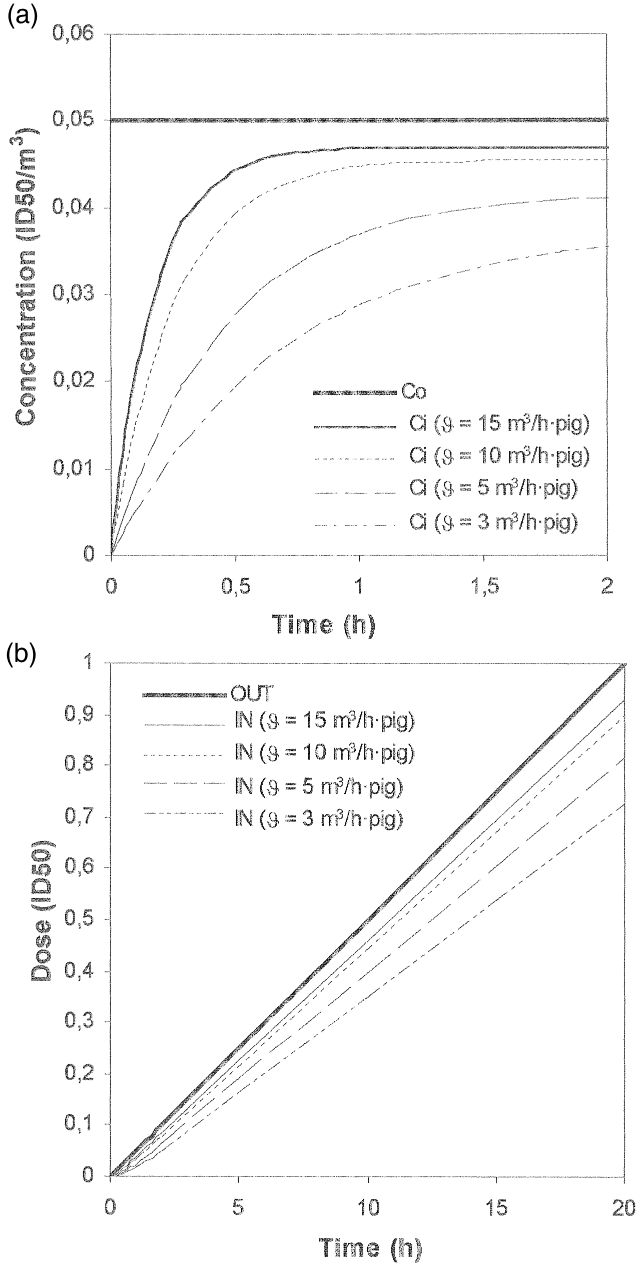

Fig. 5. Continuous source. Scenario: a farm with 500 pigs, with a volume of 3.75 m^3/pig and a respiration rate of 1 $m^3/(h \cdot pig)$; outdoor concentration: 0.05 ID_{50}/m^3, wind velocity: 2 m/s. (a) Evolution of indoor virus concentration as a function of time for four different ventilation rates. (b) Evolution of the average dose received per pig as a function of time for the different ventilation rates.

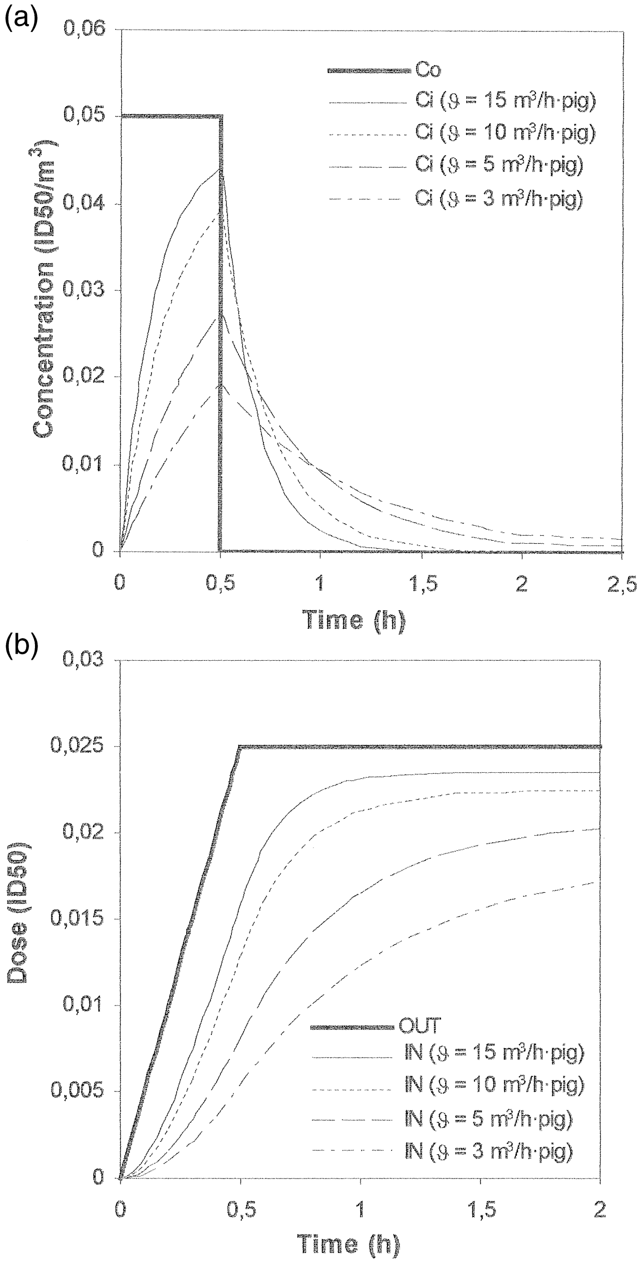

Fig. 6. Temporary source. Scenario: the same as for Fig. 5 with a 30-min release time. (a) Evolution of indoor concentration as a function of time for four different ventilation rates. (b) Evolution of the average dose received per pig as a function of time for the different ventilation rates.

The average dose of virus received by each pig varies correspondingly with the ventilation rate. Fig. 5b shows the variation as a function of time. This plot clearly indicates the magnitude of the protection offered by sheltering. All the pigs would receive a dose of 1 ID_{50} after 20 h staying outdoors. However, they would receive only 0.7 ID_{50}, after the same period, if they were indoors with a reduced ventilation rate of 3 $m^3/(h \cdot pig)$.

In the case of a temporary source, the profiles corresponding to the different ventilation rates can be seen in Fig. 6a. Now, the peak value of c_i decreases when the ventilation rate decreases. However, the reduction of c_i as a function of time once the ''puff'' has passed (i.e. once $c_o = 0$ again) is considerably slower as the ventilation rate decreases. The doses received by animals in the case of a temporary source have been plotted in Fig. 6b. The dose received by each pig outdoors after the emission period is 0.025 ID_{50}. However, indoors the dose is again lower and decreases when the ventilation rate decreases. Thus, for a reduced ventilation rate of 3 $m^3/(h \cdot pig)$ the dose is only 0.0155 ID_{50}.

4. Conclusions

The mathematical modelling presented in this paper shows that the sheltering of livestock is a valid measure for reducing the likelihood of infection by airborne transmission, as it considerably lowers the average dose received by the livestock. The model highlights the importance in these cases of the reduction of the ventilation rate; the same principle can be applied for protecting humans in the event of accidental releases of viruses or other infectious agents from industrial or military installations.

The efficiency of this shelter diminishes as the length of the episode increases. For very long periods (for example, several days with wind blowing from a particular direction), even though the indoor concentration will continue to be lower than the outdoor one, the progressive increase in the dose may ultimately lead to infection. However, this is not usually the case, considering the variability of atmospheric conditions in general and wind direction in particular.

Nomenclature

c_i	indoor virus concentration, $ID_{50}\ m^{-3}$
c_o	outdoor virus concentration, $ID_{50}\ m^{-3}$
ERF	error function $= \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2}\,dt$
ERF_c	complementary error function $= (1 - ERF(x)) = \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-t^2}\,dt$
h	source height, m
ϑ	ventilation rate, $m^3\ s^{-1}$
m	amount of virus released instantaneously, kg

m_{ads}	rate at which virus is consumed inside the building, $m^3\ s^{-1}$
M_{virus}	mass of virus inside the building, kg
σ_x	dispersion coefficient in the downwind direction, m
σ_y	dispersion coefficient in the crosswind direction, m
σ_z	dispersion coefficient in the vertical direction, m
t	time elapsed from the moment at which the plume reaches the building, s
t'	time measured from the beginning of the emission, s
t_λ	time during which the plume moves over the building, s
u	average wind velocity at a height of 10 m, $m\ s^{-1}$
V	volume of the building, m^3
x	downwind distance from the source, m
y	crosswind distance from plume centreline, m
z	height, m

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