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# Parametric laws to model urban pollutant dispersion with a street network approach

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## HIGHLIGHTS

► We discuss the street network approach for pollutant dispersion modelling in urban areas.
► We identify two main mechanisms for the street ventilation.
► A new model for the street/atmosphere turbulent transfer is proposed.
► A model for the advective transfer along the street axis is analysed.
► Both models are tested against wind tunnel measurements.

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## ABSTRACT

This study discusses the reliability of the street network approach for pollutant dispersion modelling in urban areas. This is essentially based on a box model, with parametric relations that explicitly model the main phenomena that contribute to the street canyon ventilation: the mass exchanges between the street and the atmosphere, the pollutant advection along the street axes and the pollutant transfer at street intersections. In the first part of the paper the focus is on the development of a model for the bulk transfer street/atmosphere, which represents the main ventilation mechanisms for wind direction that are almost perpendicular to the axis of the street. We then discuss the role of the advective transfer along the street axis on its ventilation, depending on the length of the street and the direction of the external wind. Finally we evaluate the performances of a box model integrating parametric exchange laws for these transfer phenomena. To that purpose we compare the prediction of the model to wind tunnel experiments of pollutant dispersion within a street canyon placed in an idealised urban district.


## 1. Introduction

Pollutant dispersion in urban areas is related to the complex dynamics of atmospheric flows within the urban canopy. These are determined by a wide range of phenomena at different scales (Belcher, 2005; Fernando, 2010; Fernando et al., 2010), such as orographic induced flows, urban heat island air circulations, flow channelling and recirculations in street canyons, increased turbulence levels and exchanges of momentum and heat between earth surface and atmosphere, compared to those occurring over rural areas.

Despite the increasing research efforts of the last decades in this field, the numerical modelling of these phenomena remains rather challenging over large domains, due to high computational costs. For several practical aspect the current use of these complex modelling tools is therefore unfeasible. This is the case for example of the evaluation of the population's exposure to airborne pollutants and to develop strategies for its reduction, which requires to compute pollutant cartographies over (large) urban areas, and for a large variety of boundary conditions (meteorology, traffic).

Alternative approaches have then to be adopted. These are usually based on the adoption of 'operational urban dispersion models', which allows non-specialist users to treat a large variety of situations, rapidly, and with limited computing resources. To these purposes, operational models require a simplified description of the mass transfer processes within and above the urban canopy. Generally speaking we can identify four different simulation strategies for operational purposes: coupling dispersion models with diagnostic flow models (e.g. Kaplan and Dinar, 1996; Chang et al., 2005; Tinarelli et al., 2007), street network models (Soulhac et al., 2011, 2012), canopy models (e.g. Di Sabatino et al., 2011)

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and adapted Gaussian models (Hertel and Berkowicz, 1989; Venkatram et al., 2004).

In this paper we discuss some aspects characterising the street network approach. A street network model is a box model formulated with explicit modelling of the exchange of flow and pollutant fluxes at urban intersections and capable of providing a detailed concentration field at the street scale over a whole urban district (Soulhac et al., 2011). These models adopt a simplified description of the urban canopy. The streets in a district are modelled as a simplified network of connected street segments represented by boxes, whose mass exchanges are modelled by means of parametric laws. The flow within each street is driven by the external wind and the pollutant is assumed to be uniformly mixed over the street. In order to compute the mean concentration within each street, these models account for three transport mechanisms: the convective mass transfer along the streets (Soulhac et al., 2008) due to the mean wind along their axis, the turbulent transfer across the interface (Salizzoni et al., 2009, 2011) between the streets and the atmosphere, the convective transport at street intersections (Soulhac et al., 2009). An example of implementation of this approach is given by the model SIRANE (Soulhac et al., 2011). The computational resources required to run SIRANE are significantly lower than those required by a CFD calculation. To give an example, the computational time on a 16 Corse PC for the simulation of a single dispersion scenario (in steady conditions) in an urban area with about 20,000 streets (over a domain of about $10 \times 10$ km$^2$) is of about 80 s. This means that the simulation of a whole year with an hourly time step on the same domain is about 8 days. Recently the performances of SIRANE were tested both against laboratory experiments within idealised (Garbero, 2008) and realistic urban geometries (Carpentieri et al., 2012) and against in-situ measurements performed in an urban district (Soulhac et al., 2003, 2012).

The aim of this paper is twofold:

- present the details of some of the parametric relations adopted in the model SIRANE (Soulhac et al., 2011), namely those related to the turbulent flux street–atmosphere and the advective fluxes within the urban canopy, induced by the wind component along the streets axis;
- discuss the reliability of parametric model to compute spatially averaged concentrations within a street canyon.

Firstly, we focus on the pollutant transfer between the canyon and the overlying atmosphere, which is modelled by estimating a vertical exchange velocity, referred to here as $u_d$. Moving from the work of Soulhac (2000) and Caton et al. (2003), we analyse a model for $u_d$, for the case of a wind direction perpendicular to the street axis (§2). We then consider the case of any wind direction for an infinite canyon and define a parametric model to compute spatially averaged concentration within it, taking into account the street/atmosphere mass fluxes and those due to mean wind along the axis of the street (§3). Finally we consider the case of a street of finite length and present the parametric models implemented in SIRANE (Soulhac et al., 2011), that are tested against experimental results provided by wind tunnel experiments (§4) performed in idealised urban geometries. This allows us to verify the reliability of the model, discuss its shortcomings and define perspective for further studies on those topics.

## 2. External wind perpendicular to the street axis

We begin by focussing on the case of an infinite street canyon, whose axis is perpendicular to the direction of the external wind. This is by far the most studied case in the literature. In this case, the only mechanism that contributes to the street canyon ventilation is the turbulent transfer in the vertical direction. This transfer has been extensively studied in the last years by means of theoretical (e.g. Hotchkiss and Harlow, 1973; Soulhac, 2000; Caton et al., 2003), numerical (e.g. Solazzo and Britter, 2007; Cai et al., 2008; Salim et al., 2011) and wind tunnel and on site studies (e.g. Barlow et al., 2004; Narita, 2007; Murena and Vorraro, 2003). In the meanwhile several parametric models of this transfer have been proposed for operational purposes (Hotchkiss and Harlow, 1973; Berkowicz et al., 1997), in order to estimate the spatially averaged concentration within a street canyon in stationary conditions. More recently, Soulhac (2000) and Caton et al. (2003) have proposed a similar theoretical model, moving from the assumption that the street/atmosphere transfer is governed by the dynamics of the shear layer taking place at roof level. In what follows we present (§2.1) the details of this model, we compare (§2.2) it to existing models of the canyon/atmosphere and we verify (§2.3) its reliability in the light of recent experimental results (Salizzoni et al., 2009, 2011).

### 2.1. Mass transfer at the street/atmosphere interface

We consider the shear layer represented on the Fig. 1, occurring between two streams characterised by a velocity difference $\Delta U = U_1 - U_2$ and with different dynamical conditions (turbulent kinetic energy $k$ and integral length scale $L_e$) and passive scalar concentrations $C$. The properties of each flow are assumed to be uniform along the stream-wise direction. Following Caton et al. (2003), we consider that $U_2 = 0$ and $C_1 = 0$.

We refer to $x$ and $y$ as the coordinates in the stream-wise direction and parallel to the street axis respectively and $z$ the vertical coordinate. The corresponding velocity components are referred to as $u$, $v$ and $w$. Overbars and primes denote Reynolds-averaged and fluctuating quantities respectively. In case of a two-dimensional stationary flow (mean flow variables are independent on $y$), the time averaged velocity and concentration fields must satisfy the following set of equations:

$$\frac{\partial \overline{u}}{\partial x} + \frac{\partial \overline{w}}{\partial z} = 0 \tag{1}$$

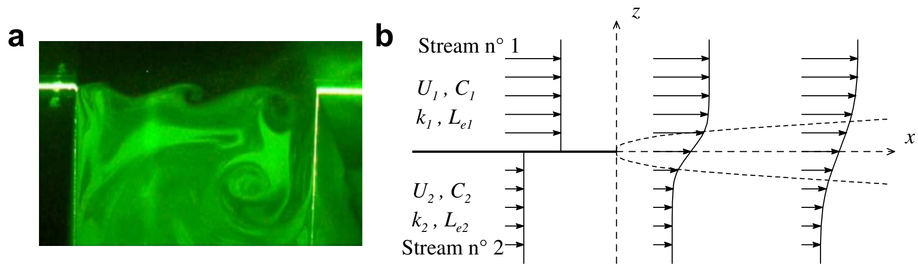


**Fig. 1.** a) Flow visualisation of the shear layer at the top of a street canyon b) Characteristic diagram of a mixing layer.

$$\overline{u}\frac{\partial\overline{u}}{\partial x}+\overline{w}\frac{\partial\overline{u}}{\partial z} = \frac{\partial}{\partial z}\overline{u'w'} \tag{2}$$

$$\overline{u}\frac{\partial\overline{c}}{\partial x}+\overline{w}\frac{\partial\overline{c}}{\partial z} = \frac{\partial}{\partial z}\overline{w'c'} \tag{3}$$

The time averaged turbulent fluxes through the interface of the mixing layer are given by the correlations $\overline{u'w'}$ for the momentum flux and $\overline{w'c'}$ for the mass flux. To model these correlations, we assume a first order closure model, adopting a same turbulent diffusivity coefficient K for mass and momentum (i.e. turbulent Prandtl number equal to 1):

$$\overline{u'w'} = -\mathrm{K}\frac{\partial\overline{u}}{\partial z} \quad \text{and} \quad \overline{w'c'} = -\mathrm{K}\frac{\partial\overline{c}}{\partial z} \tag{4}$$

The key feature is then to express the turbulent diffusivity coefficient K as a function of the flow dynamics. To that purpose, we can assume two limiting cases (Soulhac, 2000; Caton et al., 2003):

- the two flows are slightly turbulent, so that the turbulent transfer is fully driven by local shear produced turbulence;
- the two flows are highly turbulent, so that the shear layer dynamics is governed by the kinetic energy turbulent fluxes from the two streams.

If the two flows are slightly turbulent, the shear layer dynamics is driven by local production of turbulence, due to Kelvin–Helmholtz instabilities. The analytical resolution of this problem was provided by Goertler (1942). The Goertler's solution is based on the idea that the dimension of the turbulent structures generated within the mixing layer increases linearly with the distance $x$ and that the turbulent diffusivity can be expressed as

$$\mathrm{K} = \frac{xU_\mathrm{m}}{2\sigma_0^2} \tag{5}$$

where $U_\mathrm{m} = \Delta U/2$ and $\sigma_0 = 11$ (Goertler, 1942). Moving from this assumption, Goertler expressed the solution to (1) and (2) as

$$\Psi = U_\mathrm{m}xF(\xi) \tag{6}$$

where $F(\xi)$ is a self-similar function and $\xi = (\sigma_0 z)/x$ is the similarity variable.

Adopting Cauchy's stream function, we can write:

$$\begin{cases} \overline{u} = \dfrac{\partial\psi}{\partial z} = \sigma_0 U_\mathrm{m}F'(\xi) \\ \overline{w} = -\dfrac{\partial\psi}{\partial x} = \dfrac{U_\mathrm{m}}{2\sqrt{x}}(\xi F'(\xi)-F(\xi)) \end{cases} \tag{7}$$

Substituting these expressions in (2), we obtain the following differential equation:

$$F''' + 2\sigma_0 FF'' = 0 \tag{8}$$

An approximated solution of this equation writes (Rajaratnam, 1976):

$$\overline{u}(x,z) = U_\mathrm{m}\left[1+\mathrm{erf}\left(\frac{\sigma_0 z}{x}\right)\right] \tag{9}$$

where erf is the error function. The analogy of the form of (2) and (3) allows us to express the concentration field in a similar way:

$$\overline{c}(x,z) = C_\mathrm{m}\left[1-\mathrm{erf}\left(\frac{\sigma_0 z}{x}\right)\right] \tag{10}$$

where $C_\mathrm{m} = -\Delta C/2 = (C_2-C_1)/2 = C_2/2$.

The turbulent mass flux per unit area at interface between the two flows ($z = 0$) is given by:

$$\overline{w'c'} = -\mathrm{K}\left.\frac{\partial\overline{c}}{\partial z}\right|_{z=0} = C_\mathrm{m}\frac{U_\mathrm{m}}{\pi\sigma_0} \tag{11}$$

which shows that the flux scales on the mean velocity difference between the two flows and it does not depend on the longitudinal coordinate $x$.

When the two flows are sufficiently turbulent, it can be assumed that the dynamics of the shear layer are not fully determined by the locally generated turbulence. As shown experimentally by Salizzoni et al. (2009, 2011), this is the case of the shear layer developing at the top of a street canyon overlain by a turbulent atmospheric boundary layer flow. The solution of the problem depends then on $K_1$ and $K_2$. We assume here for simplicity that $K_1 = K_2 = K_\mathrm{m}$, i.e. turbulent diffusivity is uniform in the whole domain. The general behaviour of the mean flow is then completely similar to the laminar motion of a fluid of molecular viscosity $K_\mathrm{m}$. From dimensional arguments, we can identify a new similarity parameter $\xi$, defined as:

$$\xi = \frac{\sigma z}{\sqrt{x}} \quad \text{with} \quad \sigma = \sqrt{\frac{U_\mathrm{m}}{4K_\mathrm{m}}} \tag{12}$$

Even in this case the velocity profile is given by a self-similar solution, and the vertical profiles of mean velocity and concentration are then:

$$\overline{u} = U_\mathrm{m}\left[1+\mathrm{erf}\left(\frac{\sigma z}{\sqrt{x}}\right)\right] \tag{13}$$

$$\overline{c} = C_\mathrm{m}\left[1-\mathrm{erf}\left(\frac{\sigma z}{\sqrt{x}}\right)\right] \tag{14}$$

The turbulent mass flux per unit width at the interface between the two flows ($z = 0$) is given by:

$$\overline{w'c'} = -K_\mathrm{m}\left.\frac{\partial\overline{c}}{\partial z}\right|_{z=0} = C_\mathrm{m}\sqrt{\frac{U_\mathrm{m}K_\mathrm{m}}{\pi x}} \tag{15}$$

Compared to the previous case (11), the flux varies with $1/\sqrt{x}$, it does not scale linearly on the mean velocity difference $U_\mathrm{m}$ and depends also on the turbulent diffusivity $K_\mathrm{m}$ of the two flows.

### 2.2. Bulk transfer between the street and the atmosphere

Operational dispersion models provide estimates of the pollutant concentration within urban canyons. To that purpose, some of these models are based on a bulk description of the mass transfer between the canyons and the overlying atmosphere, neglecting transfers at the street intersection and adopting a box model approach (Hotchkiss and Harlow, 1973; Berkowicz et al., 1997). In this approach the mean velocity within the canyon is equal to zero ($U_2 = 0$) whereas the external velocity $U_1 = U_\mathrm{ext}$ is assumed to be uniform in the stream-wise direction (Caton et al., 2003). Similarly, the pollutant concentration within the street $C_\mathrm{street}$ is assumed to be uniform within the canyon. Since pollutant transfer at street intersection is neglected the problem is that of the ventilation of a two-dimensional street canyon. In steady state conditions, the pollutant flux between street and the atmosphere has to be equal to the intensity of the pollutant sources placed within it, i.e.

$$\dot{q}_\mathrm{s} = u_\mathrm{d}W(C_\mathrm{street}-C_\mathrm{ext}) \tag{16}$$

where $C_{ext}$ is the concentration in the external atmosphere, $W$ is the canyon width, $\dot{q}_s$ is the pollutant emission per unit length (of the street) within the canyon and $u_d$ represents the bulk mass exchange velocity between the canyon and the atmosphere. If we set $C_{ext} = 0$, the concentration within the street is then

$$C_{street} = \frac{\dot{q}_s}{u_d W} \tag{17}$$

The reliability of these models therefore mainly depends on the accuracy of the estimates of $u_d$, which is an integral variable depending on all features characterising the canyon geometry and the flow dynamics: wind velocity and direction, turbulence intensity and structure, etc… Assuming a fixed canyon geometry, negligible thermal stratification, and a wind blowing perpendicularly to the street axis, following Salizzoni et al. (2009, 2011) we can assume the dependence of $u_d$ on the velocity difference $\Delta U$ and the intensity and the structure of the external turbulence in the form

$$\frac{u_d}{\Delta U} = \alpha\left\{\frac{u_*}{\Delta U}, \frac{L_e}{W}\right\} \tag{18}$$

where $u_*$ and $L_e$ are the friction velocity and the integral length scale of the atmospheric boundary layer flow. In order to define explicitly the dependence of the function $\alpha$, we can move from the model presented in §2.1, that provides an estimate for the turbulent mass fluxes at the street/atmosphere interface. Following Soulhac (2000), we consider here the limiting cases of an atmospheric turbulence dominating the locally shear generated turbulence. Therefore, from (15) we can compute the turbulent flux per unit length at the street–atmosphere. In steady state conditions this flux equates the intensity of the pollutant sources within the canyon:

$$\dot{q}_s = \int_0^W \overline{w'c'}\,\mathrm{d}x\mathrm{d}y = WU_m\sqrt{\frac{K_m}{U_m \pi W}}(C_{street} - C_{ext}) \tag{19}$$

Setting $C_{ext} = 0$, (19) gives the following estimate for the street concentration:

$$C_{street} = \frac{\dot{q}_s}{W}\frac{1}{U_m}\sqrt{\frac{U_m \pi W}{K_m}} \tag{20}$$

In the model provided by (19), the mass transfer velocity is

$$u_d = U_m\sqrt{\frac{K_m}{\pi U_m W}} \tag{21}$$

Adopting the Prandtl mixing length hypothesis, i.e. $K_m \simeq L_e u_*$, we can rewrite (21) by defining explicitly the functional dependence in (18) as:

$$\frac{u_d}{\Delta U} = \sqrt{\frac{1}{2\pi}\frac{u_*}{\Delta U}\frac{L_e}{W}} \tag{22}$$

This relation can be further simplified by introducing some general considerations concerning the flow dynamics at roof level. The turbulent transfer across the shear layer is due to the entrainment of vortex from the external atmospheric flow and their coupling with the locally generated vortices (Louka et al., 2000; Salizzoni et al., 2011). This coupling takes place between turbulent structures whose dimensions are almost the same. Therefore, the canyon width has to be large enough to allow the vortices produced within the shear layer to grow enough and to intercept the larger scale size eddies in the external mean wind. In other words, we can assert that the characteristic turn-over time of an eddy, defined as $t_{turb} = \pi L_e / u_*$, has to be almost equal to its residence time above the street $t_{adv} = W/U_{ext} = W/2U_m$, i.e. that $t_{turb} = t_{adv}$. This assumption allows us to express $L_e$ as a function of the turbulence intensity $u_*/U_m$ at the street–atmosphere interface:

$$\frac{L_e}{W} = \frac{1}{2\pi}\frac{u_*}{U_m} \tag{23}$$

By introducing (23) into (22), we obtain:

$$u_d = \frac{u_*}{\sqrt{2}\pi} \tag{24}$$

The model given by (24) is that adopted by the street network urban dispersion model SIRANE (Soulhac et al., 2011) to compute turbulent mass fluxes at roof level. Since at roof level the r.m.s. of the vertical velocity fluctuations $\sigma_w \simeq u_*$ (e.g. Salizzoni et al., 2008), the exchange velocity can be also expressed as $u_d = \sigma_w/(\sqrt{2}\pi)$.

The pollutant concentration within the street (17) can be finally computed as

$$C_{street} = \frac{\dot{q}_s}{W}\frac{\pi\sqrt{2}}{u_*} \tag{25}$$

It is interesting to compare this street/atmosphere exchange model to previous operational urban dispersion models, namely that of Hotchkiss and Harlow (1973) and the OSPM model (Berkowicz et al., 1997). As discussed by Salizzoni et al. (2009, 2011), these models implicitly assume that the turbulent transfer at roof level is driven by the forcing action of the external flow. Therefore $u_d$ is assumed to scale on the wind speed $U_H$ at roof level (Johnson et al., 1973; Hotchkiss and Harlow, 1973; Soulhac, 2000), which has to be interpreted as a rough estimate of $\Delta U$, the velocity difference across the shear layer at the top of the canyon (Salizzoni et al., 2011). The Hotchkiss and Harlow (1973) model writes:

$$C_{street} = \frac{\dot{q}_s}{U_H W}\sqrt{\frac{U_H W}{K_m}} \tag{26}$$

where $K_m$ represents an average turbulent diffusivity. Since $U_H \simeq \Delta U = 2U_m$, we can observe that (26) is almost equivalent to our model (20) except for a factor $\sqrt{2\pi}$.

The OSPM model (Berkowicz et al., 1997) computes a 'background concentration', due to the recirculating motion within the street, as a function of the wind velocity $U_H$ and of the turbulence intensity $\sigma_w/U_H$ at roof level. This is expressed as

$$C_{street} = \frac{\dot{q}_s}{U_H W}\left(\frac{\sigma_w}{U_H}\right)^{-1} \tag{27}$$

Since $U_H \simeq 2U_m$ and $\sigma_w \simeq u_*$, the OSPM model (27) is almost equivalent to the one presented in this paper (25), except for a constant factor $\sqrt{2}\pi$. However, in OSPM the turbulence of the external flow $\sigma_w/U_H$ is supposed to be constant and equal to 0.1. This value is rather low compared to that measured in wind tunnel experiments (Rafailidis, 1997) or to in-situ measurements by Rotach (1995), which provide a value of 0.4. This difference would induce an underestimation of the intensity of the atmospheric turbulence and therefore an overestimation of $C_{street}$ compared to that given by (25). These differences in (25) are however compensated by the factor $\sqrt{2}\pi \simeq 4.44$, so that the predictions of (25) are almost equivalent to those provided by the OSPM model (27).

**Table 1**
Mass transfer velocities $u_d$ from the canyon to the external flow for a 2D square canyon ($H/W = 1$) and for different dynamical conditions ($\Delta U$, $u_*$) of the external flow. Experimental results from Salizzoni et al. (2009, 2011).

| Configuration | $\Delta U$ (m s$^{-1}$) | $u_*$ (m s$^{-1}$) | $u_d$ (m s$^{-1}$) | $u_d/u_*$ - |
|---|---|---|---|---|
| A | 1.35 | 0.33 | 0.066 | 0.200 |
| B | 1.18 | 0.36 | 0.073 | 0.202 |
| C | 1.02 | 0.41 | 0.076 | 0.185 |
| D | 0.91 | 0.46 | 0.78 | 0.171 |

### 2.3. Comparison with experimental results and discussion

Experiments were performed in the experimental set-up presented by Salizzoni et al. (2009, 2011). This consisted of a cavity, made up of two bars placed perpendicular to the wind and overlain by a neutral turbulent boundary layer. A line source was placed at ground level emitting ethane ($C_2H_6$), which was used as a passive tracer. Four different configurations were tested, referred here to as *A*, *B*, *C* and *D* (see Table 1 for details). In all four configurations, measurements were performed within a two-dimensional cavity with a fixed square section, i.e. $H/W = 1$ ($H$ is the street height), and by producing different conditions in the external boundary layer flow with increasing friction velocities $u_*$ and producing different velocity differences $\Delta U$ across the shear layer.

We focus on two kinds of experimental results:

- time averaged concentration within the shear layer at the top of the canyon measured with steady pollutant emissions (§2.3.1);
- vertical exchanges velocity $u_d$ estimated from canyon wash-out curves, with intermittent pollutant emissions (§2.3.2).

For all details of the experimental set-up we refer the reader to Salizzoni et al. (2009, 2011).

#### 2.3.1. Mixing at roof level

In §2.2 we have presented two models for the mixing within the shear layer at the top of a street canyon, which consider two limiting cases. The first model – Equations (10) and (11) – refers to the case of negligible influence of the atmospheric turbulence on the transfer within the shear layer at roof level. The second model – Equations (14) and (15) – refers to the case of negligible influence of local shear produce turbulence.

In order to verify which are the mechanisms driving the turbulent diffusion across the mixing shear layer at the top of a street canyon, we test here the models provided by Equations (10) and (14) against experimental results. Equation (10) is verified if the turbulent transfer is governed by locally generated turbulence, and therefore due mainly to Kelvin–Helmholtz instabilities related to the local mean velocity gradient. Equation (14) will be valid if the transfer is driven by the external atmospheric turbulence.

In order to verify this, we analyse the evolution of the vertical profiles of concentration for increasing distances from the upwind wall at the top of a square cavity (see Fig. 2-a). Mean concentration profiles are presented in Fig. 2-b, in case of Configuration A. As shown in Fig. 2-c, the profiles can be plotted in a non-dimensional form and collapse onto a single curve given by the equation

$$\frac{C}{C_m} = 1 - \mathrm{erf}\left\{\frac{z}{A(x)}\right\} \tag{28}$$

where $A(x)$ is a free parameter that provides the best fit of the experimental results with (28). According to the reasons specified in §2.2 we would expect $A(x) = x/\sigma_0$ in case of negligible atmospheric turbulence and $A(x) \propto \sqrt{x}$ in case of dominating atmospheric

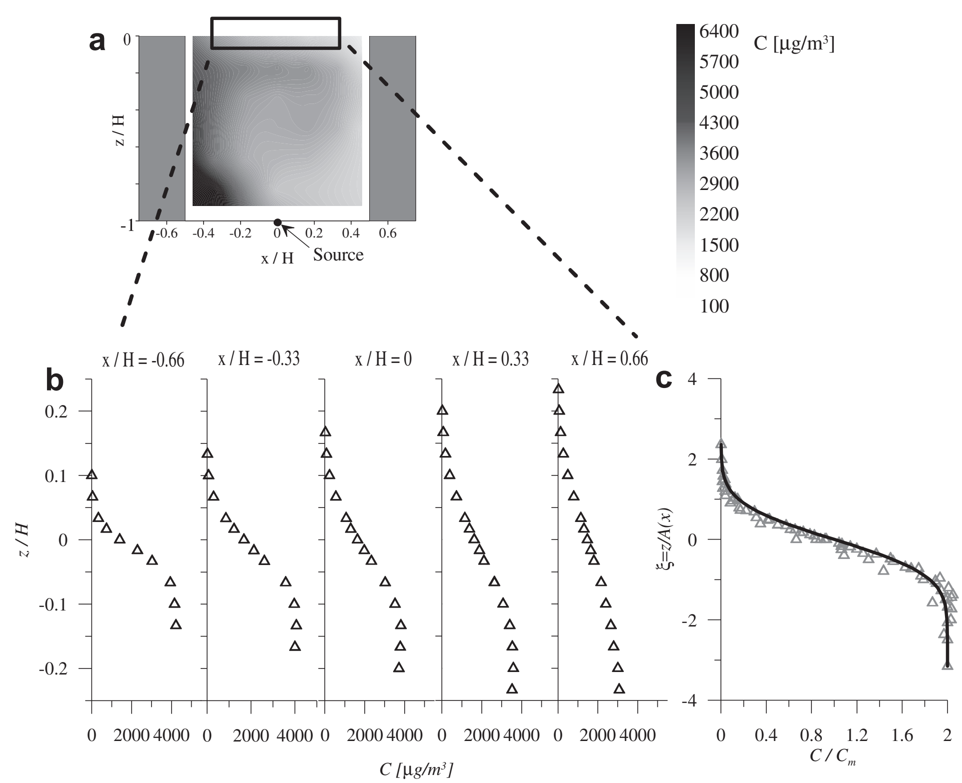


**Fig. 2.** a) Passive scalar concentration within a square canyon (Configuration A). b) Detail of the concentration profiles at roof level for increasing distances from the upwind wall. c) Comparison between experimental results and analytical model.

turbulence. The evolution of $A(x)$ has therefore been evaluated in all four configurations. The results, presented in Fig. 3, clearly show that in all cases $A \propto x$, which may suggest a dominant influence of local shear generated turbulence. However, it is worth noting that the proportionality constant is of order 0.2 ÷ 0.25, and varies slightly depending on the configurations. This is more than twice than that predicted by the Goertler model for a shear layer (10), i.e. $\sigma_0^{-1} \simeq 0.09$. The turbulent diffusivity within the shear layer has therefore to be larger than that predicted by (5), probably due to the influence of the overlying atmospheric turbulence.

This suggests that the dynamics of the shear layer therefore lay in an intermediate state between the two limiting conditions considered in our analysis, and that the turbulent mixing within it is determined both by the external atmospheric turbulence and by the local generated turbulence. This conclusion is consistent with that provided by Salizzoni et al. (2011) in the analysis on the velocity field of the identical flow configurations. Their results showed that, although the vertical profiles of mean horizontal velocity tend to scale on the velocity difference across it $\Delta U$ (just as it would happen for a dominating local shear turbulence production) the higher order moments do not, and tend conversely to scale on $u_*$, the friction velocity of the overlying atmospheric boundary layer flow.

### 2.3.2. Bulk exchange velocity

The analysis of the concentration profiles at roof level shows that the flow dynamics is not fully dominated by the atmospheric turbulence, so that the assumptions made in modelling the flux $\overline{w'c'}$ in (19), and therefore the following development of the exchange model leading to (24), are not strictly verified. We can however verify the reliability of (24) in estimating a typical transfer velocity $u_d$ by comparison against experimental results. The experimental estimates of $u_d$ are those provided by Salizzoni et al. (2009, 2011) and are given in non-dimensional form in Table 1. These have been achieved by measuring pollutant wash-out curves for different values of the external turbulence intensity $u_*/\Delta U$.

According to (24) we have that $u_d/u_* \simeq 0.22$, which is approximately 10 ÷ 20% larger than the experimental estimates given in Table 1. We can therefore assert that the canyon/atmosphere transfer model presented in §2.3 reproduces well the experimental values in case of a square canyon (i.e. for $H/W = 1$).

Although the model shows good agreement with the experimental results, its formulation deserves to be critically discussed in the light of recent experimental results (Salizzoni et al., 2009, 2011). The model provided by (24), similarly to other models presented in the literature (e.g. Berkowicz et al., 1997) and discussed in §2.3, was formulated moving from the assumption that the transfer between the canyons and the atmosphere could be described as a 'diffusive' transfer. This assumption was mainly due to experimental observations of concentration fields within canyons, characterised by almost uniform values in most of the canyon, e.g. (Meroney et al., 1996), and steep gradients close to the top of it. This spatial distribution of pollutant concentration suggested to model the canyon as a box with uniform pollutant concentration and a discontinuity surface at the top, where the mass exchange takes place. This picture of the concentration field leads straightforward to typical diffusive laws for the mass transfer (Soulhac, 2000; Caton et al., 2003). We stress here that this modelling approach is implicitly based on the assumption of an efficient mixing within the cavity, i.e. that the typical time scale of the mass transfer within the canyon is lower than that characterising the transfer across the mixing layer at the top of the canyon. However, this description of the flow dynamics is not consistent with recent experimental observations (Salizzoni et al., 2009, 2011). These clearly show that the limiting process for the wash-out of a two-dimensional cavity is related to the turbulent transfer of pollutant within the cavity itself.

There is another aspect that deserves to be discussed, that is the dependence of the transfer velocity $u_d$ on the street aspect ratio $H/W$. As shown by experimental (Salizzoni, 2006) and numerical results (Murena et al., 2009), for sufficiently narrow canyon $H/W \leq 4/3$, when a counter-rotating cell takes place at the bottom of the canyon, the exchange velocity is almost halved compared to that provided by (24). Similarly, for wider canyon, i.e. $H/W \simeq 1/2$, as the flow regime skips from skimming flow to wake interference flow, several experimental results (Salizzoni, 2006; Barlow et al., 2004) show that the turbulent transfer is abruptly increased, due to the enhanced interaction between the flow within cavity and above it. All these examples provide the experimental evidence of the dependence of $u_d/u_*$ on the canyon aspect ratio $H/W$. It is worth noting that this dependence is not consistent with the idea of a local 'diffusive' exchange at the street atmosphere interface and is conversely in agreement with the idea that the bulk transfer between the canyon and the atmosphere is regulated by the flow dynamics within the canyon and not uniquely by that in the shear layer at the top of it.

Even if the model provided by (24) has been obtained moving from a misleading assumption, i.e. that of a local and diffusive nature of the street/atmosphere transfer, its form is however consistent with two main experimental findings. Firstly, according to (24) the transfer velocity scales on the external friction velocity $u_*$ and not on $\Delta U$, the mean velocity difference across the shear layer. Secondly, the transfer velocity $u_d$ is independent on the ratio $L_e/W$, which is consistent with the idea that the street width acts as a filter on the eddies size getting into the cavity (Salizzoni et al., 2011). For these reasons, we believe that the predictions of pollutant concentration provided by (25), and therefore those provided by the OSPM model (Berkowicz et al., 1997), are reliable for a given range of street aspect ratios which are not far from unity. This reliability has been also confirmed by the good agreement of both models (e.g. Berkowicz et al., 1996; Soulhac et al., 2012) with in-situ measurements.

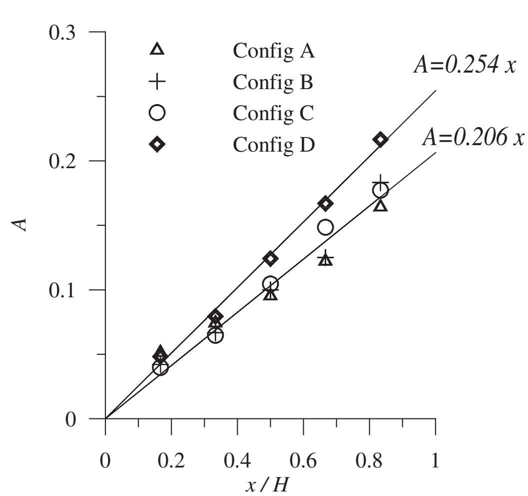


**Fig. 3.** Evolution of the parameter $A(x)$ – see (28) – with increasing distance from the upwind street wall.

## 3. Infinite street – any external wind direction

The condition of a wind direction perpendicular to the axis of the street is a case limit, that allowed us to discuss the role of the atmospheric turbulence on the canyon ventilation, but that is rarely verified. In order to study the influence of the advective fluxes along the axis of the street we consider now the case $\theta_\infty \neq 0°$, in the ideal case of a street of infinite length.

### 3.1. Infinite line source

We consider an infinite street with an infinite ground level line source placed at ground level within it. In case of a non-parallel wind ($\theta_\infty \neq 0$) the external flow provides continuously fresh air above the street, so that the external concentration remains null. Since the boundary conditions are invariant with $x$, there is no mean convective flux along the street axis. The concentration spatially averaged in the cross section of the street, referred to as $C_{\text{street}}$, is then determined by a balance between the pollutant flux emitted by the source and the turbulent flux between the street and the external atmosphere. The problem is then almost the same as that considered in §2, i.e. the case of an external wind perpendicular to the street axis, and the model for the mean concentration within the canyon is therefore identical to (25).

The only aspect that could induce a difference between the two cases is an eventual dependence of the transfer velocity $u_d$ on the wind incidence angle $\theta_\infty$. As discussed (§2.3.2), this dependence would be mainly due to the different flow structure within the canyon. As far as we are aware, very few studies have addressed this dependence. Experiments by Rotach (1995) have shown that the turbulence intensity within a street canyon was almost insensitive to the direction of the external wind. Since $u_d$ depends directly on the intensity of the turbulent velocity fluctuations within the canyon (Salizzoni et al., 2009, 2011), this result would imply that $u_d$ is independent on $\theta_\infty$, at least for an infinite (or very long) canyon. The limits of this assumption concerning canyons of finite length will be discussed further, in the §4.

We stress here that the validity of (25) is limited to the case of external wind which is not parallel to the street axis. In this case ($\theta_\infty \neq 0°$) the advection transfer above roof level prevents pollutant stagnation above the canyon and the concentration $C_{\text{ext}}$ in the external flow can be effectively considered as a background value.

### 3.2. Semi-infinite line source

In the case of a semi-infinite source (whose origin is located in $x = 0$) we can no longer consider that the concentration field is invariant with $x$. A model for the spatially averaged concentration within the street has therefore to include the effects of mean advection along the axis of the canyon. The spatially averaged concentration over the cross section of a street $C_{\text{street}}(x)$ can then be computed by means of a pollutant balance on a volume thickness d$x$ (cf. Fig. 4) as:

$$\frac{\partial C_{\text{street}}(x,t)}{\partial t} HW\mathrm{d}x = \dot{q}_s \mathrm{d}x - \dot{\mathscr{Q}}_{\text{adv}} - \dot{q}_{H,\text{turb}} \mathrm{d}x \tag{29}$$

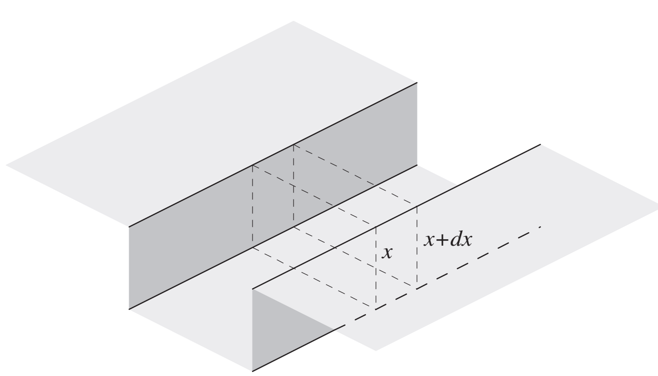


**Fig. 4.** Mass balance on a volume of thickness d$x$.

where $\dot{\mathscr{Q}}_{\text{adv}} = \int_0^H \int_0^W \overline{u}(y,z)\overline{c}(y,z)\mathrm{d}y\mathrm{d}z$ is the convective mass flux through the sections in $x$ and $x + \mathrm{d}x$, and where $\dot{q}_{H,\text{turb}}$ is the turbulent pollutant flux per unit length at the interface street–atmosphere. As shown in §3.2, this flux can be expressed as:

$$\dot{q}_{H,\text{turb}} = u_d W[C_{\text{street}}(x,t) - C_{\text{ext}}] \tag{30}$$

where again $u_d$ is assumed as independent of the direction of the wind $\theta_\infty$.

In case that the pollutant concentration within the canyon section is almost 'well mixed' $\dot{\mathscr{Q}}_{\text{adv}} \simeq HWU_{\text{street}}[C_{\text{street}}(x,t) - C_{\text{street}}(x+\mathrm{d}x,t)]$, where $U_{\text{street}}$ represents the wind velocity averaged over the canyon section. This can be modelled according to the analytical solution developed by Soulhac et al. (2008), by computing a spatially averaged velocity over the street section $U_{\text{street}} \propto \cos(\theta_\infty)$. Details for the computation of $U_{\text{street}}$ for a square street canyon are given in Appendix 1.

In steady state conditions, assuming that $C_{\text{ext}} = 0$, and for $\theta_\infty \neq 0$, (29) reduces to:

$$\frac{\partial C_{\text{street}}(x)}{\partial x} + \frac{u_d}{U_{\text{street}}H} C_{\text{street}}(x) = \frac{\dot{q}_s}{HWU_{\text{street}}} \tag{31}$$

The longitudinal evolution of the concentration is then:

$$C_{\text{street}}(x) = C_0\left[1 - \exp\left\{-\frac{x}{L_0}\right\}\right] \quad \text{with} \quad \begin{cases} C_0 = \dfrac{\dot{q}_s}{u_d W} \\ L_0 = \dfrac{U_{\text{street}}H}{u_d} \end{cases} \tag{32}$$

where $C_0$ corresponds to the spatially averaged concentration obtained for a source of infinite length, which will be attained in the far field region, i.e. for $x \gg L_0$. We show in Fig. 5 the longitudinal evolution of the concentration for different values of $\theta_\infty$. We observe that the concentration field is made up of two regions:

- A transition region, within which the concentration increases with $x$.
- A far field region, with uniform concentration.

In the far field region, the concentration is that given by an infinite line source and is independent of the direction of the wind. Conversely, in the transition region, the concentration in a fixed point increases with $\theta_\infty$. In this transition region, the distribution of concentration inside a cross section of a street is relatively complex. The plume "fills" gradually the canyon and is at the same time rolled up by the helical motion taking place within the street (Soulhac et al., 2008; Dobre et al., 2005). The length $L_0$ of the transition region depends on the mean street velocity $U_{\text{street}}$ and therefore on the direction of the wind. To show this dependence

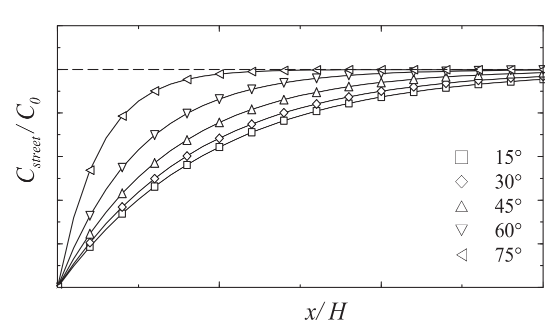


**Fig. 5.** Longitudinal evolution of the mean concentration in a street cross section (32).

and estimate the longitudinal extension of this transition region we can rewrite (32) as:

$$\frac{L_0}{H} = \frac{U_{\text{street}}}{u_{\text{d}}} = \frac{U_{\text{street}}}{\cos(\theta_\infty)U_\infty}\cos(\theta_\infty)U_\infty\frac{\pi\sqrt{2}}{u_*} \quad (33)$$

and turn to experimental values. Soulhac et al. (2008) show that the ratio $U_{\text{street}}/[|\boldsymbol{U}_\infty|\cos(\theta_\infty)]$ is approximately constant and equal to 0,3 for $0° \le \theta_\infty \le 60°$. According to experimental data (Raupach and Coppin, 1983) $u_*/|\boldsymbol{U}_\infty| \simeq 0,(05 \div 0.06)$. The length of the transition region can then be computed as:

$$\frac{L_0}{H} \simeq 1,46\cos(\theta_\infty)\frac{U_\infty}{u_*} \quad (34)$$

The dependence of $L_0/H$ on $\cos(\theta_\infty)$ for two values of $u_*/U_\infty$ is plotted in Fig. 6. If $\theta_\infty \to 90°$ then $L_0 \to 0$. Conversely, when $\theta_\infty$ is significantly different from 90°, $L_0$ increases rapidly and the fetch necessary to reach the far field region becomes $\sim 10 \div 12H$ for $\theta_\infty \to 60°$, depending on the intensity of the atmospheric turbulence $u_*/U_\infty$.

Just as for the case of an infinite source discussed in §3.1, (32) is valid only in case that the external wind is not parallel or almost parallel to the street axis. In this latter case the pollutant transported out of the street at roof level would be advected downwind along the street axis. As discussed by Soulhac and Salizzoni (2010) this would induce a pollutant accumulation above the street and pollutant concentrations within and above the street axis that would increase indefinitely.

## 4. Street of finite length

We finally focus on the case of a street of finite length, which evidently represents the most interesting case for practical applications. In the present analysis we consider a square street canyon ($H/W = 1$) of length $L = 5H$ placed within a network of connected street with same dimensions (see Fig. 14). A ground level source is placed within the network, as indicated in Fig. 14. To determine the spatially averaged concentration adopting a box model approach (Soulhac et al., 2011), we write a mass balance over the street volume

$$\frac{\partial(LHWC_{\text{street}})}{\partial t} = \dot{\mathscr{Q}} + \dot{\mathscr{Q}}_{I,\text{up}} - \dot{\mathscr{Q}}_{I,\text{down}} - \dot{\mathscr{Q}}_{H,\text{turb}} \quad (35)$$

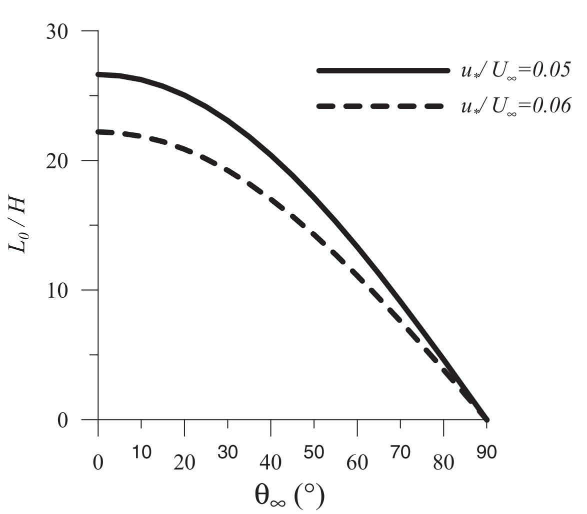


**Fig. 6.** Longitudinal extension of the transition region as a function of the wind direction (Equation (34)).

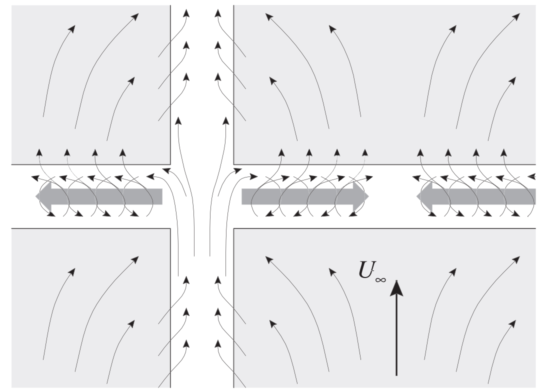


**Fig. 7.** Sketch of the three dimensional flow structure within a street network.

where $\dot{\mathscr{Q}}$ is the strength of the pollutant source within the canyon, $\dot{\mathscr{Q}}_{I,\text{up}}$ and $\dot{\mathscr{Q}}_{I,\text{down}}$ are the mean advective flux entering and leaving the street at the upwind and downwind intersection, respectively, and $\dot{\mathscr{Q}}_{H,\text{turb}}$ is the turbulent pollutant flux at roof level. The terms $\dot{\mathscr{Q}}_{I,\text{down}}$ and $\dot{\mathscr{Q}}_{H,\text{turb}}$ are modelled in the same way of a street on infinite length, i.e. $\dot{\mathscr{Q}}_{H,\text{turb}} = u_{\text{d}}WLC_{\text{street}}$ and $\dot{\mathscr{Q}}_{I,\text{down}} \approx HWU_{\text{street}}C_{\text{street}}$, which requires the assumption of a well mixed pollutant concentration within the canyon (§4.2). Since this condition is not necessarily verified, especially in case of a ground level source, one of the key point of the discussion in the next paragraph is to verify the error induced by non-uniform concentration within the canyon. Furthermore, compared to the case of an infinite street, there is another aspect that deserves to be discussed, that is the dependence of $u_{\text{d}}$ and $U_{\text{street}}$ on the 'street length', i.e. the ratio $L/W$. In a street of finite length the flow patterns within the canyon become much more complex than those taking place within an infinite street. A sketch of the flow structure is shown in Fig. 7. This shows the entrainment of air from the upper atmosphere into the streets whose axis is aligned with the wind direction, and the streamlines patterns in the crossing streets, that produces a mean advective motion along the street axes and a mean air flux towards the upper atmosphere. A particularly complex flow structure takes place close to the street intersection, where vortices with vertical axis (Fig. 8) occur. Their size and orientation depend on the angle of the incident wind and the street aspect ratios $L/W$ and $W/H$ (Garbero et al., 2010). This flow topology has an effect on both $u_{\text{d}}$ and $U_{\text{street}}$. These vortical structures contribute to a vertical advective fluxes from the urban canopy to the overlying atmosphere and therefore may induce enhanced vertical exchange velocities $u_{\text{d}}$. However still no

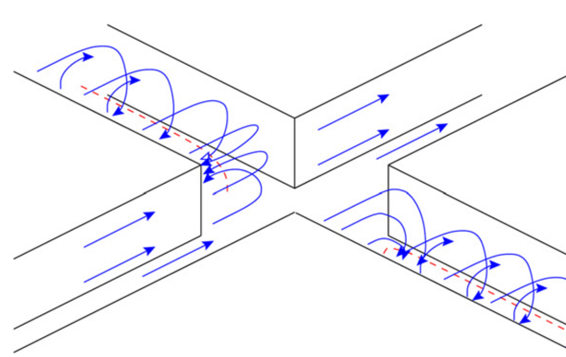

**Fig. 8.** Visualisation of the main structure of the flow in a street connected to an intersection (Soulhac et al., 2009).

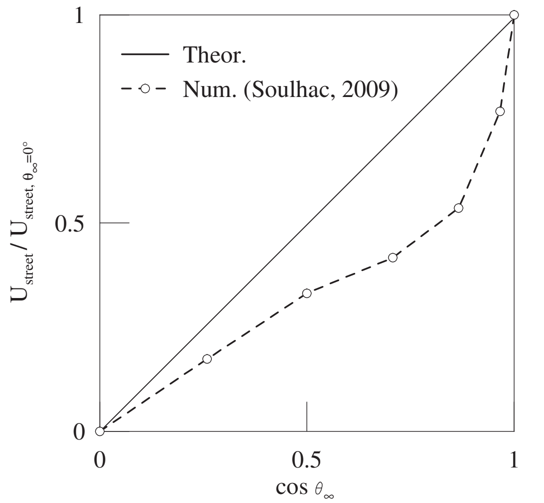


**Fig. 9.** Spatially averaged velocity within a street as a function of the external wind direction $\theta_\infty$: comparison between numerical values (Soulhac et al., 2009) and the theoretical model proposed by Soulhac et al. (2008).

exhaustive study has been conducted in order to define the dependence of $u_d$ on $\theta_\infty$, the direction of the incident wind, and on the street aspect ratios $L/W$ and $W/H$. Therefore in our modelling this dependence will be in a first approximation neglected. A detailed analysis of the influence on $U_{street}$ of intersections at the end of the street canyon for $L/H = 5$ has been given by Soulhac et al. (2009) and Garbero et al. (2010). This influence is mainly related to a reduction of the spatially averaged velocity $U_{street}$, compared to that computed for a street a finite length, due to the presence of recirculating zones at the end of the streets. An empirical correction of $U_{street}$ based on CFD results as a function of the wind incidence angle $\theta_\infty$ to take into account of this effect is presented in Fig. 9.

The other main difference with respect to the case of an infinite street is the inclusion of the term $\mathscr{Q}_{I,up}$, the mass flux entering in the canyon from the upwind intersection. A simple parametric model for $\mathscr{Q}_{I,up}$ as a function of the geometry of the street crossing and of the external wind direction has been proposed by Soulhac et al. (2009). The model is based on a balance of the air flux entering and leaving the intersection ensuring volume conservation within it and assuming that the air flux within the street is $\propto \cos(\theta)WH$ ($\theta$ is the angle of the external wind with respect to the axis of each street). The distribution of mass flux entering the intersection in the downwind street is modelled by means of repartition coefficients that depends on the street aspect ratios and on the external wind direction.

Adopting these parametric models and assuming stationary conditions the solution of (35) is:

$$C_{street} = \frac{\mathscr{Q} + \dot{\mathscr{Q}}_{I,up}}{U_{street}WH + u_d WL} \tag{36}$$

In order to test the reliability of the model provided by (36), we have performed a series of wind tunnel experiments on a small scale urban district.

### 4.1. Wind tunnel experiments

The measurements within a street of finite length were performed in the atmospheric wind tunnel of the École Centrale de Lyon in the same experimental set-up presented by Soulhac et al. (2009). Dimensions of the test section are 14 m (length) × 2.5 m (height) × 3.7 m (width). Velocity measurements in the boundary layer flows were performed with hot-wire anemometry with a frequency of 5000 Hz. An atmospheric boundary layer was generated combining Irwin (1981) spires of 1 m and roughness placed on the wall. This consisted of cubes 5 cm height that were spaced of 16 cm. The first eight metres of the test section (about ten times the height of the vortex generators) are devoted to the establishment of the boundary layer. The lower part of this incoming velocity profile is well modelled by a logarithmic law

$$\overline{u}(z) = \frac{u_*}{k}\ln\left(\frac{z-d}{z_0}\right)$$

with a friction velocity $u_* = 0.27\ \mathrm{m\,s^{-1}}$, an aerodynamic roughness $z_0 = 2.7$ mm and a displacement height of $d = 100$ mm.

After this initial fetch, we placed larger scale obstacles in order to simulate a small scale urban district, which is shown in Fig. 10. The width $W$ and the height $H$ of the streets are 10 cm, while the length $L$ is 50 cm. The distance $D$ between the lateral border of the district and the lateral walls of the wind tunnel was 0.65 m on both sides. As enlightened by Princevac et al. (2010), the non-dimensional fetch $D/H$ represents a controlling parameter of the dispersion phenomena within the array, since it has a direct influence of the lateral channelling occurring at the sides of the modelled district.

To model traffic induced pollutant emissions we used a linear source placed at ground level. This was conceived in order to guarantee a homogeneous emission over the whole source length (Meroney et al., 1996). To that purpose the source was built with a series of aligned capillary tubes (Fig. 11), whose pressure loss was sufficient to guarantee the uniformity of the emission. The tubes

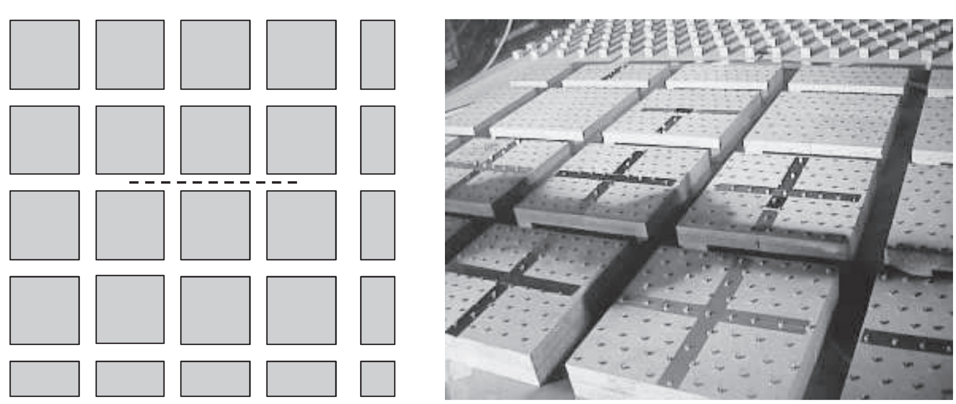

**Fig. 10.** Wind tunnel experiments: simulated urban district. The dot line represents the ground level line source.

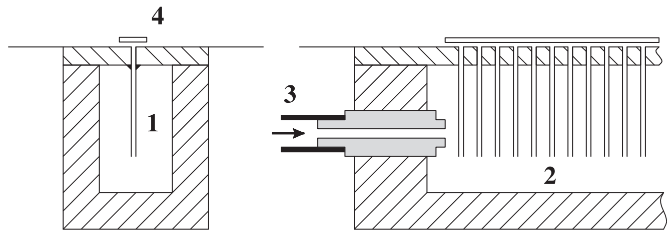


**Fig. 11.** General diagram of the linear source of tracer gas, with: **1** Capillary tubes; **2** Chamber of homogenisation; **3** Input pipe; **4** Plate to limit the impact of the jets.

were spaced of 5 mm and measure 0.25 mm in diameter and 30 mm in length. The lower part of the tubes penetrates in a chamber of homogenisation which was supplied by tracer gas at its two ends. Finally, a plate fixed above the tubes limited the perturbation induced by air ejected by the micro-jets. The ground level source was 1 m long, therefore exceeding the street length. This was placed as shown in Fig. 10: the central part of the source was located in the canyon within which we performed pollutant concentration measurement whereas the remaining part of the source was placed out of it.

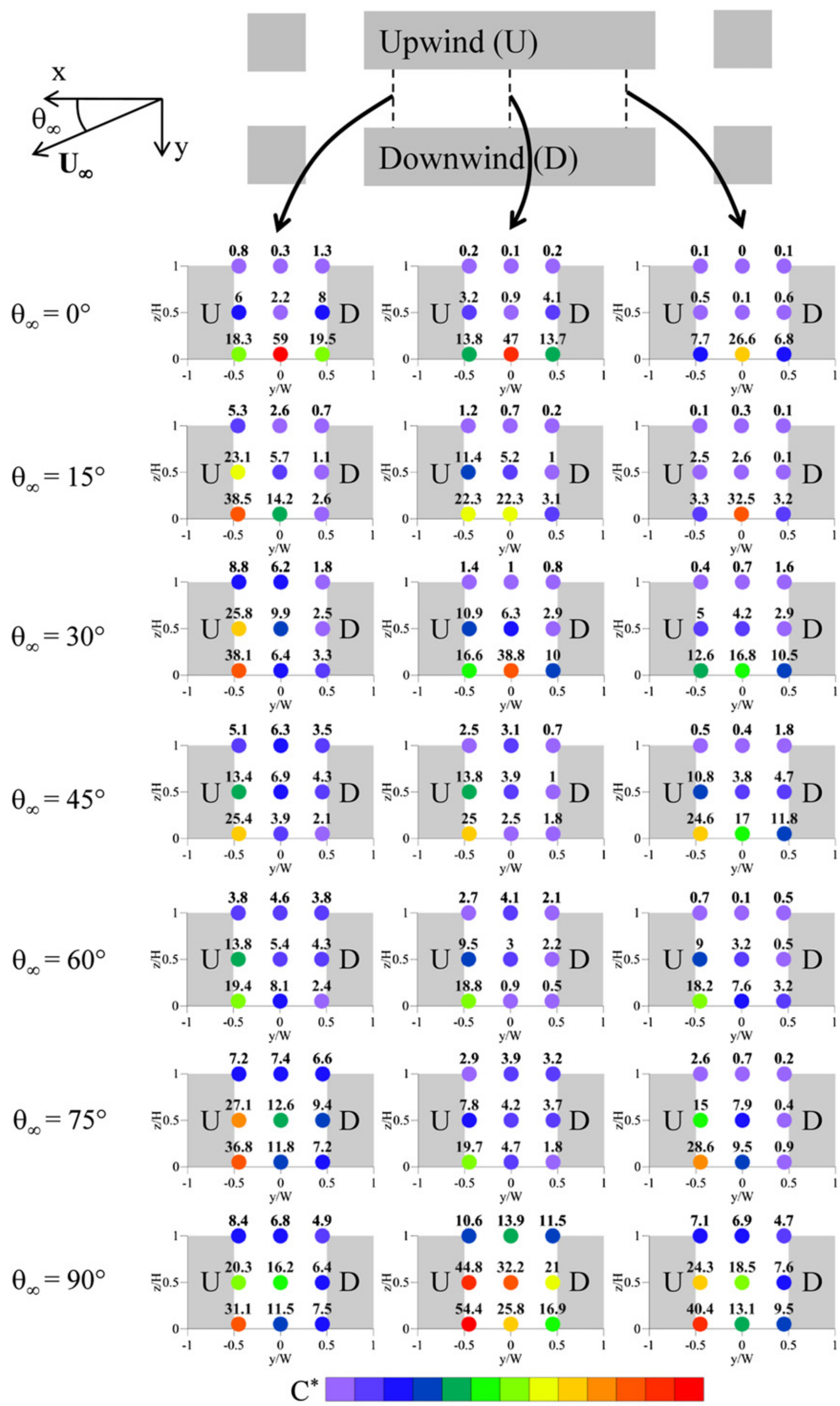


**Fig. 12.** Concentration $C^* = CU_H WL/Q$ for varying directions $\theta_\infty$ of the external wind (wind tunnel measurements). $U$ and $D$ denotes upwind and downwind street walls, respectively.

Passive scalar (ethane) concentrations were measured with a Flame Ionisation Detector (FID) and with a frequency of 500 Hz. A detailed description of the measurement techniques can be found in Salizzoni et al. (2009). Pollutant injection and measurements were performed downwind of the second row of blocks.

Passive scalar concentration was measured within a segment of street over three sections, in order to estimate a spatially averaged concentration within the canyon. The measurements were performed for varying directions of the external wind, i.e. for $\theta_\infty = 0°$, 15°, 30°, 45°, 60°, 75°, 90°. The distribution of the concentration over three different street sections as a function of the incident angle of the external wind $\theta_\infty$ is shown in Fig. 12.

In all cases considered, the concentration within the canyon is far from being uniform. Except for the case $\theta_\infty = 0$, the concentration is systematically higher on the upwind side, as a result of the recirculating motion taking place within the canyon. For low angles $\theta_\infty < 30$ the pollutant concentration on the upper part of the canyon measured on the entering section of the canyon and at the middle of the canyon shows pollutant concentration that is significantly lower than those measured for higher angles. This is due to the fact that, for almost parallel wind, the vertical diffusion of pollutant plume emitted at ground level is significantly lower than the advective transfer along the street axis. In these conditions, moving downstream from the street entrance, we can observe a canyon which is gradually filled up by the pollutant plume, which does not necessarily reach the roof level before the end of the street. Therefore the advective pollutant transfer mainly takes place in the lower part of the canyon where the wind velocities are lower. The effect of the intersections at the street borders is also detected for $\theta_\infty = 90°$. Even in this case the concentration is not uniform along *x*, the values in the centre being higher than at the ends. This effect is due to the presence of the vortex with vertical axis (see Fig. 8) developing close to the end of the street and that induces higher street ventilation (Soulhac et al., 2009).

### 4.2. Comparison with experimental results and discussion

As a final step, we test the reliability of the box model (36) in predicting the spatially averaged pollutant concentration within the canyon.

As discussed in §4.1, it is worth mentioning that one of the basic assumption of the model, that of an almost uniform concentration within the street, is not verified for the case considered here, a ground level source placed within a single canyon. It is however instructive to perform the comparison in order to enlighten the advantages and the limit of this approach. To that purpose we first need to compute averaged street concentration for varying wind angles $\theta_\infty$. These are estimated as:

$$C_{\mathrm{street}} = \frac{1}{HWLN}\sum_{i=1}^{N} C_i \Delta V_i \tag{37}$$

where $C_i$ are the $N$ time averaged concentrations measured in different locations within the street, which are considered as representative of a fraction $\Delta V_i$ of the street volume $HWL$. It is not simple to affect the level of uncertainty to these estimates, which is essentially given by an experiential error ±2% (Fackrell, 1980) and an error due to the discretisation of the concentration field by means of a limited number of $N$ values which are assumed uniform over a given control volume $\Delta V$. As a first approximation we assume here an experimental error ±15%.

These estimates of $C_{\mathrm{street}}$ have then been compared with the profile calculated from the box model (36), by making two different assumptions:

- in the case referred to as 'Model 1' we assume that $U_{\mathrm{street}}$ is that given by (36), neglecting the effect of the street intersections on the flow within the street;
- in the case referred to as 'Model 2' we apply a corrective factor on the theoretical estimates of $U_{\mathrm{street}}$ in order to take into account the effects of the vortical structures close to the street ends (Fig. 9).

The details of the application of the street intersection model to compute the term $\dot{\mathscr{Q}}_{I,\mathrm{up}}$ in (36) as a function of $\theta_\infty$ are given in Appendix 2. The comparison is shown in Fig. 13. The measured concentration varies little between 0° and 45°, it shows a minimum at 60° and a clear tendency to increase for higher $\theta_\infty$, with a maximum for $\theta_\infty = 90°$ (wind perpendicular to the street axis). For $\theta_\infty = 90°$ the model agrees well with the experimental results and tends to slightly underestimate it. This discrepancy can be interpreted as a result of two opposing errors: a possible overestimation of $u_{\mathrm{d}}$ and an error due to the fact that the intersection model neglects any flux entering or leaving the street for $\theta_\infty = 0°$. Fig. 13 shows that the Model 1 predicts quite well the averaged canyon concentration for $\theta_\infty \geq 60°$ with errors of order 20% with respect to experimental results, whereas it fails as $\theta_\infty < 45°$. The adoption of a modified model for $U_{\mathrm{street}}$ (Model 2) extends the range of validity of the model down to $\theta_\infty = 45°$, again with an error of order 20%. Even in this case however the prediction of the models diverges significantly for low angles $\theta_\infty < 45°$, when the velocity related to advective transfer along the canyon becomes much larger than related to the transfer in the vertical direction. In these conditions the pollutant plume barely reaches the roof level, even in the downwind street sections. The main assumption of the model, i.e. $C(x,y,z) \sim$ const, is not verified and the parametric relations used to model the mass exchanges are not reliable. Since the pollutant is mainly concentrated in the lower part of the street we may expect that $C_{\mathrm{street}}U_{\mathrm{street}} \neq \int_0^H \int_0^W U(y,z)C(y,z)\mathrm{d}y\mathrm{d}z$

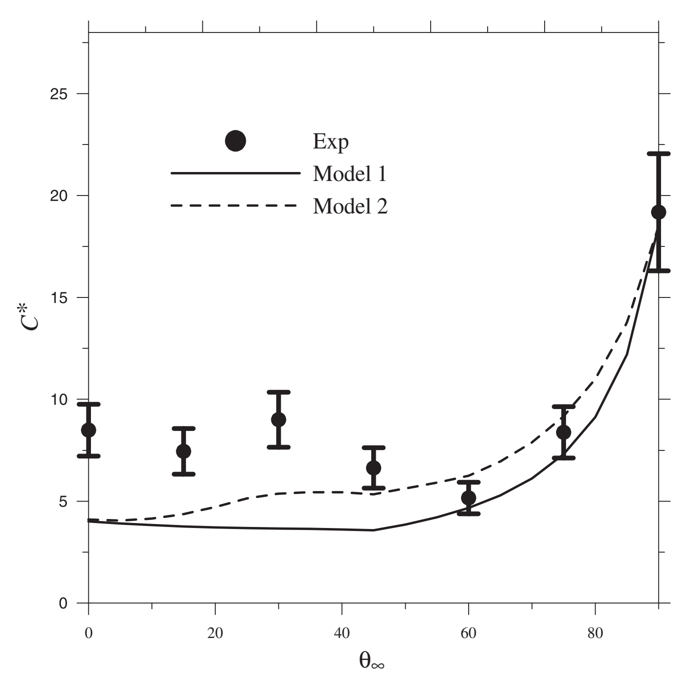


**Fig. 13.** Spatially averaged pollutant concentration within the street for varying external wind direction $\theta_\infty$. Comparison between experimental results and theoretical models (Equation (36)).

and that our model will tend to significantly overestimate the mean pollutant fluxes along the canyon axis and therefore underestimate the pollutant concentration within the street, as shown in Fig. 13.

The box model (36) is therefore reliable only in case that the pollutant plume has 'filled' the street so that, as a first approximation, we could consider that the pollutant is almost 'well mixed' within it. This condition is verified in street placed downstream of a point source placed within a densely packed building array, as observed by Garbero et al. (2010), which represents the ideal case for the application of a street network model. More uniform condition could however be observed in case of ground level line sources distributed in the whole street network, as it happens for vehicular pollutant emissions in real urban areas. The case of a ground level source placed within a single canyon therefore represents a critical case for the application of a box model, which is valid for a limited range of wind direction. In the present case we could verify that this happens for $45^\circ \le \theta_\infty \le 90^\circ$, a range that agrees well with that predicted by Belcher (2005) on the basis of simple calculations.

## 5. Conclusions

We have examined in detail the parametric relations that are needed to estimate spatially averaged pollutant concentration within a street canyon with a box model approach. This approach is based on a bulk representation of the concentration field within the canyon, which is assumed as homogeneous, and of the transfer phenomena that contribute to its ventilation.

Firstly, we have focused on the vertical turbulent fluxes of pollutant between the street and the overlying atmosphere, in the idealised case of an infinite street with a wind blowing perpendicularly to its axis and a pollutant ground level source within it. We have presented the details of the model developed by Soulhac (2000), based on a model of the dynamics of the shear layer taking place at roof level. We have compared it with existing models and we have critically discussed it in the light of recent experimental results.

Our analysis has switched then on the case of any external wind direction, with infinite and semi-infinite pollutant line sources. This has allowed us to discuss the role of pollutant advection along the street axis, a transfer process which is not taken into account in most of the current 'operational' models for urban pollutant dispersion.

Finally we consider the case of a street of finite length within a network of street. The pollutant flux balance for each street has then to be completed by taking into account the mass fluxes entering upwind the street via street intersections (Soulhac et al., 2009). The model in its final form has been tested against experimental results obtained in wind tunnel experiments, in an idealised urban district, focussing on a street canyon with a line source that slightly exceeds the canyon length. It is shown that this experimental configuration represents a critical case for a box model approach for a wide range of wind direction, and namely $\theta_\infty < 45^\infty$. Nevertheless the good agreement between model and experimental results observed for $\theta_\infty \ge 45^\circ$ shows the skills of this approach in modelling pollutant dispersion in urban areas, and suggests further study to fully explore its potentiality for operational purposes. Further studies are needed to test the uncertainties of the model prediction on more realistic urban geometries.

## Appendix 1

The spatially averaged velocity over the street section $U_{\text{street}}$ is assumed to be given by a balance between the turbulent entrainment at roof level and the drag on building walls. Following Soulhac et al. (2008), in case of a square street canyon, this is computed as

$$U_{\text{street}} = U_H \cos(\theta_\infty)\frac{W}{4H}\left[\frac{2\sqrt{2}}{C}(1-\beta)\left(1-\frac{C^2}{3}+\frac{C^4}{45}\right) + \beta\frac{2\alpha-3}{\alpha}\right] \tag{38}$$

$$\text{with}\begin{cases}\alpha = \ln\left[\dfrac{W}{2z_{0,\text{build}}}\right)\\ \beta = \exp\left[\dfrac{C}{\sqrt{2}}\left(1-\dfrac{H}{2W}\right)\right]\\ U_H = u_*\sqrt{\dfrac{\pi}{\sqrt{2}\kappa^2 C}\left[Y_0(C)-\dfrac{J_0(C)Y_1(C)}{J_1(C)}\right]}\\ \text{with } C \text{ solution of } \dfrac{z_{0,\text{build}}}{W} = \dfrac{4}{C}\left[\dfrac{\pi}{2}\dfrac{Y_1(C)}{J_1(C)}-\gamma\right]\end{cases} \tag{39}$$

where $J_0$, $J_1$, $Y_0$ and $Y_1$ are Bessel function and $z_{0,\text{build}}$ is the aerodynamic roughness of the canyon walls.

## Appendix 2

We provide the details for the computation of the pollutant flux $\dot{\mathscr{Q}}_{I,\text{up}}$ entering in the street $n^\circ 1$ (see Fig. 14), due to the pollutant emitted upwind of the street by the ground level line source. We refer to as $Q_0$ the air volume flux in the street $n^\circ 1$ and $n^\circ 3$ for $\theta_\infty = 0$. According to Soulhac et al. (2008), the distribution of the volume air flux in the street as a function of the wind direction is:

$$\begin{cases} Q_1 = Q_3 = Q_0\cos(\theta_\infty)\\ Q_2 = Q_4 = Q_0\sin(\theta_\infty)\end{cases} \tag{40}$$

Our aim is to determine the ratio of the pollutant flux coming from the street $n^\circ 3$, referred to as $\mathscr{Q}_3$, and transferred into the street $n^\circ 1$, referred to as $\dot{\mathscr{Q}}_{I,\text{up}}$ in (35), as a function of $\theta_\infty$. With a reference to Fig. 14, we express this mass flux as:

$$\dot{\mathscr{Q}}_{I,\text{up}} = Q_4C_4 + (Q_3-Q_4)C_3 \tag{41}$$

where $C_3$ and $C_4$ are the pollutant concentration in the streets $n^\circ 3$ and $n^\circ 4$, respectively, due to the contribution of a pollutant

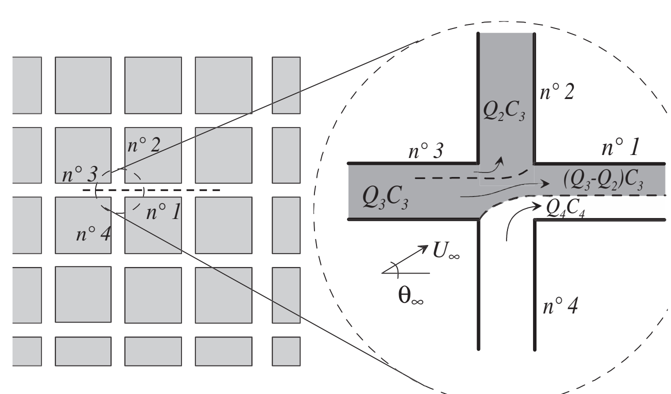


**Fig. 14.** Pollutant dispersion within an idealised street network: mass flux repartition in a simple street intersection for an arbitrary wind direction $\theta_\infty$ according to Soulhac et al. (2009). The ground level pollutant source is indicated with a dotted line.

source placed within the street n°3 only. Considering that $C_4 = 0$ and $C_3 = \dot{\mathscr{Q}}_3/Q_3$ and making use of (40), (42) can be rewritten as

$$\dot{\mathscr{Q}}_{I,\mathrm{up}} = (Q_3 - Q_4)\, C_3 = \frac{Q_3 - Q_4}{Q_3}\dot{\mathscr{Q}}_3 = \frac{Q_0\cos(\theta_\infty) - Q_0\sin(\theta_\infty)}{Q_0\cos(\theta_\infty)}\dot{\mathscr{Q}}_3 \tag{42}$$

From (36) the pollutant concentration within the street as a function of $\theta_\infty$ is then computed as:

$$C_{\mathrm{street}} = \frac{\mathscr{Q} + \dot{\mathscr{Q}}_{I,\mathrm{up}}}{U_{\mathrm{street}}WH + u_{\mathrm{d}}WL} \tag{43}$$

$$\text{with}\begin{cases} \dot{\mathscr{Q}}_{I,\mathrm{up}} = \mathscr{Q}_3[1 - \tan(\theta_\infty)] & \text{for} \quad |\theta_\infty| \le |45^\circ| \\ \dot{\mathscr{Q}}_{I,\mathrm{up}} = 0 & \text{for} \quad |\theta_\infty| > |45^\circ| \end{cases} \tag{44}$$

## References


Barlow, J., Harman, I.N., Belcher, S.E., 2004. Scalar fluxes from urban street canyons. Part I: laboratory simulation. Boundary-Layer Meteorology 113, 369–385.

Belcher, S.E., 2005. Mixing and transport in urban areas. Philosophical Transactions of the Royal Society A 363, 2947–2968.

Berkowicz, R., Palmgren, F., Hertel, O., Vignati, E., 1996. Using measurements of air pollution in streets for evaluation of urban airquality – meteorological analysis and model calculations. Science of the Total Environment 189/190, 259–265.

Berkowicz, R., Hertel, O., Larsen, S.E., Sorensen, N.N., Nielsen, M., 1997. Modelling Traffic Pollution in Streets. Tech. Rep., National Environmental Research Institute.

Cai, X.-M., Barlow, J.F., Belcher, S.E., 2008. Dispersion and transfer of passive scalars in and above street canyons – large-eddy simulation. Atmospheric Environment 42, 5885–5895.

Carpentieri, M., Salizzoni, P., Robins, A., Soulhac, L., 2012. Evaluation of a neighbourhood scale, street network dispersion model through comparison with wind tunnel data. Environmental Modelling and Software 37, 110–124.

Caton, F., Britter, R., Dalziel, S., 2003. Dispersion mechanism in a street canyon. Atmospheric Environment 37, 693–702.

Chang, J.C., Hanna, S.R., BoyBeyi, Z., Franzese, P., 2005. Use of Salt Lake City URBAN 2000 field data to evaluate the Urban Hazard Prediction Assessment Capability (HPAC) dispersion model. Journal of Applied Meteorology 44, 485–501.

Di Sabatino, S., Buccolieri, R., Paradisi, P., Palatella, L., Corrado, R., 2011. A fast model for pollutant dispersion at the neighbourhood scale. International Journal of Environment and Pollution 47 (1–4), 207–215.

Dobre, A., Arnold, S., Smalley, R., Boddy, J., Barlow, J., Tomlin, A., Belcher, J., 2005. Flow field measurements in the proximity of an urban intersection in London, UK. Atmospheric Environment 39, 4647–4657.

Fackrell, J.E., 1980. A flame ionisation detector for measuring fluctuating concentration. Journal of Physics E: Scientific Instruments 13, 888–893.

Fernando, H.J.S., Zajic, D., Di Sabatino, S., Dimitrova, R., Hedquist, B., Dallman, A., 2010. Flow, turbulence, and pollutant dispersion in urban atmospheres. Physics of Fluids 22 (5), 1–20.

Fernando, H.J.S., 2010. Fluid dynamics of urban atmospheres in complex terrain. Annual Review of Fluid Mechanics 42, 365–389.

Garbero, V., Salizzoni, P., Soulhac, L., 2010. Experimental study of pollutant dispersion within a network of streets. Boundary-Layer Meteorology 136, 457–487.

Garbero, V., 2008. Pollutant Dispersion in the Urban Canopy. PhD thesis, Politecnico di Torino – Ecole Centrale de Lyon, 153 pp.

Goertler, H., 1942. Berechnung von aufgaben der freien turbulenz auf grund eines neuen naherungsansatzes. ZAMM 22, 244–254.

Hertel, O., Berkowicz, R., 1989. Modelling Pollution from Traffic in a Street Canyon. Evaluation of data and Model Development. Tech. Rep., DMU Luft A-129, NERI.

Hotchkiss, R.S., Harlow, F.H., 1973. Air pollution transport in street canyons. Environmental Protection Agency, 1–128.

Irwin, H., 1981. The design of spires for wind simulation. Journal of Wind Engineering and Industrial Aerodynamics 7, 361–366.

Johnson, W.B., Ludwig, F.L., Dabberdt, W.F., Allen, R.J., 1973. An urban diffusion simulation model for carbon monoxide. Journal of Air Pollution Control Association 23, 490–498.

Kaplan, H., Dinar, N., 1996. A Lagrangian dispersion model for calculating concentration distribution within a built-up domain. Atmospheric Environment 30, 4197–4207.

Louka, P., Belcher, S.E., Harrison, R.G., 2000. Coupling between airflow in streets and the well-developed boundary layer aloft. Atmospheric Environment 34, 2613–2621.

Meroney, R.N., Pavageau, M., Rafailidis, S., Schatzmann, M., 1996. Study of line source characteristics for 2-D physical modelling of pollutant dispersion in street canyons. Journal of Wind Engineering and Industrial Aerodynamics 62 (1), 37–56.

Murena, F., Vorraro, F., 2003. Vertical gradients of benzene concentration in a deep street canyon in the urban area of Naples. Atmospheric Environment 37, 4853–4859.

Murena, F., Favale, G., Vardoulakis, S., Solazzo, E., 2009. Modeling dispersion of traffic pollution in a deep street canyon: application of CFD and operational models. Atmospheric Environment 43, 2303–2311.

Narita, K., 2007. Experimental study of the transfer velocity for urban surfaces with a water evaporation method. Boundary-Layer Meteorology 122, 293–320.

Princevac, M., Baik, J.-J., Li, X., Pan, H., Park, S.-B., 2010. Lateral channeling within rectangular arrays of cubical obstacles. Journal of Wind Engineering and Industrial Aerodynamics 98 (8–9), 377–385.

Rafailidis, S., 1997. Influence of building areal density and roof shape on the wind characteristics above a town. Boundary-Layer Meteorology 85, 255–271.

Rajaratnam, N., 1976. Turbulent Jets. Elsevier, Amsterdam, New York.

Rotach, M.W., 1995. Profiles of turbulence statistics in and above an urban street canyon. Atmospheric Environment 29 (13), 1473–1486.

Raupach, M.R., Coppin, P.A., 1983. Turbulent dispersion from an elevated line source: measurements of wind concentration moments and budgets. Journal of Fluid Mechanics 136, 111–137.

Salim, S.M., Buccolieri, R., Chan, A., Di Sabatino, S., 2011. Numerical simulation of atmospheric pollutant dispersion in an urban street canyon: comparison between RANS and LES. Journal of Wind Engineering and Industrial Aerodynamics 99 (2–3), 103–113.

Salizzoni, P., Soulhac, L., Mejean, P., Perkins, R.J., 2008. Influence of a two scale rough-ness on a neutral turbulent boundary layer. Boundary-Layer Meteorology 127 (1), 97–110.

Salizzoni, P., Soulhac, L., Mejean, P., 2009. Street canyon ventilation and atmospheric turbulence. Atmospheric Environment 43, 5056–5067.

Salizzoni, P., Marro, M., Soulhac, L., Grosjean, N., Perkins, R.J., 2011. Turbulent transfer between street canyons and the overlying atmospheric boundary layer. Boundary-Layer Meteorology 141 (3), 393–414.

Salizzoni, P., 2006. Mass and Momentum Transfer in the Urban Boundary Layer. Ph.D. thesis, Politecnico di Torino – Ecole Centrale de Lyon.

Solazzo, E., Britter, R.E., 2007. Transfer processes in a simulated urban street canyon. Boundary-Layer Meteorology 124 (1), 43–60.

Soulhac, L., Garbero, V., Salizzoni, P., Mejean, P., Perkins, R.J., 2009. Flow and dispersion in street intersections. Atmospheric Environment 43, 2981–2996.

Soulhac, L., Salizzoni, P., 2010. Flow in a street canyon for any external wind direction. Journal of Wind Engineering and Industrial Aerodynamics 98 (12), 903–910.

Soulhac, L., Puel, C., Duclaux, O., Perkins, R., 2003. Simulations of atmospheric pollution in greater Lyon: an example of the use of nested models. Atmospheric Environment 37, 5147–5156.

Soulhac, L., Perkins, R.J., Salizzoni, P., 2008. Flow in a street canyon for any external wind direction. Boundary-Layer Meteorology 126, 365–388.

Soulhac, L., Salizzoni, P., Cierco, F.-X., Perkins, R.J., 2011. The model SIRANE for atmospheric urban pollutant dispersion; part I, presentation of the model. Atmospheric Environment 45 (39), 7379–7395.

Soulhac, L., Salizzoni, P., Mejean, P., Didier, D., Rios, I., 2012. The model SIRANE for atmospheric urban pollutant dispersion; part II, validation of the model on a real case study. Atmospheric Environment 49, 320–337.

Soulhac, L., 2000. Modélisation de la dispersion atmosphérique à l'interieur de la canopé urbaine. Ph.D. thesis, Ecole Centrale de Lyon.

Tinarelli, G., Brusasca, G., Oldrini, O., Anfossi, D., Trini Castelli, S., Moussafir, J., 2007. Micro-Swift-Spray (MSS): a new modelling system for the simulation of dispersion at microscale. General description and validation. In: Borrego, C., Norman, A.N. (Eds.), Air Pollution Modelling and its Applications XVII. Springer, pp. 449–458.

Venkatram, A., Isakov, V., Yuan, J., Pankratz, D., 2004. Modeling dispersion at distances of meters from urban sources. Atmospheric Environment 38, 4633–4641.