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VERTICAL EDDY POLLUTANT FLUX IN URBAN CONDITIONS

Vertikalni turbulentni fluks polutanata u urbanim uvjetima

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Abstract - A method has been proposed for deriving the vertical turbulent flux of light, chemically inert pollutant from meteorological and urban parameters which are easily available. Based on the flux-gradient theory and a division of urban volume in UCL (Urban Canopy Layer) and UBL (Urban Boundary Layer) an iterative procedure has been adopted for the pollutant flux estimation with urban-sensible heat and surface roughness as the basic input. The method has been applied to a range of possible urban characteristics known from existing literature. It came out that the influence of surface roughness upon pollutant turbulent vertical fluxes predominated in all stabilities and also that it was rather insensitive of UCL height. Besides, theoretical speculations found turbulent vertical fluxes of pollutants considerably weaker than turbulent fluxes of momentum.

Key word index: Vertical eddy pollutant flux, urban canopy layer, sensible heat flux, surface roughness.

Sažetak - Izvedena je metoda za određivanje vertikalnih turbulentnih fluksova lakih, kemijski inertnih polutanata pomoću dostupnih meteoroloških i urbanih parametara. Postupak se osniva na fluks-gradijent teoriji i podjeli urbanog sloja na UCL (urbani natkriti sloj) i urbani granični sloj UBL. Pritom se procjena fluksa polutanata provodi iterativnim putem uz urbanu senzibilnu toplinu i površinsku hrapavost kao osnovne ulazne parametre. Metoda je primijenjena na širok raspon mogućih urbanih karakteristika poznatih iz literature. Pokazalo se da je upliv površinske napetosti dominantan u svim stabilnostima, a i prilično neosjetljiv na visinu UCL. Pored toga, teoretskim je razmatranjima ustanovljeno da su vertikalni turbulentni fluksovi polutanata osjetno slabiji od turbulentnih fluksova količine gibanja u gradskim uvjetima.

Ključne riječi: Vertikalni turbulentni fluks polutanata, urbani natkriveni sloj, fluks senzibilne topline, površinska hrapavost.

INTRODUCTION

There is a continuing interest in urban air pollution issues and in the features of urban areas which can affect the dispersion of air pollutants. In order to understand transport and diffusion in urban areas it is necessary not only to describe these features qualitatively but also quantify the effects wherever possible.

Vertical measurements of turbulence are very important in understanding the diffusion of air pollutants (Clarke, 1969; Oke and East, 1971). Spanton and Williams (1988) studied the structure of the atmospheric boundary layer in central London. Uno et al. (1992) observed the structure of the nocturnal urban boundary layer and discussed its evolution into a convective mixed layer. Many other studies have been undertaken to develop or test mathematical models of turbulence features and the urban boundary layer (Bennet and Saab, 1982; Mc Rae et al, 1982; Ching, 1985; Todhunter and Terjung, 1988 etc.).

There is a paucity of information on the vertical turbulent flux of pollutant in spite of the fact that it is very important for the understanding of diffusion processes and that it has a strong effect on the results of urban air quality models. This is partly due to lack of appropriate data (Guedalia et al, 1974) since these measurements require more sophisticated and expensive equipment than those for other turbulent fluxes as heat, moisture and momentum.

The present paper describes a possibility of evaluating the vertical turbulent flux of pollutant in a two layer urban volume, between the urban canopy layer (UCL), which extends vertically to an average roof level, and the urban boundary layer (UBL), extending from the top of the UCL up to the base of the subsidence inversion. A first-order closure assumption in this two-layer urban model helps to evaluate the eddy pollutant flux as a function of atmospheric stability, urban structure and the vertical gradient of pollutant concentration.

THEORETICAL CONSIDERATIONS

General

The vertical turbulent flux of pollutant may be represented by

$$F \equiv \left[\left(\overline{w'c'} \right)_z \right] \tag{1}$$

where F is the vertical turbulent flux of pollutant, w is the vertical component of the wind vector, c is pollutant concentration, the bar indicates a time average, the primes indicate turbulent fluctuations from a time average, z is an arbitrary level and the square parenthesis denote an averaging over the given plane in the (x,z) direction. F can be determined by means of various assumptions (Letau, 1970).

In this paper a first-order closure assumption is used, which makes the eddy pollutant flux proportional to the vertical gradient of $\bar{c}$:

$$F \equiv \left[\left(\overline{w'c'} \right)_z \right] = -K_c \frac{\partial \bar{c}}{\partial z} \tag{2}$$

where K_c represents the eddy diffusivity of pollutants. It is usually assumed of the same order of magnitude as the exchange coefficients for heat and momentum, which are generally much better elaborated. Therefore, we shall transform (2) in order to relate the unknown coefficient K_c to the coefficient of momentum K_m. The similarity theory gives

$$K_m = kzu_* \Phi_m^{-1} \tag{3}$$

Here, u_* is the friction velocity, defined as

$$u_* = \left(-\overline{u'w'} \right)^{1/2}$$

k is von Karman's constant (here 0.4), z is the level of interest (inside the surface layer) and Φ_m is a non dimensional function of stability. A combination of (2) and (3) gives

$$\frac{K_m}{K_c} \Phi_m = -\frac{ku_* z}{F} \frac{\partial \bar{c}}{\partial z} \tag{4}$$

In order to scale concentrations we must introduce a new parameter:

$$F_* = -\frac{F}{u_*} \tag{5}$$

The term $(K_m/K_c)F_m$, defined here as a non dimensional stability function for pollutant concentration, Φ_p, becomes now

$$\Phi_p = \frac{kz}{F_*} \frac{\partial \bar{c}}{\partial z} \tag{6}$$

Since there are indications (e.q. Mc Rae et al, 1982; Bennet and Saab, 1982) that a pollutant eddy transport is more closely related to the heat eddy transport than to the momentum one, Mc Rae et al. (1982) integrated Businger's similarity functions (Businger et al, 1971) to get the following integral forms Ψ_p of the pollutant similarity function:

stability $$\Psi_p = \int_{z_0}^{z} \Phi_p \frac{\partial z}{z}$$

neutral $$\Psi_p = 0.74 \ln (z / z_0) \tag{7}$$

stable $$\Psi_p = 0.74 \ln (z / z_0) + \frac{4.7}{L}(z - z_0) \tag{8}$$

unstable $$\Psi_p = 0.74 \left[\ln \left(\frac{x^{1/2} - 1}{x^{1/2} + 1} \right) - \ln \left(\frac{y^{1/2} - 1}{y^{1/2} + 1} \right) \right] \tag{9}$$

with $$x = 1 - 9\frac{z}{L} \qquad y = 1 - 9\frac{z_0}{L} \tag{10}$$

Here, L is the Monin-Obukhov scale length

$$L = -\frac{\rho c_p T u_*^3}{g k Q_h} \tag{11}$$

where Q_h is the turbulent flux of sensible heat, T is the air temperature, ρ is the air density, g is acceleration due to gravity, c_p is the air specific heat at constant pressure and z_o the surface roughness length.

The integration of (6), after introducing (5), finally gives

$$\left[\left(\overline{w'c'}\right)_z\right] = -k\,u_*\left[c(z) - c(z_o)\right]\Psi_p^{-1} \qquad (12)$$

with $\left(\overline{w'c'}\right)_{z_o} = 0$.

Let us take level z to be a surface of pollutant exchange between the UCL and the UBL, identical with the top of the urban canopy layer(or the bottom of the UBL). In that case, $c(z)$ becomes the area averaged pollutant concentration in the UBL, c_2, and $c(z_o)$ the area averaged concentration in the UCL, c_1, which could be compared to surface measured concentrations, so that

$$\left[\left(\overline{w'c'}\right)_z\right] = -k\,u_*(c_2 - c_1)\Psi_p^{-1} \qquad (13)$$

Both pollutant concentrations could be measured or evaluated by urban quality models. The vertical turbulent flux of pollutant is positive if it points away from the surface (if $c_1 > c_2$) and its value depends upon atmospheric stability.

Taken altogether, our approach is based on the existence of a vertical change in pollutant concentration and it also deals with the non dimensional function of stability Ψ_p, while u_* reflects the horizontal inhomogenities of urban terrain with respect to the mean wind speed.

Finally, normalising Equation (13) by the difference of pollutant concentration $(c_2 - c_1)$ leads to a new quantity

$$u_c = -k\,u_*\Psi_p^{-1} \qquad (14)$$

where u_c has a dimension of velocity and can be described as the "turbulent flux velocity of pollutant" or "pollutant flux velocity". It denotes the intensity of the addy pollutant vertical flux as a result of meteorological conditions.

Modelling procedure

Pollutant flux velocity can be estimated for various stabilities and urban conditions by an iterative procedure.

The input parameters are the roughness length, z_o, the top of the UCL, z, the friction velocity, u_*, and the Monin-Obukhov length, L. This approach stres-ses the need to specify, the sensible heat flux Q_h in urban conditions.

A partitioning of the radiant energy absorbed at the Earth's surface into turbulent fluxes of sensible and latent heat in the atmosphere and a conductive flux into the substrate appears to be different for urban and rural surfaces (Oke, 1982). The complex geometry of street canyons and the spatial heterogeneity of urban system as well as an anthropogenic heat input produce a specific urban diurnal variation of the sensible heat flux which has an indirect influence on pollutant flux velocity. The sensible heat flux can be measured (Kerschgens and Krauss, 1990) or parametrised using the energy balance approach (Oke, 1978).

Having found Q_h, we can determine the pollutant flux velocity by a common iterative procedure:

a) Find the initial value of u_* in the neutral atmosphere:

$$u_* = k\,\bar{u}\left[ln\left(\frac{z}{z_0}\right)\right]^{-1} \qquad (15)$$

b) Compute the Monin-Obukhov length L for the given value of Q_h:

$$L = -\frac{\rho c_p T u_*^3}{g k Q_h} \qquad (16)$$

c) Substitute L from the second step in Equation (17) to get a new estimate of u_*:

$$u_* = k\,\bar{u}\left[ln\left(\frac{z}{z_0}\right) - \Psi_m\left(\frac{z}{L}\right)\right]^{-1} \qquad (17)$$

where the integral similarity function Ψ_m has to be determined by means of this L value, given by Equation (16).

d) Use the value of u_* to get a new value of L in Equation (16).

In this approach, the procedure is repeated until the difference between two successive values of L becomes less than 10% of L. In general, it takes 6-10 iterations to achieve convergence.

e) With L calculated for a given z and z_o, the integral stability functions (7) to (10) of pollutant concentration can be computed-as well as the vertical pollutant flux velocity, u_c.

MODEL PERFORMANCE

The turbulent flux velocity was computed for chosen test data described common urban characteristics. The city size and structure was simulated by specifying the roughness length z_o=0.5 m (centres of small cities), z_o=1 m (centres of large towns and cities) and z_o=2 m (centres of cities with very tall buildings). The average roof level heights (UCL heights) were

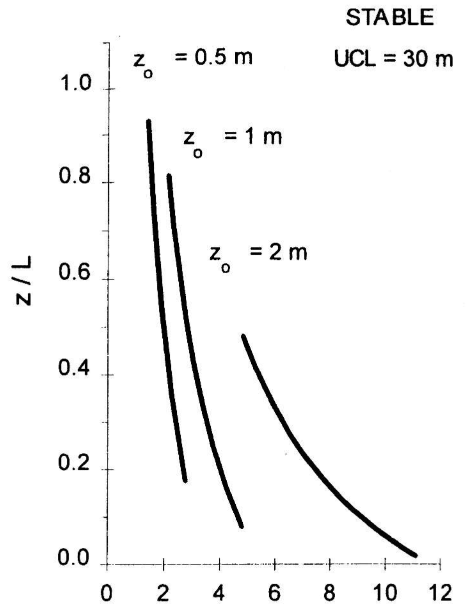

Figure 1. Pollutant flux velocity, u_c, in a stable UCL.
Slika 1. Brzina fluksa polutanata, u_c, u stabilnom UCL.

chosen as 20m, 30m and 40m. On the basis of reported values of Q_h in existing literature (Oke, 1982, 1978) an interval from -200 Wm^{-2} to 200 Wm^{-2} was chosen with computations performed in steps of 10 Wm^{-2}.

The vertical turbulent flux velocity of pollutant was calculated for each combination of Q_h, z and z_o. It varies between 10^{-2} ms^{-1} and 10^{-1} ms^{-1}.

Figure 1 illustrates the pollutant flux velocity as a function of z/L in stable air (Q_h<0 and L>0) and of surface roughness, z_o for an UCL height of 30m. The graphs for other UCL heights have been omitted since they appeared to be almost the same as the represented one. The pollutant flux velocity decreases with an increase in z/L when mechanically generated turbulence is dampened by a growing stable stratification. This decrease intensifies with greater surface roughness but still - at a fixed z/L - the pollutant flux velocity is several times greater for increased surface roughness (z_o=2m) as a result of mechanically caused turbulence.

Figure 2 depicts the behaviour of the pollutant flux velocity as a function of z/L for various z_o and UCL heights in an unstable UCL. Again, u_c increases with increasing surface roughness. The turbulent flux velocity appears to be greater for smaller heights of UCL due to the fact that our simple model does not explicitly include free convection parametrisation. In such a situation, pollutants are very soon dispersed by large addies over the entire urban volume so that a free convection condition can be successfully treated by means of one-layer scalar models.

Our model approaches such a case when the surface roughness decreases and this fact makes possible some additional speculations. In an unstable UCL, the thermal generation of turbulence interferes with the mechanical one.

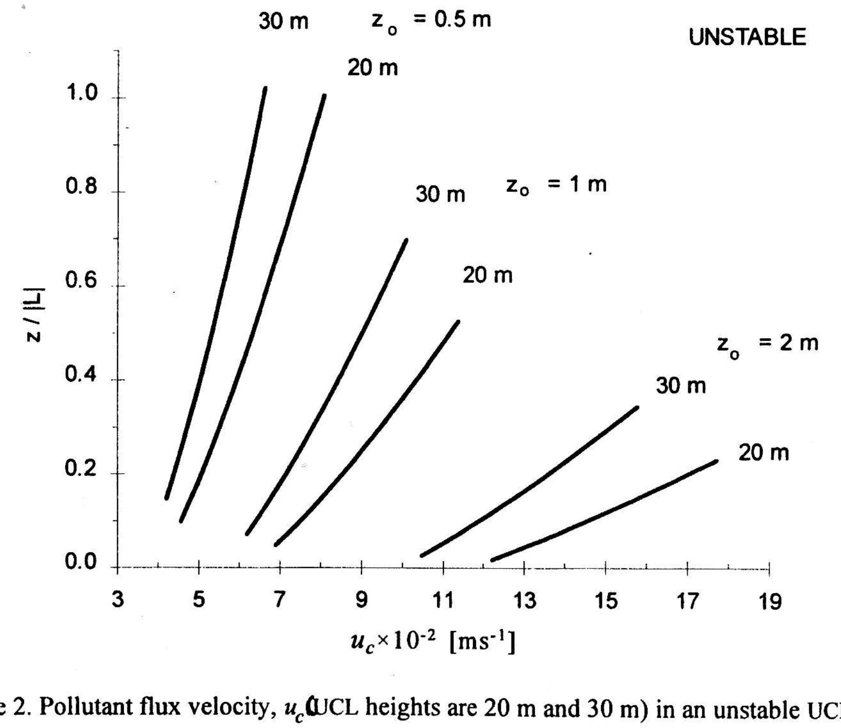

Figure 2. Pollutant flux velocity, u_c(UCL heights are 20 m and 30 m) in an unstable UCL.
Slika 2. Brzina fluksa polutanata, u_c (UCL visine su 20 m i 30 m), u nestabilnom UCL.

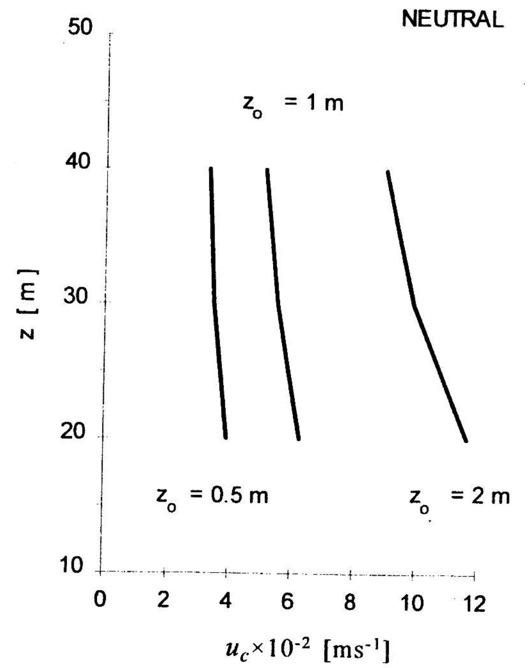

Figure 3. Pollutant flux velocity, u_c in a neutral UCL.

Slika 3. Brzina fluksa polutanata u_c, u neutralnom UCL.

Therefore, an increase in pollutant vertical transport by turbulent eddies with instability is more pronounced at greater surface roughness and Figure 2 undoubtedly indicates that the influence of z_o is still predominant.

Altogether, according to our calculations, free convection, which is a normal appearance in rural surface layers, can fully develop only above the urban canopy layer. Figure 3 shows u_c in neutral air (Q_h=0 and $L \to \infty$) as a function of z and z_o. For a given surface roughness, u_c monotonically decreases with height.

The friction velocity u_* and the pollutant flux velocity u_c represent turbulent fluxes of momentum and pollutants. Figures 4 and 5 illustrate their ratio in unstable and stable conditions as a function of Q_h and roughness length if the UCL height is 3 m. The curves for other UCL heights are not shown since they do not differ substantially from the depicted one. This fact suggests that the dependence of the pollutant flux velocity upon the UCL height is rather week.

The ratio u_*/u_c clearly illustrates the efficiency of turbulence in the vertical transport of ingredients at the top of the UCL. This transport intensity increases with mechanical and thermal generation of turbulence and, again, the first mechanism prevails.

The ratio is considerably greater than 1 and it increases with growing stability. It undoubtedly indicates that the vertical flux of pollutant in urban conditions is smaller than the turbulent flux momentum. This fact is in agreement with some recent empirical evidence of the weak efficiency of vertical turbulent transports in comparison to the horizontal ones over urban surfaces (Roth, 1993). No theoretical explanation exists for this fact since it contradicts the role of z_o in Equations

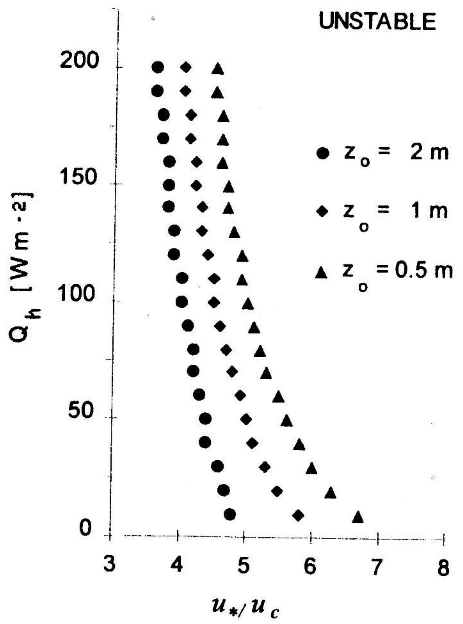

Figure 4. The u_*/u_c ratio versus Q_h in unstable conditions.

Slika 4. Omjer u_*/u_c u ovisnosti o Q_h u nestabilnim uvjetima.

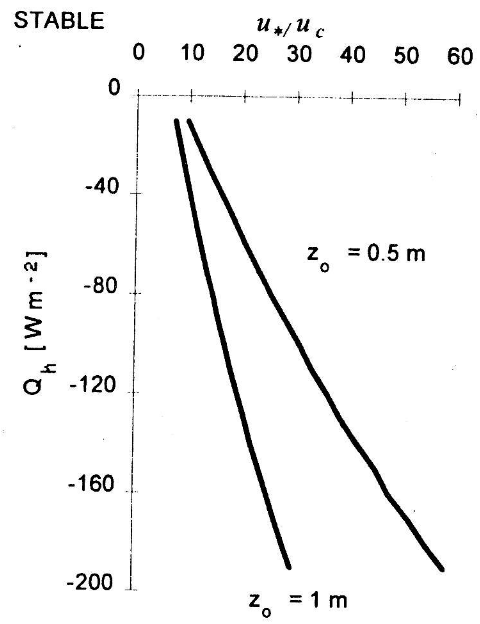

Figure 5. The u_*/u_c ratio versus Q_h in stable conditions.

Slika 5. Omjer u_*/u_c u ovisnosti o Q_h u stabilnim uvjetima.

(17), (7) and (8). We can only suspect that an increase in roughness in urban conditions may play a double role: generally it enhances turbulence but at the same time the surrounding buildings may prevent the full development of turbulent eddies.

CONCLUSION

The vertical exchange of pollutants in urban conditions can be described by the pollutant flux velocity, u_c. This quantity has been derived theoretically and its comparison with the turbulent flux of momentum i.e. the friction velocity in various urban conditions was examined. It resulted that the non dimensional vertical transport of pollutants at the top of an urban canopy layer was almost one order of magnitude less than the turbulent fluxes of momentum. Although this result should be confirmed by simultaneous measurements of u_c and u_*, it warns urban pollution modellers that they might overestimate the role of turbulent diffusion by using u_* instead of u_c. Besides, since u_c "measures" also a downdraft of pollutants, it can be a useful quantity in long-range transport models estimating the amount of pollutants which might reach the surface from above.

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