Influence of the number and position of sources on the maximal pollutant concentration inside a street canyon

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Effects of linear pollution source position and the number on the maximum pollutant concentration are numerically investigated. It is found that the lowest effect of pollutants is produced when their sources are placed near the street center or closer to the windward side. When the number of sources increases up to four at constant total emission intensity, the maximum pollutant concentration grows providing the sources are located symmetrically inside the street canyon. If the source, the nearest to the leeward side of the street, is located at equal distances from buildings, then the maximum concentration of pollutants decreases independently of the number of such sources.

Vehicles are now the main sources of the urban atmosphere pollution. When modeling the propagation of pollutants, emitted by vehicles in street canyons, these sources of pollution can be considered with sufficient accuracy as linear. When modeling, as a rule, one linear source is assumed to be located in the street center. Several linear sources located symmetrically relative to the street center imitate the multi-lane traffic.

Actually, even in the sliding flow mode, the fields of air velocity and the turbulent diffusion coefficient in the canyon bottom are essentially inhomogeneous, and the concentration of pollutants noticeably changes at any shift of the pollution source.

The effect of the pollution source position on the maximum near-ground pollutant concentration in a street canyon, which width is equal to four heights of buildings situated by its sides was studied in Ref. 1. In that case, the regime of isolated roughness was observed, i.e., eddy flows appeared near houses, and air moved between them descending in the street canyon from the above-building flow. It was shown that the maximum near-ground concentration was the greatest when the pollution source was situated close to buildings on the leeward side of the street, and was somewhat less when the source was situated on the windward side. At intermediate positions of the source $x/B = 0.25$–0.75 (x is the coordinate of the source counted from a building on the leeward side of the street, B is the street width), the maximum near-ground concentration was approximately by 1.5 times less. Note that in this work the source of pollution is considered as point and immobile.

In case of one-lane traffic, the maximum concentration near the street canyon bottom is 1.5 times higher that in case of the four-lane traffic provided the street width is equal to the height of buildings on street sides and the total intensity of emissions is constant.[2]

It seems expedient to study in more detail the effect of position of one or several linear sources of pollution, imitating emission of pollutants by vehicles, on maximum concentration of pollutants in the street canyon at different ratio of the street width to the height of buildings on its sides.

Since the distance between streets crossing another one under consideration is usually significantly greater than the street width, it is reasonable to solve the problem in two-dimensional approximation. The following variables were used in the solution: the vortex – the flow function ($\omega - \psi$) and the rough model of the turbulence, in which the generation of the turbulence energy K and the rate of its dissipation at each point were accepted equal. The turbulence scale l was determined by the distance from the nearest point of building $l_{\min}$. Such model overestimates the turbulent viscosity and the diffusion, that, to some extent, takes into account the generation of the turbulence energy by the traffic.

It has been also assumed that the effect of turbulence on the vortex is reduced to its transfer by analogy with transfer of a passive admixture. This assumption is quite rough, but the results of test calculations show that in the sliding flow mode it does not lead to an essential distortion of the pattern of air motion in the street canyon. The concentration of pollutant C was determined from solving the diffusion equation. The system of equations has the form[3]:

$$\omega = -\left(\frac{\partial^2\psi}{\partial x^2} + \frac{\partial^2\psi}{\partial z^2}\right); \quad (1)$$

$$V = -\frac{\partial\psi}{\partial x}, \ U = \frac{\partial\psi}{\partial z}; \quad (2)$$

$$\frac{\partial(\omega U)}{\partial x} + \frac{\partial(\omega V)}{\partial z} = \left[\frac{\partial}{\partial x}\left(\sqrt{K} l \frac{\partial\omega}{\partial x}\right) + \frac{\partial}{\partial z}\left(\sqrt{K} l \frac{\partial\omega}{\partial z}\right)\right]; \quad (3)$$

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$$K = \left\{ l^2 \left[\left(\frac{\partial U}{\partial z} \right)^2 + 2 \frac{\partial V}{\partial x} \frac{\partial U}{\partial z} + \right.\right.$$

$$\left.\left. + \left(\frac{\partial V}{\partial x} \right)^2 + 2 \left(\frac{\partial U}{\partial x} \right)^2 + 2 \left(\frac{\partial V}{\partial z} \right)^2 \right] \right\} / C_d; \qquad (4)$$

$$l = \frac{l_1 C_d^{1/4} \kappa l_{\min}}{C_d^{1/4} \kappa l_{\min} + l_1}; \qquad (5)$$

$$\frac{\partial (UC)}{\partial x} + \frac{\partial (VC)}{\partial z} =$$

$$= \frac{1}{\mathrm{Sc}} \left[\frac{\partial}{\partial x} \left(\sqrt{K} l \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial z} \left(\sqrt{K} l \frac{\partial C}{\partial z} \right) \right] + Q, \qquad (6)$$

where the coordinate x is directed across the street; z is directed vertically, U and V are the corresponding projections of the air velocity; Sc is the Schmidt number; κ is the Karman constant; C_d and l_1 are constants; Q is the intensity of the pollution sources, which is taken nonzero only in points, which are the nearest to the street canyon bottom, where automobiles move. The elevation of pollution sources above the street canyon bottom to some extent represents the mixing of air containing pollutants by vortices appearing behind the moving automobiles.

The equations are written in the dimensionless form. The height of buildings on the street sides is taken as the length scale l_0, and the wind velocity at the height equal to a triple height of a building is taken as the velocity scale U_0. At such height, the distortions in the wind flow caused by the buildings practically do not affect the wind velocity.[4] The turbulent energy scale is equal to the square of the velocity scale. The scale of the flow function ψ_0 is chosen so that the dimensionless coefficient in the formulas for the projections of air velocity is equal to 1: $\psi_0 = U_0 l_0$. The vortex scale $\omega_0 = U_0 l_0^2$ is determined similarly. The source intensity scale is related to the scale of concentration of pollutants so that the dimensionless coefficient in the diffusion equation is equal to 1: $Q_0 = C_0 U_0 / l_0$.

The surface of buildings and the street canyon bottom are meant impenetrable. For them $\psi = 0$, $\omega = -\partial^2\psi/\partial n^2$ and $\partial C/\partial n = 0$, where n is the normal to the corresponding boundary. At the input boundary, through which air flows into the calculation area, the power profile of the wind velocity $U = U_1(z/z_1)^n$ is set[5] with the exponent equal to 0.33. That corresponds to the neutral stratification at the roughness layer thickness equal to several meters. Less values of the exponent are used more often: 0.299 [Ref. 6] or even 0.25 [Ref. 7], but the pattern of air flow in the sliding flow mode in the street canyon, which will be considered below, practically does not depend on the exponent at its variation in the range 0.25–0.33. The vertical component of the wind velocity V at this boundary is taken equal to zero.

The value of the flow function at the input boundary is calculated from the known value of the wind velocity, and the vorticity is determined by the formula $\omega = -\partial U/\partial z$. The upper boundary is assumed to be impenetrable, where the flow function is constant, and the vorticity is determined by the formula $\omega = -\partial^2\psi/\partial z^2$. The concentration of pollutants at the both boundaries is assumed to be zero: $C = 0$. The distance from the input boundary to the leeward side of the street canyon is no less than $0.75B$. The upper boundary is at the height equal to triple height of buildings H situated on the sides of the street canyon. Calculations carried out at the upper boundary height, equal to four heights of buildings, have shown the same pattern of air flow in the canyon. The output boundary, through which air flows out of the calculation area, derivatives of the sought values with respect to the normal to the boundary are assumed to be zero: $\partial\psi/\partial x = 0$, $\partial\omega/\partial x = 0$, $\partial C/\partial x = 0$. The distance from the windward side to the output boundary is assumed to be not less than the double width of the street canyon. The height of buildings on the street sides was assumed the same.

The equations of vortex transfer and diffusion were solved by means of the "classic" finite-difference procedure of the ascertainment method.[8] To decrease the procedure diffusion, the derivatives in terms, describing convective transfer of the vortex and concentration, were approximated by finite differences of first order in the direction against the flow. To smooth solution, the results obtained at two sequential iterations were averaged.

The Poisson equation, from which the flow function was determined, was solved by the sequential upper relaxation method.[8] Calculations were carried out on the combined uniform grid with 61 nodes in the vertical direction and 151 nodes in the horizontal one. The height of buildings corresponded to 20 grid steps. Spatial steps were equal to 0.05.

The test the calculation, carried out on the grid with 91 vertical nodes (the height of buildings corresponded to 30 grid steps, and the spatial step was equal to 1/30), has shown that the maximum horizontal air velocity over the road differs from that calculated with steps of 0.05 by less than 1%, the maximum velocity of air, ascending along walls of buildings on the street leeward side, has decreased by approximately 2%, and the maximum velocity of air, descending along the building walls on the street windward side, has increased by approximately 8% due to small shift of the vortex center to the street leeward side. At a greater resolution, there appeared small secondary vortices near building foundations on both sides of the street. All these changes do not lead to a noticeable change of the field of the concentration of pollutants inside the canyon.

Since the field of pollutant concentration depends mainly on the air motion, to test the model, the calculated values of the vertical component of air velocity near the leeward and windward sides of the street canyon, related to the horizontal wind velocity in the canyon center at the level of roofs, were compared with results of experiments.[9] Figure 1 shows the comparison results at the street width B equal to the height of buildings H.

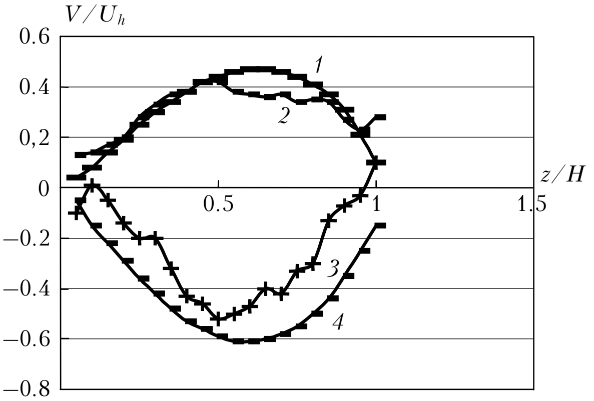

Fig. 1. Vertical velocity of air at $x/B = 0.15$ (*1* is calculation, *2* is experiment) and $x/B = 0.85$ (*3* is calculation, *4* is experiment).

It is seen that the velocity of the ascending air near the leeward side of the canyon is described in the model quite well, while in case of the windward side it is somewhat overestimated in calculations.

The maximum concentration of pollutants in the street canyon at different positions of the pollution source, normalized to the value of the concentration in case when the street width is equal to the building height (curve *1*) and the linear source is situated in the street center, is shown in Fig. 2.

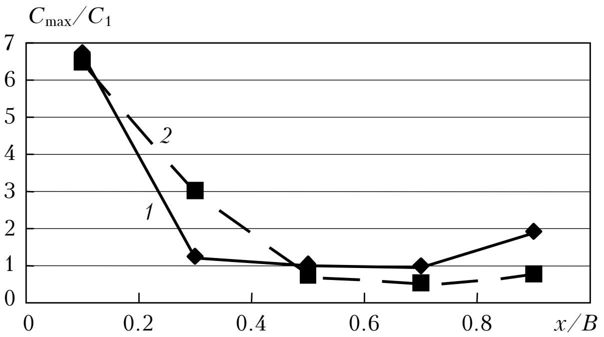

Fig. 2. The change of the maximum concentration of pollutions in the street canyon as a function of position of the source of pollution in narrow (curve *1*) and wide (curve *2*) streets.

Curve *2* corresponds to the street width twice as greater as the height of buildings. It is seen that the greatest values of the maximum concentration of pollutants are observed when the source, i.e., moving automobile, is situated on the leeward side of the street.

If the source of pollution is located closely to buildings on the windward side of the street, the maximum concentration is somewhat greater than at the source position in the street center. In wider street canyons, at the source movement from buildings on the leeward side to the center, the maximum concentration decreases slower. This is related with the presence of secondary vortex in the lower part of buildings on the leeward side. Thus, the maximum concentration of pollutants in the street canyon, as a rule, is observed in the point of the pollution source location. Only in case when the source is situated near buildings in a narrow street, the maximum concentration of pollutants, according to results of calculation, is observed near the base of these buildings.

Note that the change of position of the linear source of pollution in calculations significantly stronger affects the concentration of pollutants near buildings on the leeward side of the street than in experiments, carried out in the aerodynamic tube, when the street width is taken equal to the building height.[10] Evidently, it is connected with the turbulent diffusion coefficient overestimation in the used model.

Since the street traffic commonly is multi-lane, it is expedient to consider the change of the maximum concentration of pollutants as a function of the number and position of linear pollution sources. This is shown in Fig. 3 for two linear sources, the distance between which in all cases is equal to 0.4 of the street width, if the position of the source, situated more close to the leeward side of the street, changes.

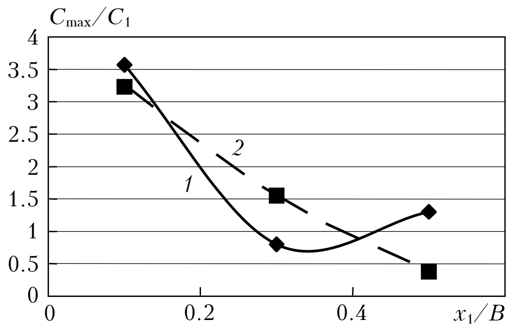

Fig. 3. The change of the maximum concentration of pollutants in the street canyon as a function of a closer position of one pollution source to the leeward side of the street, when two sources are present in narrow (curve *1*) and wide (curve *2*) streets.

It was assumed that the total intensity of two sources of pollution is equal to the intensity of one source in the cases described above, i.e., the intensity of each source is halved. In this case, the maximum concentration for two sources is less almost twice than at one source providing the street width is two times greater than the building height. The field of concentration of the pollutant near each source in this case weakly depends on the presence of the second pollution source.

If the street width is equal to the building height, the absolute distance between the sources is two times less, and though the maximum concentration of the pollutants for two sources is less than for one source in this case, its decrease is not great. Only in the case when one of the sources is situated very close to the leeward side of the street, the maximum concentration of the pollutant for two sources is almost two times less than for one.

At the increase of the number of sources from one to four, the maximum concentration of pollutants increases (curve *1*, Fig. 4) in case of their symmetrical position relative to the street center. This is attributed to approach of one of the sources to buildings on the leeward side of the street.

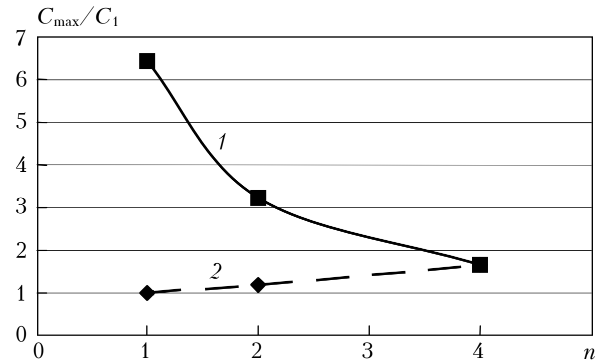

Fig. 4. Maximum concentration of pollutants in the street canyon as a function of the number of linear sources at their different position.

If only one source is considered, it is taken to be situated in the street center. For two sources $x_1/B = 0.3$; $x_2/B = 0.7$; and for four sources $x_1/B = 0.1$; $x_2/B = 0.35$; $x_3/B = 0.65$, and $x_4/B = 0.9$. Total emission from all sources is assumed the same, i.e., each of two sources emits a halved pollution as compared to single source, and each of four sources, correspondingly, a quarter. In case when the pollution sources, nearest to the leeward side, are situated at the same distance from buildings, and the distance between the sources is the same as at their symmetrical position relative to the street centre (for one source $x/B = 0.1$; for two $x_1/B = 0.1$; $x_2/B = 0.5$; and four sources are situated likewise in the previous case), the maximum concentration of pollutants decreases with the increase of the number of sources (curve *2*, Fig. 4). Note that the maximum concentration of pollutants in all cases is normalized to its value for one linear source situated in the street centre.

The obtained results make it possible to conclude that at a prevalent wind direction, often observed if the city is situated in mountains or foothills, it is expedient to locate highways nearer to the windward side of streets in order to decrease the maximum concentration of pollutants in street canyons.

References

1. A.T. Chan, E.S.P. So, and S.C. Samad, Atmos. Environ. **35**, 5681–5691 (2001).
2. G. Lanzani and M. Tamponi, Atmos. Environ. **29**, No. 23, 661–674 (1995).
3. E.S. Kamenetsky, Izv. Vysshih Uchebn. Zaved. Sev. Kavkaz Region. Estestv. Nauki, No. 10, 28–32 (2004).
4. E.I. Retter, *Architectural-building Aerodynamics* (Strojizdat, Moscow, 1984), 294 pp.
5. G. Moriguchi and K. Uchara, J. Wind Eng., No. 52, 102–107 (1992).
6. N.J. Pavitskiy, A.A. Yakushin, and S.V. Zhubrin, J. Wind Eng., No 52, 120–125 (1992).
7. J.-J. Kim and J.-J. Baik, Atmos. Environ. **35**, 3395–3404 (2001).
8. P. Rouch, *Calculative Hydrodynamics* (Mir, Moscow, 1980), 616 pp.
9. J.-J. Baik and J.-J. Kim, Atmos. Environ. **36**, 527–536 (2002).
10. P. Kastner-Klein and E.J. Plate, Atmos. Environ. **33**, 3973–3979 (1999).