Air Quality Upgrading in Residential Areas Using Architectural Methods

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Abstract. According to results of natural observations in big cities and using building models, some optimum techniques for planning and development have been revealed providing hygienic norms of emission content from vehicles in main streets within the comfortable weather classes defined by combinations of wind speed, temperature, and air moisture. Patterns of air flow transformation were revealed by the speed and direction as well as distribution of polluting substances on the cross section of urban streets with variation of their width, height, and housing density. Planning conditions have been determined contributing to the formation of the stable vortex and the elevated air pollution resulting from the closed circulation of vehicle emissions in the street canyons. Possibilities to provide the air quality are determined under the conditions of the historically formed urban development by way of realization of planning reconstructive and organization regulative measures. Special aspects to choose and realize urban planning steps are chosen aimed at air protection in various geographic areas with a typical annual trend of changing climate forcing. It is highlighted that in landscape zones with a pronounced seasonal character of climate forcing, an individual approach to choosing urban planning methods is needed to regenerate the urban environment as applicable to problems arising in different seasons.

1. Introduction

Many factors can be taken into account in architectural solutions upon which the following depends: territorial distribution, concentration level and impurity atmospheric dispersion emitted by vehicles. Already when choosing a territory for the development, its zoning by purpose and determining directions of main transportation links, the question of quantitative redistribution of air pollution in the atmospheric surface layer of the city is being practically solved.

The most considerable factors determining quality changes in the air of residential areas at the stage of development of the general plan are architectural and planning structure of the city, intensity of traffic on the main directions of freight and passenger flows, general climatic and wind regimes, forest sites and orographic conditions.

At the stage of development of projects for detailed planning of residential zones, urban planning measures to protect air from pollution are based on the regularities to which the process of forming initial concentrations and dispersion of toxic substances in the urban development is conformed when utilizing motor vehicles.

Hazardous substances concentration level in the air of urban streets is fixed as a result of a balance between the intensity of its arrival in the air basin and the intensity of its dispersion into the atmosphere.
environment. The pollution supply is determined by the number of its emission by a vehicle per travel unit and the number of vehicles passing this track section per time unit [1]. The pollutant dispersion with emissions occurring at lower height is determined mostly by the wind speed, as well as by the size of the surface through which the diffusion goes [2, 3].

By the results of the continuous on-site investigations in large cities, it was established that with wind speeds equaling 3…4 m/s, the maximum one-time admissible concentrations (MAC) of such leading components of combustion gases (CG) as carbon oxide (CO), nitrogen dioxide (NO\textsubscript{2}) and hydrocarbons (C\textsubscript{n}H\textsubscript{m}) are supplied by 40…70 % of the total length of main streets [4]. According to the weather classification proposed by I.S.Kandror et al. [5], such average wind speeds are comfortable and enable to use territories for the urban development within the wide temperature and air moisture range [6]. They are observed in the woodland sub-area during a year, as well as in the steppe area – in the summertime period and determine the self-purification reserves for the air basin of communities from vehicle emissions.

In the taiga sub-area, oases and humid sub-tropics, the lower average wind speeds are observed (up to 3 m/s) and no-wind conditions (0…1 m/s) [7]. At such an airing regime, the population experiences uncomfortable warmth feelings and the enhanced level of air pollution in the streets. It is obvious that in the given climatic zones, it is needed to strive for such methods of road location, forms and arrangement of urban elements at which the initial wind speeds are preserved to the maximum and ventilation of residential areas and public spaces is stimulated.

In the cities with rectangular compact planning of the street network with the very pronounced asymmetry of wind rose, such a measure as main road location along the dominant wind direction enabling to preserve and even to increase the incoming air flow speeds is realized approximately in 50 % of cases. In such situations in the streets with the predominant perpendicular wind direction with respect to their axis, the air speed in the street space is determined by geometric parameters of their cross-section and planning techniques.

Therefore, the planning concepts of city streets sections in the existing development providing for hygienic norms of vehicle emissions concentrations (according to the data from systematic observations) must be used by designers as tested references in the field of environmental construction along with the theoretical insights [8–12].

A variety of planning techniques for building arrangement proposed for city planning practice [7, 11–14] enables to regulate the street aerating regime aimed at prevention of their gas pollution, protection of the residential area from cold strong winds (more than 5 m/s) or preservation of initial wind speeds at the insufficient natural ventilation (up to 3 m/s and windless conditions).

However, when choosing planning concepts for transportation infrastructure, residential areas, and public spaces in communities located in landscape zones with pronounced seasonal change of climatic factors, it is necessary to develop individual approach. In different seasons, there appear various problems connected with the necessity of the micro-climate management and air protection from pollution.

In contrast to other meteorological factors impacting the concentration of hazardous gases (HG) in the air of city streets and the adjoining residential development (temperature gradient, air humidity, et al), the wind speed and direction are the most manageable factors with the potential of their regulation by architectural methods. In general, the urban planning basics for the wind regime regulation are formulated by F.L.Serebrovsky [13] in his theoretical model according to which the wind speed in a random point $i$ of a populated area can be calculated by the formula:

$$u_i = u_0 \cdot K,$$

(1)

where $u_0$ – reference wind speed measured at the meteorological station; $K$ – total coefficient of air flow transformation by its speed under the conditions of the populated area taking into account the impact of roughness of various rank:

$$K = \tau_1 \cdot \tau_2 \cdot \tau_3 \cdot \tau_4,$$

(2)
where $\tau_1$ – coefficient of transformation under the impact of the land topography; $\tau_2$ – coefficients of transformation under the impact of the area development; $\tau_3$ – coefficient of transformation under the impact of separate buildings and the development fragments; $\tau_4$ – coefficient of transformation taking into account the impact of the soil roughness, bushes, lawn, flanks, pavements, and other beautification features.

The major feature of the city streets is a prolate form in plan with a typical compositional unification of development elements with diverse number of floors and length. The impact of urban streets on the air flow, according to (2), is determined by a partial factor of transformation $\tau_3$, reflecting the air flow transformation by speed under the impact of development fragments. Hence, the level of air pollution on streets with stable size of traffic flow can be considerably different due to the wind speed change at the diverse planning techniques and development in some spots. The influence of the wind speed on the reference concentration of $\text{СО}$ – the leading component of HG is estimated by the correlation ration $r$ within 0.70…0.78 and proportionate to the impact of the vehicle density ($r = 0.85…0.90$) [15].

The traditional location of facilities of trade, social infrastructure and amenities, and administration purposes in the development breaks along the main streets of downtown area results in extraordinary overbuilding with street canyons and the increase in pedestrian volume. Under such conditions, the bilateral frontal development in main streets, representing a safe screen between the carriage-way and the surroundings, increases the gas pollution of the street space and affects the pedestrians, drivers, and passengers very adversely. Therefore, street canyons present a difficult challenge in terms of insufficient aeration and the elevated air pollution [16–20].

In the urban design practice, for a more complete account of the impact from geometric parameters of the cross section and the development density on the kinematics of the wind vortex and the air environment quality, it is needed to determine corresponding functional relationships for the average wind speed on the typical sections of main streets. Moreover, the prime significance is revealing architectural and planning features contributing to the cases of hazardous air pollution in street canyons.

2. Methods used in the experiment
To study the impact of planning parameters of streets and their development techniques upon the coefficient of wind speed transformation, an anemometric survey has been done on the open smooth asphalted site with the size of 100x100 m using development fragments in urban streets made of a thin wood fibre board on scale 1:20, a wind indicator, and cup anemometers by Hydrometpribor Plant.

The gadgets were fixed in typical points of the cross section and adjacent area, as well as in the longitudinal direction along the street axis. Moreover, to study the change of the wind speed in vertical direction, the anemometers (wind indicators) were fixed on a mast at the elevations of 0,075, 1, 2, 3 and 4 m. The results of the synchronous measurements proved a common distribution of the wind speed at different elevations to the logarithmic velocity profile.

In the experiment, the street width and the housing density were changed along the red lines $\rho$ determined by the formula:

$$\rho = \sum l_i / L,$$

where $\sum l_i$ – length of buildings along the outline of the street section; $L$ – length of the street section perimeter along the building lines.

To interpret the obtained dependencies $\tau_3$ from the geometric parameters of the street cross section, an index [14] was used calculated by the formula:

$$z = b / H,$$

where $b$ – distance from the first wind exposed facade to the street axis in meters.

The experimental technique is given in details in paper [21].
The field studies were made in three big cities in the III climate area. % on an annual basis. The share of traffic activities in the air contamination in urban environment by CO, NO$_2$ and C$_n$H$_m$ makes 85…95 %. All year seasons were covered by the observations. More than 300 sections of main streets were studied having general city and district status.

In details, the field studies technique is presented in a separate study [22].

3. Results and discussion

The coefficients of the wind speed reduction were calculated by the readings of instruments $\tau_3$ at observation points under the impact of the most typical types of building on the streets of various width (Table 1). To analyze the results of simulating the aeration regime of city streets, correlation graphs were built (Figure 1).

| Site development type | Site development parameters | Values $\tau_3$ depending on the criterion $z$ |
|-----------------------|----------------------------|-----------------------------------------------|
|                       | $l_a^a$ | $L_b^b$ | $\rho$ | 1.3 | 1.8 | 2.3 | 2.8 | 3.8 | 4.8 | 5.8 |
| 1 – 0.36              |          |        | 0.80 | 0.84 | 0.89 | 0.95 | 0.92 | 0.95 | 0.99 |
| 2 – 0.53              |          |        | 0.65 | 0.71 | 0.70 | 0.68 | 0.74 | 0.89 | 0.98 |
| 2 – 0.70              |          |        | 0.80 | 0.86 | 0.85 | 0.84 | 0.86 | 0.94 | 0.99 |
| 2 – 0.79              |          |        | 0.80 | 0.86 | 0.85 | 0.84 | 0.86 | 0.94 | 0.99 |
| 4 – 0.84              |          |        | 0.80 | 0.84 | 0.82 | 0.82 | 0.73 | 0.71 | 0.87 | 0.96 |
| 4 – 1.00              |          |        | 0.80 | 0.84 | 0.82 | 0.82 | 0.73 | 0.71 | 0.87 | 0.96 |
| 4 – 0.90              |          |        | 0.80 | 0.84 | 0.82 | 0.82 | 0.73 | 0.71 | 0.87 | 0.96 |
| 4 – 1.00              |          |        | 0.80 | 0.84 | 0.82 | 0.82 | 0.73 | 0.71 | 0.87 | 0.96 |

$^a$building length along the lines of development control.  
$^b$value of spacing between buildings.  
$^c$length of residential section (15 m).  
$^d$length of street section ($L=20l$).

Figure 1. Dependency of the air flow transformation rate by velocity $\tau_3$ above the carriageway under the impact of development with the density $\rho$: 1 – 0.36; 2 – 0.53; 3 – 0.70; 4 – 0.54; 5 – 0.79; 6 – 0.84; 7 – 1 (canyon). a – flow-over along the envelope line; b – turbulent jet flow; c – isolated flow.
The study results show that the aeration regime for the street space is controllable by changing building length along the development line, spacing between them and the street width. The incoming air flow velocity and direction – the initial wind is of prime importance.

The maximum preservation of the air flow velocity in the crosswise direction on streets of various width (Curve 1 on Figure 1) is reached at the infill construction \((l_0=l)\) with considerable spacing between buildings in rows \((l_0\geq 30\ m)\), when development and street width have little impact on their aeration regime. However, the approaching of buildings along the building line results in the air flow transformation by the velocity. By the location of curves 2 and 3 in Figure 1, it is seen that with equal distance between buildings \((l_0=15\ m)\) in the streets with the width \(B=(2…4)H\), the values of wind speed reduction with one-section development are by 10…15 % higher if compared to two-section one \((l_0=2l)\). From the comparison of curves 1 and 2, it follows that the wind velocity can be reduced by 15…30 % in the streets of equal width by cutting the distance in half between building of the infill (point) type. This can be realized with the shift of building axes in a row.

Under such conditions, the “breaking” effect of the development manifests itself by the flow energy dispersion in many horizontal vortexes pairs of small scale in reverse rotating direction occurring when air flow envelopes short gable facades. With the increase of the number of these vortexes in proportion to the frontal development breaking their impact on the wind velocity reduction above the carriageway becomes stronger than with the main air flow enveloping buildings from above.

The lateral vortexes can also influence a character of distribution of pollutants in the development [17]. Research by Heudisch and Dabbert showed [23] that the advection flows occurring near building corners result in the formation of high pollution zones at the middle of their downwind facades.

With decreasing number of breaking in the development, their impact on the wind velocity reduction becomes less relevant. Moreover, the development densification along the street length with formation of canyons is accompanied by back circulation of the main flow [17, 24]. In our experiment, the elements of such a movement appear with the street width \(B=(1…2)H\) in proportion to the transition from the infill development to the 2–3 section one (Curves 3–5 in Figure 1). The vortex between buildings acquires a stable character with the dense development of the street (Curves 6, 7 in Figure 1). In this case, there is an amalgamation of separate vortex zones formed by buildings when enveloped by air flow into a single area of the closed circulation of air masses encompassing the whole street environment.

With the multi-sectional development of streets \((l_0\geq 2l)\), the width \(B=(1…3)H\) or with \(z=1.2…2.2\), there is an increase of wind in the canyon. In this case, the closed vortex flows occurring between opposite buildings when enveloped by crosswise wind from above overcome the resistance of few lateral vortexes. Moreover, the frontal development acts here as a stimulator of the longitudinal movement of the air flow in the street environment. With slight deflection of the wind direction from the street axis, its kinetic energy is channelized along the buildings by the frontal development, and the velocity vector acquires a helicoidal trajectory [13, 14]. With the maximum density of the development \((l_0=L)\) \(t_3\) reaches the value of 1.07 (Curve 7 in Figure 1). This corresponds to the similar studies where the maximum wind speeds were stated with \(B=(2…3)H\) due to the stable vortex of the cylindrical form [19].

As it follows from the studies by Uehara et al. [25] connected with the visualization of the air flow, the strongest and most stable vortex between buildings is formed with \(B=(1…2)H\), in our experiment this corresponds to the parameter \(z=1.3…1.8\). According to the classification of air flow movement regimes in a development formulated by Bike and Kim [18], the main air flow is in the regime of flow-over “along the envelope line” (a in Figure 1) at this street width. The closed circulation of admixtures (pollutants) occurring in street canyons results in the increased air pollution.

In this regime of enveloping, the HG concentrations are the highest at the down-wind walls of the first row of buildings than at the windward walls of the second row of buildings since the velocity of the upriving part of the flow at the windward building becomes lower than the velocity of the descending part at the down-wind building. This happens due to the loss of kinetic energy of the wind flow when overcoming the opposing convective counter-flow at the windward building as well as due
to obstructions in the form of “micro-roughnesses” – elements of plant arrangement, beautification (improvement) (trees, bushes, lawns, side-slopes, head-walls) and protruding parts of buildings (balconies, bay windows and others).

With $B>3H$, according to [26], the vortex between buildings acquires an elliptic shape. There, a modulated reduction of the rotation velocity has been observed as seen by the curve run in Figure 1. Then, with some critical values of $z$ within 2.3…2.5, there is a discontinuity of the single circulation zone between the buildings with the formation of two vortices. Behind the first building, there appears a closed vortex with low pressure, and in front of the down-wind building - in the back-flow zone a re-circulation vortex flow of high pressure is formed. With these vortices interaction, at the values of $z=2.3…3.8$ or $B=(3…6)H$, a subsequent reduction of the wind velocity at the carriageway to the local minimum is observed on the streets with various development types. In the given case, a turbulent jet enveloping by the air flow is observed around the side-by-side buildings [18] (b in Figure 1).

With the subsequent increase of the street width $B$ within the range (6…10)H, the wind velocity above the carriageway increases gradually and with $B>10H$ or $z>6$, the air flow acquires features of the isolated flow-over of buildings [18] (c in Figure 1). At that, the regeneration of the initial velocity and movement path of the main air flow occurs between the vortices of low and high pressures and behind the down-wind building on the cross section of the street.

Thus, the probability of back circulation of pollution on the streets can be absolutely eliminated with their width of $B>6H$ or with the application of more sporadic construction with variable number of floors and the shift of buildings in rows. When constructing buildings with minimum number of residential sections, the street width does not have a meaningful effect on the wind transformation by speed and direction. Therefore, to reach a more efficient air exchange in the streets, it is needed to maximally limit a number of development sites to be under construction by multi-sectional frontal buildings.

According to the numerical experiments by Kim and Bike [17], a geometric criterion $H/B$ – relation of the medium height of a building to the distance between them along the development lines has a considerable effect on the efficiency of emission dispersion in street canyons. By our observation results, the degree of gas pollution on the main streets sections connected with the development with the ratio of $H/B=1$ exceeds more than two times the level registered on sites without development, when $H/B=0$ [15]. The optimum size of the cross section for street canyons correspond to the value of the parameter $H/B$ not more than 0.3 on the assumption of the least air pollutions.

In canyons with narrow width without breaks between buildings, a sharp reduction of the wind velocity is registered if some critical values of $H/B$ are exceeded, it is connected with the division of a single vortex in a vertical direction. At the convergence of building rows, there are at first two vortices and then three ones with the opposite rotational directions [18]. At $H/B=1.5…2.5$ in the lower and upper parts of the canyon, there appear two vortices. In the narrower canyon (when $H/B≥3.5$), there are three vortices in the low, middle and upper parts.

With increase of the depth of canyons and the number of vortices, the HG concentrations at the carriageway are also increased. In this case, the wind flow above the roofs in the regime of enveloping “along the envelope curve” prevents the ejection of ingredients from the street environment. According to the numerical studies by Lee and Park [27], the most efficient pollutants are blown out of the shallow canyons with one vortex. In deeper canyons with two vortices, the drifting of ingredients from the source upwards occurs due to diffusion. As seen by the curves slope 1—6 in Figure 1, the necessary air motion above the carriageway and the air quality can be provided as a result of breaking between buildings along the development line in the narrower streets at the values of $z<1$.

4. Conclusions

By the results of research it is possible to draw the following conclusions.

1. In large and largest cities, the maximum onetime MAC (maximum allowable concentrations) of toxic components in vehicle emissions on main streets are provided by architectural methods – choice of the street location and the development techniques with the possibility of adjustment of their
aeration regime within the comfortable weather classes determined by the combination of the wind velocity, temperature, and air humidity.

2. The most efficient dispersion of vehicle emissions on city streets with the dense frontal development is provided with the ratio of the height of buildings $H$ to the street width $B$ along the development lines not more than 0.25…0.3. Herewith, the design considerations about the width of main streets of various categories and the development density with the potential for using multi-sectional buildings are to have sanitary basis using the standard practice for the calculation of aeration and air pollution.

3. The probability of appearance of the closed pollutants circulation on the streets hampering the air exchange with the crosswise wind direction can be absolutely prevented when their width along the development lines is $B>6H$. It is also possible to apply the techniques of free planning with variable numbers of floors and the location with angular configuration to the development line, with the setback from the carriageway, shifting in rows and the configuration change in plan. Non-residential buildings – trade and services are to be located in the first row from the carriageway, as well as garages and other objects with temporary stay of people. These development techniques enable to prevent the cellular nature of air pollution levels on the objects of transportation infrastructure, to localize the vehicles emissions to the adjacent areas and to accomplish the zoning of residential units by the air environment quality with the more comfortable location of house construction, children's pre-school and general education institutions.

4. Under the conditions of the historically formed development in the narrow streets, the required air quality can be supported by adjusting the transportation network cutting the traffic density in some directions, eliminating traffic jams and providing high speeds of traffic flows using transportation organization and regulation methods due to the limited planning and reconstruction measures for deconcentration of the development.

5. In cities with the prevailing low wind velocities in the summertime and no-wind conditions, it is needed to correctly choose a location of main streets and to achieve the space planning decisions of the city environment providing a maximum preservation of the initial wind velocity, stimulating the natural ventilation of residential zones and public spaces. It is also necessary to use reclamation impact of the relief and water bodies on the micro-climate and the air quality taking into account valley winds and breeze circulation.

5. References

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