Aeration mode of main streets in high-density development

V V Balakin, A V Antyufeyev, V F Sidorenko
Institute of Architecture and Civil Engineering of Volgograd State Technical University, 1, Akademicheskaya Street, Volgograd 400074, Russia
E-mail: balakin-its@yandex.ru

Abstract. The aeration mode of urban areas in design practice is established for different geographic regions depending on the initial wind speed taking into account the human thermal state and the quality of atmospheric air. The purpose of the research is to assess the design, building and geometric parameters of the city streets influence on the airflow transformation and the atmospheric air pollution level. Based on the research results in full-scale conditions and on residential units’ models, the features of the main streets aeration mode formation and the gas contamination level were revealed. It was found that the variations in wind speed and the distribution of pollutants in street canyons with a change in their width are connected with the formation of buildings flow regimes: along the envelope, turbulent-jet and isolated ones. The planning conditions that contribute to the formation of a stable vortex connected with the closed circulation of impurities in the street canyons were determined. Town-planning hygienic recommendations are given to regulate the streets aeration regime in order to ensure standards for the content of residential units’ atmospheric pollution in the air, to protect urban residents from cold strong winds or to maintain the initial wind speeds in residential units.

1. Introduction
In town planning design practice, the urban areas aeration mode was established as the result of a comprehensive assessment of the environment quality, taking into account the temperature and humidity criteria that determine the thermal state of a person, as well as the atmospheric air dust and gas contamination. In addition, information on the average annual wind speeds distribution in the construction is used to assess the built-up areas wind energy potential and the selection of locations for small wind power plants [1-3].

The town planning means for regulating the aeration mode are indicated in the theoretical model of F.L. Serebrovsky [4], according to which the transformation of the air flow at any point i of the city territory occurs in the lower tier of the air basin:

\[ u_i = u_0 \cdot \tau_1 \cdot \tau_2 \cdot \tau_3 \cdot \tau_4, \]

where \( u_0 \) is the wind speed at the weather station; \( \tau_1, \tau_2, \tau_3, \tau_4 \) are the transformation coefficients that take into account, respectively, the effect of large terrain unevenness, whose height is more than twice the height of the site development of the average height – the hyper-roughness (\( \tau_1 \)), the site development itself (\( \tau_2 \)) and the site development elements (\( \tau_3 \)) – the macro-roughness and elements of improvement (\( \tau_4 \)) – microroughness.

In town planning decisions, it is necessary to make full use of the means for regulating the aeration mode, distributed in the atmosphere different layers: at a macro level (up to 200 m) – high-storied site
developments (tower type), meso-level (up to 25 m) – high-storied, medium-storied and partially low-storied site developments and micro-level (up to 3 m) – high-storied, medium-storied, low-storied site developments and elements of landscaping and gardening [2]. At the same time, the choice of the best methods for planning, building and improving the residential units in different natural and climatic conditions has its own specific features.

The role of the site development in the formation of the aeration regime and the level of air pollution in city streets is manifested, on the one hand, in the limitation of the surface area through which the exhaust gas is dispersed into the surrounding area, and on the other hand in the variation of wind speed. The wind speed influence on the concentration of the cities exhausted gases leading component – carbon monoxide (CO) is characterized by a correlation ratio \( r \) within 0.7...0.8. It is commensurate with the effect of traffic intensity \( (r = 0.85...0.9) \) and the ratio of the site development height to the street width \( (r = 0.6...0.7) \) [5].

The street main feature is an elongated form in the plan with a characteristic composite combination of site development elements of different number of storeys and lengths, which degree of influence on the airflow is taken into account, according to (1), via the partial transformation coefficient \( \tau_3 \). In its turn, these elements are fragments of more complex building layouts in residential areas, forming a “poorly streamlined aerodynamic macro-roughness”, taken into account by the transformation coefficient \( \tau_2 \), within which “vortex, jet and other more complex air flows” arise [6].

Modern building of city streets, especially in city centers, is characterized by an increased density and predominance of frontal multi-sectional buildings with all kinds of insertions between them, forming street canyons, which represent a great ecological problem, from the point of view of insolation, aeration and air pollution [7-10].

To estimate the streets planning methods and geometric parameters influence on the airflow transformation and the atmospheric pollution concentration, first of all it is necessary to establish the wind speed functional dependencies on the street width and the construction density. It is important to determine the planning conditions that facilitate the unification of the vortex zones formed by individual buildings in the course of their flow by the wind into a single region of air masses closed circulation, covering all the street space and leading to increased gas contamination of atmospheric air in the residential unit.

2. Methods used in the experiment

In accordance with the goal, a series of anemometric surveys using flat-roofed residential buildings made from a thin wood plate at a scale of 1:20 was performed on a large-scale simulation site, which is an open, level area of 100x150 m, covered with asphalt (Figure 1).

Cup-type anemometers MC-13 at a height of 75 mm made wind speed measurements. The duration of exposure was set within 1 to 2 minutes, depending on the strength of the wind. Several operators switched on and off the devices, each of them moved according to observation points in a certain sequence. The required number of wind speed repeated measurements was established as the result of test measurements. At a prescribed accuracy of 5%, there were 7 required repetitions.

To determine the air flow initial direction and to study the wind speed distribution along the height at the edge of the platform, a mast with an anemorumbometer and anemometers fixed at heights of 0.075, 1, 2, 3 and 4 m was installed. The results of synchronous measurements confirmed the correspondence of the wind velocities distribution at different altitudes to the logarithmic profile.

The buildings were arranged along the center of the site from separate residential sections with a ratio of height, length and width of 1: 0.9: 0.8 in a 300 m street stretch. With such a change in the linear dimensions of geometric bodies in the form of plates, the Reynolds number varies over a wide range \( (10^3<R_e<10^6) \) and self-similarity is observed when they flow around the airflow. The angle between the direction of the wind and the longitudinal axis of the streets was close to 90° during the experiment.
Figure 1. The scheme of points for measuring wind speed along the axis and on transverse sections of the street. B is the width of the street in the building lines, m. The numbers on the diagram are the numbers of the observation points.

In the tested models, the types of buildings, the size of the spacing between them and the width of the streets in the building regulation lines varied. The fraction of spacings in the frontal building or the degree of its blow-through by a transverse wind was established by the formula:

$$\delta = 1 - \frac{\sum l_i}{L_p},$$

where $\sum l_i$ is the total length of buildings along the perimeter of the street section; $L_p$ is the length of the perimeter of the street section along the lines of building regulation.

An important parameter widely used in studying the characteristics of airflow in street canyons is the ratio of the buildings height in opposite rows to the distance between them along the facing the street facades ($H/B$) [11]. When winds flows parallel buildings, their width also plays an important role, which the conditions for the formation of a common circulation zone depend on [12]. Therefore, the geometric criterion $z$ proposed by E.Yu. Retter [6] was adopted in the experiment as a generalizing geometric parameter characterizing the dimensions of streets along the cross-section:

$$z = \frac{b}{H},$$

where $b$ is the distance from the windward wall of the first downstream building or leeward facade of the second building upstream to the centerline of the street.

If for the class of buildings used in the experiment

$$b = 0.8H + 0.5B,$$

then, according to (3)

$$H/B = (2z - 1.6)^{-1}.$$  

3. Results and discussion
The coefficients of airflow transformation at the speed under the influence of the most characteristic building types are given in the Table 1, and are also given in the form of correlation graphs in the Figure 2 and Figure 3.
Table 1. Wind speed transformation coefficients $\tau_3$ on urban streets under the influence of site development.

| Site development type | Site development parameters | $\tau_3$ depending on the criterion $z$ |
|-----------------------|----------------------------|---------------------------------------|
|                       | $l_a^b$ $l_b^a$ $\delta$ | 1.3 1.8 2.3 2.8 3.8 4.8 5.8          |
| Infill with spacing of 30 m | $l_a^b$ | 0.64 0.80 0.84 0.89 0.95 0.92 0.95 0.99 |
| Infill with spacing of 15 m | $l_a^b$ | 0.47 0.65 0.71 0.70 0.68 0.74 0.89 0.98 |
| Two-sectional with spacing of 30 m | $l_b^a$ | 0.46 0.80 0.86 0.85 0.84 0.86 0.94 0.99 |
| Two-sectional with spacing of 15 m | $l_b^a$ | 0.30 0.77 0.84 0.82 0.73 0.71 0.87 0.96 |
| Three-sectional with spacing of 15 m | $l_b^a$ | 0.21 0.85 0.94 0.84 0.94 1.00 0.99 1.00 |
| Four-sectional with spacing of 15 m | $l_b^a$ | 0.16 1.02 1.02 0.95 0.98 0.93 0.98 1.00 |
| Multi-sectional without spacing | $L^c$ | 0 0 0.82 1.04 0.91 0.91 0.95 0.95 0.97 |

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

According to the table 1 and the nature of the curves in the Figure 2, it can be seen that under the conditions of varying building density, it is possible to regulate the aeration mode in the street space within wide limits. Maximum preservation of the initial wind speed is achieved with significant discontinuities between buildings ($l_0 \geq 30m$), when the aeration mode is insignificantly dependent on the street width (curve 1 in the Figure 2). However, the reduction in the distance between buildings in a row for point and two-sectional frontal building up to 15 m results in a decrease in wind speed.

As the length of buildings increases, the spacings between them proportion influence on the drop in wind speed on the streets is smoothed out. The few open areas between buildings already have a slight influence on the wind speed decrease in the street space (curves 5, 6 in the Figure 2).

Moreover, the increase in the frontal site development density along the length of the street is accompanied by the formation between the buildings of the airflow stable reverse circulation and an increase in its speed [8, 13]. In this case, when meeting a leeward building, part of the stream enters the canyon, reaches the surface of the earth and is directed toward the windward building, compensating for the loss of air captured from the upper part by the main airflow [14]. This movement signs are detected during the transition from point-to-point site development to 2-3-sectional frontal building with spacings between buildings of 15 m (curves 2, 3 and 5 in the Figure 2), as well as its compaction in a row (curves 3 and 4 in the Figure 2). Moreover, the reverse circulation is most pronounced with insignificant discontinuities in the building or their absence. In this case, with the width of the street $B = (1...3)H$ or $z = 1.2...2.2$ with multi-sectional ($l_0 \geq 2l$) and continuous frontal building ($l_0= L$), some wind speed increase (curve 6, 7 in the Figure 2).

This fully corresponds to the results of similar tests [11, 15-17], when significant gradients of wind speed were detected near the walls of buildings located at a distance $B = (2...3)H$ or at $z = 1.5...2.3$ due to a stable vortex. With this street width the vortex between the buildings has a circular cylindrical shape and the rotation maximum speed.

As Uehara and others showed in their paper [18], where an airflow was visualized, a strong stable cavity vortex flow is formed at a ratio of the width from the building to the building and the height of the street canyon $B/H = 1...2$, which corresponds to $z = 1.3...1.8$. Under these conditions, the vortex between buildings is extremely stable [19]. However, it should be borne in mind that such planning
situation on the streets can cause cases of dangerous air pollution due to the impurities closed circulation in the street, stimulated by constrained frontal site development.

Figure 2. Regimes of airflow around buildings and the change in the coefficient of wind transformation at speed $\tau_3$ over the carriageway at the altitude of 1.5 m, depending on the parameter $z$, with a fracture in the building $\delta$: 1 – $0.64 (l_b = l; l_0 = 2l)$; 2 – $0.47 (l_b = l; l_0 = l)$; 3 – $0.30 (l_b = 2l; l_0 = l)$; 4 – $0.46 (l_b = 2l; l_0 = 2l)$; 5 – $0.21 (l_b = 3l; l_0 = l)$; 6 – $0.16 (l_b = 4l; l_0 = l)$; 7 – 0 ($l_b = L_0 = 20l; l_0 = 0$). a is the envelope flow regime; b is the turbulent-jet flow regime; c is the regime of isolated flow

In the indicated range of values of $z$, the wind transformation when encountering the site development acquires the signs of the envelope flow regime (a in the Figure 2), according to the classification given in Oka [20], Hunter et al. [21], Sini et al. [22], Grimmond et al. [23] papers. In this flow regime at $H/B = 1$, according to the pollutant concentration fields in the street canyon, the gas contamination highest level is noted near the leeward side of the windward building, where there is a strong ascending flow that has passed through the source of contamination [11].

For $B>3H$ ($z>2.3$) the shape of the vortex becomes elliptical [19]. According to our data, this happens with the airflow some slowing down (Figure 2). In the $z$ range from 2.3 to 3.8 or $B$ from 3 to 6$H$ for specific types of the site development, the wind speed in the streets, according to the graphs in the Figure 2, reaches a local minimum.

If the criterion $z$ increases beyond its critical value in the range from 2 to 2.5, which determines the position of the change points in the curvature of lines 1-7 in the Figure 2, the main flow is separated, when a winding building forms a low-pressure recirculation vortex, and on the leeward building front wall the elastic closed high-pressure vortex flow appears. As the result of the interaction of these vortices, the wind speed at the axis of the street decreases. At the same time, the incoming airflow turns into a turbulent-jet flow past the elements of the roughness (b in the Figure 2). On streets with a dense buildings arrangement along the building lines (curves 5-7 in the Figure 2) this occurs at $z>2$ or $H/B<0.42$. According to the Baik and Kim’s numerical “experiments” using a two-dimensional airflow system, turbulent-jet flow occurs at $H/B = 0.4$ [11].

With further increase in the street width, the wind flow regains its trajectory after meeting with each of the buildings. At $z>3.8$ or $B>6H$, the relative wind speed increases smoothly in streets with different building density, and at $z>6$ or $B>10H$, the airflow becomes an isolated flow around separate buildings (c in the Figure 2). At the same time, the maximum speed of air movement in the street space is marked between the low and high-pressure recirculation vortices that appear correspondingly behind the first building and in front of the leeward building.

A similar result was obtained in the research of industrial air pollution, where the length of a single circulation zone between two parallel buildings is limited by a critical distance of 10$H$ [15]. When this value is exceeded, this zone is divided into two separate zones – the wind zone of the first building
upstream and the zone of the second building support. After that, industrial buildings should be regarded as stand-alone ones.

Thus, the danger of increased atmospheric air pollution in city streets connected with closed circulation can be eliminated by using single-sectional buildings with large discontinuities (curve 1 in the Figure 2) or with an increase in the width of canyon $B$ larger $(9...10)H$ (at $z=5.3...5.8$). The possibility of a closed air flow circulation in the street space, which prevents air exchange at transverse, mainly prevailing type of wind, and also eliminates the possibility of using more free methods of building planning with a limited number of multi-sectional buildings. When adjusting the layout methods in the design practice, when the buildings are located along the streets, it is possible to shift their axes in a row with an increase in the indent from the roadway at an angle to the building lines, alternation of storeys and configuration changes in the plan. In these cases, the site development influence on the wind speed in street space is leveled, and a closed vortex between buildings collapses.

At the same time, by changing the spacing amount and number in the frontal building, it is possible to regulate the street space aeration mode. As can be seen from the slope of curves 2 and 4 in the Figure 2, with an almost identical spacings value, the indicators of wind speed decrease in point (single-sectional) site development are $15...20\%$ higher than for the site development of a street with two-sectional buildings. And according to the comparison of curves 1 and 2 in the Figure 2, it is possible to reduce the wind speed to $30\%$ by reducing the distance between buildings in dotted building by half with the width of the street $3H$. This is due to the peculiarities of the flow around the winds of point type buildings.

With the increase in the “perforation” of continuous frontal site development, the increase in the number of small-scale horizontal vortices occurs at the windward buildings rear lateral corners. They can occur regardless of the street width under different flow conditions – along the envelope, turbulent-jet, isolated ones. Such multiple pairs of rotation opposite direction transversal vortices that arise in the end parts of buildings in case of spot construction can introduce a more noticeable inhibitory influence on the main airflow than the vortex flows formed when flowing from above the buildings.

The lateral closed vortices play an important role in the distribution of pollutants in the site development [8]. Khoidish and Dabbert showed [24] that advection flows from the corners of the building to its center, resulting from paired lateral vortices, cause the flow of polluted air to converge with the formation of atmospheric pollution high concentration areas in the middle of the building.

By the nature of the curves in the Figure 3, it can be seen that the building blowdown degree influence on the decrease in wind speed is most significant at $\delta$ in the range from 0.3 to 0.5 (curves 1-5). At the same time, the values $\delta=0.5...1.0$ correspond to the sections of the curves that characterize the gradual weakening of this building property as it decomposes.

The spacings ratio in building influence on the drop in wind speeds is also smoothed as the length of the buildings in the raw increases. The resulting decrease in $\delta$ from the optimal values $(0.3...0.5)$ to zero is accompanied by the formation of a stable vortex between buildings on the street cross-section and the increase in wind speed (curve 6 in the Figure 3). In this case, closed vortex flows arising between multi-sectional buildings when flowing over them by transverse wind, overcome in their rotation insignificant obstacles in the form of lateral vortices.

In case of limiting building compaction, the initial wind speed above the carriageway increases, when $\tau_3$ reaches the value $1.07$ (curve 7 in the Figure 2). This phenomenon is connected with an active effect on the rotational speed of the eddy flow of frontal building. The continuous two-sided building appears here as a kind of stimulator of the airflow longitudinal movement in the street space – in case of deviation from the perpendicular, the main airflow is directed along the street, acquiring a helical trajectory [4, 6].

For $z<1$, or for some critical $H/B$ values, there is a sharp drop in wind speed in street space (curve 7 in the Figure 2) with no spacings in the building line. In this case, as the buildings converge in opposite rows of site developments, a single circular cylindrical vortex divides into two, and then into three vortices with the opposite direction of rotation [11].
Figure 3. Dependence of ratio of airflow velocity transformation above the carriageway from the spacings ratio \( \delta \) between buildings in the building line at the values of \( z \): 1 – 1.3; 2 – 1.8; 3 – 2.3; 4 – 2.8; 5 – 3.8; 6 to 5.8.

At \( H/B = 1.5...2.5 \), two vortex flows appear in the upper and lower parts of the street canyon. And when the \( H/B \) reaches the value of 3.5, three vortices appear in the upper, middle and lower part of the narrow space between the buildings. The threshold value of the \( H/B \) for the transition of the airflow from one- to two-vortex regimes lies in the interval 1...1.5, and from two- to three-vortex regimes is within the range of 3...3.5 [11]. In the diagrams of the figure 2, these intervals of the parameter \( H/B \) correspond to the values of \( z \) from 0.9 to 1.3, at which there is a sharp decrease in the wind transformation coefficient in speed in the lower part of the canyon.

With the decrease in the street width, along with the decrease in wind speed, the nature of pollutants distribution changes when the airflow moves from one-vortex to two- and three-vortex motion. Here we can cite the results of using a two-dimensional numerical model [11], where a regularity with pollutants dispersion in the narrowest canyons in the streets, where two or three vortices are formed, is established with a one-vortex motion. It follows that a higher (lower) concentration of ingredients at different levels of the canyon is observed where the airflow moves up (down), or at the leeward (windward) building at the bottom and at the windward (leeward) building at the top of the canyon.

In canyons of small width, the fresh air inflow from the upper part to the lower part of the canyon is difficult, since most of the flow, which is in the flow around the envelope, does not enter the space between the buildings. Simultaneously, the wind flow over the buildings roofs prevents the pollutants dispersion from the street space, but only supports the vortex flow rotation, sending it the impulse of movement. Therefore, as the canyon depth and the vortices number increase, the car exhaust concentration in the carriageway increases. As follows from the Lee and Park’s numerical model [25], pollutants are more efficiently dispersed from a shallow canyon where there is one vortex flow, whereas from a deep canyon where two vortex flows are formed, the transfer of ingredients from the lower region to the upper one occurs mainly by diffusion.

In such conditions, as can be seen from the location of curves 1-6 in the Figure 2, the necessary air mobility and air exchange in the street space can be provided only through spacings in the perimeter site development, and their number and width play a leading role in the narrowest streets aeration.

4. Summary and conclusions
In each geographic area, when choosing planning solutions and ways of building settlements, in order to protect their inhabitants from strong winds during winter and to increase the microclimate’s favorable climate in the warm season, it is worthwhile to work out a consensus in relation to the aeration regime. In order to minimize the damage to the population health, in town planning practice it is necessary to apply an integrated approach to assessing the residential environment quality, taking
into account the main environmental factors. It is also important to predict the nature of the pollutant concentrations distribution in the various widths city streets canyons, to take into account the storeys amount and the density of site development influence on their aeration regime.

Environmental assessment of design solutions is of particular importance in the modernization of transport systems in large and major cities with historically formed overcrowded site developments. Here on the limited width main streets the gaseous atmosphere of the car exhaust in combination with the leading factor of the microclimate – the wind regime, because there is a reverse functional connection between them, is the dominant environmental factor.

The parameters of airflow transformation in flowing buildings and the variety of planning and building methods [1,2,4,6,26,27] given in this paper open up wide possibilities for regulating the aeration mode of city streets in order to prevent their gas contamination and dustiness, to protect adjacent residential areas from cold strong winds or maintaining the initial wind speeds for their effective ventilation.

References

[1] Myagkov M S 2013 An example of microclimatic conditions modeling for Volgograd Vestnik VolgGASU.Seriya: Stroitelnstvo i arkhitektura 32(51) 220–8
[2] Egorychev O O and Dunichkin I V 2013 Questions of urban environment microclimate forecasting for estimating the building wind energy potential Vestnik MGSU 6 123–31
[3] Titkov V V, Bekbayev A B, Munsyzbai T M and Shakenov K B 2018 Construction of autonomous buildings with wind power plants Magazine of Civil Engineering 4(80) 171–80
[4] Serebrovskiy F L 1985 Aeration of Inhabited Areas (Moscow: Stroiizdat) p 170
[5] Balakin V V 2008 Methodology for assessing air pollution on the city's road-traffic network Problemy avtomobilno-dorogogo kompleksa Rossii: Materialy V mejdnarodnoy naychnotekhnicheskoy.conf.(Penza May 21–23 2008) (Penza: PGYAS) 2 184–9
[6] Retter E I 1984 Architectural and Construction Aerodynamics (Moscow: Stroiizdat) p 294
[7] Addison Paul S, Currie John I, Low David J and McCann Joanna M 2000 An integrated approach to street canyon pollution modeling Environmental Monitoring and Assessment 65 (1–2) 333–42
[8] Kim Jae-Jin and Baik Jong-Jin 1999 A numerical study thermal effects on flow and pollutant dispersion in urban street canyons Journal of Applied Meteorology 38(9) 1249–61
[9] Assimakopoulos V D, ApSimon H M and Moussiopoulos N 2003 A numerical study of atmospheric pollutant dispersion in different two-dimensional street canyon configurations Atmospheric Environment 37(29) 4037–49
[10] Kameneckiy E S 2008 Concentration of pollutants in the street canyon with different heights of houses on the sides of the street Izvestiya VUZov. Severo-kavkazskiy region. Seriya: Estestvennye nauki 6(148) 31–5
[11] Baik Jong-Jin and Kim Jae-Jin 1999 A numerical study flow and pollutant dispersion characteristics in urban street canyons Journal of Applied Meteorology 38(11) 1576–89
[12] Hassan A A and Crother J M 1998 Modelling of fluid flow and pollutant dispersion in a street canyon Environmental Monitoring and Assessment 52 281–97
[13] Nuterman R B and Starchenko A V 2005 Air pollution spread modeling in a street canyon Optika atmosfery i okeana 8 649–57
[14] Uehara Kiyoshi, Murakami Shuzo, Oikawa Susumu and Wakamatsu Shinji 2000 Wind tunnel experiments on how thermal stratification affects flow in and above urban street canyons Atmospheric Environment 34(10) 1553–62
[15] Nikitin V S, Maksimkina N G, Samsonov V T and Plotnikova L V 1980 Aeration of industrial sites and areas adjacent to them (Moscow: Stroiizdat) p 200
[16] Chan T L, Dong G, Leung C W, Cheung C S and Hung W T 2002 Validation of a two-dimensional pollutant dispersion model in an isolated street canyon Atmospheric Environment 5 861–72
[17] Jicha Miroslav, Pospisil Jiri and Kftolicky Jaroslav 2000 Dispersion of pollutants in street canyon under traffic induced flow and turbulence Environmental Monitoring and Assessment 65(1–2) 343–51

[18] Uehara K, Murakami S, Oikawa S and Wakamatsu S 1998 Wind tunnel evaluation of flow fields within streets canyons with thermal stratification Journal Architecture, Planning and Environmental Engineering (Transaction of AIJ) 510 37–44

[19] Tomson N M 1947 Aeration of urban area (Moscow: Izd. AMN SSSR) p 122

[20] Oke T R 1988 Street design and urban canopy layer climate Energy and Buildings 11 103–13

[21] Hunter L J, Watson I D and Johnson G T 1990/91 Modelling air flow regimes in urban canyons Energy and Buildings 15–16 315–24

[22] Sini J F, Anquentin S and Mestayer P G 1996 Pollutant dispersion and thermal effects in urban streets canyons Atmospheric Environment 30(15) 2659–77

[23] Grimmond C S B and Oke T R 1999 Aerodynamic Properties of Urban Areas Derived from Analysis of Surface Form Journal of Applied Meteorology 38(9) 1262–92

[24] Hoydysh W G and Dabberdt W F 1988 Kinematics and dispersion characteristics of flows in asymmetric street canyons Atmospheric Environment 22 2677–89

[25] Lee I Y and Park H M 1996 Parametrization of the pollutant transport and dispersion in urban street canyons Atmospheric Environment 28 2343–9

[26] Dmitriev M G, Kitrosskii N A and Alperin V Z 1971 Cities’ highways air toxicity dependence on traffic intensity, height and constructionsdensit Izvestiya vuzov 3 120–4

[27] Manual on the wind conditions assessment and regulation for residential buildings 1986 (Moscow: Stroiizdat) p 59