Numerical research of the influence of wall heating on the turbulent flow pattern in an idealized street canyon

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Abstract. The work is aimed at the study of the flow structure and the distribution of impurities in an idealized street canyon, depending on the intensity of heating of the street canyon walls.

1. Introduction

The relief of the modern city is formed by structures and surfaces made of concrete and asphalt. These materials have a low heat capacity, which causes significant daily changes in surface temperature. Therefore, it is important to study the influence of temperature heterogeneity on the air circulation dynamics in a street canyon, which is a basic element of the architecture of a modern city.

A lot of research works are devoted to the solution of this problem. In [1], the authors carried out a study of the influence of several parameters on the flow structure in a street canyon. The influence of wind velocity and buoyancy forces caused by temperature differences between the environment and one of the walls of a street canyon heated by solar radiation was studied. The value of the Froude number \( Fr = \frac{U_{ref}^2}{gh \left( T_W - T_{ref} \right) / T_{ref}} \), which characterizes the influence of buoyancy forces on the motion of a continuous medium, was used as a variable parameter. It was possible to have different effects on the flow pattern inside the canyon by changing the wind velocity, the temperature difference and/or the canyon geometry. The authors carried out simulations with 25 different cases of the Froude numbers. According to the results of this work, the authors showed that for large Froude numbers \( Fr > 30 \) one large main vortex forms, and for Froude numbers \( Fr \approx 3, 30 \) a secondary vortex forms along the heated wall near the ground.

A similar study was carried out in [2]. In this work, the authors applied the computational fluid dynamics model based on the RANS equations in combination with the RNG turbulence model to study the flow structure in a street canyon. The ratio of the height \( H \) and width \( W \) of the canyon was taken: \( H/W = 1 \). The following cases of the temperature difference between the walls of the street canyon were considered: \( \Delta \theta = 2, 5, 10, 15^\circ C \). The relative influence of the thermal effect was estimated by bulk Richardson number \( R_b = \frac{gL_{\theta_n}(\theta_n - \theta)}{\theta_n u_0^2} \). In the course of the work, the dependence of the appearance of secondary vortices was revealed. Secondary vortices
are formed as a result of heating various surfaces of the canyon caused by solar radiation. A significant effect on the structure of the flow inside the canyon was shown by the case when the windward wall of the canyon is heated. In this case, the buoyant forces increase their effect on the main vortex and as a result a secondary vortex is formed, the dimensions of which depend on the temperature difference.

In [3], the authors carried out a study of the pollutants transport in urban street canyons with different size ratios and different bottom temperatures of the canyon. The simulation was carried out using the LES-model. The dependence of the flow structure on the geometry parameters of the street canyon and on the intensity of heating of the canyon bottom is shown. The authors examined 9 cases: a combination of 3 cases of heating the underlying surface (strong, weak and neutral heating) with 3 options for the ratio of the height of the canyon \((H)\) to its width \((W): H/W = 1, 2\) and 0.5. Of all the simulated cases, significant changes in the flow structure caused by ground heating showed cases when \(H/W = 2\) and 0.5. Strong ground heating in a street canyon when \(H/W = 2\) can change the two-vortex flow structure into a single-vortex flow. Strong heating of the ground leads to a more symmetrical vortex structure in street canyons when \(H/W = 1\) and 0.5.

Based on the results of the review we can conclude that the problem of studying the flow structure in a street canyon under conditions of temperature heterogeneity by methods of computational fluid dynamics is of interest. There are interesting results that indicate the possibility of the formation of a complex recirculation flow in a street canyon, and under certain conditions a multi-vortex structure may arise. This may be the reason for the formation of increased concentrations of impurities that enter the canyon from the source.

In this paper, based on the developed original micro-scale M2U mathematical model [4], we study the effect of heating of the surfaces forming the canyon on the flow structure and the air quality inside the street canyon. The mathematical model is based on the Reynolds averaged Navier-Stokes equations. The closure of the system of differential equations is carried out using the two-parameter \(k-\varepsilon\) model, taking into account the influence of buoyancy forces on the turbulent flow structure, and the Boussinesq gradient-diffusion hypothesis. The numerical solution is based on the finite volume method, the monotonized approximation scheme for convective terms, and the SIMPLE algorithm for matching the velocity and pressure fields [5].

In contrast to the aforementioned papers [1, 2, 3, 4], the emphasis in this work is on the study of changes in the maximum and average concentration in the human breathing zone (up to 2 meters from the ground) depending on the temperature difference between the environment and the street canyon forming parts. Seven variants of a combination of heated surfaces were considered and for each variant there were four variants of temperature difference with the environment: 5, 10, 15 and 20\(^\circ\)C.

2. Physico-mathematical statement of the problem

Stationary nonisothermal turbulent air movement in the surface layer above an inhomogeneous underlying surface with elements of large-scale roughness is considered. The roughness elements are motionless, impenetrable to the flow obstacles (buildings). The dimensions of buildings are commensurate with the dimensions of the study area (Figure 1). Point source of harmful emissions of constant intensity is considered.
The mathematical model includes Reynolds-averaged continuity equations, Navier-Stokes equations, equations of the pollutant transfer [5, 6] and heat transfer:

\[
\frac{\partial \bar{u}_i}{\partial x_i} = 0,
\]

\[
\frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_i} \left( \nu \frac{\partial \bar{u}_i}{\partial x_j} \right) - \frac{\partial \bar{u}_i' \bar{u}_j'}{\partial x_j} + g_i \frac{(T - T_0)}{T_0},
\]

\[
\frac{\partial T \bar{u}_j}{\partial x_j} = \frac{\partial}{\partial x_j} \left( a \frac{\partial T}{\partial x_j} \right) - \frac{\partial T' \bar{u}_j'}{\partial x_j},
\]

\[
\frac{\partial \bar{C} \bar{u}_j}{\partial x_j} = \frac{\partial}{\partial x_j} \left( D \frac{\partial \bar{C}}{\partial x_j} \right) - \frac{\partial \bar{C}' \bar{u}_j'}{\partial x_j} + S, \quad i, j = 1, 2, 3.
\]

where, \( \bar{u}_i, \ u_i' \) – averaged and pulsating projections of the velocity vector on the coordinate axis; \( \bar{p} \) – pressure; \( \rho \) – density; \( \nu \) – kinematic viscosity of air; \( T \) – temperature; \( \bar{C} \) – averaged pollutant concentration; \( S \) – function describing the distribution of point pollutant sources; \( \bar{u}_i' \bar{u}_j' \) – Reynolds stress tensor; \( a, D \) – thermal diffusivity and diffusion coefficient; \( g_i(0, 0, g) \) – gravity acceleration components.

The closure of the described system of equations is carried out using the Boussinesq gradient-diffusion hypothesis [5]:

\[
\bar{u}_i' \bar{u}_j' = -\nu_T \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) + \frac{2}{3} k \delta_{ij},
\]

\[
T' \bar{u}_j' = -\frac{\nu_T}{Pr} \frac{\partial T}{\partial x_j},
\]

\[
\bar{C}' \bar{u}_j' = -\frac{\nu_T}{Sc} \frac{\partial \bar{C}}{\partial x_j}.
\]

To calculate the turbulent viscosity, a two-parameter \( k-\varepsilon \) turbulence model [7] (that takes into account the influence of buoyancy forces) is used:

**Figure 1.** Illustration of the physical statement of the problem.
\[ \nu_T = C_\mu \frac{k^2}{\varepsilon}, \]

\[ \frac{\partial k \bar{u}_j}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \left( \nu + \frac{\nu_T}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right) + P + G - \varepsilon, \]

\[ \frac{\partial \varepsilon \bar{u}_j}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \left( \nu + \frac{\nu_T}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right) + \frac{\varepsilon}{k} C_{\varepsilon 1} (P + C_{\varepsilon 2} G) - C_{\varepsilon 2} \frac{\varepsilon^2}{k}, \]

where \( \nu_T \) – turbulent viscosity, \( k \) – kinetic energy of turbulence, \( \varepsilon \) – dissipation of turbulent kinetic energy, \( \beta \) – coefficient of thermal expansion. Turbulence model coefficients: \( \sigma_k = 1.0 \), \( \sigma_\varepsilon = 1.22 \), \( C_{\varepsilon 1} = 1.44 \), \( C_{\varepsilon 2} = 1.92 \), \( C_{\varepsilon 3} = \text{tanh} \left( \frac{|u_3|}{|u_1|} \right) \), \( C_\mu = 0.09 \), \( Sc_T = 0.5 \), \( Pr_T = 0.9 \).

The method of wall functions is used to set the values of velocity, turbulent parameters, friction and heat flux near a solid surface [8]. The model does not take into account the deposition of impurities on walls, roofs and the underlying surface. Therefore, at the boundaries, the derivatives of the concentration with respect to the surface normal are set equal to zero. The boundary conditions at the outlet and at the open upper boundary are set as the equality of derivatives with respect to the normal to zero. Uniform velocity profiles \( k, \varepsilon, \bar{T}, \bar{C} \) are used for inlet boundary conditions.

To calculate flows around buildings, the fictitious domain method was used, the essence of which is that the values of vector and scalar quantities in the barrier region are zero and there are no diffusion flows at the boundaries of fictitious finite volumes [5].

3. Approximation of a differential problem and a numerical solution method

Discretization of the differential problem is performed by the finite volume method on a structured Cartesian grid. The approximation of the convective terms of the transport equations is carried out using the upstream MLU Van Leer scheme [9]. The approximation of diffusion terms is carried out using a second-order central-difference scheme. The result of discretization is an implicit difference scheme of the second order of approximation in space. The SIMPLE method [10] was used to match the velocity and pressure fields. An iterative computational procedure has been developed for matching the velocity and pressure fields and sequentially solving systems of grid equations, which are implicit discrete analogues of the advection-diffusion equations of a nonlinear problem based on the Buleev incomplete factorization method. A more detailed description of the approximation and the numerical method of solving an example of a two-dimensional problem is presented in [5, 6].

Additional mesh thickening was carried out to reliably take into account the influence of obstacles on the direction and strength of the surface wind near streamlined surfaces.

4. Verification of the constructed mathematical model

Figure 2 presents the results of comparing the calculated normalized values of the pollutant concentration near the windward and leeward vertical walls of the canyon with the Hoydysh and Dabberdt measurements obtained during the wind-tunnel experiment [11]. It is seen that the calculation results are consistent with the experimental data.
Figure 2. The calculated and measured [11] vertical profiles of the normalized pollutant concentration on the windward (left) and leeward (right) sides of the canyon.

Also, to verify the model, a study was made of the flow structure and the nature of the propagation of impurities in the street canyon, depending on the ratio of its width and height. It was established that the model reproduces the main flow regimes in the canyon, which are also shown in [12], where turbulence was simulated by the Large Eddy Simulation method (LES).

5. Simulation of flow and parametric calculations

The analysis of the influence of heating surfaces forming a street canyon on the maximum and minimum concentrations of impurities in the breathing zone (up to 2 m from the ground) and in the whole canyon is carried out. The geometric characteristics of the street canyon are: height \(H\) and width \(W\) 20 m, depth \(L\) 30 m. The calculations were carried out on a structured Cartesian grid \(110 \times 62 \times 100\) along the axes \(Ox, Oy\) and \(Oz\), respectively. The mesh was compacted at the border nodes. The size of 5 border cells in the direction normal to the solid boundary was 0.1 m. This is done to get the dimensionless \(y+\) into the recommended range from 30 to 300.

The source of pollutant of constant intensity was located in the center of the street canyon near the surface. The viscosity of the medium is considered to be \(\nu = 15 \times 10^{-6} m^2/s\), which corresponds to the viscosity of the air at 20°C. The boundary conditions were set as follows: at the inlet boundary, the horizontal velocity \(U_{in} = 1 m/s\); at the outlet boundary, the normal velocity derivatives are equal to zero; non-slip conditions are set on the upper wall. Initial conditions: the longitudinal velocity is equal to the inlet velocity (1 m/s), and the vertical velocity and pressure are zero.

The obtained data are presented in Table 1 and on figures: 3, 4, 5, 6. An analysis of the results shows that in all cases, except for heating the windward wall, the maximum pollutant concentrations are decreasing when the temperature gradient in the street canyon are increase and the other parameters remain unchanged (Figure 3). This is due to the fact that an increase in the temperature gradient contributes to an increase in the velocity of the main air flow inside the street canyon and the pollutant is more intensively carried out by the wind. Similar results were obtained for the average concentration of impurities in the breathing zone (Figure 4).

The heating of the windward wall leads to the formation of an upward flow of warm air. The resulting flow is directed in the opposite direction relative to the motion of the main vortex.
This leads to the compression of the main vortex and the formation of a new one in the zone between the main vortex and the windward wall of the building. Figure 6 (on top) shows the vector velocity field and the pollutant concentration field corresponding to the case under consideration. In this case, the dissipation of pollutants deteriorates, the pollutant circulates in the vortex and accumulates in the canyon.

Figures 5 and 6 show six cases for a temperature gradient of 20°C. The first two cases (when the windward or leeward walls are heated) are the most unsuccessful from the point of view of ventilation. In both cases, the maximum concentration in the canyon and the average concentration in the breathing zone are more than two times higher compared to other cases. The heating of two or more surfaces leads to an increase in the average velocity of the main vortex and, as a result, the pollutant is more intensively carried out from the street canyon.

| Heated surfaces          | Temperature difference | Maximum concentration | Minimum concentration | Average concentration |
|-------------------------|------------------------|-----------------------|-----------------------|-----------------------|
|                         |                        |                       | Breathing zone        | Canyon                |
| No heating              | 0                      | 1.334                 | 0.00000471            | 0.0000255            | 0.0009761 | 0.0003171 |
| Leeward wall            | 5                      | 1.158                 | 0.00000431            | 0.0000253            | 0.0008982 | 0.0002844 |
|                         | 10                     | 1.072                 | 0.00000381            | 0.0000166            | 0.0008174 | 0.0002572 |
|                         | 15                     | 1.002                 | 0.00000361            | 0.0000153            | 0.0007617 | 0.0002383 |
|                         | 20                     | 0.943                 | 0.00000343            | 0.0000152            | 0.0007181 | 0.0002238 |
| Windward wall           | 5                      | 0.923                 | 0.00000662            | 0.0000276            | 0.0011767 | 0.0004099 |
|                         | 10                     | 1.181                 | 0.00000611            | 0.0000216            | 0.0011695 | 0.0003808 |
|                         | 15                     | 2.285                 | 0.00001544            | 0.0000248            | 0.0014396 | 0.0004546 |
|                         | 20                     | 2.321                 | 0.0001087             | 0.0000157            | 0.0012571 | 0.0003672 |
| Ground                  | 5                      | 0.768                 | 0.00000162            | 0.0000078            | 0.0007569 | 0.0002640 |
|                         | 10                     | 0.548                 | 0.00000444            | 0.000019             | 0.0004900 | 0.0001504 |
|                         | 15                     | 0.462                 | 0.0000017             | 0.000007             | 0.0003881 | 0.0001087 |
|                         | 20                     | 0.413                 | 0.0000008             | 0.000003             | 0.0003304 | 0.0000861 |
| Leeward and ground      | 5                      | 0.889                 | 0.0000323             | 0.0000159            | 0.0007362 | 0.0002506 |
|                         | 10                     | 0.574                 | 0.0000086             | 0.0000040            | 0.0005263 | 0.0001765 |
|                         | 15                     | 0.498                 | 0.0000072             | 0.0000035            | 0.0004477 | 0.0001496 |
|                         | 20                     | 0.446                 | 0.0000064             | 0.0000033            | 0.0003960 | 0.0001319 |
| Windward and ground     | 5                      | 0.636                 | 0.0000125             | 0.0000052            | 0.0006037 | 0.0001984 |
|                         | 10                     | 0.509                 | 0.0000020             | 0.000007             | 0.0004038 | 0.0001116 |
|                         | 15                     | 0.440                 | 0.0000006             | 0.000002             | 0.0003279 | 0.0000825 |
|                         | 20                     | 0.397                 | 0.0000003             | 0.000001             | 0.0002857 | 0.0000673 |
| Leeward and windward    | 5                      | 0.743                 | 0.0000233             | 0.0000105            | 0.0007392 | 0.0002478 |
| walls                   | 10                     | 0.604                 | 0.0000116             | 0.0000051            | 0.0005652 | 0.0001772 |
|                         | 15                     | 0.520                 | 0.0000058             | 0.0000025            | 0.0004633 | 0.0001353 |
|                         | 20                     | 0.465                 | 0.0000033             | 0.000015             | 0.0004030 | 0.0001118 |
| All surfaces            | 5                      | 0.545                 | 0.0000045             | 0.0000018            | 0.0004850 | 0.0001412 |
|                         | 10                     | 0.417                 | 0.000009              | 0.000003             | 0.0003383 | 0.0000860 |
|                         | 15                     | 0.354                 | 0.000003              | 0.000001             | 0.0002780 | 0.0000661 |
|                         | 20                     | 0.315                 | 0.000002              | 0.000001             | 0.0002433 | 0.0000557 |
**Figure 3.** Illustration of the dependence of the maximum concentration of impurities in a street canyon on a combination of heated surfaces and the intensity of their heating.

**Figure 4.** Illustration of the dependence of the average concentration of impurities in the breathing zone (up to 2 m from the ground) on the combination of heated surfaces and the intensity of their heating.
Figure 5. The vector velocity field against the background of contours of the pollutant concentration at a temperature gradient of 20°C and \( U = 1 \) m/s. From above - the leeward wall is heated, in the center - the windward wall is heated, from below - the ground is heated.
Figure 6. The vector velocity field against the background of contours of the pollutant concentration at a temperature gradient of 20°C and $U = 1\ m/s$. From above - the windward wall and ground are heated, in the center - the leeward wall and ground are heated, from below - the windward and leeward walls are heated.
6. Conclusion
A micro-scale model of turbulent non-isothermal air movement and pollutant transfer in street canyons is presented, taking into account the influence of the buoyancy force on the flow pattern and its turbulent structure. The developed model was verified using known experimental data for pollutant transfer in a stationary isothermal turbulent flow in a canyon.

For a non-isothermal turbulent air flow in a canyon, it has been studied how different heating options for street canyon forming parts affect the flow structure and the accumulation of incoming impurities inside it. The integral characteristics of the pollutant concentration in the whole street canyon and in the breathing zone (up to 2 m from the ground) were calculated and analyzed. It was found that only heating the windward side and increase its intensity leads to a significant increase in the values of the maximum and average pollutant concentrations in the street canyon.

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