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ANALYSIS OF POLLUTANT DISPERSION IN FLOW AROUND THE OBJECTS IN TANDEM ARRANGEMENT

ANALIZA ROZPRZESTRZENIANIA SIĘ ZANIECZYSZCZEŃ GAZOWYCH WOKÓŁ OBIEKTÓW W UKŁADZIE TANDEM

Abstract: The problem of pollution dispersion throughout atmospheric boundary layer has grown in importance since human activity has become so intense that it started having considerable impact on natural environment. The level of concentration of pollutants has escalated, particularly in urban areas and it impacts on their inhabitants.

The paper presents the results of the complex research program aimed at understanding a character of the flow field in neighborhood of bluff-bodies immersed in a boundary layer and characteristics of pollutants dispersion in that area. Analysis of gas pollutants dispersion process requires in-depth identification of the structure of flow around the buildings. The analysis has been performed for the 3D case of two in-line surface-mounted bluff bodies, arranged in tandem, which were placed with one face normal to the oncoming flow. The mean concentration profiles of tracer gas (CO_2) for various inter-obstacle gaps were measured in wind tunnel. Characteristic feature of flow field around groups of buildings in urban areas is high level the unsteady phenomena resulting from itself character of the wind or from the interference of the wake flow connected with a process of vortex shedding. This is the factor affecting process of the dispersion of pollutants in the built-up area acting more complex the mechanism of propagate of small parts explained on the basis of processes of advection and turbulent diffusion. The local characteristics of flow were obtained by the use of commercial CFD code (FLUENT).

Keywords: buildings arrays, pollutant dispersion, experimental and numerical modelling

Introduction

The problem of pollution dispersion throughout atmospheric boundary layer has grown in importance since human activity has become so intense that it started having considerable impact on natural environment. The level of concentration of pollutants has escalated, particularly in urban areas and it impacts on their inhabitants [1, 2].

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Ensuring adequate air quality requires proper aeration of these areas. Its efficiency depends mainly on wind direction, configuration of buildings and locations of emissions sources. The process of pollution dispersion is mainly influenced by mechanisms of mass diffusion, caused by concentration gradients and advection which transfers pollutants in flow direction through mean air movement. The specific flow conditions generated around bluff bodies arrangement make it possible to study the gas pollutant dispersion for the case of very complex velocity field typical for built environment. Curved streamlines, sharp velocity discontinuities, high level flow oscillations and non-homogenous turbulence disperse effluents in a complicated manner related to source configuration and object geometry [3]. Improvement in air quality on a local scale and limitation of effect of pollution on human health requires consideration of all the listed factors.

An important role in increasing knowledge about dispersion processes that occur in the atmosphere is played by the investigations carried out inside wind tunnels. They also deliver data necessary for verification of the results obtained by means of numerical modelling. During model testing of environmental aerodynamics, actual shapes of ground object are typically replaced with their simplified versions. In the case of buildings, this usually means cuboids of different height. The goal of the present work was to determine impact of object configuration, level of their ‘immersion’ in boundary layer and location of emission source on dispersion of the emitted gas marker [4, 5].

This paper presents the experimental test of the qualification of the relation between a structure of the flow field in complex urban terrain (in the built-up area) and characteristics of pollutants dispersion. The aim of this work was to determine the impact of objects configuration, their degree of “immersion” in the boundary layer and location of emission source for the spread of the tracer gas emitted in the vicinity of two rectangular blocks in tandem arrangement.

Methods of analysis

The program of this study consists of: wind-tunnel measurement of the mean concentration profiles in the inter-body gap for different body “immersion” in boundary layer, comparison of concentration field with aerodynamic characteristics (obtained as a result of numerical simulation performed at the Institute of Thermal Machinery of the Czestochowa University of Technology (ITM CzUT). The numerical simulation was performed with the use of k-ε turbulence model in realizable version. The flow conditions of the computational domain were the same as those in the experiment. The boundary conditions imposed at the inlet to the computational domain were the same as those obtained from the wind-tunnel experiment.

The experiments were carried out in an open-circuit wind tunnel (Fig. 1). The test section was 400 × 400 mm square and 4000 mm long. All the measurements were carried out for the $Re_D = 3.4 \cdot 10^4$ based on the free stream velocity $U_\infty = 13$ m/s and the cube width D = 0.04 m. Figure 2 presents the geometries of the analyzed cases of two obstacles, where H_1/H_2 describes their height ratio and S/D = 2.5 (constant) the distance between them.

Analysis of pollutant dispersion in flow around the objects in tandem arrangement

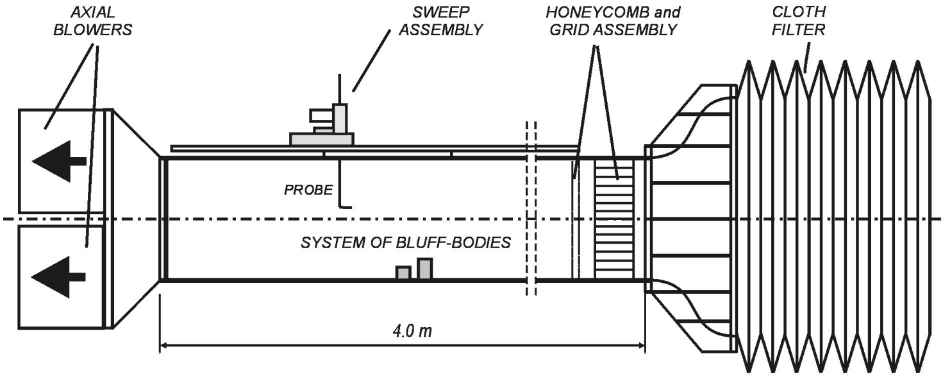

Fig. 1. Two-dimensional channel flow with the system of bluff-bodies

The source of emission of carbon dioxide used as a gas marker during the investigations was a brass pipe with inner diameter 3 mm, located before the windward object at the distance of 1.5 D. CO_2 flow rate was maintained at constant level Q = 5 dm^3/min, which produced output speed of U_{CO_2} = 11.8 m/s. In order to measure mean concentration of gas marker a Guardian plus CO_2 Analyzer was used. Measurement probe in the form of aluminium pipe with inner diameter of 2.6 mm was connected with analyser inlet by means of supple pipe. Location of the source and the measurement probe in relation to the investigated arrangement of the objects as well as the assumed coordinate system are presented in the Fig. 2.

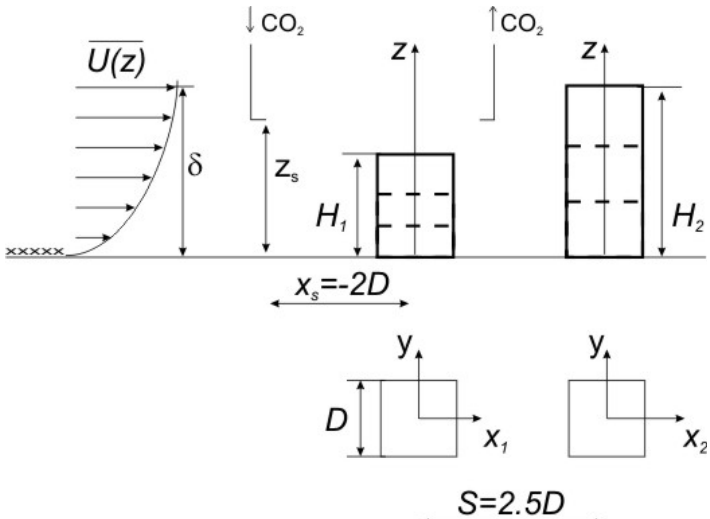

Fig. 2. Schematic presentation of the set-up and nomenclature

The measurements were carried out for configurations of two elements with different height, aligned in one line. The results of testing presented in this work relate to a fixed ratio of object height $H_1/H_2 = 0.6$ and three values of their "immersion" in boundary layer $H_2/\delta = 0.3$; 0.6 and 1.0.

For all the considered configurations, an identification of the structure of flow by means of surface oil visualization was performed. Measurements of concentration CO_2 were taken in the gap between the elements in measurement cross-sections x/D = 0.5; 0.625; 0.75; 0.875; 1; 1.25 both in system axis and along the edges of external objects, for two different positions of emission source $z_S = 0$ and H_1 situated at the distance of 1.5 D in front of the windward object. In order to visualize the flow-modifying impact of the leeward object, some measurements of concentration CO_2 profiles were also taken for a single object.

Discussion of the results

Analysis of gas pollutants dispersion process requires in-depth identification of the structure of flow around the buildings. The flow structure around three-dimensional bluff-body located on the surface with formed boundary layer is characterized by a high level of complexity. In the presented spatial diagram of flow line (Fig. 3), the following characteristic areas in this type of flow can be distinguished: area of the horseshoe

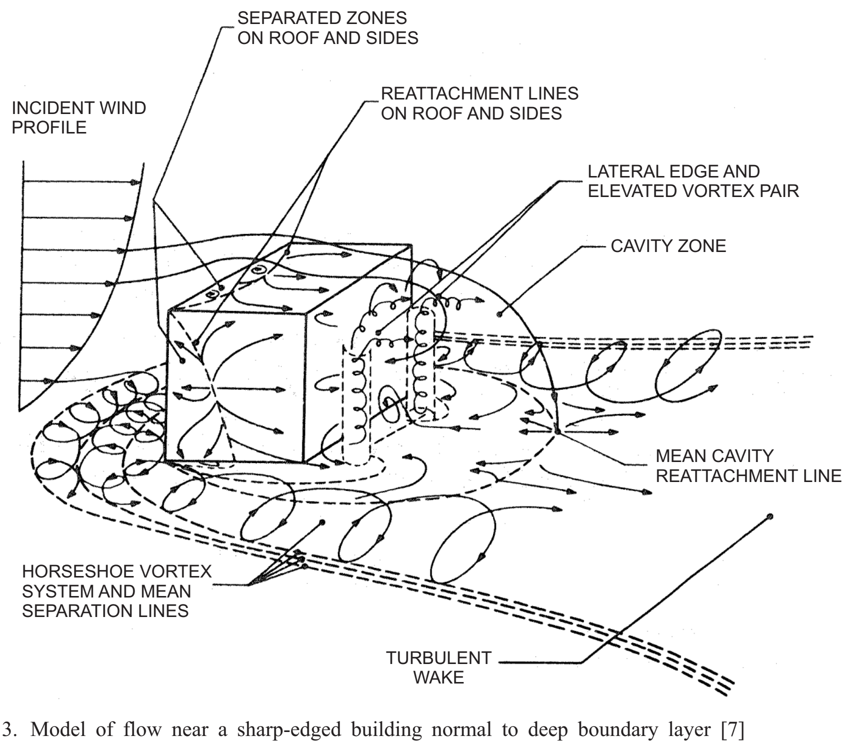

Fig. 3. Model of flow near a sharp-edged building normal to deep boundary layer [7]

vortex forming in front of the object upper flow, close and farther wake zones. According to Hunt [6] interpretation, flow around the object is composed of a range of separation and adherence points classified as singular nodal and saddle points. The zones typical of flow around cuboids are clearly visible in the image (see Fig. 3) being the result of oil surface visualization. One can distinguish here a horseshoe vortex, whose name derives from its characteristic shape, and post-edge vortices, located in close distance from rear side of the object. White spots in the image are identified as the areas of flow stagnation. However, black color is associated with areas of high flow rate such as wide band of lateral flow, which extends over the considerable distance behind the object.

Object impact zone, *ie* area where velocity field is strongly disturbed by the presence of the obstacle, changes considerably if another object is placed in the aerodynamic wake. The case under consideration in this work concerns tandem arrangement which is characterized by H_1/H_2 parameter, which is conducive to occurrence of downwash effect. This effect consists in washing of front side of the leeward object with large air masses, which results in strong air circulation in the area between objects, which determines flow structure between them.

This situation is presented in Fig. 4, which gives a comparison of surface oil visualization (Fig. 4a) within the numerical results of mean velocity distributions (Fig. 4b) obtained with the steady-state (RANS) method for tandem arrangement of two cuboids for three values of their "immersion" in boundary layer $H_2/\delta = 0.3$; 0.6 and 1.0. Disturbing impact of the second object, expressing particularly in location of the couple of post-edge vertices behind windward object and changes in the shape of lateral flow is distinctly visible. The level of modification of flow around the analysed arrangement of objects of tandem type depends on many factors. Change in height of the elements of the arrangement impacts on changes in the immersion parameter in boundary layer. As results from Fig. 4, this parameter has significant impact on the flow structure.

The biggest changes in flow field are observed in the area between objects. Rise the object height in relation to layer thickness causes rise in impact of windward object and increase in width and length of recirculation zone and extension of the area taken by vortices. Aerodynamic wake of the leeward object is wider than the width of its horseshoe vortex of the windward object. Spacing in lateral edge vortices behind windward object is bigger than in lateral edge vortices behind leeward object and it rises with the object height.

Such a statement can also be confirmed by the distributions of streamwise mean velocity component in that area presented in Fig. 4b. The level of mean velocity in the inter-body space seems to be important for the recognition of interference mechanisms in flow system considered. The data juxtaposed in Fig. 4a refer to the changes of velocity flow field observed on Fig. 4b for different values of parameter H_2/δ. As has been mentioned previous the ratio of the objects height to the incoming boundary layer thickness H/δ has an important influence on the flow structure, and on the separation regions upstream and downstream the obstacle.

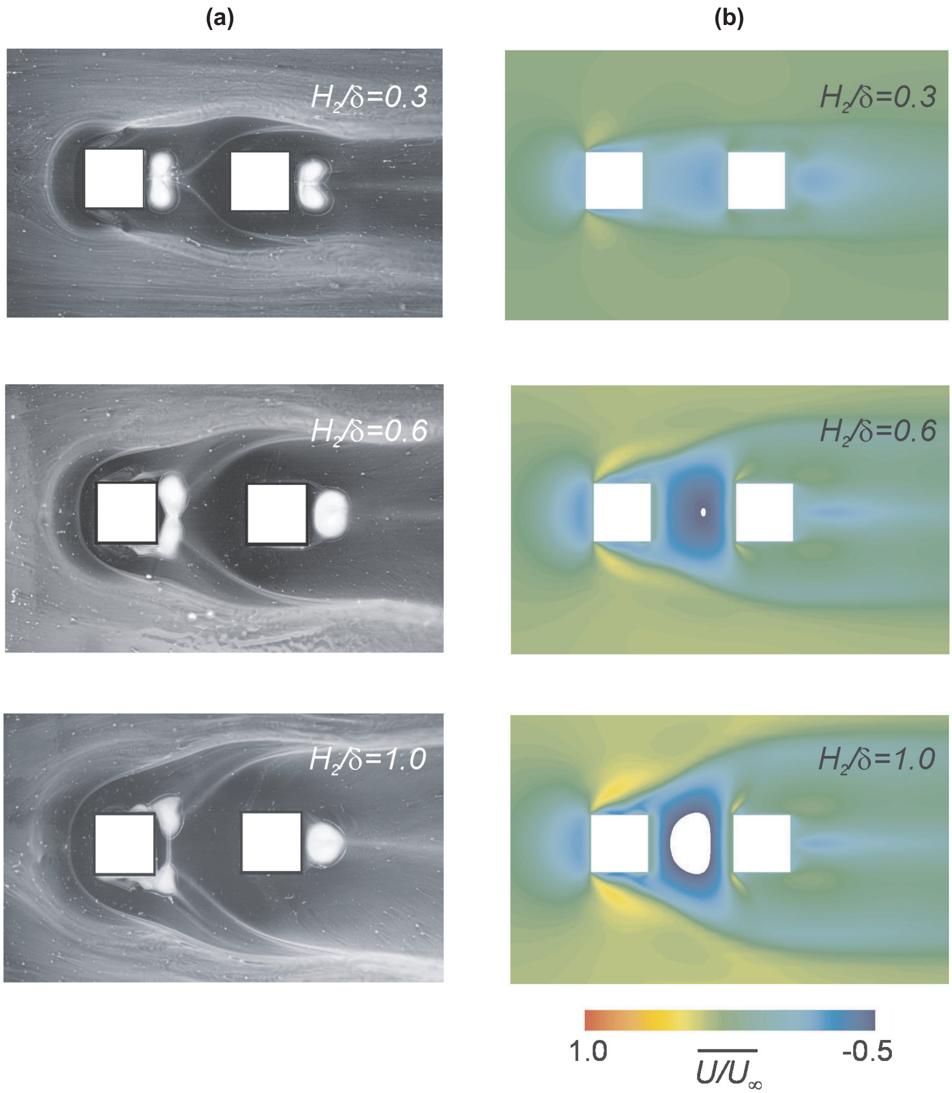

Fig. 4. The surface flow patterns obtained with oil-film technique (a) and distributions the streamwise component of mean velocity on pedestrian level (b) around configurations of two elements (S/D = 2.5 H_1/H_2 = 0.6) for different the immersion parameter H_2/δ = 0.3; 0.6; 1

Scope and method of the objects interaction on their wind environment changes as a function of distance from the ground. It is clearly visible on the distributions of the streamwise mean velocity component for example configuration (Fig. 5). Closer to the ground, on pedestrian level ($z/H_2 = 0.008$) observed very different velocity flow field with strong gradients. With increasing distance from the ground impact zone of objects arrangement on the flow narrows and U/U_∞ approaching unity.

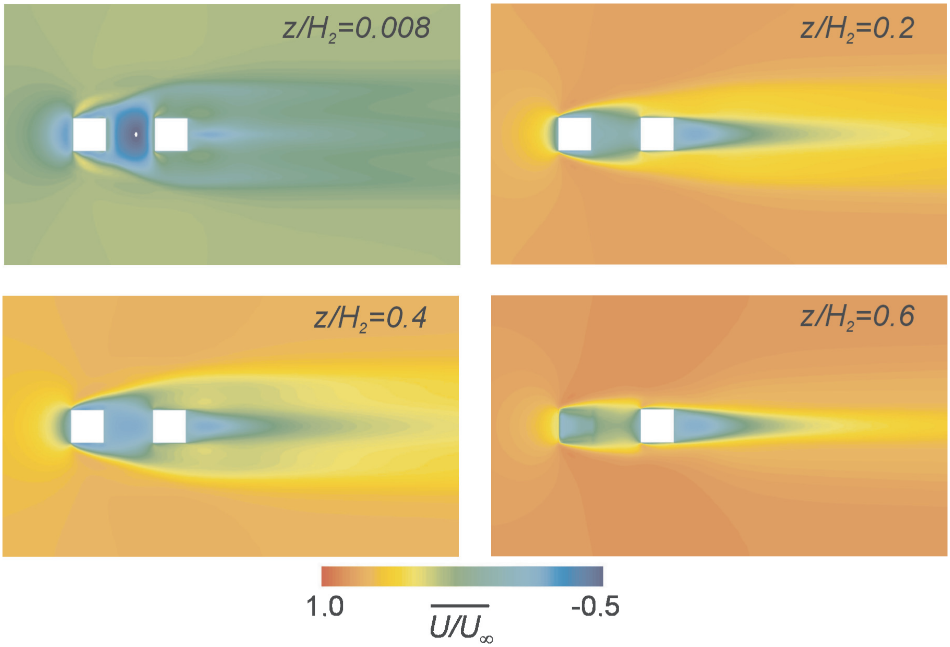

Fig. 5. Distributions of the longitudinal component of mean velocity for objects in tandem arrangement ($S/D = 2.5$ $H_1/H_2 = 0.6$) as a function of distance from the ground

The observed modifying impact of interaction between the objects in tandem arrangement is reflected in the results of measurements of concentration of the gas marker emitted in their environment. Figure 6 presents cross-sectional distribution of concentration in the gap between objects for three of the considered configurations.

It is remarkable that highest values of concentration of gas marker can be observed for $H_2/\delta = 0.3$. The effect of downwash manifests strongest in the case $H_2/\delta = 1$. Impact of the leeward object on flow field around the tested arrangement, increasing with the height of the objects, maintaining the same distance between each other, is undoubtedly connected with the fact that the increase in windward object height causes that leeward object gets more and more into the aerodynamic wake of the first one. The scope of the close wake behind the cuboids object increases proportionally to its height, which is caused by higher, in the case of higher elements, kinetic energy of the upper flow that delays its adhesion to the base [3]. In the case of emission source being located at the height of windward object, gas marker is moved mainly through upper flow, which is reflected in distribution of its concentration shown in the Fig. 6. Lower kinetic energy and, in consequence, lower flow rate, results in higher concentration of gas marker in the zone above the windward object. Ascent of the trail of carbon dioxide for the objects with highest level of immersion ($H_2/\delta = 0.3$) reaches three heights of the windward object and decreases with the height of the objects. Analysis of the carbon dioxide concentrations along the rear wall of the windward object (Fig. 6) reveals that for each of the three cases there is a minimum concentration in its neighborhood, in roughly half

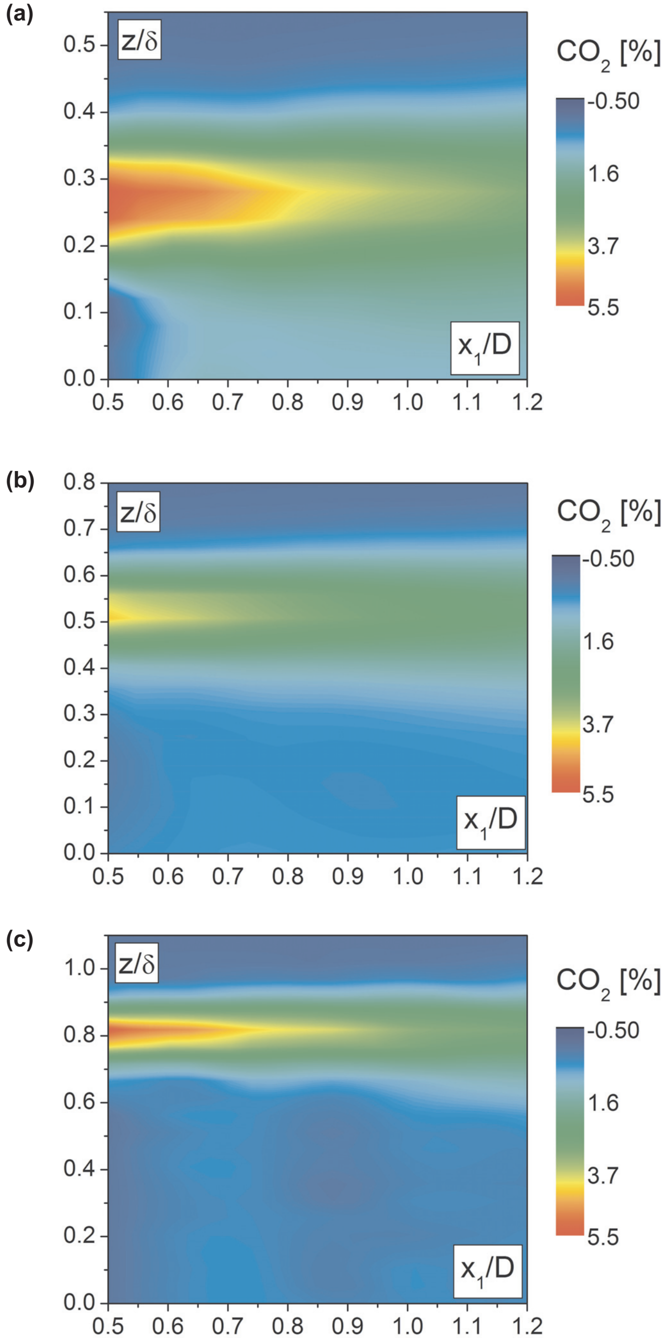

Fig. 6. Distribution of mean concentration CO_2 ($z_S = H_1$; $y/D = 0$) in the inter-obstacle gap for different the immersion parameter (a) $H_2/\delta = 0.3$, (b) $H_2/\delta = 0.6$ and (c) $H_2/\delta = 1$

of the building height. Moreover, in the case of the traverse that crosses the line connecting axes of post-edge vortices, which occurs for the arrangement with immersion $H_2/\delta = 1$, one can see a distinct reduction in concentration CO_2 in upper half of the building. Slightly higher concentration of the gas marker next to the base is probably caused by additional contribution of horseshoe vortex to its transport.

Impact of the location of emission source on the dispersion of marker gas in the environment of object arrangement of tandem type was analysed for two source heights, $z_S = 0$ and H_1. Figure 7 presents distribution of concentration in the gap between elements for the source located at the height of the windward object (black lines) and for emission source located on the base (red lines). The measurements were taken in the

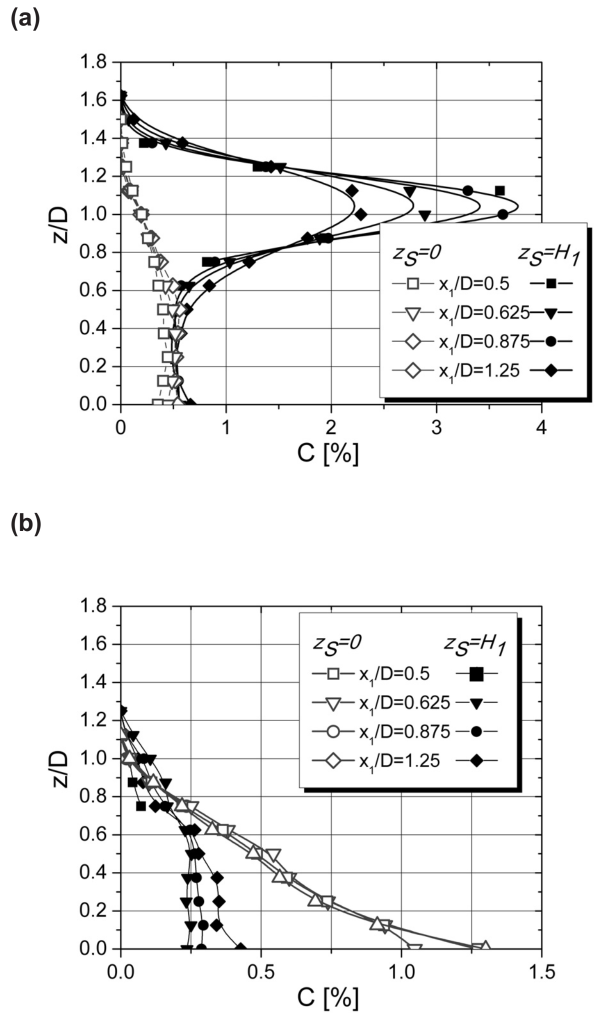

Fig. 7. Tracer gas concentration in the gap between objects in tandem configuration and single windward object for parameters $H_2/\delta = 0.6$; $z_S = 0$ and $z_S = H_1$; a) $y/D = 0$, b) $y/D = 0.5$

arrangement axis y/B = 0 (Fig. 7a) and also along the outside edges of its elements y/B = 0.5 (Fig. 7b).

For different heights of emission sources a diametrically opposite concentration CO_2 distribution was obtained. In the case of source located at the height of windward object, a dominating contribution to the transport of gas marker is from upper flow while for $z_S = 0$ value marker gas is moved mainly through surface vortex structures. Comparison of the results for both objects and single object indicates modifying impact of leeward object on the concentration field. This impact is essential and correlates with images of flow shown in the Fig. 4.

The differences appear practically for each location of the source and each measuring traverse. The highest values of marker gas in tandem arrangement axis (y/D = 0) – higher for $z_S = H_1$ than for the source located on the base – are observed in the area above the height of windward building. In the case of the measurements along the outside edges (y/D = 0.5), maximal concentration of CO_2 values appear in the base.

Conclusions

In present study the influence of bluff-bodies arrangement on computational velocity signals in flow around the prisms configuration in tandem arrangement has been discussed for analysis of pollutant dispersion in bodies neighborhood. The main attention of this paper was to determine the impact of objects configuration, their degree of "immersion" in the boundary layer and location of emissions sources for the spread of the tracer gas emitted in the vicinity of two rectangular cubes in tandem arrangement. The obtained results revealed that characteristics of the velocity field can be affect on the dispersion of pollutants in the built-up area.

The presented results show how important for ensuring adequate air quality, proper formation of wind-related environment of ground objects is.

Acknowledgements

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ANALIZA ROZPRZESTRZENIANIA SIĘ ZANIECZYSZCZEŃ GAZOWYCH WOKÓŁ OBIEKTÓW W UKŁADZIE TANDEM

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Abstrakt: Problem rozprzestrzeniania się zanieczyszczeń w przyziemnej warstwie atmosfery nabrał znaczenia, gdy działalność człowieka stała się na tyle intensywna, że zaczęła wywierać istotny wpływ na stan środowiska naturalnego. Poziom koncentracji zanieczyszczeń nasilony jest zwłaszcza w obszarach zurbanizowanych, oddziałując na jego mieszkańców. W pracy przedstawiono wyniki modelowych badań dotyczących procesu dyspersji zanieczyszczeń gazowych w strefie zabudowanej. Ich celem było określenie wpływu konfiguracji obiektów, stopnia ich „zanurzenia" w warstwie przyziemnej, a także położenia źródła emisji na rozprzestrzenianie się znacznika gazowego (CO_2) emitowanego w ich otoczeniu ze źródła skupionego. Analiza procesu dyspersji zanieczyszczeń gazowych wymaga dokładnego rozpoznania struktury przepływu wokół elementów zabudowy. Badany układ typu tandem stanowiły dwa trójwymiarowe modele budynków o różnych wysokościach ustawione w jednej linii. Profile koncentracji gazu znacznikowego (CO_2) dla różnych konfiguracji obiektów zmierzono w tunelu aerodynamicznym. Cechą szczególną pól prędkości w otoczeniu grupy opływanych budynków jest wysoki poziom niestacjonarności wynikający zarówno z samego charakteru wiatru, jak i z faktu generowania przez obiekty zjawisk periodycznych związanych z procesem schodzenia wirów. Jest to czynnik, który oddziałuje na proces dyspersji zanieczyszczeń w obszarze zabudowanym, czyniąc jeszcze bardziej złożonym mechanizm rozprzestrzeniania się cząstek, tłumaczony na podstawie procesów adwekcji i turbulentnej dyfuzji. Wykorzystywane w pracy charakterystyki aerodynamiczne opływu budynków uzyskane zostały z wykorzystaniem programu FLUENT.

Słowa kluczowe: dyspersja zanieczyszczeń, układ budynków, modelowanie eksperymentalne i numeryczne