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FLOW AND DISPERSION IN THE PRESENCE OF SURFACE-MOUNTED CUBES

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Abstract

The paper discusses the qualification of the relation between a structure of the flow field in neighborhood of bluff-bodies immersed in a boundary layer and characteristics of pollutants dispersion in that area. The experimental modeling of the flow around the body arrangement and the mean concentration profiles of tracer gas (CO_2) was supported and extended with numerical simulations performed with the use of the commercial CFD code (FLUENT). The analysis has been performed for the case of two surface-mounted square cylinders arranged in tandem $H_1/H_2 = 0,6$, for different location of emission source.

Key words: experimental and numerical modeling, pollutant dispersion

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 [2, 7].

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. Important role is also played by turbulent transport processes [6]. 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 modeling. During model testing of environmental aerodynamics, actual shapes of ground cuboids are typically replaced with their simplified versions. In the case of buildings, this usually means cuboids of different height. 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 in ITM CzUT). In frame of numerical part of the study the threedimensional steady and unsteady RANS simulations have been carried out using a commercial CFD code, FLUENT v.6.3, with the RNG version of a $k - \varepsilon$ turbulence model. According to the literature [1] this model is widely used for flows in a build environment. Numerical experiments comprised: modeling of wind conditions in flow approaching cuboids in tandem arrangements and surface wall shear stress.

The experiments were carried out in an open-circuit wind tunnel at the Institute of Thermal Machinery of the Czestochowa University of Technology. All the measurements were carried out for the Reynolds number $Re_D=3,4\cdot10^4$ based on the free stream velocity U_∞ =13m/s and the cube width D=0.04m. Figure 1 presents the geometries of the analyzed cases of two obstacles, where $H_1/H_2=0.6$ describes their height ratio and S/D = 2.5 the distance between them.

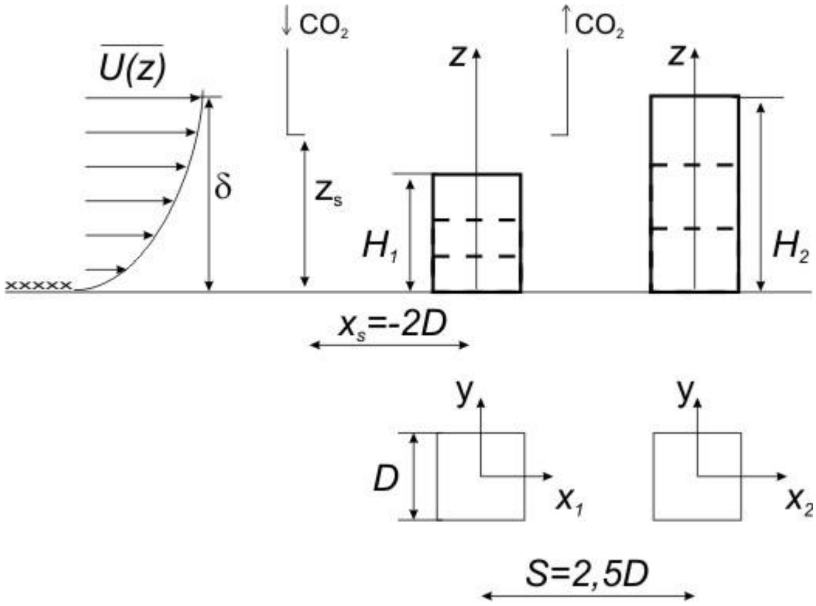


Figure 1: *Schematic presentation of the set-up and nomenclature*

The source of emission of carbon dioxide used as a tracer gas during the investigations was a brass pipe with inner diameter 3mm, located before the windward object at the distance of 1,5D. CO_2 flow rate was maintained at constant level *Q*=5l/minute, which produced output speed of U_{CO2}=11,8m/s. In order to measure mean concentration of tracer gas a Guardian plus CO_2 analyzer was used. Measurement probe in the form of aluminium pipe with inner diameter of 2,6mm was connected with analyzer inlet by means of supple pipe. Location of the source and the measurement probe in relation to the investigated arrangement of cuboids as well as the assumed coordinate system are presented in the figure 1. 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/δ=0,3; 0,6 and 1,0.

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 four different positions of emission source z_S=0; 0,5H_1; H_1 and 1,5H_1 situated at the distance of 1,5D in front of the windward cuboid. 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 one.

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 single bluff-body located on the

surface with formed boundary layer is characterized by a high level of complexity. In this type of flow can be distinguished: area of the horseshoe vortex forming in front of the object, upper flow, close and farther wake zones. According to Hosker [4] interpretation, flow around the object is composed of a range of separation and adherence points classified as singular nodal and saddle points. 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.
Object impact zone, i.e. 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 so-called “downwash” effect H_1/H_2=0,6. 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 cuboids, which determines flow structure between them. This situation is presented in figure 2, which shows the result of numerical modeling of shear stress distribution on the ground surface. Rise in H_2/δ parameter causes deeper effect of windward object to the front of the flow. 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 analyzed 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 figure 2, this parameter has significant impact on the flow structure.

a) b) c)

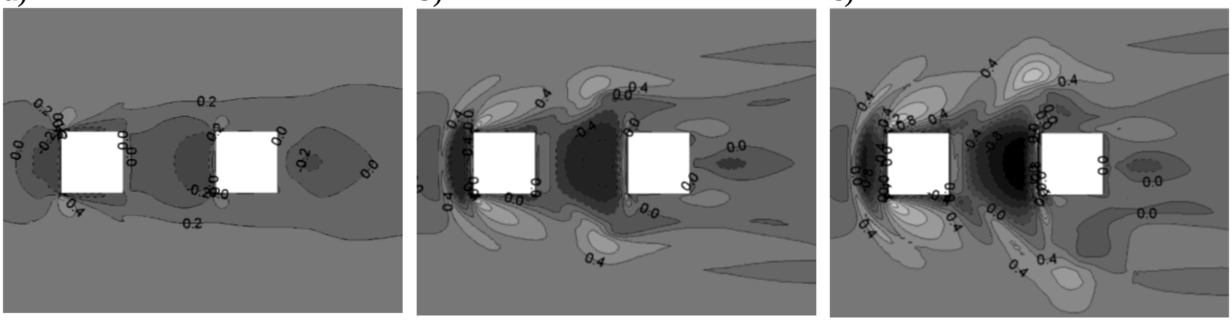


Figure 2. *The x-component of mean skin friction (τ_x) on the ground for the immersion parameter a)H_2/δ=0,3, b)H_2/δ=0,6, c)H_2/δ=1*

The influence of flow pattern around two cubes in tandem arrangement on the behavior of the skin friction distributions obtained as a result of numerical simulation is strongly marked in the space between cuboids and behind of second one. The biggest changes in flow field are observed in the area between objects. Rise in 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 influence of the leeward object is wider than the width of its horseshoe vortex of the windward object. Changes also concern the width of the zone, which for H_2/δ=0,3 considerably exceeds the line which is an extension of side surface of cuboids, whereas recirculation zone in H_2/δ=1,0 is considerably bigger than object width.

The observed modifying impact of interaction between the objects in tandem arrangement is reflected in the results of measurements of concentration of the tracer gas emitted in their environment.
From the perspective of pedestrians, the most interesting is the concentration of pollutants at ground level. The concentration of the tracer gas at the ground level in the gap between objects for the emission source height $z_s=H_1$ is shown in Fig. 3.

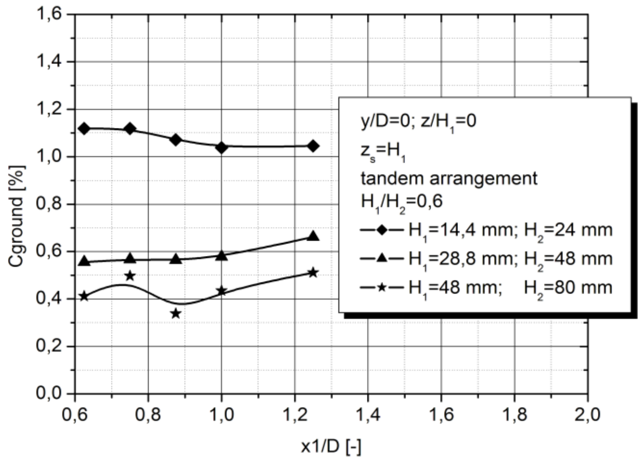


Figure 3. *Ground level centre line concentrations for tandem arrangement with different immersion parameter $H_2/\delta=0,3$; 0,6 and 1.*

As it can be seen, the higher the windward object the lower level of the tracer gas is. A similar effect for a single object was observed by Lawton&Robins [5]. In the case of the tandem arrangement, being considered here, furthermore "downwash" effect was observed and according to Fig. 2 it is most intensive for H_2/δ ratio equal to 1. An additional relatively high object situated among the low-height elements can contribute to the intensification of mixing processes and consequently lead to improved air quality at the pedestrian level as it was pointed out by Vanweert&vanRooij [8]. Appropriate design of the wind environment with the presence of emission sources is very important especially taking into account human health and life comfort.
Configuration of the objects as well as location of the emission sources strongly influences pollutant dispersion. Maps of the gas tracer concentration for the $H_2/\delta=0,6$ and different positions of the emission source ($z_s=0$; $0,5H_1$; H_1 and $1,5H_1$) located at the same distance from the windward object ($x_s=-2D$) are shown in Figs. 4 - 5. In order to illustrate the modifying effect of the leeward object the maps of concentration for a single element, being placed identically as the windward object in tandem arrangement, were superimposed.

For different emission source height different distributions of the tracer gas concentration were obtained, which is an effect of various transport mechanism. The highest qualitative and quantitative differences in the distributions of CO_2 concentration are observed for $z_s=0$ (Fig. 4ab). In this case the tracer gas is mainly transported by the subsurface structure vortices and that is why maximum values of concentration are found at the ground level. It should be noted that the maximum values of CO_2 concentration in case of single object are more than two times greater than in tandem arrangement configuration. According to Gnatowska&Moryn [3] disturbing effect of the second object causes the spanwise displacement of the location of the post-edge vortices pair behind the windward object and changes the lateral flow pattern. As it can be seen this leads to modification of the distribution of the tracer gas concentration. In the case of tandem arrangement more uniform and reaching the height of the windward building distribution is observed which in turn leads to relatively lower values of C_{ground} both at the axis of symmetry (y/D = 0) and along the outside edges (y/D = 0.5) when compared to single object case as it is shown in Fig. 6a.

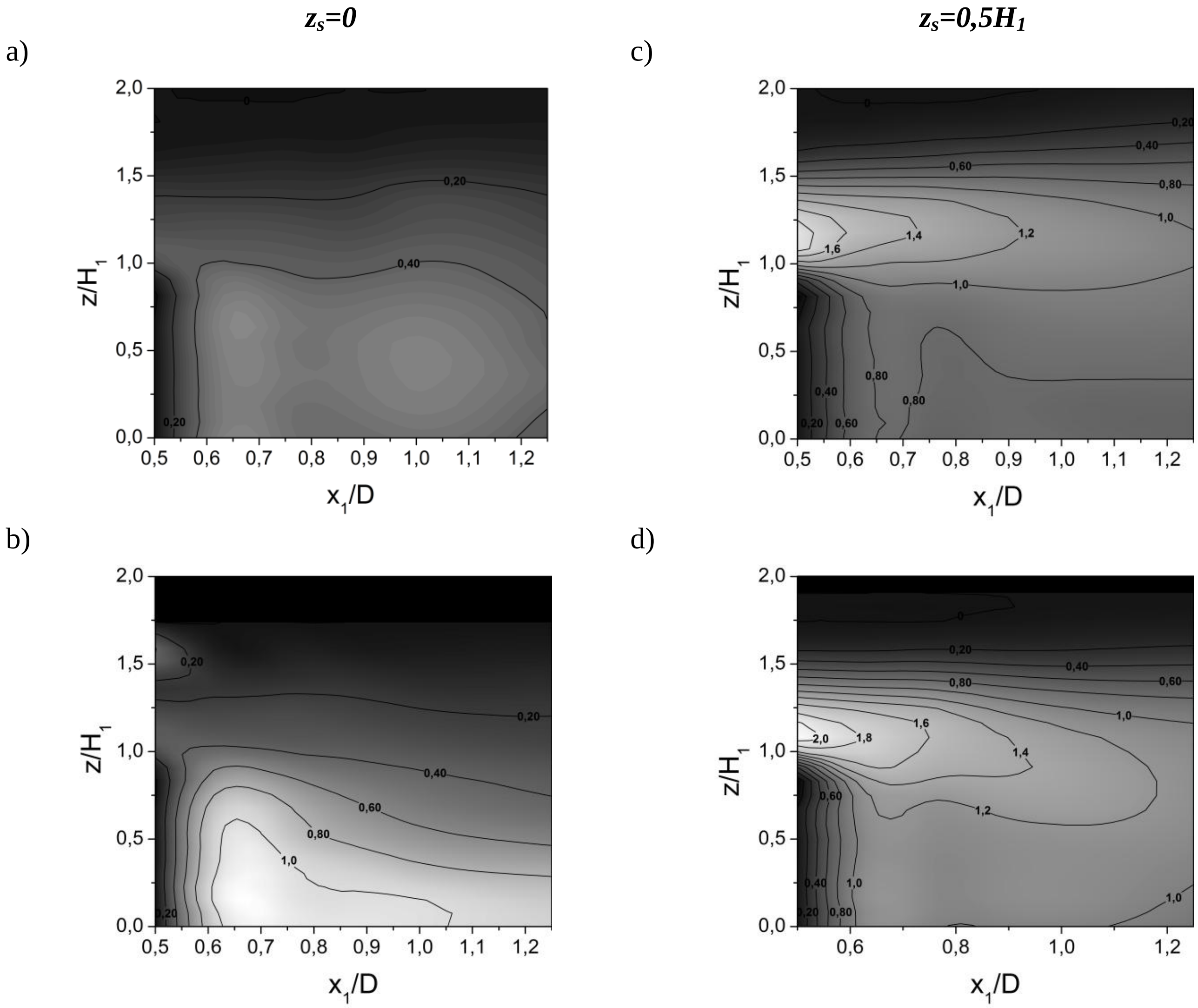


Figure. 4. *Distribution of mean concentration C [%] in the inter-obstacle gap for location of emission source z_s=0; a) and c) tandem arrangement H_1/H_2=0,6, b) and d) single windward object*

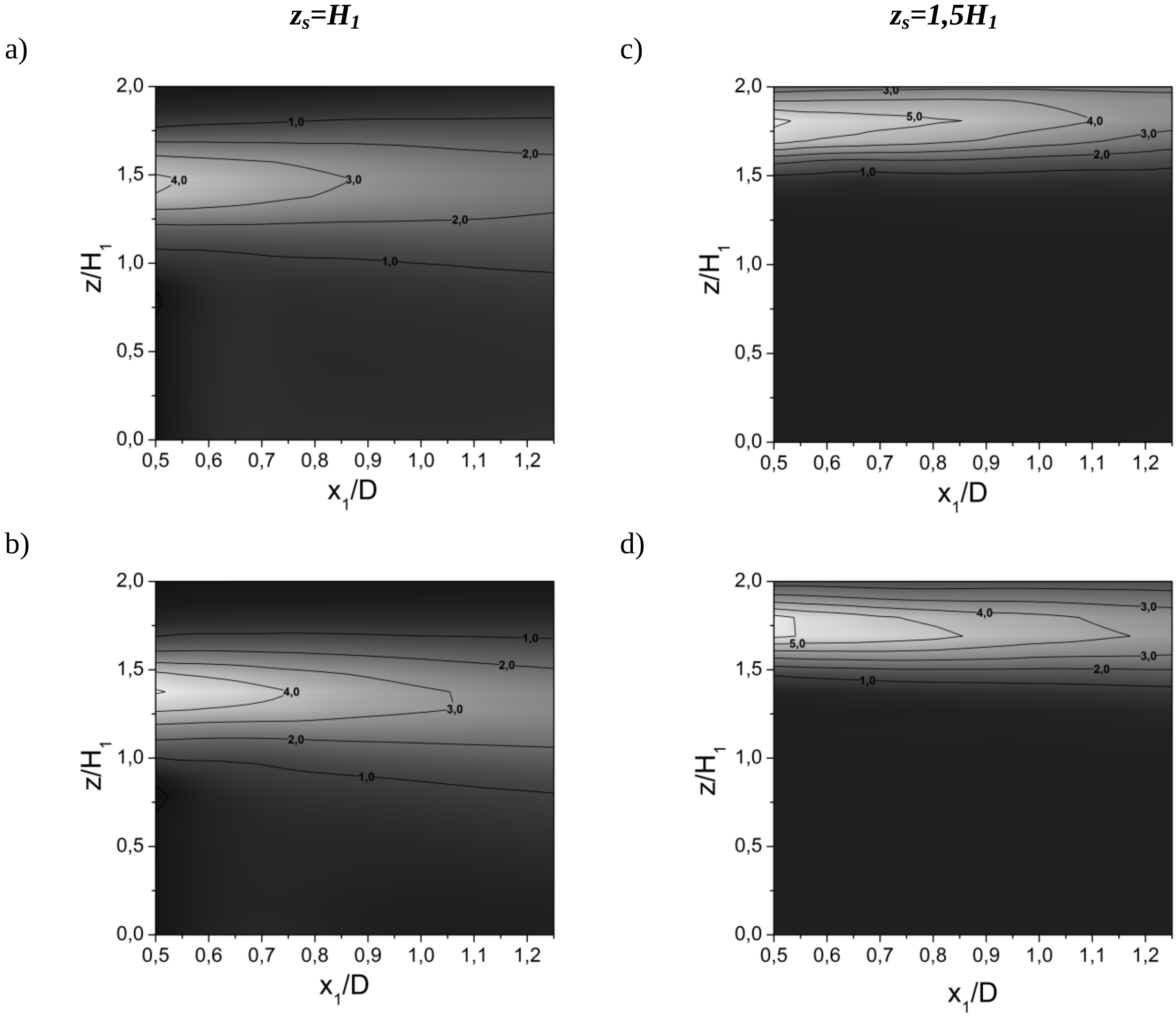
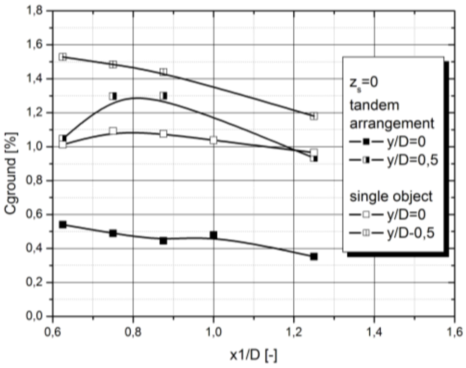


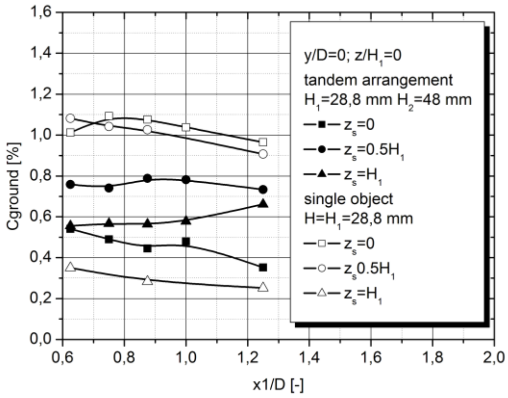
Figure 5. *Distribution of mean concentration C [%] in the inter-obstacle gap for location of emission source $z_s=H_1$; a) and c) tandem arrangement $H_1/H_2=0,6$, b) and d) single windward object*

Quite different tracer gas (CO_2) distributions are found for the emission source height $z_s=0,5H_1$ and $z_s=H_1$. Qualitative agreement is observed, however some quantitative discrepancies are present. For $z_s=0,5H_1$ the maximum values of gas marker concentration in the tandem arrangement case are equal $C_{max}=2\%$, and for a single object $C_{max}=2,2\%$, while for $z_s=H_1$, these values are equal 4,5% and 5,5%, respectively. In addition, for $z_s=0,5H_1$ the maximum concentration values are slightly above the height of the first object, while for $z_s = H_1$ clearly above the height of the windward object. In both cases modifying effect of the leeward object presence on the distribution of the tracer gas in the gap between objects is very clear, although it has different character. It may be explained by different transport mechanism, i.e. for $z_s=0,5H_1$ gas marker is drifted by the upper and surface flow, while for $z_s=H_1$ case CO_2 transport is caused mainly by the upper flow. In the case $z_s=1,5H_1$ (Fig. 5cd) effect leeward building presence is minimal, mainly because the CO_2 stream is lifted over the object, thus the gas tracer concentration at ground level is $C_{ground}=0$.

a)



b)



c)

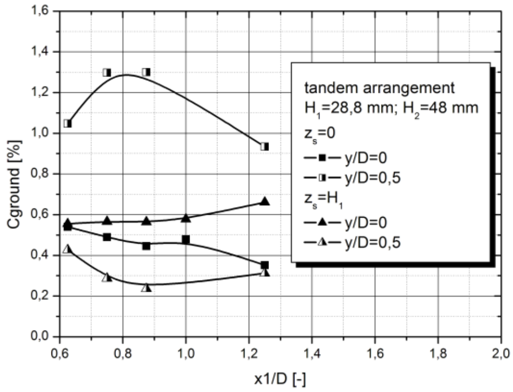


Figure 6. *Ground level concentrations for tandem arrangement and single windward object for y/D=0 and 0,5* and *different height of emission source z_s*

The level of tracer gas at ground in the axis of symmetry for different position of emission sources is shown in Fig. 6b, except $z_s=1{,}5H_1$ for which C_{ground} is equal to 0. For comparison corresponding results for a single object are also presented. One may notice influence of the emission source height as well as the object configuration on the tracer gas distribution at ground level. The highest and similar values of C_{ground} in case of a single object were estimated for $z_s=0$ i $z_s=0{,}5H_1$, while the lowest values were found for $z_s=H_1$. Only in the last case, the leeward object increases the level of CO_2 concentration at the ground. In other cases, for tandem arrangement lower values than for a single object are observed, but more than twice reduction in concentration at the ground level is observed for $z_s=0$.

However the problem of the location of emission sources and air intakes for ventilation systems in case of existing or proposed buildings is not straightforward.

For z_s=0 and the tandem arrangement we observe low level of tracer gas in the axis of the system (y/D=0), while approximately doubled along the edge (y/D=0,5) as it is shown in Fig. 6c. For $z_s=H_1$ the situation is reversed: the level of CO_2 concentration for y/D=0 is more than twice greater than for y/D=0,5. This confirms the important role of experimental and numerical modeling in spatial planning.

CONCLUSIONS

Wind comfort in built-up areas may be affected by a large range of parameters, mainly by wind velocity around building and adequate air quality. Those criteria are often in contraction, because ensuring proper air quality requires adequate ventilation built-up areas. Its effectiveness depends on wind direction, building configuration and location of emission sources.

The presented results showed that the appropriate location of buildings and the emission sources is very important especially taking into account human health and wind comfort. The choice of emission source shape and size may positively influence on the pollutants dispersion emitted in building environment and in turn may lead to improved air quality at the pedestrian level. The performed experimental and numerical research was aimed primarily at the development of the existing knowledge of the interaction between objects located on the ground and its influence on the pollutant dispersion. Such studies may contribute to the better understanding of physical processes and provide necessary information for the development of numerical modeling.

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