LOCAL WIND AND RAIN CONDITIONS IN SEMI-CLOSED NARROW CORRIDORS BETWEEN BUILDINGS

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ABSTRACT

Presented work is devoted to numerical analysis of wind flow in vicinity of recently renovated historical building. The analysed building is a part of larger old post industrial complex transformed into cultural centre. The original building was completely exposed to external climatic factors. During the recent modernization, the new buildings were built around the existing one forming external, narrow corridors.

In the first part of this study several cases of different layouts and dimensions were analysed and compared with the original case (building fully exposed to external weather conditions). The analysed environmental parameters were limited to direction and intensity of wind and rain according to climate weather database.

In order to investigate the wind flow pattern in narrow corridor around analysed building numerical simulation have been done using *realizable K - ε* model. CFD simulations provided wind directions and velocities on several levels of the corridors. Initially the analysis were done for constant inlet wind speed 5m/s and two wind directions. From the obtained results the most favourable and unfavourable wind directions were identified based on the following criteria. Finally, west wind direction was chosen for further analysis of wind flow in the existing corridor.

INTRODUCTION

The renovation of old, post industrial areas in the city centres has many different aspects and used to be recognized as a part of sustainable development. In nineteenth and in the beginning of twentieth century industrial zones were closely connected with residential areas. Following urbanization process many of them found themselves in city centres, wrapped by new building. Density of buildings in former, industrial areas became higher as the result of revitalization processes and economical factors. Such an increase of building density can have distinctive impact on local microclimate. Therefore, the detailed analyses of environmental conditions and microclimate parameters, within new urban structure are essential during architectural and urban design.

The average life span of a building usually exceeds 100 years. If this statement is true let's consider the length of life cycle after revitalisation. Is it possible to extent it for another one hundred years and how to achieve this in a most efficient way? Simulation techniques may offer the answers for such questions. Moreover, obtained results should allow possible mistakes and subsequently damages of building materials or structures to be avoided.

Before and after modernisation, a building envelope is under the continuous influence of external and internal climatic conditions. External factors are determined by weather parameters such as wind, air temperature and solar radiation. On the other hand there are many internal factors associated with building occupancy, especially heat and moisture gains. These parameters may change significantly in the case of buildings adopted to the new functions e.g. old factories transformed into loft apartments. In such cases attention should be also paid to air pollutions transferred into building elements by heat and mass exchange processes. The surface layer of ceramic wall can be removed by mechanical tools to obtain smooth finish. However such a removal may facilitate rain water penetration in masonary wall. All factors mentioned above cause slow deterioration of construction materials depending on their resistance to environmental factors.

The presented study is devoted to problems of simultaneous effect of wind and rain on vertical, external partitions of revitalised, historical buildings. Special attention has been paid to unusual behaviour of air stream in passages between buildings.

CFD ANALYSIS OF WIND FLOW AROUND BUILDING

In urban areas, due to the interference of buildings, the near ground flow exhibits sudden changes in speed and direction, which are difficult to predict. The wind flow around buildings is the result of complex interaction between the wind (mean vertical speed gradient, turbulence) and the buildings themselves (shapes, sizes, position etc.).

In front of the building, wind speeds are lower due to positive wind pressure gradient. When the mean wind speed of the Atmospheric Boundary Layer meets the windward face of the structure it diverges. Part of the flow deviated over the building and part of it flows around the building. At the windward face the flow at about 70% of the building height form the front stagnation point with maximum pressure. From this point flow is deviated to the lower pressure zones of the façade. Part of the flow goes down until it reaches the ground where it forms a large vortex (Fig.1). The air entering the vortex escapes around the building corners where separates and create corner streams. Flow in this area is considerably faster than the incident wind at the same height. Pressure at the upwind edge of the building sides is highly negative due to the separation of flow and becomes less negative with downwind distance (Cook, 2000).

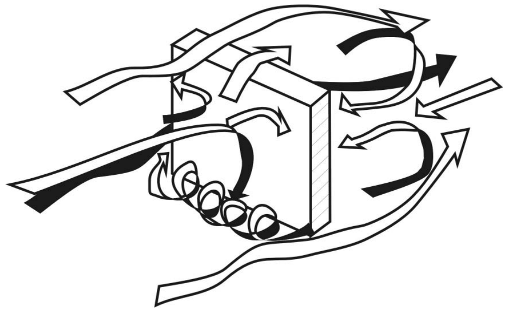

Figure 1 Wind flow pattern on windward face

In the lee of the structure, a large separation of flow occurs and a recirculating wake is formed. It is responsible for the creation of vortices behind the building. In the area located between these vortices and corner streams a zone with high velocity gradients occurs. The flow in the lee of bluff structures is very unsteady with the vortices described in the wake of a building being periodically shed.

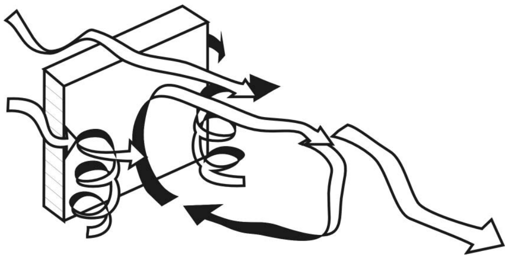

Figure 2 Wind flow pattern on leeward face

The presence of multiple buildings with different configurations and dimensions complicate the wind flow and give rise to local increase in wind speed and turbulence. As a result even for a single wall different characteristic of wind speed and direction can be observed.

Architects and engineers require detailed data on the wind flow characteristic in the vicinity of the buildings to protect the building envelopes against deterioration caused by local outdoor climate Application of numerical simulation allows prediction and assessment of wind flow in complex urban environment (Bottema, 1993), (Wisse et al., 2002) . One of the advantages of CFD is fact that it directly yields the detailed wind flow at every point in vicinity of analysed buildings.

Numerous wind tunnel experiments and CFD calculations determined influence of building configurations on forming characteristic aerodynamic effects (Baskaran and Kashef, 1996), (Peterka et al., 1985). It allows for indication of zones particularly exposed to disturbances in wind flow like passages between buildings and through buildings. These areas were analysed among others by (Stathopoulos and Storms, 1986) (Blocken et al. 2005) (Wiren, 1975).

Although Computational Fluid Dynamics (CFD) has been developed over twenty years ago there are still several problems with practical applications of numerical solutions. Difficulties with modeling interaction between atmospheric turbulence and turbulence flow generated by structures in the areas where flow separated can lead to uncertain or sometimes even erroneous predictions. Therefore the existing turbulence models need to be constantly improved and validated (Murakami et al., 1997) (Shih et al., 1995). Nevertheless in some cases application of CFD methods can give satisfactory results. These are mainly cases related to environmental issues such as pedestrian level winds, snow dispersion and accumulation, dispersion of pollutants in the near-building and urban environment (Westbury et al., 2002).

DRIVING RAIN DISTRIBUTION

One of the climatic factors, which has the serious effect on performance and durability of facades is driving rain. As the one of the main sources of the moisture in building partitions it contribute to many destructive processes like frost damage, rain penetration or salt migration. In order to assess its impact on vertical building façade the simultaneous effect of wind and rain has to be considered.

The intensity of horizontal rain R_h is described by amount of rain water falling through a horizontal plane during a certain period of time in open field (without any obstruction of the buildings). The free wind driving rain R_v passing an imaginary vertical surface is a function of the horizontal rain intensity, wind speed and the terminal velocity of the raindrop.

$$R_v = R_h \cdot U \cdot u_t^{-1} \qquad (1)$$

R_h – intensity of horizontal rain [mm/h];
U – wind speed [m/s];
u_t – terminal velocity of the raindrop [m/s]

In real condition rainfall consists of different fractions of raindrops depending on many factors like rainfall intensity or relative humidity. In practice it is assumed that drop size distribution is a function of the rainfall intensity. According to Best (1950) for small intensity rain R_h<10mm/h, average diameter of raindrops is about 2mm. In the case of heavy rain 10mm/h<R_h< 100m/h, diameter varies between 2 and 3mm.

The terminal velocity of the raindrop depends on their size. The larger the raindrop, the faster it fall and the higher is its terminal velocity. The falling velocity of raindrops of different sizes has been studied by Gunn and Kinzer (1949).

In the real condition falling raindrop is under the influence of horizontal velocity characterized by turbulent inner structure. Thus, wind component of the driving rain is not a constant value. This phenomenon causes unequal increase in wind pressure and consequently different intensity of driving rain on vertical building wall. The actual driving rain intensity on the building facade depends on many factors like building geometry, position of the envelope or local wind speed.

In order to asses the effect of driving rain on building wall the local intensity coefficient is introduced.

$$B = \frac{R_{vb}}{R_v} \quad (2)$$

R_{vb} – the wind driving rain intensity at given point on vertical building wall [mm/h];

R_v – the free wind driving rain (open field) [mm/h]

COUPLED HEAT AND MASS TRANSFER

Coupled heat and moisture transport in building elements (Häupl P. et al. 1994) can be simulated using advanced numerical model. CHAMPS (Bomberg et al. 2006) or WUFI (Künzel H.M. 1995) are examples of computer software dealing with the effect of driving rain on building envelopes. External boundary conditions are determined by climatic condition (meteorological data). Occupancy impact profile (heat and moisture fluxes) defines boundary condition of the inner side. Moisture mass flow is usually determined by vapour diffusion (mass and enthalpy of the diffusive water vapour flux), wind driven rain and water contact (mass and internal energy of the liquid water flux). Using the standard rain model, the rain flux density normal to the wall surface is calculated from the rain flux density on a horizontal plane, the wind direction and the wind velocity using the wall parameters orientation and inclination. The following weather parameters are neccesary:

- rain flux density on a horizontal plane,
- wind direction of ambient air,
- wind velocity of ambient air,
- temperature of ambient air,
- relative humidity of ambient air.

Knowing the rain flux density normal to the wall surface the liquid water flux over the boundary can be calculated. The maximum liquid water flux over the boundary is determined by multiplication of the liquid water conductivity of the material with a capillary pressure gradient calculated from the difference of the moisture content in the surface volume element to its saturation value (immediate surface saturation is assumed in case of rain penetration).

The results of water content distribution in ceramic, brick wall obtained using CHAMPS model is presented in Figure 3.

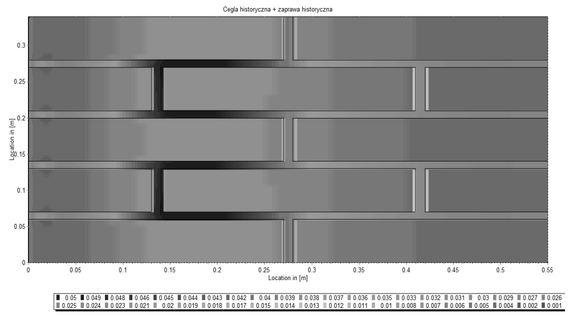

Figure 3 Water content in brick wall with lime-cement mortar

WIND FLOW AROUND ENCLOSED BUILDING

Multiple transformation in urban grid, with retained historical buildings, result in localised increase in town densities. Protection of cultural heritage and on the other hand increasing prices of the ground in downtowns creates new modern structures in the close neighborhoods of the old ones. If they do not have a common wall, minimum distance between them results in creating new, inner open spaces (few meters wide). Usually, they have a form of joining corridors but sometimes are inaccessible. Depending on geometry of building arrangement different flow patterns can be observed. In comparison with a wind flow around a single building the air movement in more complex structures is characterised by local disturbances in wind speed and direction.

Geometry and lining shape of the new buildings can be divided on three general types (Fig. 4):

- sheltered by one side (screened),
- sheltered by two sides (semi surrounded),
- sheltered by three sides (nestled).

For the purpose of the presented study the dimensions of existing building (case 0) was assumed to be 10×10×10 meters. Other cases (from 1 to 3) were created by adding new surrounding elements as presented in Figure 4.

The distance between existing and additional building is determined by national level regulation and conditions, height and local interactions between buildings.

The joint effect of wind and rain on building façade depends among other things on the distances to neighbourhood buildings. According to Oke (1988) for winds roughly perpendicular to the canyon three basic flowing regimes can be identified.

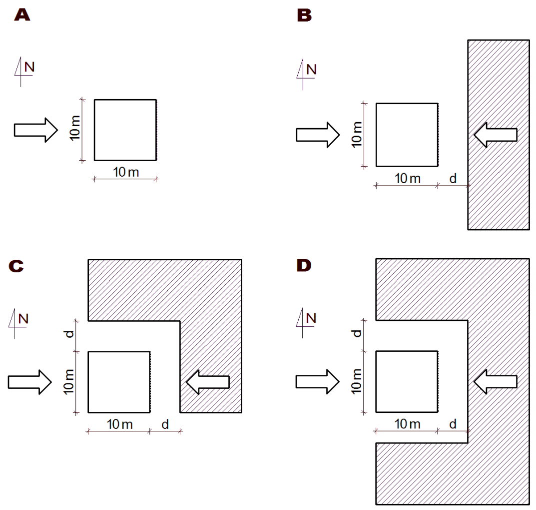

Figure 4 Analysed cases of main building and its surrounding

Isolated roughness flows. If the value of the building height to street width ratio (h/d) is less then 0.4 the flow zones of each building are separated and the buildings do not influence on each other.
Wake interference flows. In the case of 0.4<h/d <0.7 the wake of upstream building disturbs flow field of downstream structure.
Skimming flows. If h/d>0.7 majority of the flow "skimming" above the top of the canyon but in the same time inside the canyon trapped vortex can be observed.
In the analysed cases only narrow passages were taken into account. Three distances between buildings were examined ¼h, ½h and 1h (d = 2.5, 5 and 10m) (Fig. 4).
Considerations were limited to the west and east wind directions. The main aim of the study was local wind condition in the narrow passage between buildings. Therefore the wind speed were analysed on the vertical plane located 0.5m from the east elevation of existing building (Figure 4).
In order to predict steady – state wind flow pattern around the buildings CFD technique has been used.
Analyses have been done using realizable K - ε model developed by Shih (et.al.1995) and wall function. It has been found that for wide range of flows including separated flows realizable K- ε model perform better than standard model (Shih et al. 1995). The wind simulations are performed on an unstructured tetrahedral grid with about 900000 cells. A higher mesh density has been defined in the vicinity of the buildings.
In the inlet of the computation domain logarithmic mean wind profile has been established.

$$u = \frac{u^*}{0.4}\ln\left(\frac{z}{z_o}\right) \qquad (3)$$

u^* - shear velocity[m/s];
z – height [m];
z_0 – roughness length [m]

As the reference wind speed u_{10} = 5m/sec (at an altitude of 10 m above the ground level and on a field with z_o = 0.03m) has been assumed. Taking into account the updated Davenport classification (Wieringa 1992) roughness length z_o has been assumed to be 0.25m (for rural area). Building roughness was taken as 0.002m.
The dimensions of the computational domain differ in accordance with analysed case and direction of approaching flow. In all cases the dimensions of computational domain had to meet the following conditions. The distance from the built area to inlet, top and lateral boundaries were equal to 5h (where h – height of the building), to outlet boundary – 10h.

WIND CONDITIONS AROUND ENCLOSED BUILDING - RESULTS

Analyses of wind conditions were based on vertical profiles of wind velocities located in the central line of the wall and in the distance of 0.5 from the façade. Independently of wind direction introducing new structures cause local increase in wind speed near the analysed wall.

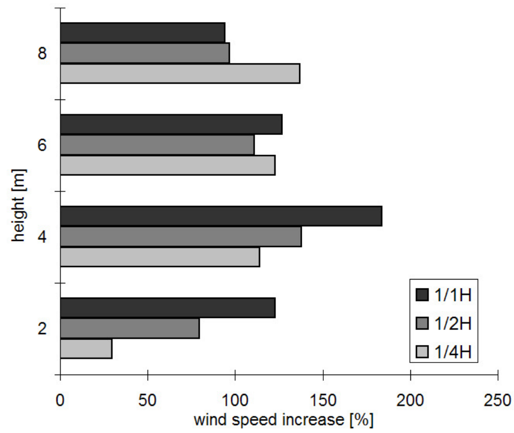

Figure 5 Average wind speed increase for different width of the passage

Results presented in Figure 5 were cumulated and averaged for each wind directions. In the lower part of building façade (2 and 4 meters above ground level) the highest speeds were obtained for passage width equal to buildings height (almost 200% of wind speed for base case – case A). On the other hand on the top of the façade (at 8m) the worst conditions were recorded for 1/4h. Relatively high wind speed (more than 100%) at attic level were noticed also for other cases.
In some cases wind speed distribution in front of the wall demonstrates considerable spatial diversification. It can be clearly seen for type C (semi surrounded building). The neighourhood buildings reflect and accelerate the flow in the passage especially when d=2.5m. Figure 6 presents an example of assymetric wind speed distribution in vicinity of the façade.

Increasing the distance between buildings to 10m result in gradually reduction of spatial differences of wind velocity. In the case of other types of building arrangement and wind directions distribution of wind speed has more even character as can be seen on Figure 7.

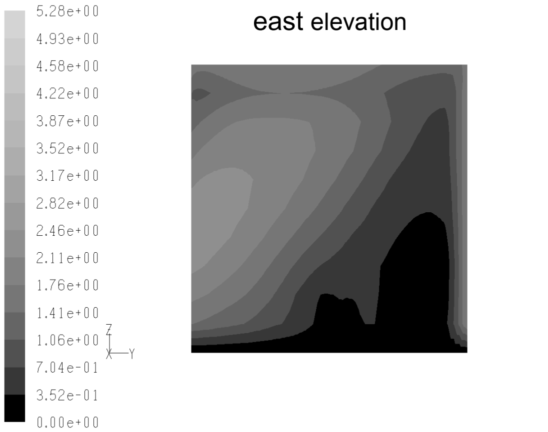

Figure 6 Contours of wind velocity in the vertical plane 0.5m from the east façade (case C, d=2.5m, west wind direction)

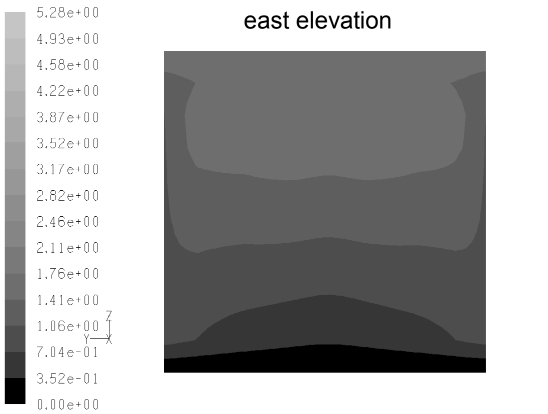

Figure 7 Contours of wind velocity in the vertical plane 0.5m from the east façade (case D, d=2.5m, east wind direction)

TYPICAL WIND & RAIN WEATHER CONDITIONS

Climatic conditions can be defined by a total of 20 variables. The following nine parameters describing the conditions of the outdoor climate are usually considered during analysis of heat and moitures transfer in building envelope ie.: temperature, relative humidity, direct and diffuse solar radiation, wind direction and speed, pressure, cloud cover and rain density. Sets of climate parameters can be obtained using long-term meteorological data. Weather data colected by meteo stations are obtained ususally from open area. The wind is measured at gound level of 10 meters. It means that for exact numerical model the weather conditions should be modified including the way of the wind from measured point to building façade.

Three meteorological parameters are used to determine the quantity of rainwater reaching the external wall surface - wind direction, degree of cloud cover and type of rain. Precipitation occurrence as well as its type and intensity were specified in the precipitation file. Additional weather parameters for which data sets were determined comprised wind speed, dry-bulb thermometer temperature, relative humidity, intensity of direct and diffuse solar radiation and total pressure.

The weather data file were rewised regarding the rain intensity and wind flow (speed and direction). The probability density function of rainfall (based on measured data) are presented in Figure 8. This profile shows that for analysed local climate the probability of rainfal is for wind speed between 1 and 4 m/s. Above 10m/s the rainy weather is exceptional.

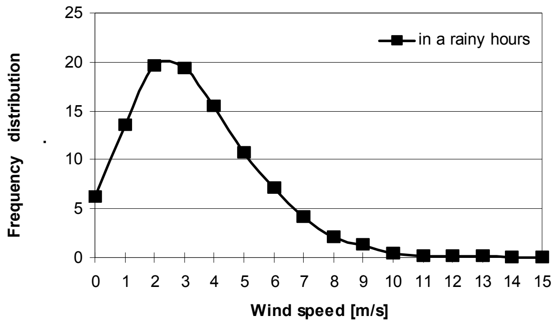

Figure 8 Frequency distribution of wind speed for rainy hours during Typical Meteorological Year

Considering the wind direction (Figure 9) the superior wind during rainy periods comes from west and west-south. It means that south and west elevation for single building will be the most exposed on rainwater induce.

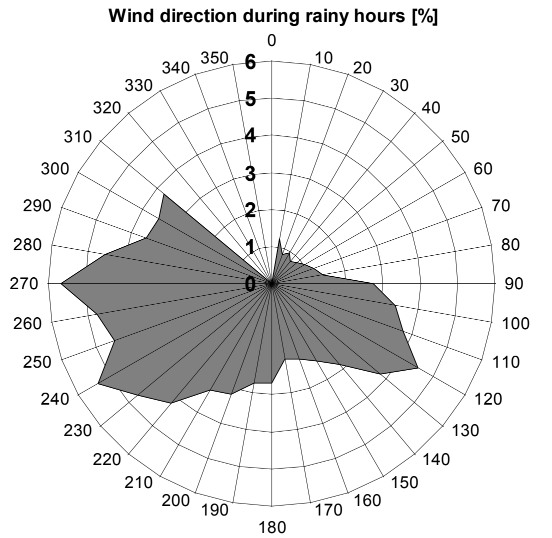

Figure 9 Wind rose for rainy hours during Typical Meteorological Year

POST INDUSTRIAL BUILDINGS

The unique character of 100 years old post industrial buildings results from masonry bricks elevations with precise ornamentation and sophisticated details. The proper restoration should retain and reconstruct the original structure of the walls. Any changes of wall properties such as adding of new layers (insulations or plasters) is at variance with cultural heritage protection. Therefore the wall structures as well as geometry of external surface have to remain unchangeable. An example of such detailes is presented in Figure 10.

Figure 10 Architectural details of XIX century buildings after restoration

The complicated geometry of wall elements causes physical processes more complex (Heim & Klemm 2008). There are a lot of environmental factors which determined the magnitude of this effect. One of them is the air flow around building and single elements. The higher roughness of the wall creates small zones characterized by low speed and turbulent wind flow with small eddies. On the other hand near the sharp edges of the architectural elements the flow accelerates creating different conditions for the heat exchange processes (convection). The second factor which is an additional source of heating energy during a day is solar radiation. When the surface is completely flat and exposed the effect of sun beam radiation is even. But when the geometry becomes more carving the sticking elements obscure part of the wall causing difference in temperature between shadow and full sun areas (spatial temperature distribution on wall surface). The acces of solar radiation and temperature differences on the selected elements are also connected with availability of water evaporation from external surfaces.

CASE STUDY – WIND FLOW IN NARROW CORRIDORS

Case study presented here is based on a complex of two buildings located at *Manufactura,* post-industrial zone in a centre of Poland. The renovated building is an old textile factory converted into museum. From north and west side it is surrounded by new commercial centre. The passage formed by the buildings is very narrow, about 4.5 meters wide, what corresponded to 1/5 of the building height. In the result of revitalization the north façade of the museum was nearly completely obscured. However the historical character of the wall composition (windows, ornaments etc.) was retained. The unique character of analysed case is visualized on Figures 11 and 12.

Figure 10 Passage between buildings

Figure 11 North elevation of the old factory

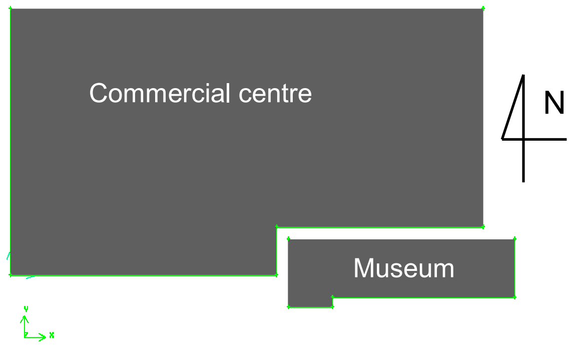

Figure 12 Spatial model of analysed buildings

Spatial model of analysed buildings is presented in Figure 12.

The dimensions of the museum building are: W=85m, L=25.5m, H=20m and commercial building W=177.5, L=100m, H=14m.The wind flow pattern in the narrow passage between analysed buildings was examined by numerical simulation. Special attention has been paid to wind speed characteristic in close neighbourhood of north façade of museum building.

As the west wind direction is dominant analyses have been limited to this particular case. The general wind flow pattern has been presented in Figures 13 and 14.

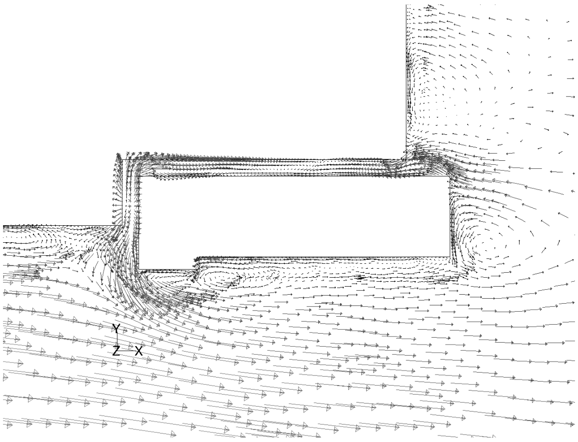

Figure 13 Wind flow pattern in the passage of analysed buildings. Velocity vectors in the horizontal plane at 3m above the ground.

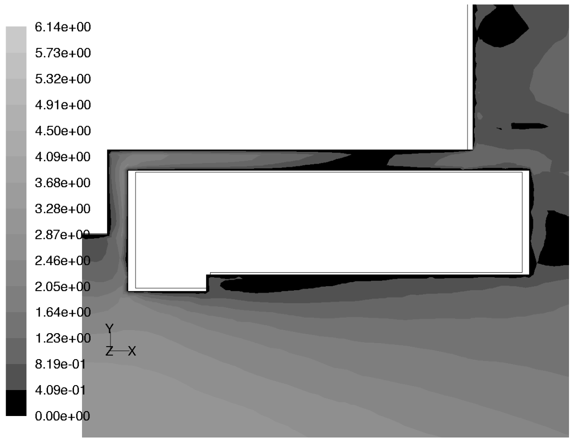

Figure 14 Contours of wind velocity in a horizontal plane at 8m height above ground

When the approaching wind meets the western facade of the museum the flow separates and escapes around the building corners. Part of the flow got inside a narrow passage and moves towards the wall of commercial centre building. In the corner of the passage the flow violently accelerates and changes the direction for parallel to the north façade of the museum. Additionally it merges flow deflected from commercial building. The moving air gradually slows down and in the central part of the corridor it reaches the lowest value. Near the east side of the wall another increase in wind speed can be observed, caused by corner streams. In the leeward side of the analysed building recirculating flow separates from the corners and turn back into the passage. Disturbances in wind flow in narrow corridor between buildings can also affects pedestrians comfort. Steady winds can interfere with people's activities by affecting their balance, walking, hair, clothes etc. Wind conditions near building corners can be dangerous because of very sudden changes in wind speed and wind direction. A sudden increase of wind speed to 15m/s or more can be sufficient to bring people out of balance [Murakami et al. 1980].

SIMULATION RESULTS

In order to investigate the influence of surrounded building on local wind conditions detailed analyses have been done for the north façade of the museum. Figure 15 presents wind velocity distribution in vertical plane in the distance of 1m from the wall.

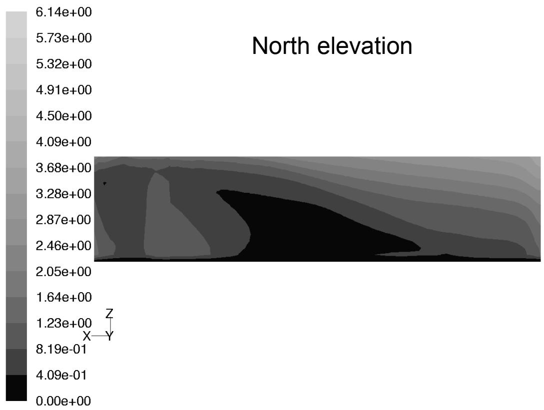

Figure 15 Contours of wind velocity in the vertical plane 1m from the north façade

Wind velocity distribution in the close neighbourhood of the analysed façade has a clearly asymmetric character. In the vicinity of the western edge high gradients of wind speed can be observed as the result of flow acceleration in corner streams. The main direction of the wind is in accordance with general western flow. In the central part of the wall there is a large zone characterised by low velocities and change of wind direction. Near the ground the air flows along the wall from eastern direction while in upper parts it starts to go up. Due to flow separation near eastern corners of the building another increase in wind speed appears. In this case the effect is not so strong but it result in another change in wind direction, which can be seen in Figure 16.

As can be seen from the above analysis the wind flow characteristic in the vicinity of the sheltered wall has a complex character. There are noticeable differences in wind speed distribution within the wall. The maximum differences in wind speed within the wall reach 3.14m/s. Apart from the change in wind speed there are also significant disturbances in wind direction.

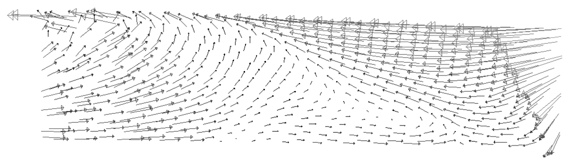

Figure16 Velocity vectors in vertical plane 1m from the north facade.

FINAL REMARKS

This study is a part of extensive research project devoted to stability of existing buildings in renovated urban zones. One of the factors, which have a significant influence on this process, is wind. In presented paper wind flow pattern in narrow passage created by different buildings arrangement have been assess. In all analysed cases increase in wind speed in passage between buildings were observed. In some situations it exceeded four times values obtained for isolated building. Depending on assumed geometry the highest increases were recorded in central and upper part of the wall. Variations in wind velocities were observed not only in vertical profiles but also in whole plane of the façade. The similar tendency took place in the case study of revitalised postindustrial building.

In analyses of wind driven rain changes in wind speed and wind direction in front of the façade should be included. Especially in the case when analysed wall is surrounded by other buildings. This problem can be very important in modern cities characterised by dense and complex building development.

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