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WIND INFLUENCE ON A BUILDING WITH THE NATURAL SMOKE REMOVAL SYSTEM

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Abstract

The natural smoke removal is a common way of protection of the escape routes in Poland. The operation of such systems is based on the phenomenon of buoyancy. The intensity of this effect depends on the temperature difference between smoke and ambient air. The second factor influencing the natural smoke flow inside a building is wind. The wind influence is significantly important for buildings equipped with smoke removal windows. However, also the other natural smoke removal systems could be affected by the wind impact under adverse ambient conditions.

There are the features of the wind described in the first section of the paper. Next, the impact of the wind on a building is shown. Two wind speeds and two wind directions were considered. A building model in the extended computational domain was built. The model was solved with the use of Ansys Fluent. The distributions of dynamic pressure caused by the wind on different facades of the building were presented. The particular attention was paid to the dependence of pressure distribution on the wind direction.

Streszczenie

Oddymienie naturalne budynków jest powszechnym sposobem ochrony dróg ewakuacyjnych w Polsce. Działanie systemu opiera się na sile wyporu termicznego. Wielkość tej siły uzależniona jest od różnicy temperatury miedzy temperaturą dymu a temperaturą otoczenia. Drugim czynnikiem wpływającym na naturalny przepływ dymu w budynku jest wiatr. Oddziaływanie wiatru ma największe znaczenie dla budynków wyposażonych w okna oddymiające. Jednakże również pozostałe systemy oddymiania naturalnego mogą w niekorzystnych warunkach pozostawać pod wpływem działania wiatru. W pierwszej części artykułu omówiono cechy charakterystyczne wiatru. W dalszej kolejności pokazano jaki wpływ na budynek może wywierać wiatr. Rozważono dwie prędkości napływu wiatru oraz dwa kierunki napływu. Zbudowano model budynku wraz z poszerzona domeną obliczeniowa. Model rozwiązano wykorzystują program Ansys Fluent. Zaprezentowano rozkłady ciśnień, które mogą tworzyć się na fasadach budynku w przypadku działania wiatru na budynek. Zwrócono uwagę na wpływ kierunku napływu wiatru na tworzący się na fasadach układ ciśnień.

Keywords: Natural smoke removal; Wind influence; Ansys Fluent.

1. INTRODUCTION

The smoke removal systems are common method of support rescue teams and protection of partial evacuation in the case of fire. They can operate naturally or can be supported mechanically. In the mechanical systems a supply fan causes the inflow of compensation air or a smoke removal fan drains the smoke from the protected volume. In the natural systems the smoke outflow is forced by thermal buoyancy.

The natural smoke removal systems are willingly used in Poland. The main components of such system are smoke removal vents located on the roof or smoke removal windows located on facades, aeration inlets or simply the entrance door. Such systems are applied in public utility buildings and public housing, as well as some low-rise buildings or in large-volume objects.

The use of smoke removal windows in this system according to EN 12101-2 requires that they are placed on two facades and work together with a wind detection system [1].

Since the natural smoke removal process is based on thermal buoyancy, it is strongly affected by the ambient conditions [2, 3]. The natural smoke removal process is affected by ambient temperature and wind speed and wind direction. The natural smoke removal will go on properly if thermal buoyancy is the prevailing factor, which determines the conditions in a staircase or inside a large-volume building. However, if the power of developing fire is too low or the wind impact is high the process of natural smoke removal will be significantly disturbed [2, 3, 4, 5, 6]. Many researches proved that wind had considerable influence on smoke migration due to causing additional pressure on the facades of a building [2, 7, 8, 9, 10].

The influence of ambient temperature, which determines the intensity of thermal buoyancy is well known and easy to specify. The wind impact is much more difficult to determine. The problems of estimation of wind impact arise from high variability of wind phenomenon in time (it concerns both speed and direction) and next from complex nature of wind influence on a building, where such features like building height, its shape, tightness of its outer shell and its surroundings are of great importance.

The intensity of thermal buoyancy given as additional pressure can be determined as follows:

$$\Delta p_B = \left(\rho_{out} - \rho_{in}\right) \cdot g \cdot h \tag{1}$$

where:

- the ambient air density, kg/m^3 ; ρ_{out}

- the density of inner mixture of air and *O*; smoke, kg/m³;
- gravitational acceleration, m/s²; g
- h - building height, m.

Assuming air to be ideal, but incompressible gas - the pressure changes are too low to cause density changes, one can obtain the formula expressing relation between temperature and density:

$$\rho_2 - \rho_1 = \rho_1 \left(\frac{T_1}{T_2} - 1 \right)$$
 (2)

where ρ_1 , ρ_2 denote air densities at temperatures respectively T_1 and T_2 .

The pressure exerted by the wind (dynamic pressure) can be calculated from the equation: e:

$$\Delta p_W = \frac{1}{2} \cdot c_p \cdot \rho_{out} \cdot v^2 \tag{3}$$

- wind pressure coefficient, C_p

- wind speed, m/s. υ

For simplified analyses the value of c_p can be assumed as constant for each of building facades in dependence of relation of a facade to the wind direction. Actually the value of c_p factor slightly varies in dependence on type of surrounding terrain. The full set of values of c_p factor for different wind directions and for all building facades can be found in literature [11].

2. WIND FEATURES

The wind is the movement of atmospheric air with prevailing horizontal component. It is caused by nonequilibrium distribution of atmospheric pressure due to uneven heating of Earth surface by solar radiation. This process is unstable, so air movement along Earth surface is a very turbulent flow.

There are two main features describing the wind: presence of gusts and vertical velocity profile. A gust is a momentary random change of the wind speed or the wind direction. The gusts can be observed in Figure 1, where the rapid changes of speed and direction at three heights above ground are presented. Figure 1 shows the average wind speed, maximum wind speed and its direction at heights of 10 m, 30 m and 100 m.

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Figure 1.

Variability of wind speed and wind direction. The data are obtained from the station belonging to the Department of Climatology at the Department of Earth Sciences at the University of Silesia in Sosnowiec

The second important wind feature is the dependence of the average speed on the height above the ground, it is known as vertical wind profile. Vertical wind profile depends on the type of terrain surface, which can be described as roughness.

The air flow just above the terrain surface is disturbed due to obstacles such as buildings, hills or forest. Thus the wind speed in this superficial layer is decreased and it gradually increases with the height due to viscosity. The common empirical formula describing the vertical wind speed profile can be used:

$$v_x = v_0 \left(\frac{h_x}{h_0}\right)^{\alpha} \tag{4}$$

where v_0 denotes the known wind speed at height h_0 (upper wind) and v_x is the sought wind speed at height h_x .

The exponent α depends on the roughness of surrounding terrain and on the wind speed (it is not strictly constant). Generally it can take values ranging from 0.1-0.6, the more rough the surface is, the greater value of α should be assumed. For weak upper winds (of speed smaller than 4 m/s) the value of α is often assumed to be greater than 0.4, for stronger upper winds the values of α close to 0.1 are appropriate [12]. Figure 2 shows examples of wind profiles for two speeds of upper wind and different values of α .

Despite of discussed above high wind variability there are some statistical regularities, which are typical for given region. A wind rose is a chart which shows the contributions of winds blowing from different directions. Figure 3 presents the wind rose for Katowice, a city in southern Poland.

As well as wind directions contributions the informa-









Cumulative distributions of wind speed for Katowice

tion on typical wind speeds is important from the considered point of view. Figure 4 presents the cumulative distributions of wind speeds for Katowice.

As it can be seen most of the time the winds are rather weak or moderate. Really strong winds (over NVIRONMEN

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12 m/s) are very rare. Both charts were prepared basing on data available on the website of Ministry of Infrastructure and Construction [13].

3. NUMERICAL MODEL

As it was shown by equation (2) the dynamic wind pressure strongly depends on the wind direction and obstacle shape. The applied coefficient can take both positive and negative values. To examine the issue accurately a numerical model was built and solved with the use of Ansys Fluent, which is willingly used in airflow issues [14, 15]. The numerical analyses for 4 cases were conducted. The examined building was assumed to be of cuboidal shape, the dimensions of its base are 20 m x 10 m, the height is 30 m. The whole computational domain is much larger: it is a cube of edge of 60 m. It is to avoid the flow disturbances at the boundaries (Figure 5).



One of the walls of the computational domain is of type "velocity inlet" to model the wind, all other side walls are of type "pressure outlet". There are two User Defined Functions (UDF) applied:

- to introduce the vertical wind profile according to equation 4 (for "velocity inlet" plane),
- to model the variability of the static pressure with the height above the ground, according to the formula $p_x = p_0 - \rho_{\text{ghx}}$ (for all side planes of the domain).

The air is assumed to be ideal gas – its density depends on temperature and pressure.

The mesh was created with the use of "cut cell"method, what allowed to obtain almost regular mesh. The computational domain was divided into 220 000 cells, the mesh in the close vicinity of the building was much more dense (edge size less than 0.5 m) for better reproducing the airflow near the building walls. The minimum orthogonal quality of the mesh was 0.27, while the lowest recommended value is 0.1 [16].

The k-epsilon realizable turbulence model is applied because it is suitable for modeling of both free flows and flows near surface. The summary of the numerical model features is shown in Table 1.

The summary of the numerical model		
Feature		Value
Turbulence model		k-epsilon realizable
Fluid material		Air (ideal gas)
Operating pressure		101325 Pa
Operating temperature		288 K
Gravitational acceleration		9.81 m/s ²
Solver		Pressure based
Pressure / velocity coupling		Simple
Under-relaxation factors	Pressure	0.3
	Momentum	0.5
	Energy	0.9
	Others	Default

Table 1.The summary of the numerical model

4. RESULTS AND DISCUSSION

For detailed analysis of pressure distribution at facades of the building the numerical calculations were done for four cases (Table 2).

Analyzed cases		
Case	Windward facade	Wind speed, m/s
Case 1	Wide (front) facade	4
Case 2	Wide (front) facade	10
Case 3	Narrow (side) facade	4
Case 4	Narrow (side) facade	10

The wind flowing near the building changes its flow direction and speed, it generates as well eddies and regions of increased and decreased pressure. There are selected results concerning the distribution of air

Table 2



Figure 6. Distribution of wind speed around the building for case 2



Figure 7.





Figure 8. Distribution of dynamic pressure on building facades for case 1



Distribution of dynamic pressure on building facades for case 2

velocity shown in Figures 6 and 7. There are vertical symmetry plain of the system and horizontal plane located at half of building height selected in all below figures for visualization purposes.

Figure 6 visualizes the vectors of wind speed for wind blowing on wide façade (upper wind speed equal to 10 m/s). The stream separation and wind speed rise are visible over the roof. Behind the building, on leeward the speed decreases and small eddies can be observed. They cause the pressure decrease on leeward.

Next figure (Figure 7) visualizes the vectors of wind speed for wind blowing on narrow facade (upper wind speed equal to 10 m/s, case 4).

If the windward facade is the narrow one, the distribution of air velocity around the building is changed in comparison with the case considered previously (Figure 6). The separation of the stream is less steep, although the eddies behind the building are larger.

The discussed above disturbances of air flow results in additional pressure (dynamic pressure) on building facades. This pressure in turn influences the smoke movement inside the building due to presence of openings.

There are pressure distributions for wind of speed 4 m/s and 10 m/s inflowing on wide (front) building facade shown in Figures 8 and 9. The zones of underpressure and overpressure are arranged similarly for both cases because the wind blows on the same facade. The absolute values of the pressure are obviously different, what arises from different wind speeds. Thus a finding can be formulated: in the N V I R O N M E N J

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Figure 10.





Figure 11.

case 4



Distribution of dynamic pressure on building facades for

Figure 12.

Dependence of the pressure due to buoyancy on the smoke temperature

examined range of wind speeds the value of wind speed does not affect the distribution of pressure zones but determines just the values of the pressure.

There are pressure distributions for wind of speed 4 m/s and 10 m/s inflowing on narrow (side) building facade shown in Figures 10 and 11. As for previous cases one can observe that the wind speed has no influence on distribution of dynamic pressure on building facades. The wind speed results just in different values of pressure generated on the facades. However, when comparing Figures 9 and 11 it can be observed that the difference between values of pressure generated on facades despite the wind velocity is the same in both cases and equal to 10 m/s. These differences on corresponding facades result from the facade which is selected as the windward one. If the wind blows onto wide (front) facade the generated overpressure is equal to 78 Pa. Whereas if the wind blows onto the narrow (side) facade the overpressure is lower and is equal to 40 Pa. Taking into account the pressure generated on the leeward facade it can be noticed that for wind blowing onto wide facade this pressure is near 0 Pa, while for wind blowing onto narrow facade the value of this underpressure is equal to 12 Pa.

Considering the interaction between wind and buoyancy the pressures generated by both phenomena should be compared. Figure 12 visualizes the additional pressure due to buoyancy in relation to the temperature of hot gases (according to the Equations 1 and 2, the height of the building is assumed to be 30 m). A simplifying assumption is that the smoke admixtures do not significantly change the density.

The vertical extend of shaded area corresponds to the range of pressures exerted by the wind in discussed above cases. Thus, if the temperature of the smoke is less than 100°C the wind would suppress the buoyancy effect. This can happen in the first stage of the fire development, which is the most important for evacuation. This can also take place when the fire is developing in a room far from staircase and the smoke is being cooled. Although winds strong enough to cause this effect are relatively rare (Figure 4) gusts can appear more often.

Another phenomenon can be mentioned here - isochoric process in a case when a room inside a building is tight. The overpressure resulting from air heating in such circumstances is many times higher than this caused by buoyancy. For instance, if the temperature difference is 100°C (the reference value is 20°C) the overpressure reaches the value of 340 hPa (according to the ideal gas state law). It means the

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smoke will be gustily ejected from such room into surrounding spaces. This can entirely change the considered situation, but such cases are rather rare and in real situation fire gases can spread freely.

5. CONCLUSIONS

The wind flowing in the vicinity of a building causes additional pressure at its facades. Depending on direction of wind inflow the underpressure or overpressure can emerge. Due to presence of openings in building shell the pressure emerged at the facades impacts on the inner pressure distribution. Eventually the additional pressure generated by the wind can strongly influence the smoke movement inside the building.

The above considerations are of great importance particularly in the case of building equipped with smoke removal windows. Obviously, the efficiency of facade smoke removal windows is strongly dependent on wind influence. High variability of speed and wind direction causes that placing windows on two facades cannot guarantee the reliability of their operation. If the wind inflows onto the facade with smoke removal windows their efficiency could drop to zero.

However, the wind influence could disturb as well the process of smoke removal by roof smoke removal vents. The high values of overpressure emerging on windward facade could lead to relative underpressure inside the building. If the developing fire is of low power the buoyancy could be too weak to overcome the pressure difference. In such situation the momentary wind speed and direction will determine the direction of smoke movement inside the building. Thus the natural smoke removal system does not ensure the proper operation in all cases. Anyway, the local weather conditions, particularly the wind rose and the cumulative distributions of wind speed should be taken into account at design phase of a natural smoke removal system. Such analyses should also take into account the surroundings of examined building because the nearby buildings can significantly change the wind distribution and then in consequence can affect the pressures generated on the facades.

Additional solutions may include the use of smoke extraction devices of a special design or the use of mechanical ventilation which will direct the flow of air towards the smoke vents.

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