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CFD PREDICTIONS OF INDOOR AIR MOVEMENT INDUCED BY COLD WINDOW SURFACES

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Abstract. During the past decades, large windows and glazed façades have become an important part of modern architecture and they are designed frequently in both public and residential buildings. However, besides the positive effect of such a design on building occupants, large windows may cause thermal discomfort. Cold inner window surface may generate draught in the occupied zone. Thermal comfort in rooms is usually assessed by measuring air temperature, relative humidity, air velocity and heat transfer due to radiation. In this study computational fluid dynamics (CFD) methods have been used to investigate these phenomena. Air movement caused by cold vertical window surfaces was evaluated and its impact on thermal comfort conditions in rooms have been outlined. Windows of different constructions and having different heat transmission coefficients were modelled (2.4, 1.6 and 1.0 W/m²K). CFD predictions showed that even in cases of low window thermal transmittance coefficient (U value), thermal discomfort conditions may appear in the room if the height of the window is more than 2.0 meters.

Keywords: thermal comfort, air movement, window, downdraught, CFD modelling.

1. Introduction

Human thermal comfort is influenced by a combination of physical, physiological and psychological factors. It is usually assessed by measuring air temperature, relative humidity, air velocity and heat transfer due to radiation. Occupants' clothing and activity levels are taken into account as well. It is documented that unsatisfactory thermal conditions lead to a reduced performance of office work by adults and to decreased children productivity in schools (Wargocki *et al*. 2005). Even a 1 % increase in productivity in commercial buildings gives a considerable financial benefit (Olesen 2005).

Glazed part of a building envelope has a significant effect on microclimate and building energy consumption. Windows may cause both local and overall body thermal discomfort leading to occupants' dissatisfaction and health problems. As it is well known, window replacement is a key action solving building refurbishment problems (Pikutis and Šeduikytė 2006). However, large windows and glazed façades are a part of the modern architecture and they are designed not only in commercial and public buildings, but in residential buildings as well.

Window induced thermal discomfort can be caused by radiation from the warmer body to the colder glass as well as by direct solar radiation through the glazed part of the window. In this paper only thermal conditions and air movement caused by natural convection were considered. Such factors as solar radiation and air leakage of the window are neglected.

In cold periods, temperature of the inner window surface is always lower than air temperature in the room. Therefore, cold vertical surface generates downward airflow. Ge and Fazio (2004) found that large tall windows may generate air speed up to 1 m/s (close to the surface). This problem is usually solved by installing heating devices below the windows. Airflow, caused by buoyancy forces, in such cases suppresses the downdraught effect. Given that the thermal transmission coefficient of modern windows is quite low (sometimes 1.0 W/m²K and less), the main objective of this study was to evaluate the scale of downdraught generated by windows of different constructions. The further task was to determine if it is necessary to install heating equipment below windows if its U value is lower than 1.0 W/m²K. Additionally, an analysis was carried out in several cases with high rooms having glazed façades (up to 5 m height) with and without convector heaters below the windows.

2. Factors having major influence on downdraught

The basic factors determining air speed close to the window are the height of the cold surface and the temperature difference between the surface and the air in the room. Heiselberg (1994) presented an empirical equation to calculate maximum air speed (close to the floor surface). It depends on the distance from the external wall or window (x value):

$$v_{max} = 0.055 \cdot \sqrt{\Delta\theta \cdot H}, \text{ if } x < 0.4 \text{ m}, \quad (1)$$

$$v_{max} = \frac{0.095}{x + 1.32} \cdot \sqrt{\Delta\theta \cdot H} \text{ if } 0.4 \text{ m} \le x \le 2.0 \text{ m}, \quad (2)$$

$$v_{max} = 0.028 \cdot \sqrt{\Delta\theta \cdot H} \text{ if } x > 2.0 \text{ m}, \quad (3)$$

where $\Delta\theta$ is the temperature difference between the inner surface of the window or wall and the air temperature in the room, H – the window or wall height.

The temperature of the inner window surface depends on the outside air temperature and window heat transmittance coefficient. In this study it was calculated as follows:

$$\theta_{si} = \theta_i - \frac{U \cdot (\theta_i - \theta_e)}{h_{si}}, \qquad (4)$$

where θ_i and θ_e are respectively internal and external air temperatures, U is thermal transmittance coefficient of the window glazing and h_{si} – the heat transfer coefficient at the inner surface of a glazing (considered 7.7 W/m²K).

Three types of window glazing and two cases of external conditions were analysed in this paper. Old fashioned, modern and well-insulated window glazing was selected and outside temperatures were set according to extreme conditions (–20 °C) and average conditions of the coldest month in Lithuania (–6 °C). Results of the internal surface temperature calculations for these cases are in Table 1.

Table 1. Calculated inner window surface temperatures that were used as the boundary conditions in CFD (subscripts indicates temperature difference between the inside air and the outside air)

Window type		U value, W/m²K	Inner surface temperature θ_{si} 40, °C	Inner surface temperature θ_{si} 26, °C
A	Old fashioned, double glazed	2.40	+7.5	+11.9
B	Conventional, double glazed with argon gas between the panes and emissive layer coating	1.60	+11.7	+14.6
C	Well insulated, tripple glazed with krypton gas between the panes and emissive layer coating	1.00	+14.8	+16.6

The other important factor for air movement induced by cold windows is window sill or window bay construction. Larsson, Moshfegh (2002) examined different cases of window installation and came to a conclusion that the window bay width affects the downdraught in two different ways: by deflection of the flow and loss of the momentum. The authors also concluded that although window frame construction is one of the weak points in terms of heat loss, it has a minor effect on the total downdraught. Therefore in this work windows were modelled as whole glazed surfaces without frames.

Manz and Frank (2004) observed that Heiselberg‘s equations do not take into account the influence of furniture or of a heating system or buoyancy flows at heat sources in the room. They concluded that experiments performed in empty rooms tend to underestimate the maximum air speed that occurs in real furnished rooms with heat loads. Consequently, they suggested modifying Heiselberg‘s correlations by a factor of 1.5. However, these suggestions were made according to CFD predictions only. Authors used k-ε turbulence model for their study. And although the set of k-ε equations are mostly used in room airflow predictions, it has some limitations in predicting a three dimensional wall jets as it was described by Schälin and Nielsen (2004). Accordingly, in this work both correlations presented by Heiselberg and Manz&Frank are taken into account.

3. Thermal comfort parameters used in this study

In order to evaluate window generated downdraught, air speed profiles were drawn for the cut planes close to the floor. According to CEN Report 1752 (1998) and Lithuanian construction regulation standard STR 2.09.02:2005 (2005), air speed in the occupied zone should be no more than 0.15 m/s.

Air temperatures were analysed as well as a vertical temperature gradient. Heat sources in the room were modelled to keep air temperature at +20 – +24 °C. Thermal comfort conditions according to vertical temperature difference between head and ankles (1.1 m and 0.1 m above the floor) were considered up to 3 °C.

Thermal comfort indices such as PMV and PPD (both presented by Fanger, 1972) were calculated using CFD software in this study. Descriptions of the indices are presented in ISO 7730 (1994) standard.

PMV (Predicted Mean Vote) index indicates the mean response of a large group of people according to the thermal sensation scale (+3 – hot, +2 – warm, +1 – slightly warm, 0 – neutral, –1 – slightly cool, –2 – cool, –3 – cold).

Mathematically, PMV index is expressed as follows:

$$PMV = (0.303 \cdot e^{-0.036 \cdot M} + 0.028) \cdot L, \qquad (5)$$

where M is metabolic rate, L – thermal load defined as the difference between the internal heat production and the heat loss to the actual environment for a person hypothetically kept at comfort values of skin temperature and evaporative heat loss by sweating at the actual activity level.

The PMV value should be in the range from –0.5 to +0.5.

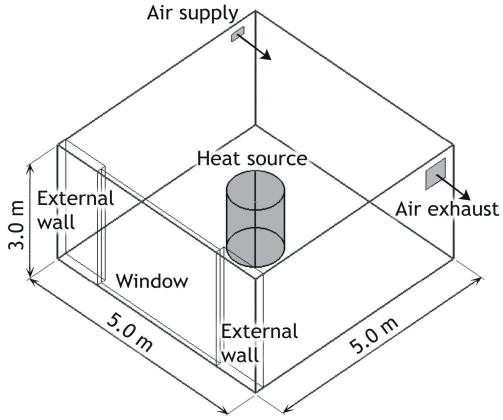
The PPD (Predicted Percentage of Dissatisfied) value predicts the number of thermally dissatisfied persons among the large group of people and is defined as a function of predicted mean vote (PMV):

$$PPD = 100 - 95 \cdot e^{-\left(0{,}03353 \cdot PMV^4 + 0{,}2179 \cdot PMV^2\right)}. \qquad (6)$$

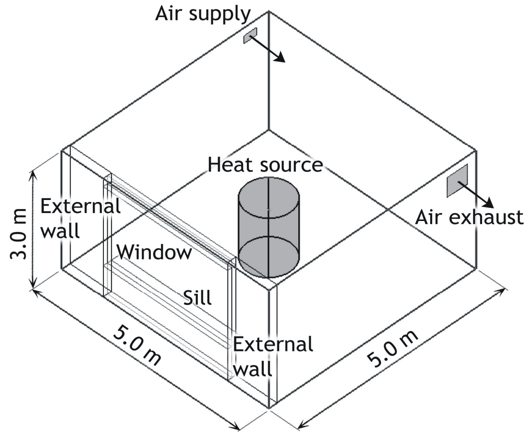
In order that thermal conditions were kept within comfort limits in the occupied zone, the PPD value should be less than 10 %. It corresponds to PMV value limits of –0.5 – +0.5.

4. Creating a CFD model

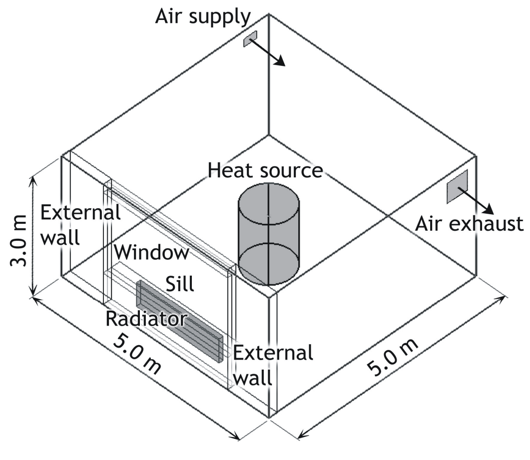
The CFD (Computational Fluid Dynamics) allows solving a set of partial differential equations to predict fluid velocities, temperatures, contaminant dispersion etc.



Case 1. Window dimensions – 3.0 x 3.0 m.
No heating equipment modelled below it.
Heat source is modelled in the centre of the room,
at the 0.4 m above the floor



Case 2. Window dimensions – 3.0 x 2.0 m.
More traditional window installation with the 20 cm
width windowsill



Case 3. Window dimensions – 3.0 x 2.0 m.
Traditional window installation. Radiator is
simulated below the windowsill

Fig. 1. Cases and geometries modelled by means of CFD

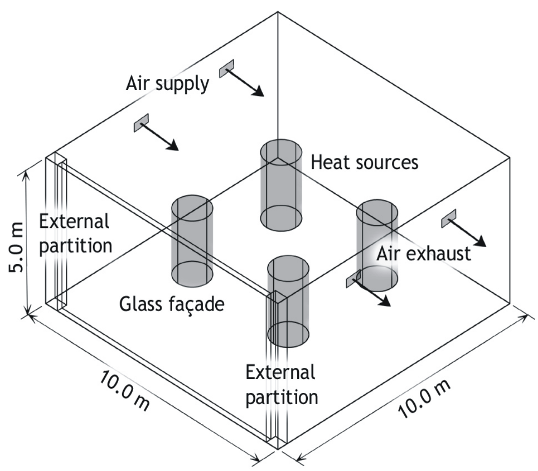
The *k*–ε turbulence model with the first order upwind scheme for momentum, turbulence kinetic energy and turbulence dissipation rate was chosen for this study. As it was mentioned before, this turbulence model is not very precise in predicting wall jets. However, the main goal of this study was to compare environmental conditions in the room in cases of different window properties. Therefore, *k*–ε turbulence model was considered to be a sufficient one to observe these differences.

A room with one external wall was created and the heat source was designed in the centre of this room to cover the heat losses. Air supply and exhaust openings were modelled on the opposite corners of the room. The airflow was selected according to air exchange rate requirements for offices. Three basic models were created (Fig. 1):

1) window installed throughout the whole wall height with no heating equipment below (heat source imitates person, computer and other possible heat emitting equipment);
2) the window height is 2.0 m, with a windowsill below it and no heating equipment under the sill;
3) model similar to the case 2, but radiator is designed below the window to cover most of heat losses.

All these cases were modelled with three types of previously mentioned window types (A, B and C) and two external conditions.

The above-mentioned geometries and conditions are relevant to residential or office buildings. Yet, the results may not be precise for high glazed façades. Therefore, several cases with high windows (up to 5 m height) and a room twice as big as the previous cases, was also examined in this work. Fig. 2 shows the view of the analyzed room with external glazed façade (case 4). Window dimensions were selected 8.0 x 5.0 m. Several heat sources were modelled in order to avoid air movement created by one powerful source and several cases with or without heating equipment were modelled. In the case with no heating equipment below the window, all heat losses were covered by heat sources in the room.



Case 4. Room with glazed façade (window dimensions – 8.0 x 5.0 m)

Fig. 2. Additional cases with high windows (glazed façades) were modelled by means of CFD

5. Quality control and validation of CFD model

A hexahedral grid was selected for simulations in this study and the optimal number of grid cells was defined from 110.000 to 600.000 thousands depending on the case. It was selected considering results of several simulations with different number of grid cells. The size of the cells was decreased close to the surfaces (maximum cell height close to the window was selected 2 cm).

In order to check if the CFD prediction results reflects the nature of the physical phenomenon, the study performed by Ge and Fazio (2004) was used. As the authors presented experimental data of the comparable model, CFD simulations were performed with the same boundary conditions as were used by Ge&Fazio. U value of the window was selected equal to 1.53 W/m²K, external temperature was set at –18 °C. The geometries of the model were equated to the experimental chamber used by the authors. Fig. 3 shows the differences between experimental data performed by Ge&Fazio and CFD prediction results. Air speed values obtained during the experiment and predicted by CFD differs in the zone close to the window bay. CFD simulation gives about 15 % lower values close to the window bay. Yet, the shape of the air speed profiles is analogous. Differences might be caused both by inequalities of the boundary conditions and prediction errors (limitations of k–ε turbulence model). Air velocity vectors and contours at the same and most critical section is presented in Fig. 4.

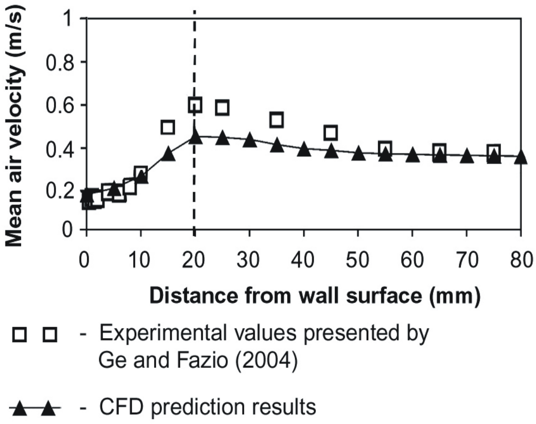


Fig. 3. Comparison of experimentally obtained and predicted by CFD mean air velocities at 10 mm below the upper edge of the frame in relation to the distance from the wall surface

Heiselberg's equation was used in order to check reliability of the prediction results in the occupied zone.

Fig. 5 shows maximum air speed in the zone close to the floor calculated according to Heiselberg's equation, Manz & Frank corrected Heiselberg's equation compared to the simulation results. CFD model did not show exactly the same results in the zone close to the window. But 0.5 m distance is usually marked as a border of the occupied zone. And within this zone the simulation results coincides with Heiselberg's correlation results quite well.

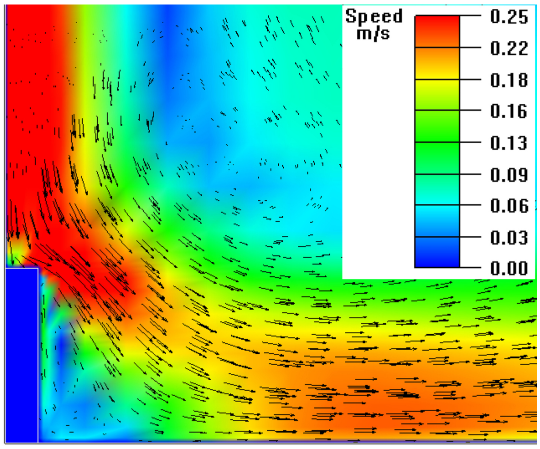


Fig. 4. Air speed contours and vectors in the zone close to the window surface, when geometries were modelled according to Ge and Fazio (2004)

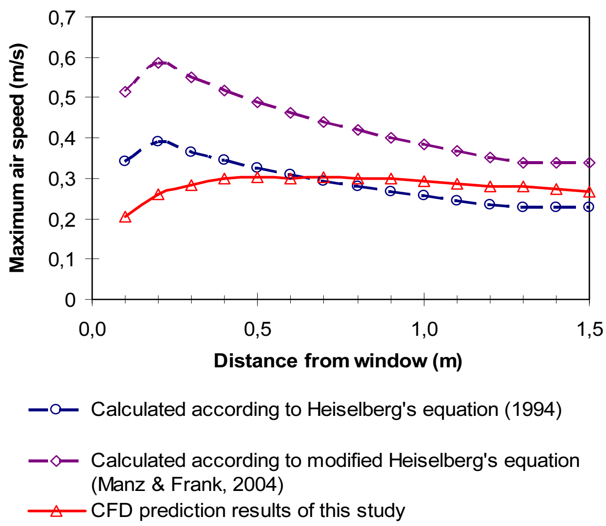


Fig. 5. Predicted air speed in the centre plane and close to the floor of the room compared to the same values calculated according to both Heiselberg's and Manz & Frank corrected Heiselberg's equations (Case 1, window type A, external temperature –20 °C)

6. CFD prediction results

6.1. Air movement in rooms with glazed façades (up to 3 m height)

CFD predictions showed that even in cases of low window U value (1.0 W/m²K) thermal discomfort conditions may appear in the room, if the height of the window is more than 2.0 metres. It is not possible to avoid cold downdraught if external temperature is –20 °C (Fig. 7). Fig. 6 gives a more detail view of cold air jet development in the occupied zone.

In cases when a window with the U values up to 1.6 W/m²K is used, air velocity in the occupied zone exceeds 0.3 m/s. In the 1.5 m distance from the cold surface, maximum velocity is decreased and the value is above 0.15 m/s.

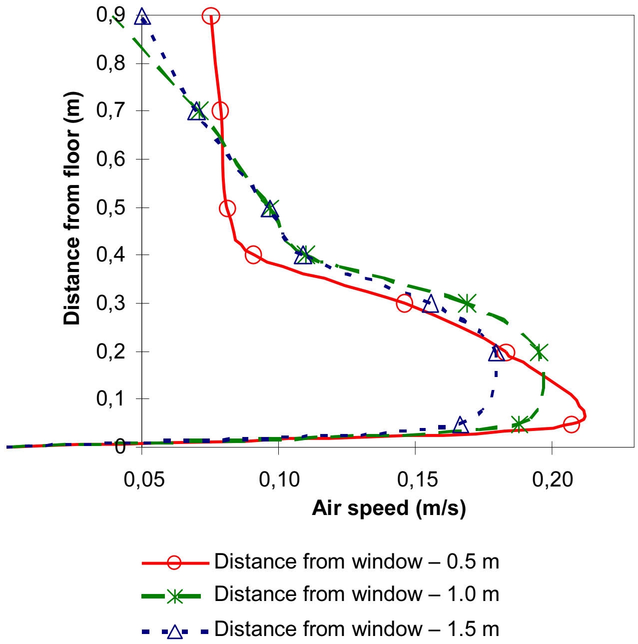


Fig. 6. Air speed profiles showing air jet development in the centre of the room

Isosurfaces shown in Fig. 8 reveals that the radius of zone of the high velocities is quite large. If workplaces would be installed in this area, occupants would feel draught at the ankle level (0.1 m above the floor).

These conditions appear also in the case where the outside temperature is around –6 °C (Fig. 9). In this case the air speed in the occupied zone is lower, but still it is over 0.15 m/s. Therefore a window U factor equal to 1.0 W/m²K is not a sufficient value to prevent the draught in the occupied zone.

6.2. Air movement in rooms with traditional window installation

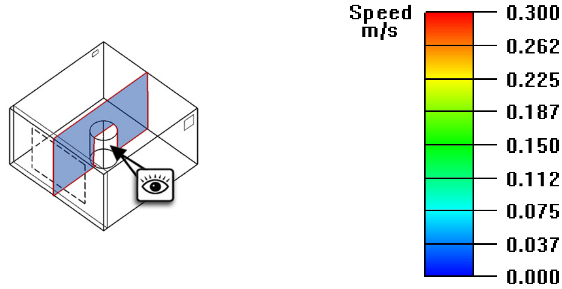
Window height of 2.0 metres was selected for this case and window sill together with window bay forms a plane obstacle for the dropdown air jet. Fig. 8 shows the air speed values in the centre plane of the room in cases with different window heat transmittance coefficients.

Both in case when U value is 2.4 W/m²K and 1.6 W/m²K, air speed in the occupied zone exceed 0.15 m/s. But in case when well insulated window glazing is used (U = 1.0 W/m²K), the draught appears only in the zone close to the windowsill.

0.5 m from the edge of the windowsill is the safe distance for workplace set up. The maximum air speed in the occupied zone, when highly insulated windows are used, is around 0.12 m/s. And this speed will appear only in case of extreme outside conditions (external temperature was set at –20 °C).

6.3. The effect of heating equipment on air movement in rooms

Installation of heating equipment has a significant impact on thermal comfort conditions in rooms. It depends on thermal properties of the window, heat load emitted by the heating device as well as the geometry of the windowsill. Fig. 10 shows an isosurface where air speed is equal to 0.15 m/s in the room with radiator below the sill.



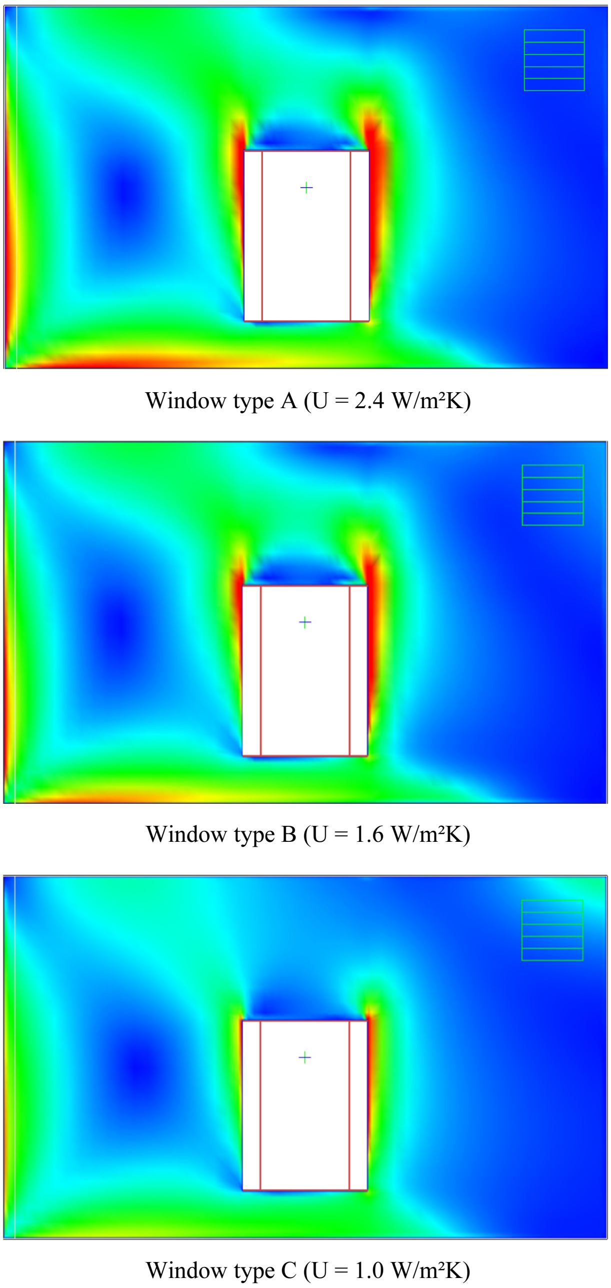


Fig. 7. Air speed in the centre of the room (Case 1, external temperature –20 °C)

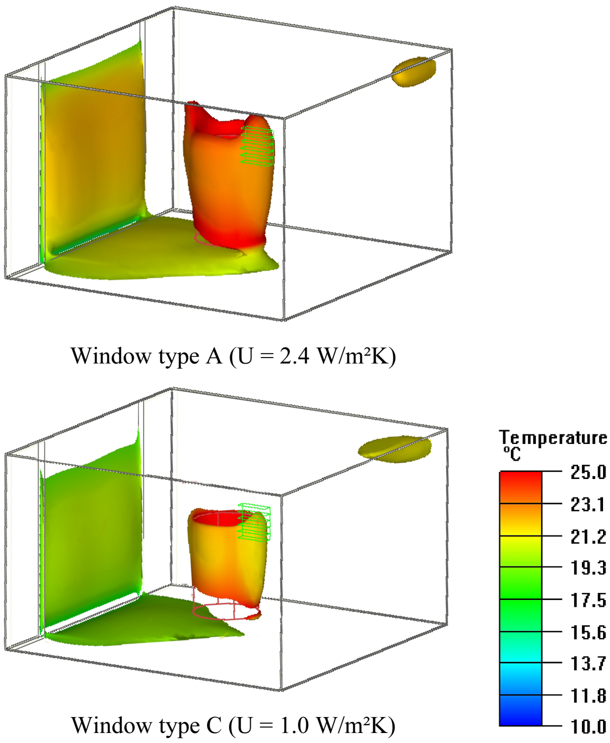


Fig. 8. Three dimensional isosurfaces marking areas where the air speed is higher than 0.15 m/s coloured in accordance to the air temperature on the surface (Case 1, external temperature –20 °C)

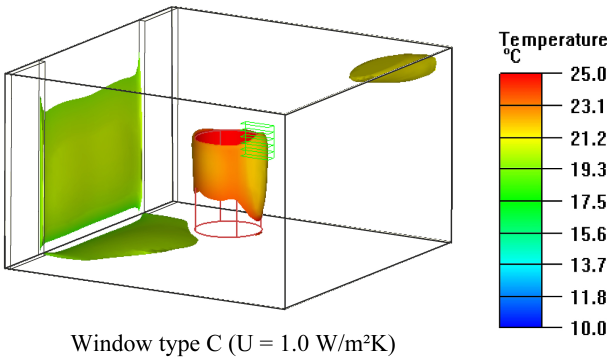


Fig. 9. Isosurface marking 0.15 m/s speed area coloured in accordance to the air temperature on the surface (Case 1, window type C, external temperature –6 °C)

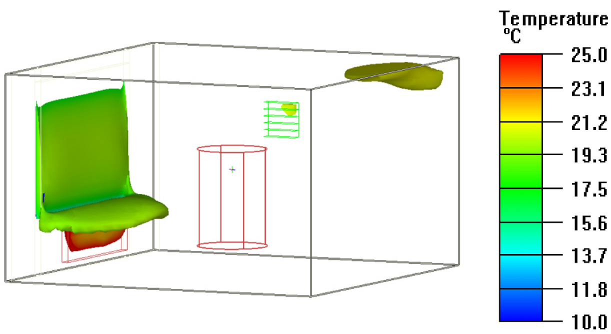


Fig. 10. Isosurface marking 0.15 m/s speed area coloured in accordance to the air temperature on the surface (Case 3, window type B, external temperature –20 °C)

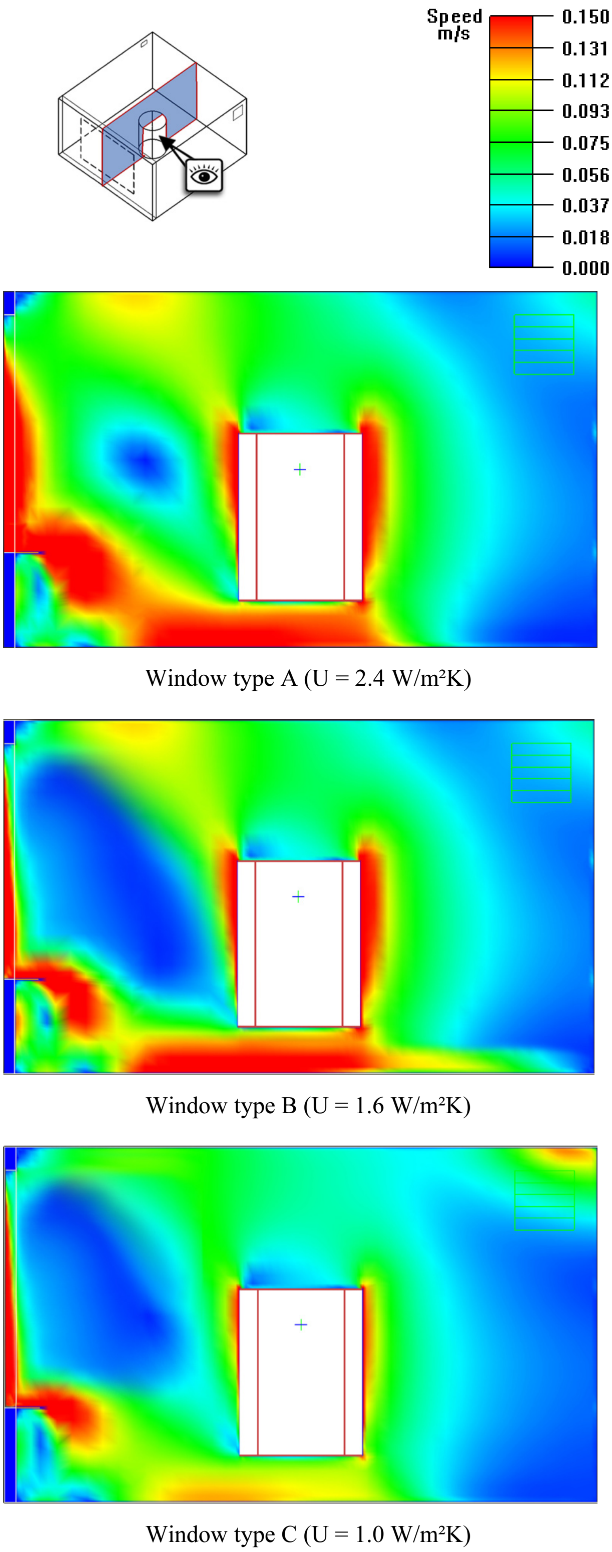


Fig. 11. Air speed contours in the centre of the room (Case 2, external temperature –20 °C)

In case when the sill covers fully the width of the radiator and conventional (U = 1.6 W/m²K) window is installed, air speed in the occupied zone is distinctly above 0.15 m/s. Besides, it does not drop directly to the floor area, but moves straight to the occupied zone. Fig. 12 shows the air speed vectors determined by the air temperatures and windowsill geometry.

In order to neutralise dropdown of the cold air, less extensive sill design was chosen but the prediction results were quite similar to the ones presented in Figs 11 and 12. Therefore openings or a grill should be made in the windowsill to prevent the formation of the jet. This solution was examined by Ruegg *et al.* (2001). Authors described the possibilities to use grills and openings in order to avoid draughts in the occupied zone as well.

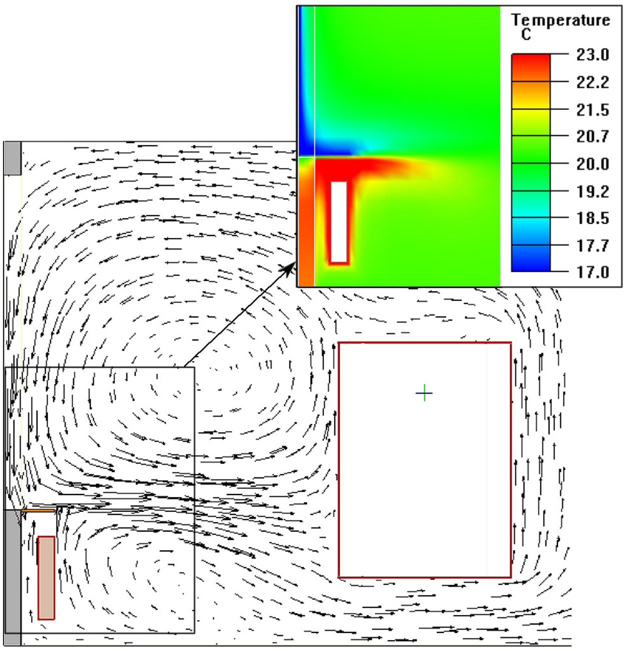


Fig. 12. Air velocity vectors in the zone close to the window surface and air temperatures in the sill region (Case 3, window type B, external temperature –20 °C)

6.4. Thermal comfort conditions in buildings with traditional window installation and glazed façades (up to 3 m height)

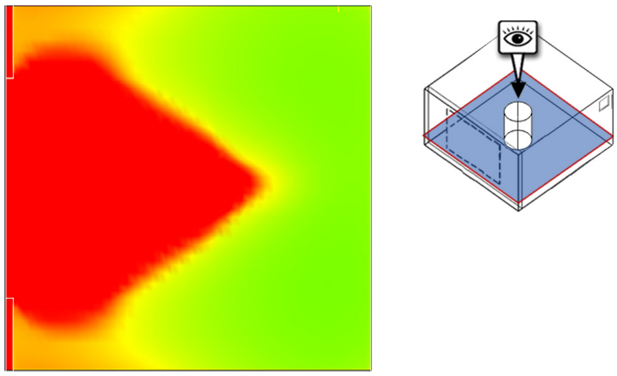
CFD predictions showed that even in cases of low window U value (1.0 W/m²K), thermal discomfort conditions may appear in the room if the height of the window is more than 2.0 m. Fig. 13 shows simulation results for two cases with well insulated windows. This study revealed that heating devices are needed to prevent the downdraught in rooms of buildings with glass façades. Otherwise, percentage of persons dissatisfied with thermal comfort conditions (PPD value) will be much higher than recommended 10 % limit.

However, using of highly insulated glazing seems very reasonable in case with traditional window installation. Such decision improves thermal conditions in the room significantly and PPD value does not exceed 10 %.

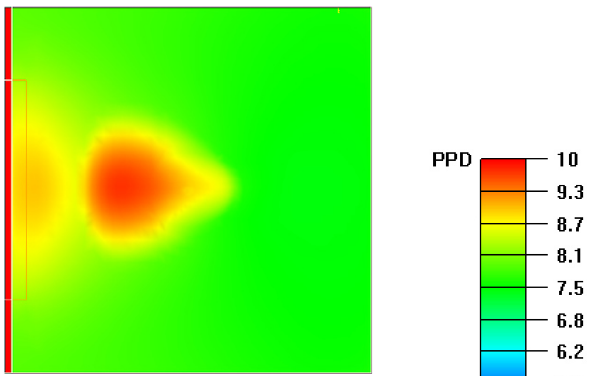
6.5. Air movement in rooms with large and tall glazed façades (up to 5 m height)

Previously presented data gives the view of window induced air movement in rooms of lower height than 3 metres. Therefore in this work we also included several simulations in order to predict the influence of cold window surface on thermal comfort in high rooms (up to 5 m). As a result, it is possible to make conclusions about the corresponding conditions in public buildings such as shopping centres, exposition halls, swimming pools etc.

A room with glazed façade was modelled for that (Fig. 2) and three cases were analysed. Firstly, a well insulated window (U = 1.0 W/m²K) was simulated without any heating equipment below it. All heat losses were covered by heat sources in the room. CFD prediction results showed that speed of the cold air jet reaches up to 0.3 m/s in the occupied zone. Afterwards a case with heating convector device below the window was simulated with anticipation that the cold air dropdown problem will be solved this way. Yet, CFD modelling results showed that in case of such window height, air jet caused by buoyancy forces is insufficient to suppress the draught in the room.



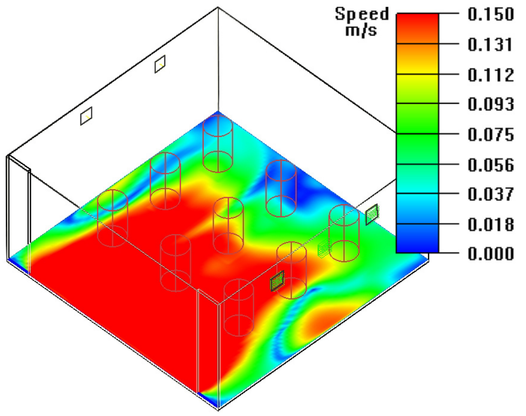
Case 1, window type C
(U=1.0 W/m²K)



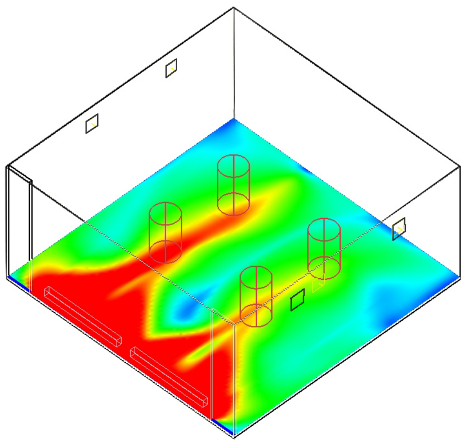
Case 2, window type C
(U = 1.0 W/m²K)

Fig. 13. Predicted percentage of persons dissatisfied with thermal comfort conditions (PPD value) 0.1 m above the floor (external temperature –20 °C)

Examined the most distinctive section in the rooms seems to be the section close to the floor. Fig. 14 shows air speed in the 0.1 m height above the floor in these two cases. Air temperature contours and air speed vectors presented in Fig. 15 shows that if heating equipment is installed in the typical 10 cm height above the floor, cold air effuses below the air heater and the draught zone forms.

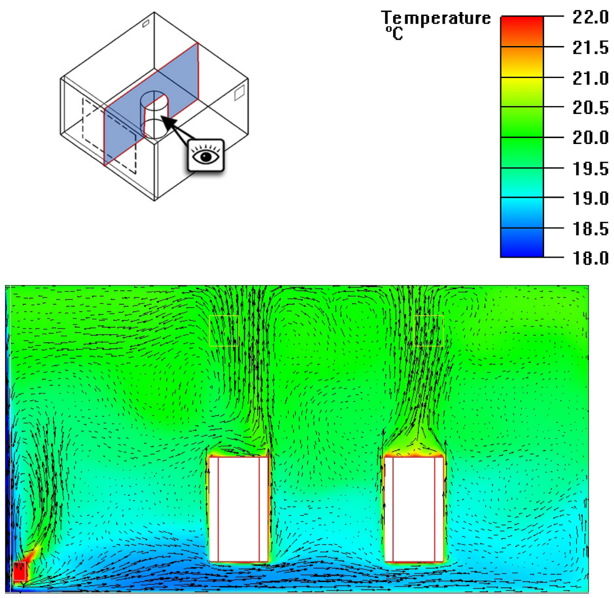


Window type C (U = 1.0 W/m²K) without convector heater below the glazed façade



Window type C (U = 1.0 W/m²K) with convector heater below the glazed façade

Fig. 14. Air speed contours at 0.1 m height above the floor (external temperature –20 °C)



Window type C (U = 1.0 W/m²K) with convector heater below the glazed façade

Fig. 15. Air speed contours in the centre of the room (external temperature –20 °C)

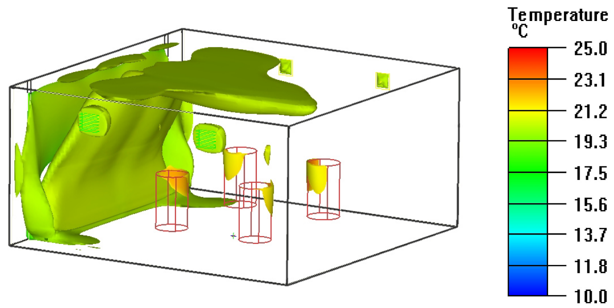


Fig. 16. Isosurface marking 0.15 m/s speed area coloured in accordance to the air temperature on the surface (window U = 1.0 W/m²K with warm air supply equipment below the glazed façade, external temperature –20 °C)

The best method to solve this problem in high rooms seems to be creating a warm air jet directed against the cold window air dropdown. Such heating equipment as floor convectors with fans or other mechanical air supply devices should be used (Fig. 16).

Fig. 17 shows air speed contours in previously described cases with or without heating equipment below the high glazed façade compared to the case when room heating is implemented by means of floor heater equipped with fan.

Warm air is supplied against the cold air jet at the speed of 1.0 m/s. This speed is sufficient to suppress the cold air dropdown (window U value is 1.0 W/m²K and external temperature was selected –20 °C) (Fig. 14).

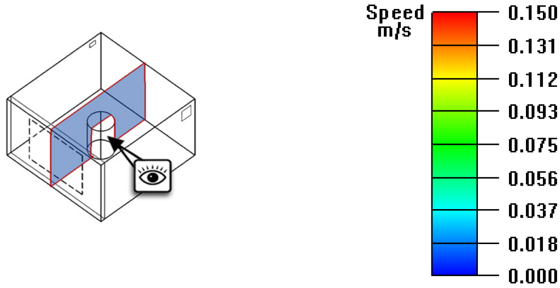
In this case it is important to install extensive heating equipment below the window. In the presented case floor convector with a smaller width compared to the window width was modelled. Therefore two zones of thermal discomfort emerged in the window border regions.

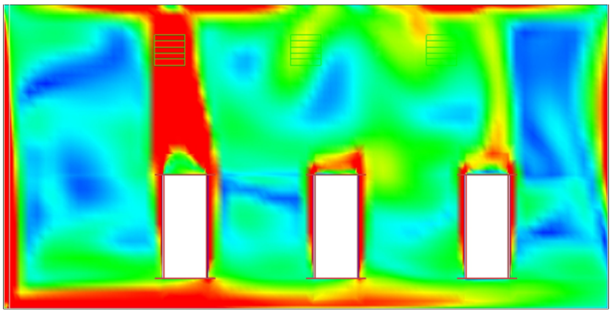
7. Conclusions

According to the results of CFD simulations the following conclusions were drawn.

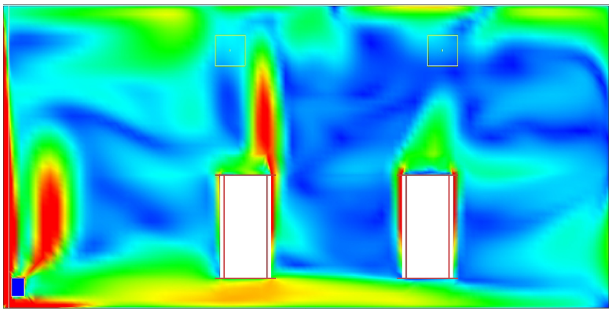
1. Thermal discomfort conditions may appear in rooms even in cases when well insulated windows are used (U value is 1.0 W/m²K), if the height of the window is more than 2.0 metres. Whereas high glazed façades (up to 5.0 metres) may cause significant draught in the larger half of the occupied zone. Therefore modern windows whose thermal transmission coefficient equals 1.0 W/m²K should be considered as potential draught generators as well, if external temperature is lower than –5 °C. However, well insulated windows showed good results in case of traditional residential window installation. In this case heating equipment is not necessary to prevent draught in the occupied zone (U value is 1.0 W/m²K and window height is about 1.5 m).

2. Installation of heating equipment below the windowsill can have a crucial effect on air movement. It might create two air jets (warm jet and cold jet) which mix and flow directly into the occupied zone. In order to avoid this phenomenon, openings or grills should be installed in the windowsills.

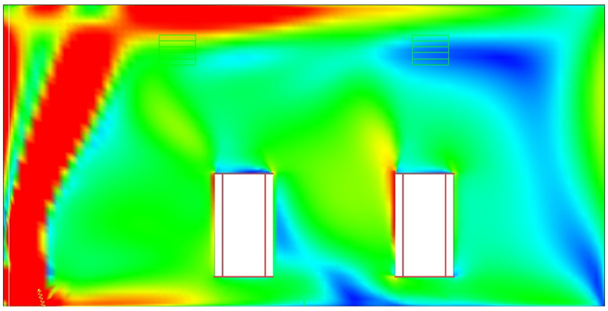




Window type C (U = 1.0 W/m²K) without convector heater below the glazed façade



Window type C (U = 1.0 W/m²K) with convector heater below the glazed façade



Window type C (U = 1.0 W/m²K) with warm air supply equipment below the glazed façade

Fig. 17. Air speed contours in the centre of the room (external temperature –20 °C)

3. Free standing heating convectors do not suppress the dropdown air jet if the height of the glazed façade is about 5 m or higher even in case when well-insulated windows (U value is 1.0 W/m²K) are used. As these units are usually installed at 10 cm height above the floor (mounted on the stalks), cold air effuses below the air heaters and still it causes draught in the occupied zone. The best heating equipment to solve this problem seems to be floor heaters with fans.

Surely there are more factors which should be taken into account in order to draw the final conclusions. Air leakage should be considered as well as effects of ventilation system performance (air distribution method, supply air temperature etc). In this study, some limitations of *k*–ε turbulence model were experienced in the zone close to the window surface. Field measurements and experiments are needed to get more precise results and to analyse the combinations of the factors mentioned above. Some of the errors might be eliminated by precise definition of the h_{si} value, which represents heat transfer coefficient at the inner surface of a glazing. As it is directly influenced by air movement on the surface of the window, it may be defined in the CFD according to the experimental data obtained in accordance to different window constructions and thermal properties.

In order to analyse local thermal discomfort close to the windows, draught rate (DR) index should be calculated as well. This would allow assessment of thermal conditions including evaluation of air turbulence intensity.

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VĖSIŲ LANGŲ PAVIRŠIŲ SUKELIAMO ORO JUDĖJIMO TYRIMAI PASITELKIANT KOMPIUTERINIO MODELIAVIMO METODUS

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Santrauka

Dideli langai ir stiklo fasadai tapo neatsiejama šiuolaikiškos architektūros dalis. Jie projektuojami ne tik visuomeniniuose, bet ir individualiuose namuose. Nekalbant apie teigiamus tokios architektūros aspektus, didelių matmenų langai gali tapti šiluminio diskomforto priežastis. Už patalpos orą vėsesnis vidinis stiklo paviršius sukelia žemyn nukreiptą oro srautą, kuris tam tikru greičiu patenka į žmonių gyvenamąją arba darbo zoną. Vėsių stiklo paviršių sukeltų oro srovių intensyvumas priklauso nuo lango šiluminių savybių, jo konstrukcijos bei šildymo prietaisų įrengimo vietų. Dažniausiai mikroklimato sąlygos patalpose vertinamos matuojant oro temperatūrą, santykinį drėgnį, oro judrumą ir šilumos mainus spinduliavimu. Straipsnyje pristatomas tyrimas, kuriam buvo pasitelktas kompiuterinis oro judėjimo modeliavimas (skaitiniai skysčių ir dujų dinamikos metodai). Buvo tiriama oro judėjimo patalpose priklausomybė nuo langų bei stiklo fasadų konstrukcijų ir šiluminių savybių. Modeliuojant įvertinti trys langų tipai, kurių šilumos perdavimo koeficientų vertės: 2,4; 1,6 ir 1,0 W/m²K. Rezultatai parodė, kad net ir mažiausiai šilumai laidūs langai gali sukelti neleistiną oro judėjimą patalpose, jei jų aukštis viršija 2 metrus.

Reikšminiai žodžiai: šiluminis komfortas, oro judėjimas, langai, skersvėjis, kompiuterinis modeliavimas.

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