Influence of Airflow on Thermal Comfort in an Energy-Saving House

D Adamovský and M Kny
University centre for energy efficient buildings CTU in Prague, Třinecká 1024, Buštěhrad
daniel.adamovsky@fsv.cvut.cz

Abstract. The current thermal properties of building external structures including openings are supposed to suppress effects of draft to thermal comfort. But is it true expectation? The subject of the paper is the analysis of airflow around the window in three types of heating systems with predominant radiant as heat transfer. The analysis is based on experiments in the climatic cabin representing the room of a low-energy family house. To obtain the relevant data, a series of particle image laser velocimetry measurements were performed to visualize and quantify the airflow in the investigated area. The paper present results of the thermal comfort of the inhabitants of the room, which prove that with the influence of draft it is necessary to count on modern energy-saving buildings. They prove that old well-known rules about the position of the heating surface apply to the most cooled constructions and bring interesting conclusions about underfloor heating.

1. Introduction
High thickness of thermal insulation, sealed outer structures, windows with low U-value and every detail solved to the highest possible degree. These are common values of a new and refurbished todays buildings. Parameters that build up great expectations for low energy consumption. Therefore, presumption of high quality of thermal comfort seem to be in place also. Many parameters support this hypothesis, such as high surfaces temperatures avoiding unpleasant excessive radiation from a human body or limited draught.

However, general effort establishing energy saving buildings as a standard shall not compromise quality of indoor environment for its occupants in homes, workplaces, etc. [1], otherwise entire idea will be rejected by building users especially in a case of renovations.

The questions behind this paper are:

- What conditions of thermal comfort we may expect in today buildings?
- Is still important location of heating bodies beneath a window?
- And if not, how does it change an occurrence of draught?

2. Methodology
Experiments with heating systems took place in a parallel test cabin with a controlled ambient environment where the "outside" temperature was maintained on average -15 °C, air velocity up to 0.5 m/s and limited radiation. This cab consists of two parallel booths, which are divided by the inner partition. The interior dimensions of one cabin are 4.4 m x 3.1 m x 2.85 m. The values of the heat transfer
coefficient (in W/(m$^2$.K)) of the envelope are 0.132 for floor, 0.103 for ceiling, 0.134 for walls and 1.2 for window. Window dimensions are 1.45 x 1.45 m. The wall between booths was considered adiabatic.

Thermal comfort analysis was performed by a thermal manikin. The manikin has 36 independently heated and measured zones (Newton by Thermetrics). It is a device for accurate analysis of thermal comfort in steady state conditions. The analysis is based on measure of heat exchange (convection, conduction and radiation body heat losses) in either direction of either the entire surface or in selected zones.

Experimental conditions represented a seated person with low activity, for example a person in a home environment sitting in a chair and reading his book. Position of a person was in the middle of cabin facing window. The distance from the window was 1.5 m. Person’s clothing has thermal resistance 0.132 m$^2$.K/W (0.85 clo). Air temperature was maintained by heating system controller (PWM control) in steps 19, 20, 21, 22 and 25 °C.

Verification of measuring conditions has been done in 4 heights besides the manikin; the lowest (ankles) at 0.1 m, lower (belly of a sitting person) at 0.6 m, higher (head of a sitting person) at 1.1 m and the highest (head of a standing person) at 1.7 m. Measured values were air temperatures (all 4 heights), globe temperature (0.6 and 1.1. m), relative humidity (0.6 m), air velocity (0.6 m). Supporting values provided surface temperature sensors on the window, walls and others.

Analysis of air flow was performed by particle image velocimetry (LaVision) consisting of a laser Nd:YAG Litron NANO TLR PIV, 15 Hz, 325 mJ and two cameras ImagerPro X11M at scanning frequency 2.4 Hz. The flow was seeded with Expancel particles (0.03 mm). The measuring layer was located in the middle of the window and neglect situation on the margins. Due to the turbulent nature of the air flow, vector arrays are further represented by the average of 60 bi-images (corresponding to 25 s of real time) for floor and ceiling heating and 40 bi-images (equivalent to 16.6 s) for radiant panel. Two identical cameras were available, while it was possible to measure flow in two selected areas (Figure 1).

Cabin air temperatures are limited to 20 °C and 23 °C.

In these experiments were involved three different electric heating systems – radiant panel, underfloor heating and ceiling heating. Each system had 500 W nominal electric input.

Analysis of obtained data were performed by regular procedure of EN ISO 7730 [2]. For thermal manikin was applied also EN ISO 14505-2 [3] which principle of assessment is based on the measurement of the equivalent temperature using a thermal manikin. From equivalent temperature is then calculated PMV index for particular body part [4].
3. Results

3.1. Heating system attenuation
The first variant is the analysis of the air flow at the time of heating system attenuation, when the heating system was switched off due to reached set point temperature and did not affect the flow of air in the room. The aim was to describe the conditions that represent the attenuation and allow the free flow of the window around and the window sill.

![Figure 2. Air velocity pattern above the floor when the heating is attenuated](image1)

![Figure 3. Air velocity pattern at the sill level when the heating is attenuated](image2)

From the results it is clear that the cold descending air flow from the window reaches relatively high speeds, beyond the sill edge of up to 0.19 m/s. and by window up to 0.18 m/s, see Figure 2 and 3. The air flow drops to the floor and flows further above the floor surface from the window to the room. At the height of up to 50 mm above the floor, the fastest layer of flowing air is created at a speed of up to 0.17 m/s.

Due to the low temperatures of the sill and floor surfaces, this airflow is slowed down very slowly above the floor and these conditions can be perceived by the user as a slight draft.

3.2. Radiant panel
Radiant panel is a local heating system with high fraction of thermal output exchanged by radiation (around 50 to 55 %) due to the high maximum surface temperature reaching up to 82 °C. The panel has been located beneath the window and the set point temperature was 20 °C.

The above described falling air flow developed close to the window sill is completely reversed by vertical heated air from heating radiant panel at the surface temperature 34 °C and higher. For this surface temperature a maximum flow velocity of 0.259 m/s was achieved in resulting flow, while air velocity above the floor was about 0.075 m/s. With increasing surface temperature also increases maximum velocity of warm air. When temperatures close to maximum are reached air velocity rises up to 0.65 m/s. Figure 4 shows development of the air flow above radiant panel at different surface temperatures.
3.3. Floor heating

Floor heating was measured in steady state for a thermostat set point temperature of 23 °C and for two outside air temperatures $t_e$, -12 °C and 5 °C.

Figure 4. Air velocity patterns above radiant panel at different surface temperatures

Figure 5. Air velocity patterns above the floor with electric heating ($t_e = -12$ °C, surface temperature of the sill 20.5 °C, floor surface temperature 29.0 °C)
Additionally, the air temperature distribution over the floor, the wall under the window and the window sill were measured. Sensors were elevated to the height of 50 mm above floor and protected from radiation of heating floor. Their distance from the wall is 300 mm, 900 mm and 1500 mm.

For temperature $t_e = -12\, ^\circ\text{C}$, a maximum flow velocity of 0.2 m/s was achieved above the floor. The flow of air descending from the window had a velocity of about 0.14 m/s at the level of the bottom of the sill. Subsequently, above the floor air flow decreased the height and increased the speed which gradually decreased to a distance of 1.5 m where the velocity of was about 0.16 m/s (Figure 5). At this location a sitting person has his feet.

While outside air temperature rises to $5\, ^\circ\text{C}$, the air flow velocity slightly decreases, however, the differences are negligible compared to the previous state. The maximum flow velocity above the floor was 0.16 m/s at a distance of 650 mm from the wall. The air flow descending from the window reached a speed of about 0.11 m/s (Figure 6). The velocity at the location of feet was approximately 0.125 m/s.

Interesting is to compare air temperatures above the floor, they do not change significantly. The reason is lower thermal output of floor heating necessary to reach the set point temperature against lower heat losses of the cabin. This is apparent from decrease of the surface temperature from $29\, ^\circ\text{C}$ at $-12\, ^\circ\text{C}$ to $26.9\, ^\circ\text{C}$ at $5\, ^\circ\text{C}$.

### 3.4. Ceiling heating

Ceiling heating was measured only for temperature conditions $-12\, ^\circ\text{C}$ and set point temperature $23\, ^\circ\text{C}$. The flows were measured in two areas above the floor, as in the case of floor heating. Also air temperatures above the floor were measured.

The flow over the floor was similar to that of floor heating. The maximum air flow velocity above the floor was 0.175 m/s. The flow of air descending from the window was at a velocity of about 0.16 m/s (Figure 7). The velocity close to feet of a sitting person was approximately 0.145 m/s.

Compared to underfloor heating, where vertical upward currents occurred in the current array, the flow in the floor was only horizontal. The flow above the floor is lower in the ceiling heating when averaging the image and the flow is sharply delimited above (a higher gradient of velocity is present).

The floor temperatures were lower by about 0.7 K compared to floor heating. The coldest was the air in the sill area ($20.52\, ^\circ\text{C}$) and the warmest in the feet area ($22.8\, ^\circ\text{C}$).

Under the ceiling, the highest speeds near the window were measured at about 0.09 m/s. Under the ceiling, the maximum speeds were slightly lower, about 0.08 m/s.

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**Figure 6.** Air velocity patterns above the floor with electric heating ($t_e = 5\, ^\circ\text{C}$, surface temperature of the sill 21.6 $^\circ\text{C}$, floor surface temperature 26.9 $^\circ\text{C}$)
3.5. Resulting conditions of thermal comfort

The above described conditions have a strong influence to thermal comfort of occupants. With noticeable air flow above the floor for floor and ceiling heating, it is important to find out its direct influence to thermal sensation of a sitting person oriented toward the window.

Following results presents only a few of results obtained by the thermal manikin. The main focus is at his feet, head and a whole body. Feet are considered to describe possible draught and head for radiation from heating ceiling.

Charts in figures 8 to 10 represents calculated PMV index for particular body area (feet, head) and whole body according to data obtained directly by manikin and by regular procedure of EN ISO 7730. Thermal sensation described by PMV index depict Table 1.

The most sensitive to conditions in the cabin are feet of a sitting person as it is clearly visible from figures 8 to 10. For all heating systems PMV index of this body area is the lowest. The order from the lowest values of PMV is ceiling heating, radiant panel and floor heating. At room air temperature 21 °C values of all systems fall to range \(-0.9, -1.5\) so in PMV scale from slightly cool to cool.

Exist few reasons why a ceiling heating causes the worst results, partially it is because of a low surface temperature of ceiling 35 °C, long distance of heating surface to feet and an air flow above the floor caused by cabin window.

Unfortunately, floor heating is not significantly better than the other two systems. In contrast with usual expectation, thermal sensation in feet area for temperatures under 22 °C fall beneath neutral state down to slightly cool. It is important to consider that the highest surface temperature of floor is only 29 °C (at outside air temperature -12 °C) and manikin represents sitting person, with low activity, not walking.

Optimal temperature for neutral thermal sensation PMV for individual heating systems are 22.65 °C for floor heating, 22.72 °C for radiant panel and 23.18 °C for ceiling heating. Values were determined by interpolation based on PMV evaluation in Figures 8 to 10. It indicates the cabin air temperature at the given activity, position and clothing of the heating system used. The differences between the individual values result from the different effect of the radiant heat flux of the heating system on the thermal mannequin. As the cabin is insulated up to the level of a low energy building, surface temperatures of most surfaces except the window are similar, therefore differences among optimal temperatures of heating systems are very small.
4. Discussion

The most significant influence to thermal comfort of a low activity person sitting in the middle of well insulated room facing the wall with window is air flow caused by the window itself. Despite high quality of envelope parameters a window with $U$-value over 1 W/(m²·K) will cause a similar air flow. This could be important for some building renovations in which application of triple glazed windows with lower $U$-value is not possible. Similar issue may appear when tall windows with limited height of a sill are designed.

Previous results prove that a heating element located beneath the window influence descending air flow. In case of a radiant panel (or convector, etc.) respecting the old rule of length equal to 0.8 · length of the window, the problem is resolved. But in cases of floor or ceiling heating the problem persists, because of low heat flux from distanced surface.

This raises the need for solutions that support floor and ceiling heating and solve the problem of falling airflow. It is proposed to add a secondary heating surface to the window sill. But what must be its thermal output?

The answer is given in Figure 11, which shows the air flow around the window sill with a 60 W electric heating film installed. It is evident that due to the rising warm air flow from the foil, the sudden drop of the air flow to the floor is avoided. The current flows into the room where the speed drops below 0.1 m/s at a distance of about 1 m.
Figure 11. Air flow around window sill with installed heating foil with 60 W electric input.

These results put the expectation of eliminating the flow of air descending down the floor into the feet area of the seated person and increasing its thermal comfort on this part of the body. However, this conclusion has not yet been experimentally verified.

5. Conclusion
This article aimed to assess the conditions of thermal comfort in an energy-saving residential building. The basic question was, whether modern buildings of this type could offer improved conditions of thermal comfort. The results of the experiment confirmed as expected that they clearly did. This is due to better technical properties of the envelope and more efficient heating building systems.

On the other side the experiments also proved, that during the design process, it is important to keep well known rules about location of a heating elements. They still should find the best location beneath a window.

In a case of popular floor and ceiling heating, is predictable risk of an air flow descending from window and flowing above the floor. Results shows that low activity person may recognize this as slightly cooling his feet. Solution may be in a little supplementary heating element with low electric input located right on the edge of a window sill. Obviously a proper technical solution is necessary to develop.

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