Façade Improvements to Avoid Draught in Cold Climates – Laboratory Measurements

Michael Gruner*[1], Maria Justo-Alonso[1], and Tor Helge Dokka[2]

1 SINTEF Building and Infrastructure
Høgskoleringen 7B
7465 Trondheim, Norway
**Corresponding author: Michael.Gruner@sintef.no*

2 Skanska Teknikk
Lakkegata 53
0187 Oslo, Norway

ABSTRACT

With the goal of increasing building flexibility and reducing energy use, yet ensuring IAQ, the feasibility of natural ventilation in a building in Oslo is studied. However, the use of direct outdoor air poses some challenges in the Norwegian cold climate, particularly the risk of thermal discomfort due to draught and low local temperatures. The goal of this paper is to study the most suitable solution to avoid draught in cold climates while maintaining the required airflow rates.
In the presented test these airflow rates are studied to be supplied only by window opening with unidirectional airflow. Experiments are done in a full-scale model of an office for 2 persons in laboratory facilities with a temperature difference between indoor and outdoor of ca. 25 degrees. 16 types of potential improvements are studied at two airflow rates. Principle solutions to reduce the risk of thermal discomfort are presented.

KEYWORDS

Natural ventilation, full scale experiment, thermal discomfort

1 INTRODUCTION

Due to stricter requirements regarding reduction of energy use, airtightness has become the state of the art in new buildings, and therefore the need to ensure minimum airflow rates by ventilation has increased. While mechanical ventilation is the common solution in cold climates, natural ventilation is considered by some as an alternative to mechanical ventilation. Natural ventilation can reduce investment and energy costs. It is space-efficient and provides health, comfort, productivity advantages, and increased control of users over their environment (Emmerich et al., 2001). However, the biggest challenges for natural ventilation in cold climates are linked to supply of low temperature outdoor air, which can cause local discomfort problems linked to draught. For instance, the annual average outdoor temperature in Oslo is 6.3 °C while the limit of outdoor temperature for natural ventilation is stated as 6..10 °C (Fitzner & Finke, 2012). This poses the challenge of feasibility of window opening. EN 15251 with reference to ISO 7730 states the criteria of local discomfort. In Norway, regulations are harmonised to recommended criteria for ISO 7730 category B with a maximum draught rate (DR) of 20 %. Additionally, the Guideline 444 "Climate and Air Quality in the Workplaces" (Arbeidstilsynet, 2016) requires the air velocity to be lower than 0.15 m/s in the occupied zone. The occupied zone is defined according to NS-EN 13779as virtual space 0.60 m from the walls and between 0.10 and 1.80 m height above floor.

There is scarce literature on how to reduce the risk of discomfort of natural ventilation in cold climate. Heiselberg et al. (Heiselberg et al., 2001) investigated the characteristics of airflow from windows and developed models for the prediction of thermal comfort parameters in the

occupied zone from laboratory experiments. It was concluded that bottom hinged windows located near the ceiling are preferable in cold climate because they increase the distance to the occupied zone. Bjørn et al. (Bjørn et al., 2000) determined 5 possible principal flow patterns from bottom hinged windows, and a relationship with the Archimedes number. They found that at low airflow rates and low supply air temperatures, air will behave similar to downdraught from a cold wall. Earlier, Heiselberg et al. (Heiselberg et al., 1995) investigated horizontals obstacles to stop downdraught from fully glazed façades. They found a dependency of the maximum air velocity and the minimum temperature in the occupied zone on the flow characteristic and the size of obstacle. Below a critical width of the obstacle, the airflow reattaches to the wall surface, but in the occupied zone air velocity decreases and temperature increases nonetheless. Above the critical width, the flow is diverted into the room, and comfort depends only on the distance of the lowest obstacle to the floor. However, obstacles were studied only in the context of natural convective flow. Only rectangular obstacles were investigated. Heights over 2 m between obstacles apply for larger multi-storey façade, but can rarely be achieved in normal situations within one floor. Later, Heiselberg et al. (Heiselberg et al., 2002) investigated also the effect of guiding plates, which block the secondary jet through the triangular areas on either side of the bottom hinged window. The effect was judged negative because air velocity increased in the primary jet above the opening sash and at floor level. Field experiments by (Fitzner & Finke, 2012) show the influences of features around windows, such as window sills and heaters, on the characteristics of airflow from the window. It was found that radiators under the window improve comfort as long as they are warm. Mysen et al. (Mysen et al., 2005) documented a low-cost solution for retrofitting. Unfiltered outdoor supply air was supplied via a short insulated duct from the façade with air supply nozzles in each room. Stale air was extracted via a central mechanical fan. In order to reduce the reported draught problems, a more uniform distribution with a continuous row of small nozzles or a continuous narrow slit was suggested, but not tested. Zhang et al. (Zhang et al., 2016) developed a more successful concept for air intake from the façade at ceiling level. Outdoor air is supplied to the space between the suspended ceiling and the floor slab, and supplied to the room through diffuse ceiling panels. Even at supply air temperatures of -7 °C, the draught rate was below 10 %.
From the existing research, it can be concluded: a) The preferred solution is a bottom hinged, horizontal vent located near the ceiling; b) In case of low supply air temperature, air will flow down the façade and enter the occupied zone at floor level; c) Horizontal obstacles show potential to reduce discomfort also when the airflow reattaches to the surface; d) Deeper obstacles and larger vertical distances between obstacles are preferable.

The present study takes solutions found in literature, and develops them further with the goal to avoid discomfort in the occupied zone. This is done by testing obstacles with different sizes, shapes and materials in a full-scale model at low outdoor temperatures. This work is linked to the ongoing building project Gullhaug Torg 2A (GT2A) (Snøhetta, 2015), a pilot project of the research project "Naturligvis ("Naturally") – Natural conditioning of office buildings". GT2A is planned as a mixed-use building north of the city centre of Oslo, where floors 3 to 6 are office floors which are envisaged to be exclusively naturally ventilated. Components such as grilles, window ventilators, or active or passive wall ventilators are not considered. The presented work is limited to unidirectional flow and focus is on steady-state condition under continuous ventilation: Other ventilation strategies like intermitted pulse ventilation are not investigated. As the study is linked to a building project, many parameters in the experiments are restrained to the project's specifications. The effects of e.g. varying size and angle of the vent, or airflow rates could not be studied. Furthermore, the available experimental setup with a room height of 2.40 m may not fully represent an office environment, where clear heights of 2.70 m or higher are common.

2 EXPERIMENTAL SETUP

The experiments are conducted in a thermally insulated test room with inner dimensions of 7.0 x 3.0 x 2.4 m made of 100 mm PUR-sandwich panels. The room is divided in a cold "outdoor" section, and a warm section representing an office environment with inner dimensions of 3.6 x 3.0 x 2.4 m. XPS insulation was used to model walls, vent, and obstacles due to easy handling. The partition wall is made of 200 mm XPS (U-value 0.17 W/m²K). An area of 1.8 x 1.8 m (45 % of the wall area) is made of 30 mm XPS (U-value 0.93 W/m²K) in order to represent a glazed façade. Figure 1 shows a photo of the test room and a vertical section of the vent.

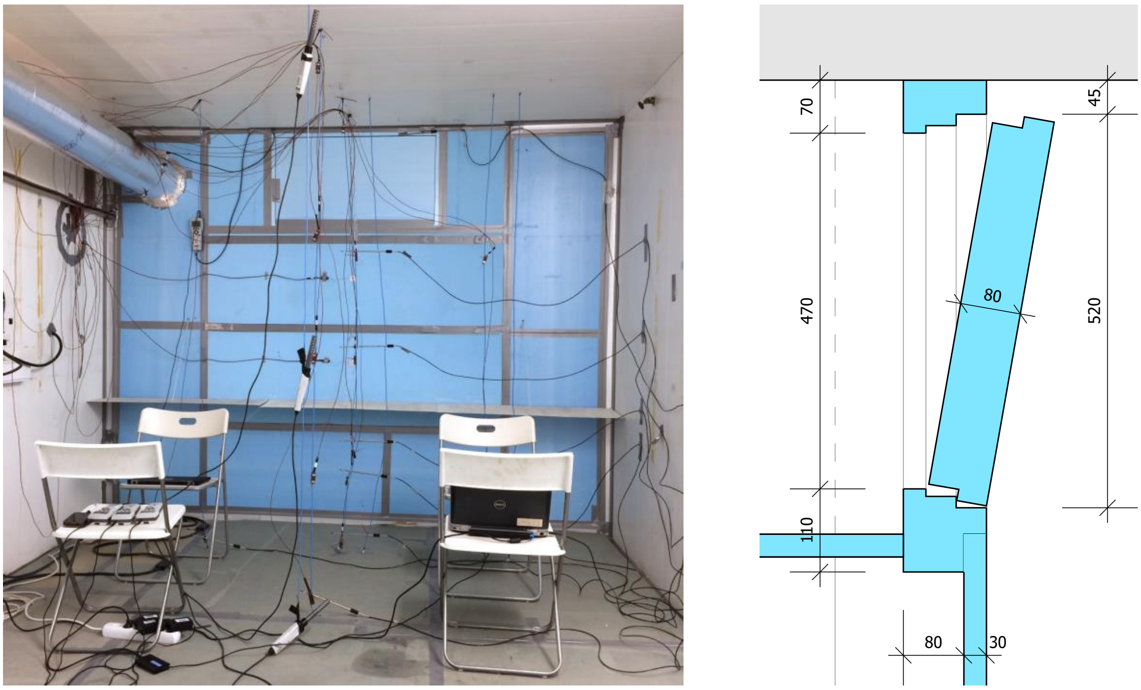


Figure 1: view inside the test room (left), section of the vent (right)

The vent sits flush with the inner surface of the façade and corresponds to a bottom-hinged inward-opening window. The frame profile emulates a typical Norwegian window profile for triple glazing (NorDan, 2017) on all 4 sides. The clear opening is 900 x 470 mm (0.43 m²), with the height given by GT2A, and the width chosen in order to measure the airflow rate directly at the vent with a flow hood. A vent opening angle of 10° follows GT2A and is kept constant in all measurements. A settling chamber is mounted in front of the vent on the cold side in order to reduce the influence of turbulences caused by the fan of the cooling system.

The warm section is heated by electric floor heating covering the entire floor. The setpoint temperature of 23 °C is given by measuring point A.2.3 in the middle of the room. Heating is controlled by a simple instantaneous on/off control with a power ca. 550 W with a hysteresis of 0.1 °C. The cold section is conditioned by a JULABO recirculating cooler with a flat plate heat exchanger as emitter in combination with an air to glycol heat pump emitting by an air cooler finned coil heat exchanger. Fans are used to force the flow through the exchangers and to mix the air to a uniform temperature in the cold section. Unidirectional airflow from the cold section through the vent into the warm section is controlled by an extract fan in the wall opposite of the façade (centre of duct ca. 220 cm above the floor) in order to achieve the desired airflow rate. Targeted airflow rates were at 12 and 24 l/s according to the specifications from GT2A and Norwegian building regulations. Airflow was measured with flow hood Testo 420 both at the window and at the extract inlet in order to determine and adjust airflow rates and adventitious infiltration.

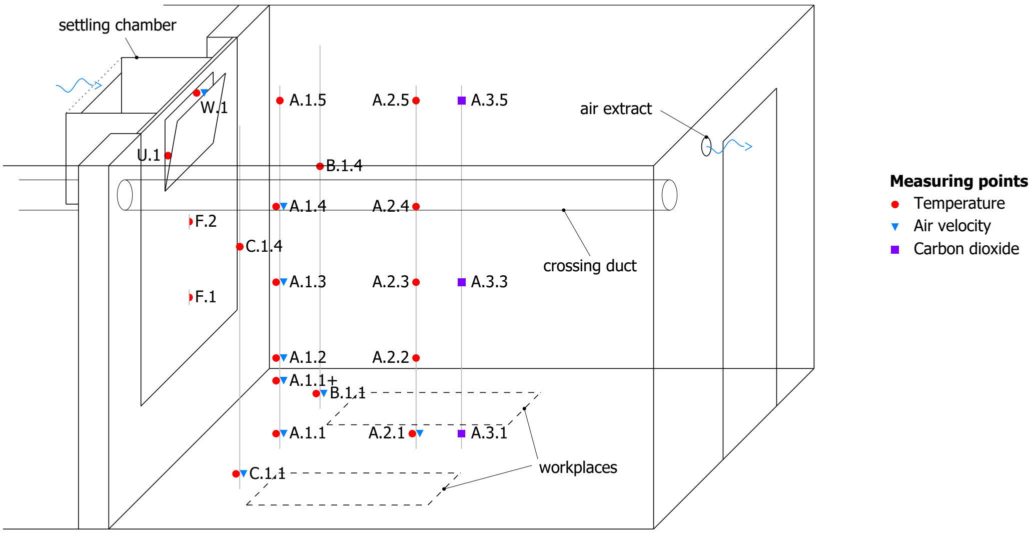


Figure 2: Test room (warm section) with measuring points

Figure 2 shows the measuring points in the test room. Temperature, air velocity were measured at selected points 0.60 and 1.50 m distance from the façade. CO_2 stratification was measured in the centre point of the room at three heights. Table 1 provides an overview over the used devices.

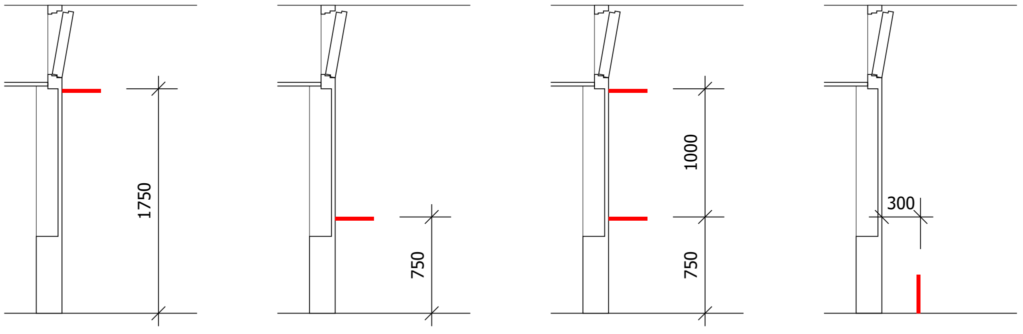
Table 1: Measurement equipment and properties

Parameter	Equipment	Number	Location	Accuracy
Temperature	Thermocouple type T	16	> Poles: 0.10, 0.60, 1.10, 1.60, 2.30 m above floor > Vent: outside (side) and inside (top) of opening > Façade (surface): 1.00, 1.50 m above floor	Accuracy ±0.5 °C
Air velocity	SensoAnemo 5100SF	9	> Poles: 0.10, 0.60, 1.10, 1.60, 2.30 m above floor > Vent: inside (top) of opening	Range(0.05-5.0 m/s) Accuracy ±0.02 m/s
Carbon dioxide	Vaisala M170	5	> Pole A.3: 0.10, 1.10, 2.30 m above floor	Accuracy ±0.035%
Airflow rate	Testo 420	1		Accuracy ±3 %

Figure 3 shows the four different types of obstacles that were investigated – rectangular solid panels, rectangular slotted panels (grille), rectangular perforated panels, and tubular obstacles mounted in a line.

Figure 3: Testes types of obstacles: solid panel, slotted panel, perforated plate, tubes (from left to right)

The intention of the last three types was to slow down and diffuse the supply airflow before entering the occupied zone. The solid and the slotted (5 mm gaps, c/c 25 mm, 20 % openness) panels are made of 30 mm XPS. The perforated panel is a 2 mm thick, perforated steel plate (5 mm holes, 40 % openness). Printing paper was rolled as tubes of 25 mm diameter with 15 mm gaps in between (37.5 % openness). The obstacles stretched over the entire width of the façade. Figure 4 shows the investigated placements of the obstacles – three are mounted on the façade and one on the floor. 0.75 m above floor corresponds to the usual height of window sills. Additionally, obstacle depths of both, 0.15 and 0.30 m were tested in some cases.



"175" "75" "75+175" "F"

Figure 4: Tested alternative positions of obstacles

Table 2 shows a matrix of the investigated elements. All cases with solid panels were tested. Other test cases were chosen iteratively based on the most promising results.

Table 2: Matrix of test cases

			Façade-mounted		**Floor-mounted**
Type	**Depth/height**	**1.75 m**	**0.75 m**	**0.75 + 1.75 m**	
Rect., solid	0.15 m	S.175_15	S.75_15	S.75+175_15	S.F_15
	0.30 m	S.175_30	S.75_30	S.75+175_30	S.F_30 S.F_30+P.F_30
Rect., grille	0.15 m	–	–	G.75+175_15	–
	0.30 m	–	G.75_30	–	–
Rect., perf.	0.30 m	–	P.75_30	P.75+175_30	P.F_30 P.F_30+S.75_15
Tubular	0.30 m	–	T.75_30	–	–

In a first stage, the potential of every alternative was studied for an airflow rate of 14 l/s and one person occupancy. The person was sitting still between pole A.3 and the door, and was working on two laptops. In a second stage, the 3 most relevant solutions were studied at two airflow rates under realistic conditions with 2 persons seated close to the border of the occupied zone (to evaluate discomfort subjectively). Consequently, internal heat loads are related to lighting (1 LED light, 1.5 W) in all stages and first one sitting person with 2 laptops (90 W and 65 W) and later two sitting persons with 3 laptops (90 W, 2 x 65 W).

3 RESULTS AND DISCUSSION

Table 3 provides the pairs of measured supply and extract airflow rates corrected for standard conditions (21 °C, 1013 hPa).

Table 3: Measured extract and supply airflow rates.

Airflow rate at vent (l/s)	**Airflow rate at extract (l/s)**
14 (N.N...22)	14 (N.N...22)
24 (15..32)	29 (22..36)

A leakage of ca. 17 % of the extract airflow was estimated for the higher airflow rate. This leakage through gaps and cracks is most likely due to cable passages through walls from outside and the cold section. Its value decreased with smaller airflow rates. During the test with low airflow rates a bidirectional and inconstant flow was observed. 14 l/s represents the average of the measured airflow rates in the 'right' direction. Extract airflow rates were later confirmed by CO_2 measurements. For the second stage the settling chamber was modified yielding the desired airflow rates.

Figure 5 and Figure 6 show the results of the first stage for the relevant measuring points 10 cm above the floor and the different points in pole A.1. Results are an average over 5 min with steady state conditions.

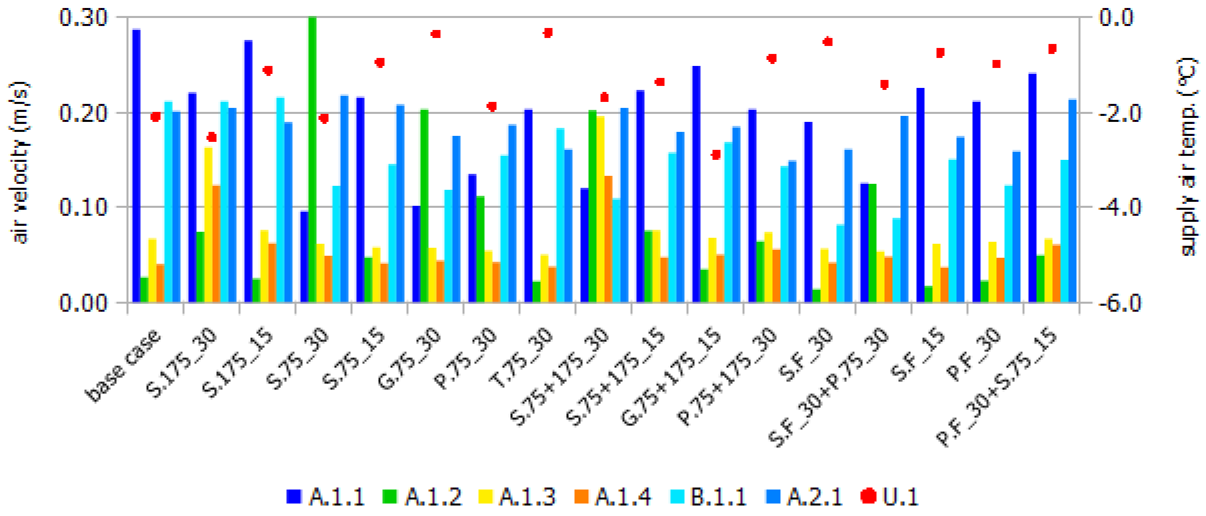


Figure 5: Stage 1, air velocities, and supply air temperature U.1

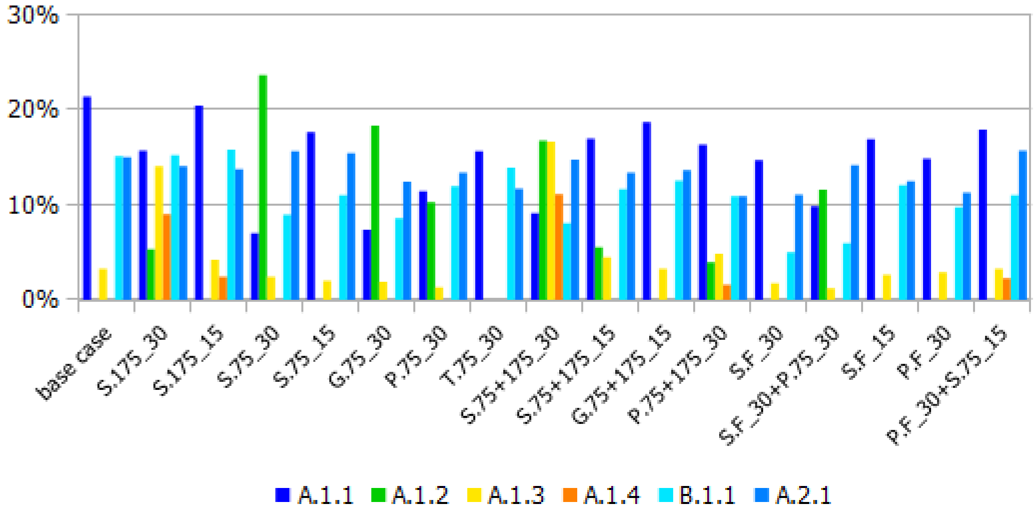


Figure 6: Stage 1, draught rate

In all cases, the lowest measured temperature is less than 2 K below the air temperature at point A.2.3 near the centre of the room. Measured maximum air velocities are expectedly high, particularly found at ankle height at around 0.2 m/s and more. However, the maximum calculated draught rates for the test cases are mostly less lower than 20 % and therefore rather low, probably due to the elevated room temperature of 23 °C and the low turbulence intensities, which were determined based on the logged air velocities.

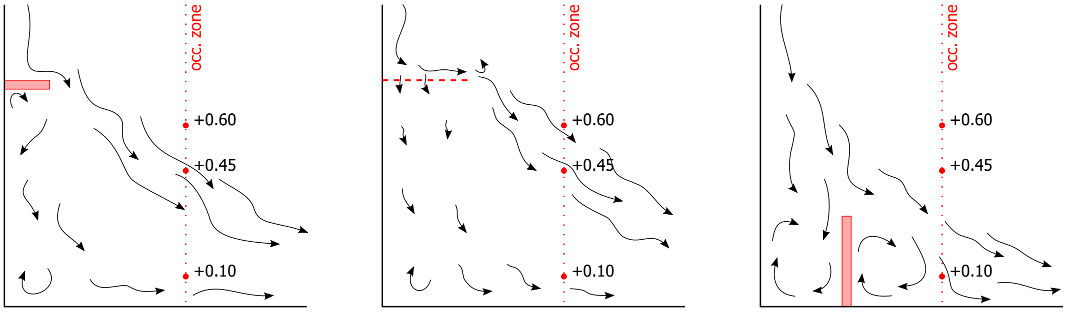


Figure 7: Qualitative visualisation of cases "S.75_15" (left), "P.75_30" (centre) and"S.F-30" (right)

High positioned (cases "175") façade-mounted cases do not reduce air velocities effectively. In addition to increased velocities 0.1 m above the floor, they also create problematic elevated velocities at higher points where deflected airflow drops into the occupied zone. Low obstacles (cases "75") reduce the air velocity at ankle height, but in some cases they cause increased velocities at 0.6 m above the floor, where the deflected air enters the occupied zone similar to cases with high positioned obstacles (see Figure 7, left and centre). Combinations of low and high obstacles show no or little improvement. Generally, obstacles with small depth are also less effective.

The permeability of the obstacles affects the velocity distribution at the border of the occupied zone considerably. Depending on the degree of openness, but also of the shape and material of the panel, a characteristic pattern of velocities at different heights develops. This was also visualised with smoke. The cold airflow separates into an airflow that penetrates the panel, where a pressure drop reduces its velocity, and an airflow that is diverted into the room (see Figure 7, centre). Permeability appears to be a promising solution, but requires optimisation of the degree of openness in order to balance the two airflows.

In the floor-mounted cases, the air velocities reduce significantly for case "S.F_30", but less prominently for the others cases. Visualisations with smoke showed that the panel divides the downstream into two airflows. The stream falling behind the panel creates vortices reducing the velocity and positively affecting the air velocities at low heights (see Figure 7, right).

The test cases "P.75_30", "S.F_30", and "S.75_15" were selected for the second stage. The first two have shown promising performance, "S.75_15" was chosen as a minimal solution, interfering less with the interior than the other two cases. It may also represent the impact of a window sill on the airflow.

Figure 8 and Figure 9 show the results of the second stage. As a results of the smoke visualisations and reported draught sensation, measuring point A.1.1+ was introduced at 45 cm over floor level as a spot of potentially high velocities.

The lowest temperatures at the border of the occupied zone are found for both airflow rates at ankle height near the façade (point A.1.1) at ca. 2 K below the temperature at point A.2.3 near the centre of the room.

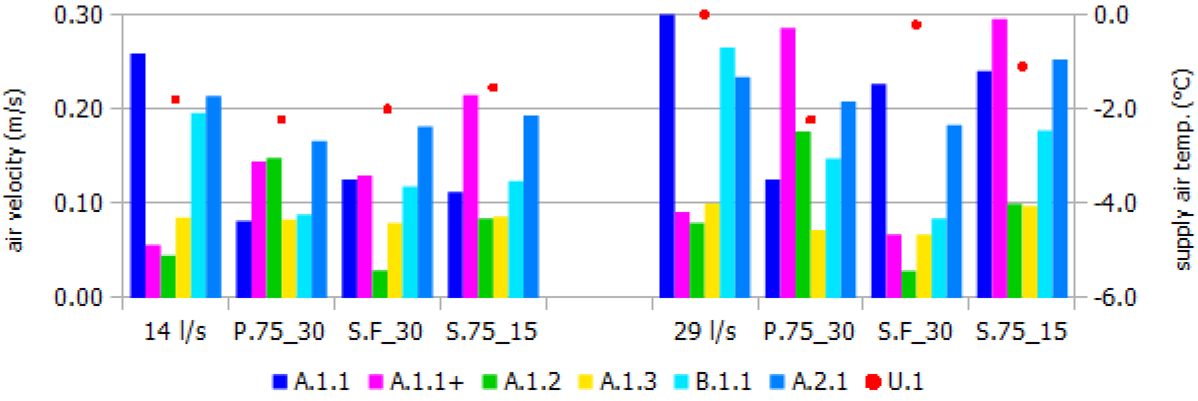


Figure 8: Stage 2, air velocities, and supply air temperature U.1 (cases with 14 l/s left, cases with 29 l/s right)

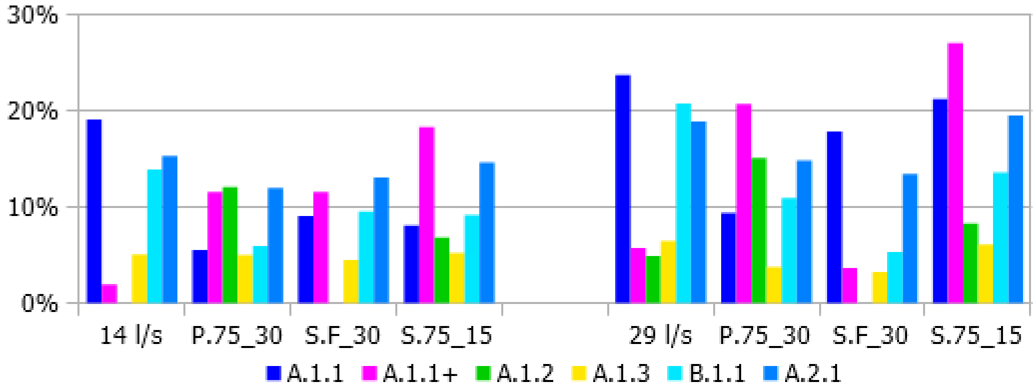


Figure 9: Stage 2, draught rate (cases with 14 l/s left, cases with 29 l/s right)

For airflow rate 14 l/s, the maximum air velocities near the façade are reduced compared to the base case and mostly lower than 0.15 m/s, also with two occupants. Elevated velocities are measured at 0.45 m above the floor, and the highest velocities in the room are measured at point A.2.1, further from the façade. Draught rates are below 20 % in all cases for 14 l/s airflow rate, also for the base case without obstacle.

At the higher airflow rate, air velocities at ankle height are reduced compared to the base case, particularly for case "P.75_30". However, the maximum velocities remain over 0.20 m/s in all cases and are allocated at point A.1.1+ for the 2 façade-mounted cases. Velocities at point A.2.1 are higher than 0.18 m/s (case "S.F_30") in all cases. Along with the air velocities, temperatures at point A.2.1 vary slightly between 21 °C (case "S.75_15") and 22 °C (case "P.75_30"). Only in case "S.F_30", the maximum draught rate is below 20 %.

The positioning of the heat sources, people and computer also can show an effect on the airflow distribution in the room. In the second stage the occupants' plume may have affected the results obtained at measuring points at the border of the occupied zone.

CO_2 measurements were conducted during the second stage. Results show similar CO_2 levels at the three measured heights, with corresponding temperatures at points A.2.1, A.2.3, and A.2.5 at ca. 22 °C, 23 °C, and 23.5 ° throughout all cases. While this indicates full mixing in the room, a tendency for stratification is noticeable when persons in the room sat still during tests. However, the duration of tests was short (ca. 15..20 min per test case) and stratification ceased when people moved again.

From the studied examples, case "S.F_30" shows the larger potential to effectively reduce risk of discomfort both at the lower and the higher airflow rates. However, velocities at ankle height in the central axis of the window, A.1.1 and A.2.1, remain high, particularly for the higher airflow rate. On the other hand, velocity in point B.1.1 75 cm beside the central axis is nearly equal to the velocity in point A.1.1 at 14 l/s, but significantly lower at the higher airflow rate, indicating a change in flow pattern with different airflow rates. This can also be concluded from velocities in points A.1.1 and A1.1+ which show similarities with the base case at the higher airflow rate. It also suggests, that the effectiveness of the obstacle may decrease at increasing airflow rates and/or decreasing outdoor air temperatures.

For all test cases, the impact of the obstacles in air velocities is primarily noticeable close to the façade respectively the location of the obstacle, while regions deeper in the room (e.g. around point A.2.1) seem less affected. There, velocities remain nearly as high as in the base case. This indicates that the effect of elements may be limited to their near vicinity, which suggests that local solutions at the workplace are more suitable.

Moreover, in some cases measured velocities at certain points were higher than in the base case without additional elements, and reached critical values. This raises the issue that solutions that are supposed to reduce draught actually may introduce a new risk of discomfort to the occupants at a different part of the room. The design of the elements must therefore be well considered.

4 CONCLUSIONS

16 potential solutions to reduce thermal discomfort linked to window opening at cold outdoor supply air temperatures have been studied in a full scale model experiment. All investigated solutions have in common, that they do not reduce the airflow rate through the vent. Horizontal, perforated plates at window sill height and low, vertical elements at the floor between façade and the border of the occupied zone are chosen as the most promising principle solutions. Their presence disturbs the draught flow reducing its velocity and allowing the air to get warmed up before entering the occupied zone. Generally, the solutions found seem more suitable for lower airflow rates, and are mainly effective near the elements.

It was found that these flow deflectors may create discomfort risks at other locations. Careful design and testing is therefore advised. Furthermore, consequences for all points in the room possibly exposed to draught risk need to be evaluated, not only at standard locations at the border of the occupied zone. In addition, although the occupied zone in terms of indoor climate considerations does not stretch until the façade, it is usually desired to use the entire spaces, where obstacles would disturb when protruding into the room. The further development of deflectors should consider this.

The present study uses only a restrained set of parameters. Further studies with a wider range of airflow rates, outdoor temperatures, and types of elements regarding dimensions, material, and placement and integration is necessary.

5 ACKNOWLEDGEMENTS

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