# Experiences regarding draught effects for ventilative cooling in cold climate


Maria Justo-Alonso [1*], Solveig Blandkjenn [2], Hans Martin Mathisen[2]

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

*2 Norwegian University of Science and Technology,*
*Kolbjørn Hejes vei 1b,*
*7491 Trondheim - Norway*



## ABSTRACT

New buildings have to satisfy stricter standards regarding energy efficiency and consumption. This results in higher insulation levels and lower air leakages that reduce heating demands. However, together with the heating demands reductions, higher temperatures in summer and particularly shoulder season are more frequent even at moderate to cold climates. In order to ensure acceptable indoor environment quality, removal of excess heat becomes unavoidable. Using mechanical cooling in residential buildings is considered incompatible with achieving zero energy buildings (ZEB). Using ventilative cooling (VC) one can combine mechanical ventilation to supply minimum hygienic airflow rates and windows opening to supply cooling. The ZEB's ventilation systems gain larger importance as they can ensure minimum air quality, provide heating and in summer months remove excess heat.

The Living Lab in Trondheim (Norway) is built as zero emission building. In Norway, 100 % of the cooling needs can be covered by ventilative cooling, either by mechanical or natural ventilation. The ventilative cooling potential depends on many variables; the internal gains, solar gains, use of solar shading, windows g and U values, heat loss coefficient of the building, ventilation flow rate, indoor and outdoor temperatures, etc. One additional consideration for cold climates is over cooling; this is an extra limitation on the use of window opening for cooling. Over cooling is related to thermal discomfort and extra energy use for heating.

The Living Lab has six motorized windows that enable for cross and buoyancy driven ventilation. In addition, three sliding doors can be used for cooling purposes with the restriction that their opening can only happen during occupied hours.

The goal of this paper is to develop a control system based on measurements. The control has to ensure sufficient cooling and hygienic airflow rates. This control ought to ensure thermal comfort without incurring increased energy use. The control is applied to the building in shoulder seasons and the measurements of the performance are presented.



## KEYWORDS

Ventilative cooling, energy saving, simulations IDA ICE, motorized window opening


## 1 INTRODUCTION

Super insulating buildings is the obvious solution to reduce energy use for space heating in cold climate countries. Modern super insulated buildings are constructed in materials with low U values and high airtightness. In airtight building's controlled ventilation has a major role to improve the indoor air quality (IAQ) and comfort (Sundell 2004). Accumulated "free heat gains" become negative when heating is not needed. Thermal discomfort due to high temperatures is experienced more often in super insulated buildings and to reach acceptable indoor climate, removal of excess heat is compulsory. The potential for ventilative cooling becomes larger (Finocchiaro, Wigenstad, and Hestnes 2010).

Windows in cold climates are often dimensioned with high g-factors, so that a larger share of the solar radiation is used for heating. In shoulder season and summer, this means that the gains due to solar radiation are a relevant heating source. Solar shading can be used to control this heat gain to a certain extent, but are seldom efficient enough to give full control of the solar radiation. Many occupants that have manually operated shadings often forget to close or intentionally leave the shading open when leaving home. For these reasons, cooling must be considered. With the goal of achieving the nZEB level, mechanical cooling is not considered as a satisfactory solution to limit over temperatures.

Mlecnik (Mlecnik et al. 2012) did some post occupancy questionnaires and concluded that 34 % of his respondents experienced high indoor temperatures "sometimes" in the living room and 49 % complained about bedroom over temperatures during summer. Samuelson's (Samuelsson 2009) research revealed that 50 % of the residents were dissatisfied due to the high summer temperatures in passive houses in Sweden. In Norway, Georges (Georges, Wen, Justo Alonso, et al. 2016) (Georges, Wen, Alonso, et al. 2016; L. Georges, F. Håheim, and Alonso 2017) and Berge (Berge and Mathisen 2016; Berge, Thomsen, and Mathisen 2016) came to the same conclusion, users are dissatisfied due to too high temperatures in bedroom yielding the need to open windows, partly also during the winter.

VC should be perceived as a part of a total strategy that includes use of solar shadings, minimization of internal heat gains and intelligent use of thermal mass (Venticool 2013). Natural ventilative cooling is considered in this context a very good solution for removal of thermal loads. (Kolokotroni and Heiselberg 2015). In cold climates, the theoretical potential of heat removal by VC is 100 %. However, in these locations the risk of over cooling has to be considered in detail (Justo Alonso, Kirkøen, and Mathisen 2015). Degree of window opening, window size, temperature differences between outdoor and indoor, etc., prove to have high relevance for the cooling potential (Kolokotroni and Heiselberg 2015).

The scope of this paper is the performance evaluation of the Living Lab natural VC control solution concerning thermal comfort and energy consumption. The resulting optimal control is compared in the same terms to improved window opening sizes, building cardinal orientation and building insulation levels

## 2 LIVING LAB

The Living Lab is a test facility installed in Trondheim, Norway (63ºN) constructed to obtain the zero emission level (Finocchiaro et al. 2014). This residential single family house has a gross volume of approximately 500 $m^3$ and a heated surface (floor area) of approximately 100 $m^2$ (Finocchiaro et al. 2014).

Table 1 - Thermo-physical properties of building envelope components(Goia, Finocchiaro, and Gustavsen 2015)

| **Thermo physical properties** | |
|---|---|
| U-value wall | 0.11 $W/m^2K$ |
| U-value floor | 0.10 $W/m^2K$ |
| U-value roof | 0.10 $W/m^2K$ |
| U-value windows (south façade) | 0.65 / 0.69 (when ventilated) $W/m^2K$ |
| U-value windows (north façade) | 0.97 $W/m^2K$ |
| U-value windows (east-west façade) | 0.80 $W/m^2K$ |
| U-value skylight | 1.0 W/m2K |
| g-value for windows | 0.5- |
| Air tightness, $n_{50}$ | 0.5 ach |

The building is equipped with a very comprehensive data acquisition system with access to 330 sensors that measure energy demand for heating, ventilation, lighting and appliances, and renewable energy produced by a roof-integrated PV system and façade-integrated solar thermal panels. The accumulation tanks and indoor environment are also fully monitored (Finocchiaro et al. 2014).

The installed ventilation is a mixed-mode hybrid system with mechanical balanced ventilation and motor controlled windows. The mechanical ventilation is a balanced mechanical system with heat wheel recovery with 85 % rated efficiency and additional electric heating coils (Blandkjenn 2017). Supply units are placed in the living room and bedrooms and extracts are placed in the kitchen and bathroom. Table 2 shows the supplied and extracted airflow rates for each room in Living Lab (Blandkjenn 2017).

Table 2: Airflow rates in Living Lab during normal occupancy

| **Supply** | **Airflow rate [m$^3$/h]** | **Extract** | **Airflow rate [m$^3$/h]** |
|---|---|---|---|
| Small bedroom | 52 | Bathroom | 78 |
| Master bedroom | 52 | Kitchen | 52 |
| Living room | 26 | | |
| Total supply | 130 | Total extract | 130 |

The dwelling has operable windows on every facade in order to profit from both stack and cross flow ventilation through mechanical opening of windows. On the north side, an elongated window is implemented. It is constructed with hinges at the top, and opens outwards to a maximum angle of $51^{\circ}$. On the west and east side there are glass sliding doors. Two sets of rooftop skylight tripled glazed windows faces to the north. They open to a maximum angle of $32^{\circ}$. The south windows opens to a maximum of $32^{o}$, it is a double skin window. See **Error! Reference source not found.** to see the location of the controllable windows.

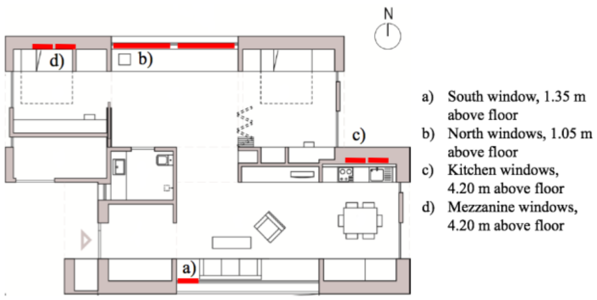


Figure 1. Position of automatically controlled windows in Living Lab (Blandkjenn 2017)

Table 3:Window areas and maximal openable areas(Finocchiaro et al. 2014)

| **Window** | **Number of windows** | **Area per window [m$^2$]** | **Maximum openable area per window [m$^2$]** |
|---|---|---|---|
| North | 2 | 1.21 | 0.786 |
| South | 1 | 10.5 | 1.130 |
| Skylights | 4 | 0.484 | 0.338 |

## 3 OPTIMAL WINDOW CONTROL

In order to develop a reliable control strategy, measurements have been done in Living Lab and then these results have been used to develop a control strategy based on simulation with the program IDA ICE (EQUA 2016). The main results and graphs of this and next chapter are taken from the Master thesis of (Blandkjenn 2017).

### 3.1 Measurements results

Blandkjenn (Blandkjenn, 2017) carried out an extensive measurement campaign to reveal the most affecting parameters when creating a window control algorithm.
The southern window is a double skin window, where air might preheat before being supplied to the room. As this window is placed close to the sofa of the living room, the draught risk from this window needs to be assessed. Figure 2 shows the positioning of the measurement points for air velocity and temperature.

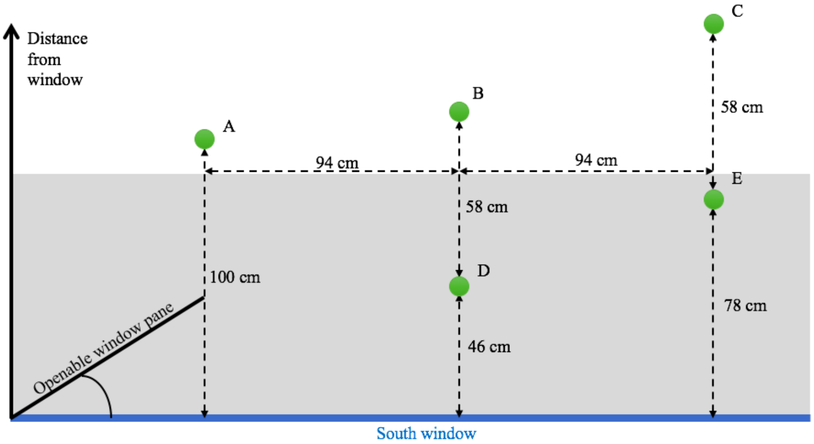


Figure 2. Measurement points near the south window

To determine the opened window's cooling effect the temperature difference between the airs flowing from the window and the room air has been studied. Figure 3 shows the difference between the temperature measured one meter from the window and the room air. This graph distinguishes between the different levels of solar irradiance through the window (not specified). When the solar irradiance is above 600 W/m$^2$, the pre-heating of the air is so large that the air one meter from the window has the same temperature as the room.

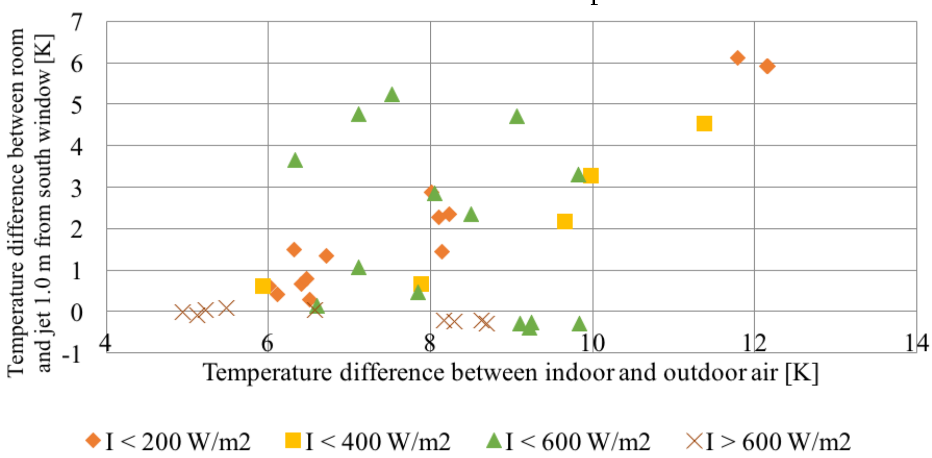


Figure 3. Temperature difference between air in the room and air in the jet 1 m from window, for different levels of solar irradiance.(Blandkjenn 2017)

When solar irradiance is lower than 600 W/m$^2$, the temperature difference increases with the temperature difference between indoor and outdoor air. It seems, Figure 4 left, that when the temperature difference between the indoor and outdoor air ($\Delta T_{in\text{-}out}$) is below 6 K, the DR is very low. Even when the air in the jet is warmer than the average temperature of the room, air velocities above 0.2 m/s are still measured. This has a cooling effect on the people sitting in the room, even if the air temperature is not reduced. Jet temperatures were not measured 0.4 K over the room air. This means that the south window can be opened in most weather conditions without risk of increasing the overheating, but the cooling capacity will be limited. In addition, the pre-heating of air through the south window reduces the risk of overcooling on cool days.

## Draught rates under different climatic conditions

Measurement proved that draught rates generally increased with $\Delta T_{in\text{-}out}$. However, there were many outlying measurements, especially when the temperature differences were low. The temperature difference is the main driving force for natural ventilation at higher temperature differences, but at lower temperature, differences in wind and solar conditions influence the airflows largely. The draught rates in front of the window were lower when the solar irradiance was higher. When the irradiance is larger, the $\Delta T_{in\text{-}out}$ is lower because of the larger heating effect of the double skin window. A lower solar irradiance gave higher variance within the measuring points; this can be explained by sudden changes in cloudiness on warm days.

It is seen from Figure 4 right that there is no occurrence of draught rates lower than 20 % when the solar irradiance is below 70 W/m$^2$. **This is therefore chosen as a lower limit for solar radiation to open the south window.**

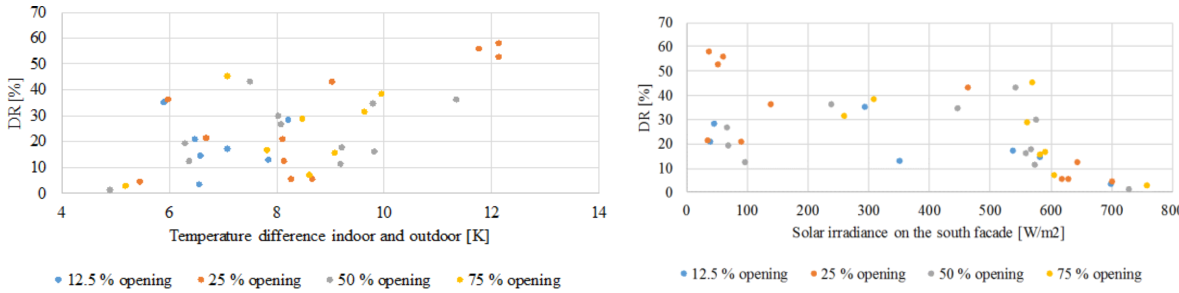


Figure 4 (left)Draught rates as a function of temperature difference, (right ) Draught rates as a function of solar irradiance, for different window opening sizes measured in point D (Blandkjenn 2017)

The wind speed is studied, and it is measured to have a lower effect on draught rates than the temperature difference and the solar irradiation. **However, when the wind speed is above 2.0 m/s, the lowest measured draught rates are over 20 %. This is therefore chosen as an upper limit for the wind speed during openings of the south window.**

To establish rules for the use of the south window, the limits for $\Delta T_{in\text{-}out}$, wind speed and solar irradiance were chosen based on the measurements done 1.0 m from the window at 0.05 m height.

The maximum allowed $\Delta T_{in\text{-}out}$ is defined as 10 K, the maximum wind speed is set to 2.0 m/s and the lower limit for solar irradiance is 70 W/m$^2$. Figure 5 shows the measurements within these restrictions and for them, draught rates above 20 % only occur with window opening larger than 50 % and 75 %. When the window openings are restricted to 12.5 % and 25 % the thermal discomfort in reduced below 20 %. Due to limitations in data from the experiments, draught might still occur, but the hours of discomfort are assumed to be within the 3 % allowed deviation.

Because of the double skin construction, cooling will not always be achieved by opening the south window. It has been seen that the cooling effect of opening the south window has been near zero when the temperature difference between the indoor and outdoor air is below 6 K.

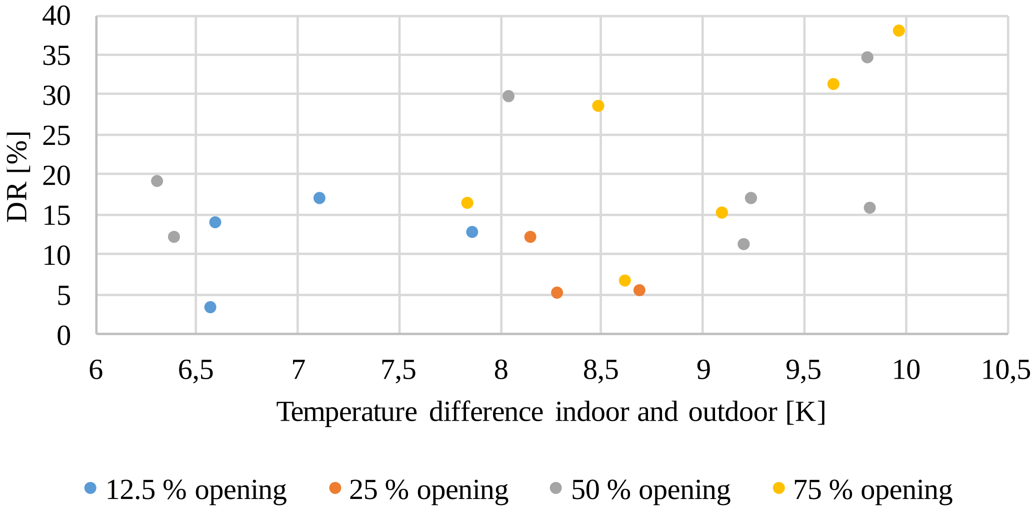


Figure 5. Measurements with dT < 10 K, v < 2 m/s and I > 70 W/m$^2$ (Blandkjenn 2017)

A similar study was done for the north window concluding:
For $\Delta T_{in\text{-}out}$ equal to 5.7 K, there was only unacceptable draught rates outside the occupied zone (less than 1m from the window). For $\Delta T_{in\text{-}out}$ equal to 8.4 K and 9.5-9.9 K higher draught rates were measured. This indicates that the north window can be opened automatically if the outdoor temperatures are high enough. The draught rates increased as the opening was increased. The high risk of local thermal discomfort was expected for the north window as this window delivers unheated outdoor air at body height. Due to the limited number of measurements, it was possible to perform; it is hard to determine the exact temperature difference at which the north window can be opened without thermal discomfort. However, a limit of 6 K is proposed in this work. In addition, the cooling effect of the south window is very low for $\Delta T_{in\text{-}out}$ below 6 K.
The wind speed was low during all experiments, and the prevailing wind direction was south-west. It is not possible to derive how variable wind conditions would influence the results. The same applies for the irradiance, and therefore these two parameters are not introduced in the control of the north window.
The purpose of the experiments was to investigate the local thermal discomfort caused by the window openings under different climatic conditions, and determine rules for when and how to use the windows for ventilative cooling. The rules established about the climatic conditions that allow for window ventilation in Living Lab are presented in Table 4

Table 4. Climatic rules for ventilative cooling through windows in Living Lab (Blandkjenn 2017)

| Window combination | Temperature difference between indoor and outdoor | Wind speed | Solar irradiation |
|---|---|---|---|
| South window and one kitchen skylight | 6 K – 10 K | < 2 m/s | > 70 W/m$^2$ |
| North window and one kitchen skylight | < 6 K | NA | NA |

When these climatic requirements were satisfied, the draught rates 1.0 m from the north and south windows were deemed satisfactory when the north window was opened 25 % or 50 %, and when the south window was opened 12.5 % or 25 %. Therefore, these rules were chosen for the IDA ICE simulations to determine the thermal climate and energy consumption when applying the defined window control.

### 3.2 Simulated control

Simulations were realized using IDA ICE. Based on the results from Justo Alonso (Justo Alonso, Kirkøen, and Mathisen 2015), using a PI-control does not improve the performance of the control and contrarily increases its difficulty. Improving the simulation form (Kirkøen 2015) a new model of the Living Lab was produced. The control was done following Table 4. In addition, from (Kirkøen 2015) and (Blandkjenn 2017), the windows opened when the average temperature is above 24 °C, and they close when the minimum temperature is below 22 °C.

Table 5. Thermal comfort and energy consumption with different window opening sizes (Blandkjenn 2017)

| | **Hours of thermal discomfort** | | | | **Heating and cooling energy** | |
|---|---|---|---|---|---|---|
| | **Living room [h]** | **Building total [h]** | **Decrease living room** | **Decrease building total** | **Value [kWh]** | **Increase compared to closed windows** |
| No openings | 105 | 303 | | | 126.2 | |
| Mech. Cooling | 0 | 0 | 100 % | 100 % | 341.8 | 171.8 % |
| S12.5%, N25% | 17 | 57 | 83.8 % | 81.2 % | 139.4 | 10.5 % |
| S12.5%, N50% | 15 | 47 | 85.7 % | 84.5 % | 144.9 | 14.8 % |
| S25%, N25% | 15 | 48 | 85.7 % | 84.2 % | 138.9 | 10.1 % |
| S25%, N50% | 13 | 38 | 87.6 % | 87.5 % | 145.1 | 15.0 % |

Table 5 shows that all the window opening sizes were efficient reducing the over temperatures significantly in the simulated period. However, only the largest opening yielded a number of hours of overheating within the 44 h limit. For the building as a whole, the hours of thermal discomfort decreased at least 81.2 %. Opening the north window 50 % decreased the hours of over temperature by 10 h compared to opening it 25 %. Opening the south window 25 % decreased the over temperature by 9 h compared to opening it 12.5 %. Therefore, it is concluded that larger opening size in both windows will give higher thermal comfort as long as windows are closed within the stated temperature limits. To maximize the thermal comfort without incurring in larger energy use, the north window should be opened 50 % and the south window opened 25 %.

The living room was the warmest zone in the building, with the lowest thermal comfort according to NS15251. Similarly, to the building as a whole, the thermal comfort in the living room increased with the window opening size. With the largest allowed window openings, only 13 hours of occupancy (against 105 without window opening) were outside the comfort requirements categories I and II in the standard. These simulations assume no solar shading, despite that previous studies (Kirkøen 2015; Risnes 2016) have shown the positive effects of solar shading in Living Lab. By using solar shading actively, the thermal climate can be improved further. The energy consumption for heating increased about 10 % in the scenarios where the south window was opened 12.5 %, and ca 15 % in the scenarios where the south window was opened 25 %. Due to the low outdoor temperatures, high indoor temperature may happen during cold outdoor, and heating needs are triggered when opening windows. The size of opening in the south window was a bigger influence on the energy consumption than the opening in the north window. This is because the south window was used when the outdoor temperatures were lower and therefore the risk of undercooling is higher when the opening is larger. Given the double skin of south window, when the opening is smaller, the airflow is smaller, and will be heated more from the solar gains and heat loss through the inner pane than if we had a larger airflow. The lowest energy consumption is for opening the north window 50 % and the south window 12.5 %. This means that you have a small opening in the cooler periods and large openings when the heating demands are low. The conclusion drawn from the simulations with different window sizes is that a good thermal climate can be achieved with window ventilation without a high increase in energy consumption for heating. Generally, increased openings in the north window gave better thermal comfort - without increasing largely the energy consumption. According to the simulations, the operative temperatures can be kept within comfort categories I and II for 97 % of the time using the largest allowed window openings. Table 6 presents the results of a year energy simulation for this alternative.

Table 6. Full year simulation

| Opening sizes | Hours of thermal discomfort [h] | Heating energy [kWh] |
|---|---|---|
| No openings | 664 | 5361.0 |
| N 50 %, S 25 % | 134 | 5392.4 |

The allowed number of hours of thermal discomfort is 259 h, so the chosen solution gives thermal comfort within these limits. The energy for heating increases with 31.4 kWh per year, and ca.86 % of this difference occurs in April and May.

### 3.3 Levels of insulation

This chapter presents simulations done with increasing insulation levels to investigate the effect of natural VC in different types of buildings. The three simulated insulation levels; are the TEK10 (Direktoratet for byggkvalitet 2011), the low-energy building (Norge 2013) and a passive house.(Norge 2013). Table 7shows the U-values of walls, roof and floor for the different simulations, and the average U-values of the building body including windows and doors.

Table 7. U-values for simulation scenarios

| | U-value walls [W/m2] | U-value floor [W/m2] | U-value roof [W/m2] | Average U-value [W/m2] |
|---|---|---|---|---|
| TEK10 | 0.18 | 0.15 | 0.13 | 0.20 |
| Low-energy building | 0.15 | 0.10 | 0.10 | 0.18 |
| Passive house | 0.10 | 0.08 | 0.08 | 0.15 |

These simulations were done for May and June in Trondheim. Table 8 presents the thermal comfort and energy consumption when applying ventilative cooling in buildings with the different insulation levels.

Table 8: Thermal comfort and energy consumption with and without window cooling

| | Hours of thermal discomfort in building | | Floor heating energy | |
|---|---|---|---|---|
| | Value [h] | Decrease | Value [kWh] | Increase |
| TEK10 closed | 193 | | 282.4 | |
| TEK10 open | 33 | 82.9 % | 327.7 | 16.0 % |

| | | | | |
|---|---|---|---|---|
| Low-energy closed | 280 | | 155.1 | |
| Low-energy open | 41 | 85.4 % | 176.9 | 14.1 % |
| Passive house closed | 452 | | 57.5 | |
| Passive hours open | 44 | 90.3 % | 72.3 | 25.7 % |

Without window cooling the thermal comfort was worse for buildings with lower U-values, because more heat is trapped within the building. However, when applying window cooling the achieved thermal comfort is almost identical in the three simulated scenarios. Therefore, the higher is the insulation level, the larger is the ventilative cooling potential. This corresponds to the findings in literature that the potential of ventilative cooling is larger in well-insulated buildings (Finocchiaro, Wigenstad, and Hestnes 2010). The absolute increase in energy consumption is lowest when the U-value is lowest. Interestingly, the percentage increase in energy consumption when applying ventilative cooling is the smallest in a low-energy building. This can be explained by the very low energy consumption with passive house standard, where even the small amount of 14.8 kWh is a 25.7 % increase.

## 4 CONCLUSIONS

This paper presents a control strategy for providing ventilative cooling by means of window use in a zero emission building located in a cold climate. The results from the simulations implied that there would be a severe risk of overheating in Living Lab if no active or passive cooling techniques are applied, mostly because shading is not considered. The results showed nonetheless that ventilative cooling could prevent overheating without significantly increasing the energy demand. This is proved achievable with a control grounded on on-off regulation and temperature difference limits, as they seem to be the most affecting parameters. The opening of the windows is very much based on the draught rate limitations; it proves that increasing window opening yields larger heating demands if the control is not accurate.

The building insulation level also affects the energy consumption for both the heating and cooling, the lower the U-value, the lower demands for heating but higher demands for cooling and the larger the ventilative cooling potential.

## 5 ACKNOWLEDGEMENTS

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