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Energy Procedia 132 (2017) 592–597

Energy Procedia

www.elsevier.com/locate/procedia

11th Nordic Symposium on Building Physics, NSB2017, 11-14 June 2017, Trondheim, Norway

Analysis of reduction of energy demands for Zero Emission Renovated Office Building by using thermal mass and ventilative cooling

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Abstract

Zero emission buildings (ZEB) are characterized by high levels of insulation and air tightness. Powerhouse Kjørbo is the first Zero Emission Renovated Office Building in Norway. In 2013-2014 the building from 1985 underwent a major renovation to passive house standard (class A), keeping only the concrete framework to reduce emissions. The building has been monitored for one year. The data has been used to build and validate an IDA ICE simulation model in order to study possible improvements in energy consumption by changing the thermal mass and the ventilation strategies.

The thermal mass effect is strongly dependent on the volumetric heat capacity and the thermal admittance. Thermal mass placement within the structure would modify the energy use for heating and cooling. For instance, placing the thermal mass in the internal walls will not have the same effect as placing it between the floors. The interaction with the ventilation system also affects the energy use. Using nighttime setback with heavy walls, (large thermal inertia) proves to reduce cooling demands during summer time. Other strategies of window control with heavy mass during daytime are studied focusing on reduced energy demands.

The conclusion for the studied case is that given that the concrete structure was already built, the use of thermal mass is smart. However, when designing to achieve ZEB, increase of thermal mass in the form of concrete must be thoroughly thought as it would decrease cooling demand and shift temperature peaks, but will not be so beneficial for heating. At the same time increased thermal mass will increase the greenhouse gas emissions.

Peer-review under responsibility of the organizing committee of the 11th Nordic Symposium on Building Physics.

Keywords: Thermal mass; Ventilative cooling; Thermal comfort; Energy use

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Peer-review under responsibility of the organizing committee of the 11th Nordic Symposium on Building Physics
10.1016/j.egypro.2017.09.750

1. Introduction

New buildings are to comply with more demanding requirements related to reduction of energy use. The use of thermal mass in these buildings with high insulation levels is much discussed. On the one hand, the thermal mass increases the building's inertia making it less responsive to sudden changes of outdoor temperature. On the other hand, a smart coordinated use of the thermal mass and the energy systems makes the building to become a thermal storage.

The thermal mass behavior is strongly dependent on its volumetric heat capacity (quantity of heat storage in the material) and its thermal admittance (quantity of heat transfer from material to air when subjected to cyclic variations in temperature). The depth of penetration of the diurnal heat waves' in the material depends on its thermal diffusivity [1]. If heat is stored beyond a certain thickness it would take longer to transfer it back to the indoor air. This would mean, in the worst case, that the heat would be released when heat demands are lower, incurring on increased cooling demands to dissipate the stored heat from the walls [1]. The concrete has low thermal mass diffusivity, which means it slows the heat transfer through the material; stores large amounts of heat; and is less sensitive to temperature differences in the surrounding environment.

Indoor lightweight materials exposed to sun will quickly heat up and transfer heat to the room air by convection. Heavy materials exposed to solar radiation will be able to absorb more heat without increasing their temperature, keeping the room air temperature constant[2]. Heat transfer coefficients for convective exchanges to and from the surfaces of the walls are greater for vertical walls than floors and ceilings[3], unless the room is ventilated by air diffusers near ceiling as then it becomes a radiant cooling surface.

The general assumptions for this paper are that (1) during cooling season the use of thermal mass stabilizes the internal temperature, which in turn, will reduce the building cooling demands [4]. In the evening, because of the evening air-temperature drop, night ventilation and thermal mass will easy remove heat accumulated in the building. The cooled mass is efficiently used to lower the building cooling demands only if the building envelope is well-insulated [1]. (2) During heating season, south-facing windows transmit solar radiation that will be stored in heavy thermal mass materials. When the solar radiation ceases, the stored heat will be released, reducing the heating loads[5]. (3) High thermal mass materials such as concrete could delay the internal temperature peak for several hours. Given a delayed temperature peak to after-work-hours and reduced heat gain, the required cooling energy decreases[5].

In this paper, based on measurements obtained from Powerhouse Kjørbo (PK), an IDA ICE model was developed to study the effect of thermal mass on energy consumption.

2. Measurements Powerhouse Kjørbo

Powerhouse Kjørbo is defined after the Powerhouse Alliance [6] as a building whose" *primary energy balance over its lifespan must be positive. Plus-energy implies that the building during its lifetime shall produce and export renewable energy that compensates for energy use for other life cycle stages. ".* In addition, it is the first Norwegian building renovated to ZEB-OM÷EQ level according to the definition of the Norwegian ZEB centre [7].

PK has a high-quality airtight building envelope with low average U-value and a VAV ventilation system with very low SFP factor and high-efficiency heat recovery from the extracted ventilation air and efficient solar shading. PK is equipped with an energy-efficient heating and cooling system with heat pumps. During the renovation of PK, the structural concrete constructions were maintained in order to reduce emissions due to materials.

During 15 days, temperatures were measured in (C, in Figure 1) ca. 8 meters away from the concrete walls in the middle of the open area at 1.2 m from the floor. Orientation Northeast. (D) on the concrete outside the ventilation shaft. 1.2 m from the floor. Orientation North-West. No excavation or scratching on the concrete surface was done. The occupancy and number of PC screens were measured from May 19th to May 21st; from Tuesday to Thursday.

Fig 1 shows the temperatures for this period for Sensor D on concrete wall and sensor C in the landscape. From these measurements, a delay between both measurements placed on the same room is seen. When employees come to work and the CO_2 concentration levels are not high enough to trigger the increase on ventilation rates, the temperature in the room increases. Meanwhile the temperature in the concrete is slowly rising but with a delay of almost two hours. Sensor C shows values for the open plan, which are up to 0.8 °C higher than the value for the same period on the concrete (at the beginning of the day).

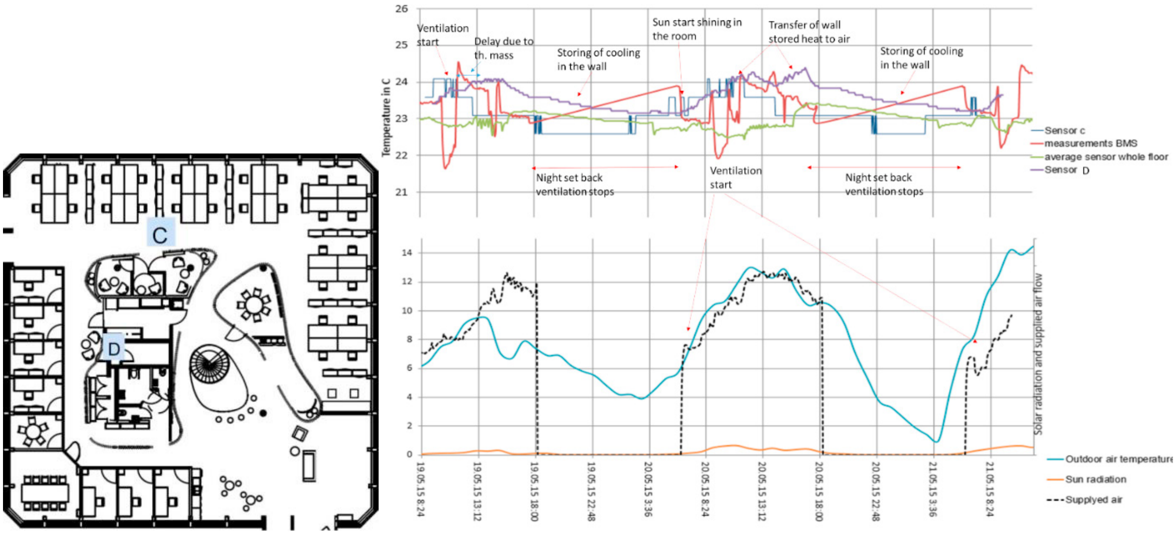

Fig 1 Measurements on selected places in Powerhouse Kjørbo third floor

Eventually when CO_2 concentration or air temperature threshold are surpassed, the ventilation rates are increased and the air temperature drops (sensor C) simultaneously to a temperature increase of the wall surface (sensor D). Probably, because the sensor not being placed inside the wall surface the peak delay is shortened. Given the low thermal diffusivity of the concrete, further inside the wall the temperature is probably still high at the time that it starts to decrease at the surface. We can see from

Fig 1 that concrete delays the temperature increase in the wall, probably since the heat is stored further inside the concrete mass. This is concluded because of the delayed temperature increase and the consequent temperature increase when the air temperature starts to decrease. On the second day, the sun shines and starts warming up the room before occupants come to work, justifying the early morning temperature increase and that the delay due to thermal mass happens even before workers arrival. Night cooling by increase of ventilation is run to reduce accumulated heat.

The accuracy of sensor C is ±0.5°C whereas for the thermal mass (Sensor D) is of ±0.1°C. Note the difference of resolution in the presented values. Outdoor temperature and solar irradiation are taken from the measurements of the same day for Lier (E-lima website [8]), the closest weather station to Kjørbo. The measurements for the airflow are presented in m^3/h. The presented measurements are used for validation of the simulations on IDA ICE.

3. Simulations with IDA ICE

With the goal of studying the effect of thermal mass and ventilation on energy use, a model of PK has been developed. To validate the simulations with IDA ICE, the measurements collected from May 19th to the June 2nd have been used. Regarding the heat loads, occupancy was measured for May 19th to May 21st and the number of PC screens per person and extra lighting were recorded every fifteen minute. It seems on average to be two or three screens per person and many leave the computer on overnight.The occupancy patterns were extrapolated to the other days and slightly modified taking into account that Fridays are days with lower occupancy. The average occupancies were 38 % in the landscape, 47 % in the single offices, and 31 % in meeting rooms (but this last varying between 5 and 57%). No measurements were taken of the sun and the cloud coverage, only simple visual observations. This is a source of error on the simulations.

3.1. The model

The simulations are mainly focused on building 4 from which measurements are available. In the simulation, due to the air exchanges between building 4 and 5, both buildings are included in the simulation model (See Figure 4a). Building 4 is a four stories office building whereas building 5 is a three-storey building. Basements are not included in the simulations. The small offices are simulated as independent zones and the landscape as a single zone. The displacement ventilation could not be simulated, as IDA ICE requires a squared floor area for this. Occupancy was simulated as observed and the weather file used is Lier [8]. In addition, in the PK there is the possibility to use free cooling from ground source exchange that is not simulated in this paper, as the goal was to study the effect of the mass alone not introducing extra cooling systems. Roofs were modelled with a U value of 0.078 W/ (m²*K), external walls 0.145 W/ (m²*K), internal walls 0.317 W/ (m²*K), windows 0.8W/ (m²*K). Infiltration were simulated as 0.5 ach at 50 Pa. The balanced mechanical ventilation supplied 0.7 l/(s*m²) and 7 l/(s*person). The ventilative cooling is set when the indoor temperature exceeds 26 °C. For the simulated week, the supply temperature from the air-handling unit is constant 19 degrees, during the 21st and 22nd of May the air flowrates from the air-handling unit vary between 2500 and 3200 m³/h per floor.

3.2. Simulation validation

To validate the simulations with IDA ICE the measurements from May 19th to June 2nd in 2015 have been used. Landscape 4241 is placed in building 4 on the second floor (See Fig 2b). It has 30 working stations though the occupancy is much lower. The heaters and air supply are placed around the central walls in Landscape 4241. Temperatures in landscapes 4241 and 4341 have been monitored using iButton® with accuracy of ±0.5 °C in open areas and ±0.1 °C on the concrete surface sensor. IDA ICE assumes mixing ventilation on open areas. However, and as the results of Søgnen show [9], it is proven that a mixing ventilation flow pattern is more probable than displacement in the open area of Kjørbo and therefore the mixing assumption in IDA ICE does not seem wrong.

The simulation has been tuned for the monitored week. Occupancy, outdoor weather, and additional information mirrored measured values. The results obtained are shown in Fig 2c. The difference between measurements and simulation is always below 0.5 °C so we can assume the simulation validated. It seems that the simulation under predicts the effect of the thermal mass as temperature variations in simulation are bigger than in measurements. However, no correction of real solar gains and solar shading is done in simulation, as no measurements were available. Despite the large airflow rates and low occupancy, the temperatures are measured to be around 24 degrees that the occupants report to be comfortable (cf. interviews realized during the measurement campaign [10]).

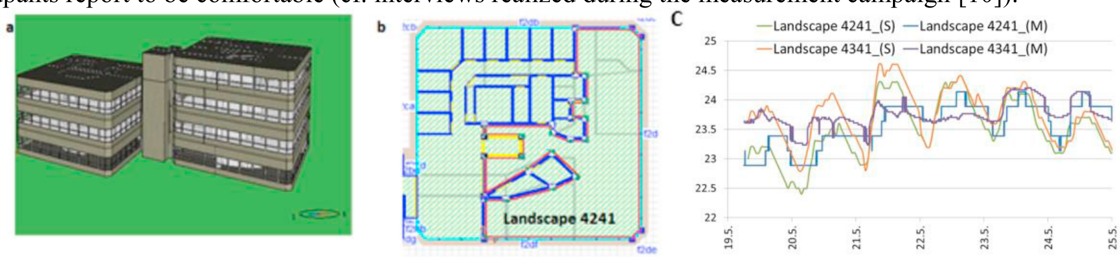

Fig 2 (a) drawing of the simulated building 4 and 5. (b) Landscape.4241 at the second floor in Building 4 from IDA ICE. (c) Results, (S) = simulated, (M) = Measured.

The question to be answered is whether the thermal mass will change the cooling demands during warmer outdoor periods (and probably sunnier) or how to design walls to reduce energy demands. To answer this question, whole year simulations (normal year) were performed for the existing design.

The following cases have been studied and compared: (1) Powerhouse as built cf. called "Powerhouse" in results, (2) with all walls in concrete called "all-concrete", (3) with all walls with wood called "all wood", (4) with all walls made in concrete with controlled night ventilation called "All concrete control window". For the simulations 2, 3 and 4, the real walls were replaced by concrete and wood. In the simulated case, the construction layering is (1) burnt wood for cladding (2) insulation in between layers and (3) internal layer of concrete or wood. The interior walls were constructed in concrete for the "all-concrete" cases. The simulated "all concrete" and "all concrete with controlled windows" have the same structural properties, but the difference is that for the latter windows are openable in a hybrid control when the indoor temperature during the night is above 22 °C.

4. Results and discussion

In order to analyze the effect of the thermal mass and its suitability to reduce cooling demands and over temperatures, simulation of the building as measured and various wall-materials have been done. Figure 3 shows the distribution of temperatures for the cases with “all concrete”, “all wood” and the existing PK. Increasing the thermal mass of the walls yields a slower change of the temperatures. However, it also proves that once the temperature increases it lasts longer to cool down the room as seen from the slope of the cooling period in "all-concrete". In "all concrete window control", the variation is faster because of the active use of window opening for cooling.

The varying occupancy has a big effect on the room temperatures together with the solar irradiation. Tuesday 19th all the rooms start at the same initial temperature and then the room made of wood is the first one to be warmed up because of the increasing solar irradiation and the increasing occupancy. The maximum temperature occurs at 11am right before that the workers go for lunch. In four hours the temperature increases in this case is 3.2 °C while for the same time period it increases 2.2 °C for the real case and 1.5 °C for the case where all the walls are made in concrete and 0.5 for the case "all concrete" with controlled windows. At five fifteen, all the occupants are leaving the room and most of the screens and computers are turned off. Therefore the temperature in the room drops. Given the low thermal mass of the wooden walls, the temperature drops very fast. The cooling slope is 14 % for the all-wood case and 7 % for the concrete cases, showing that the heavier the construction the less reactive both for cooling and heating. For the "all-concrete" cases, the temperature initially rises less on May 19th because of being the mass further cooled the night before. Remember that the represented temperatures are air temperatures and therefore varying more than the wall temperatures. Note as well that the global radiation is measured on a weather station some kilometers away of the PK in an area without trees. In Kjørbo, the trees around effect the total solar radiation received in the room.

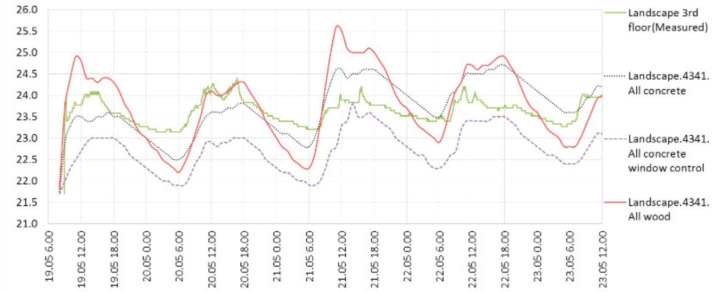

Figure 3 Measured temperatures in the landscape and simulated values for the same room for all the thermal mass levels

An increase on the morning temperature is seen in the "all-concrete" case throughout the weekdays with the morning temperature of Friday 1.5 °C higher than the morning temperature of the first day. The real case has a night set back strategy during this warmer period and this proves to be efficient regarding lowering the temperature in hotter periods, the same proves the "all-concrete case with controlled windows". During the weekend because of the lower occupancy and the minimum ventilation the temperature eventually drops.

The energy use is for the simulated building and is not exactly matching the real building because the data server room is not included on the simulation. The cooling demand only regard personal and lighting demands. The comparisons presented here are for ideal cooling, heating and air-handling unit. Given the lower morning temperatures due to night set back in the "as-built" case, a strategy was introduced in the “all-concrete” cases, after 18:00, the windows would be open when the indoor temperatures are higher than 22 °C.

Table 1. Energy use for heating, and AHU heating and cooling

	Sum of Ideal heaters PK [kWh]	Sum of AHU heating coil PK [kWh]	Sum of AHU cooling coil power PK [kWh]	Sum of Ideal coolers PK [kWh]	Energy from walls for heating [kWh]	Energy from walls for cooling [kWh]
PK "as built"	102059	92031	12034	9	790	1286
PK "All- concrete"	92659	99109	11192	310	2059	1630
PK "All- wood"	106020	91879	12044	6	-130	730,03
PK "All- concrete windows controlled"	104207	91932	10590	4	2350	1747

Using heavier mass yields an energy saving but at the same time the greenhouse gas emissions due to more concrete should be considered as to achieve a zero balance regarding emissions. The effect of the increase of thermal mass was smaller than 1 % of the total heating demands (this can also be read as energy savings) for the heaviest construction and close to nothing for the lightest. Regarding cooling demand, the reduction was more considerable, about 12 % of the cooling demands for the heaviest-mass cases, values in line with those obtained by Høseggen [11]. Table 1 shows the values for sum of ideal heating and cooling for a whole year, the sum for heating and cooling provided through ventilation and extracted heat from thermal mass in walls.

5. Conclusions

The use of thermally heavy rooms has been considered. Using a validated IDA ICE simulation of the first ZEB prototype in Norway, the effect on energy use has been studied. In order to make parametric analysis a validated simulation is needed. From the results, one can conclude that the use of heavy thermal mass combined with ventilation (in this case only controlled window opening) gives a very small reduction in energy use for heating, but up to 12% in cooling demands. In Norway, with its average low temperatures, ventilative cooling could have theoretically covered cooling demands (disregarding over cooling) and the increase of mass would not be justified just for cooling. This conclusion cannot be further expanded to countries with different weather, outdoor temperatures and solar irradiation. When designing with the goal of achieving the zero balance on emissions, it should be cautiously considered as the emissions will increase substantially and the increase of energy saving would not be that high. Solutions combining different ventilative cooling strategies, free ground cooling and heavy mass constructing materials and other efficient cooling solutions for lighter and heavier mass buildings should be studied.

Acknowledgment

This work has been supported by the Research Council of Norway and several partners through the SINTEF/NTNU "The research centre of Zero Emissions Buildings" (ZEB). Grant number 193830.

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