DO HEALTHY BUILDINGS NEED TECHNOLOGY?

Walter Hugentobler[1*], Peter Widerin[2], Lars Junghans[3], Willem Bruijn[4]

[1] Institute of Primary Care, University Hospital Zurich, Switzerland
[2] T.A.U. GmbH, Lustenau, Austria
[3] University of Michigan, Ann Arbor, MI, USA
[4] BE, Lustenau, Austria

[*]*walter.hugentobler@uzh.ch*

SUMMARY
The Building 2226 in Lustenau (Austria) has no heating, ventilation or cooling system. In the last years, the discussion on sustainable building design has focused on net-zero energy buildings. Building 2226 goes beyond this net-zero energy concept by introducing an office building without any conventional active systems for heating, cooling and ventilation. The Building 2226 was realized in July 2013 and is located in the cold climate of Austria.
The innovative "Concept 2226" rests on two strategies: (1) design of a state of the art high performance building envelope, and (2) integration of novel building automation.
Results from over 26 months of building operation show that in Building 2226 fluctuations in air temperature as well as temperature differences between air and the enclosing surfaces are minimal. Radiant temperature asymmetries are way below typical building standards. The consistency of air temperature in time and space creates excellent thermal comfort.
Year-round relative humidity stays between 35 and 60 percent. In combination with CO2 levels remaining below 1000 ppm this results in a healthy indoor air quality.

PRACTICAL IMPLICATIONS
A building with no conventional heating, ventilation and cooling technology that provides comfortable and healthy indoor conditions with very low maintenance costs.

KEYWORDS
heat capacitance, thermal inertia, minimal temperature fluctuations and radiant asymmetry, comfortable and healthy indoor climate, sensor based controlled natural ventilation, high performance building.

1 PHYSICAL AND ENERGY CONCEPT

In the last decade, the discussion on sustainable building design has focused on net-zero energy buildings. While buildings designed with this goal have proven to be technically efficient (Torcellini et al., 2006) they are expensive to operate because they use cost intensive high efficient heating, cooling and ventilation systems and depend on onsite or grid storage systems (Voss et al., 2007). Furthermore, there are technical challenges, such as complex automation systems, that have not yet been perfected (Marszal, 2012).
The concept of Building 2226 goes beyond the conventional net-zero energy goal by introducing an office building without any conventional energy consuming systems for heating, cooling and ventilation (Eberle and Aicher, 2015). The name 2226 refers to the worldwide accepted comfort temperature range of 22 to 26 degrees Celsius. Building 2226 was realized in July 2013 and is located in the cold climate of Austria, see Fig.1. The innovative "Concept 2226" rests on two strategies: (1) design of a state of the art high performance building envelope and (2) integration of a novel building automation.

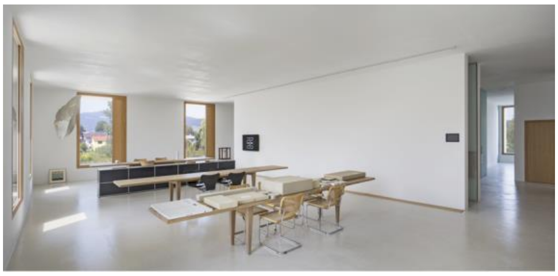


Fig. 1. exterior view Building 2226 interior view of one office
archphoto, inc. © baumschlager eberle.

In order to achieve comfortable indoor conditions and an optimal Indoor Air Quality (IAQ) in heating season and winter, the building envelope has both extremely low heat transfer and high thermal capacity. The lengthy time delay of heat flow through the 76cm external wall construction helps maintain comfortable indoor conditions even in periods of extreme outdoor cold (Weller et al.,1996). In addition, a triple glazing system combined with a high performance window frame results in U-value of 0.7 W/m^2K. The external dimensions of the building include 24x24x24 meters and is thus extremely compact.

The goal of combining energy-saving with a maximum comfort and IAQ without the use of mechanical HVAC units is achieved through the use of innovative automated window openers. Novel technology ensures comfortable room conditions in all seasons using natural ventilation. Window openings are controlled by measuring carbon dioxide concentration, room temperature, external temperature and relative humidity (El Mankibi and Michel, 2009). The building automation controls natural ventilation openings individually for each room.

A balance must be found between supplying fresh air for optimal IAQ and heat conservation during the heating season (Heisselberg et al.,1999). Conflicts arises in the transition period and the heating season when natural ventilation is needed for fresh air supply and the external temperature is below the minimal indoor comfort temperature (Heisselberg, and Tjelflaat, 2006). However, natural ventilation in the heating season is a heat sink and the intervals for natural ventilation should be as short as possible.

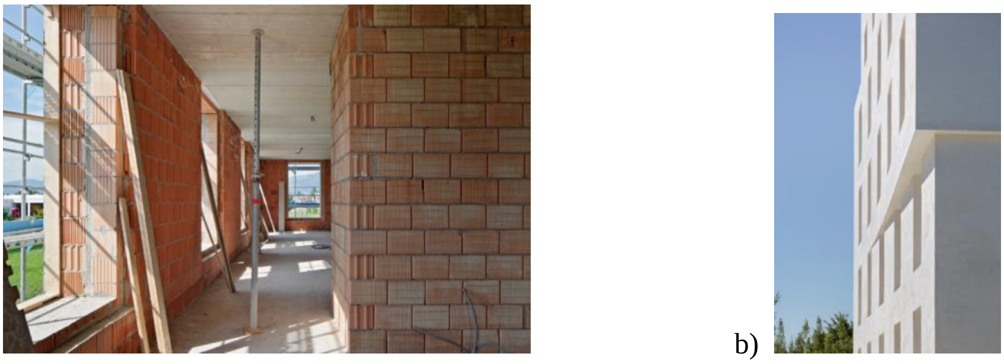
Nighttime ventilation is used to cool the internal thermal mass in the summer (Haase and Amato 2009).

2 MATERIALS/METHODS

Building 2226 has an envelope with both extremely low heat transfer and high thermal capacity. The building properties are as follows:

- Wall U-value average 0.12 W/m^2K and
- Roof U-value of 0.1 W/m^2K
- Triple glazing with a U-value of 0.7 W/m^2K and a SHGC value of 0.5
- Controlled automated natural ventilation openings next to each window
- Extremely airtight building envelope with an air change of n=0.1 1/h (n50=0.51 1/h).
- Glass to wall ratio is 16% on all façade orientations.

The reason for the 76 cm high performance brick wall (see Fig.2) is to decouple the room temperature as much as possible from short-term exterior temperature fluctuations.



a) b)

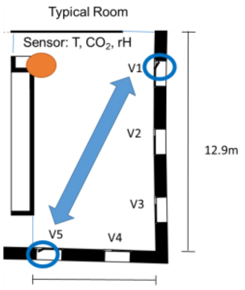
Fig.2. a) brick walls b) deep window reveals, archphoto, inc. © baumschlager eberle

Thermal diffusivity is the speed of heat diffusion measured by temperature fluctuation and is described as $\alpha:=\lambda/\rho c$. The thermal diffusivity in a brick wall is low because of its low thermal conductivity λ and its high heat capacitance ρc. As a result, the wall acts as a low pass filter for temperature fluctuations. The timescale τ for this low pass filter is proportional to the thermal diffusivity and grows quadratically with increasing wall thickness. In the case of Building 2226 the thick brick walls prevent disruption of daily indoor temperatures with a timescale for significant change in the order of one week.

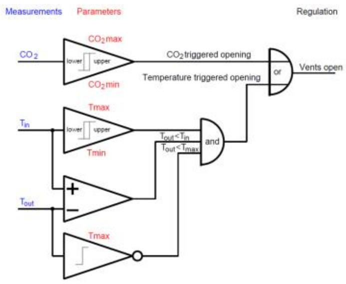
The windows in the building are optimized for daylight illumination and reduce the need for artificial lighting. Vertical openings allow uniformly distributed interior levels of light. The window dimensions and reveals are optimized to provide maximum daylight and solar radiation in the winter and optimal shading in the summer. The window to wall ratio is 16%. The goal of the building automation design is to operate the natural ventilation openings to achieve an optimal comfort and IAQ without the use of conventional HVAC units. To maximize the performance of the automated natural ventilation openings, a control logic was developed and tested in the simulation model. The logic is based on the complementary mixed mode design strategy described by El Mankibi and Michel (2009). It uses an on-off controller with death band, (also known as hysteresis controllers) to actuate natural ventilation openings, mechanical ventilation, and heating and cooling devices.

Building 2226 hybrid control logic also manages the interior artificial lighting. The control of the artificial lighting ensures illuminance values which meet the required threshold value of 500 Lux at occupied working spaces. Artificial lighting can also provide additional internal heat gains in extremely cold periods in the heating season.

Temperature and IAQ of Building 2226 are measured by sensors for temperature, CO_2-concentration and humidity in each of the 24 rooms separately. Each room, see Fig. 3, is located in a corner of the building, with a total of five windows facing in two different directions. The vents placed in diagonal corners (V1 and V5) are opened and closed based on sensor measurements, allowing natural cross ventilation and maintain optimal indoor conditions. The other vents (V2, V3, V5) can be opened individually by the user at any time. The control algorithm for the automated vents responds to CO_2 concentrations and the room temperature in the following way: Whenever a pre-determined maximum CO_2 concentration is reached, vents V1 and V2 open, allowing natural cross ventilation to dilute the CO_2 to a preset value. In a similar way room temperatures are controlled using the nighttime cooling strategy. A preset upper temperature value triggers the opening of all five vents as long as indoor temperature stays above the temperature of incoming air.



a)



b)

Fig.3 a) automatic cross ventilation b) simplified basic control algorithm

The air change in winter is demand driven to avoid heat loss when the offices are empty or the air quality is persistently good. The air change rate by hour of the building envelope is low (n=0.1/h), but sufficient to maintain good perceived IAQ even when CO_2 driven ventilation is inactive.

Each room in Building 2226 is equipped with sensors for air temperature, relative humidity and CO_2 concentration. The sensors are located on an inside wall at a height of 1.1 m. The temperature, humidity and CO_2 sensors are GIRA SK01. The sensor provides an accuracy of 0.3 K for the temperature, 3 % for the humidity and 50 ppm for the CO_2 concentration.

3 RESULTS

The measurement data for temperature, CO_2 concentration and humidity in each of the 24 rooms of Building 2226 have been logged in 10 minute intervals since April 2014. As an example we show data from a room used as meeting room and permanent office for 4 people. The room is located on the first floor with windows oriented in south and east direction.

The room temperatures are shown as box-whiskers plots for every week (median, first and third quartile, lower and upper extremes and outliers) in Fig. 4. The temperature band of 22°C to 26°C is indicated by the grey region. The room temperature (median) stays within the band even during warm summer weeks. The room temperature drops to 21°C during the non-occupied winter vacation because of the reduced internal loads of electrical light, computers and occupants. The temperatures in other offices show a similar behavior. Summer temperatures in offices with west facades are approximately 1°C higher.

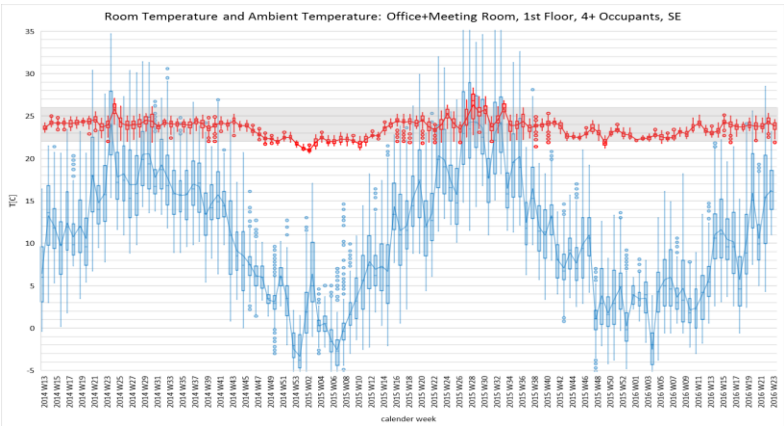


Fig.4
Office temperatures, for 26 months' period.
The outside temperature (blue) and the interior temperature (red) as well as the comfort band of 22°C to 26°C are displayed.

The CO_2 measurements are calibrated to a lowest value of 400ppm in the winter vacation period. The median of the concentration stays below 800ppm (dark green region) for the entire time. Measurements above 1000ppm occur very rarely. The CO2 concentration directly at the desks can be about 100ppm to 200ppm above these measurements and depends on activity and number of occupants. The CO_2 concentration in offices with more permanent occupants (e.g. 8 to 10) might be higher, but the median never exceeds 1000ppm.

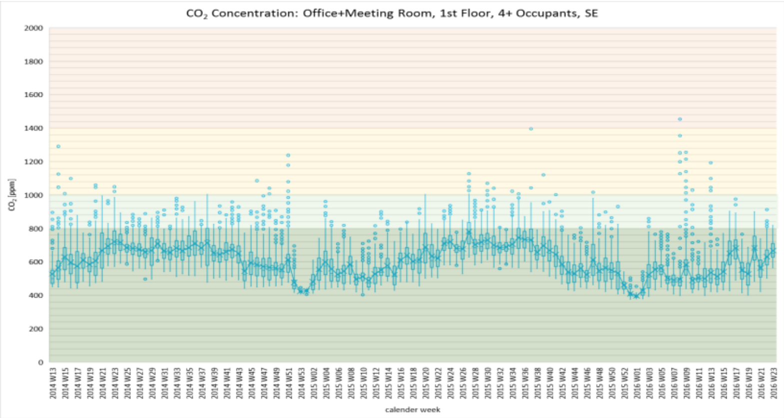


Fig.5
CO2 concentration in typical office over a 26 month' period: The range of good air quality (<1000ppm) is drawn in green, acceptable air quality (<1400ppm) is drawn in yellow, low air quality is drawn in red. The CO2 measurements are calibrated to 400ppm.

COMFORT AND HEALTH ASPECTS

The essential distinction between occupant comfort and health became blurred during the last thirty years of indoor climate research. Comfort refers to a state of physical and psychological ease (Wikipedia), whereas health encompasses comfort but goes far beyond to include signs and symptoms of diseases.

ASHRAE 55-2013 Standards describe six primary factors that affect thermal comfort: air temperature, radiant temperature, humidity, air speed, metabolic rate and clothing insulation. We will address the first three topics, while the last two issues are characteristics of occupants. CO_2 levels and air microbial counts and cultivation are the IAQ parameters we measured. No measurements of indoor air particulate matter were done.

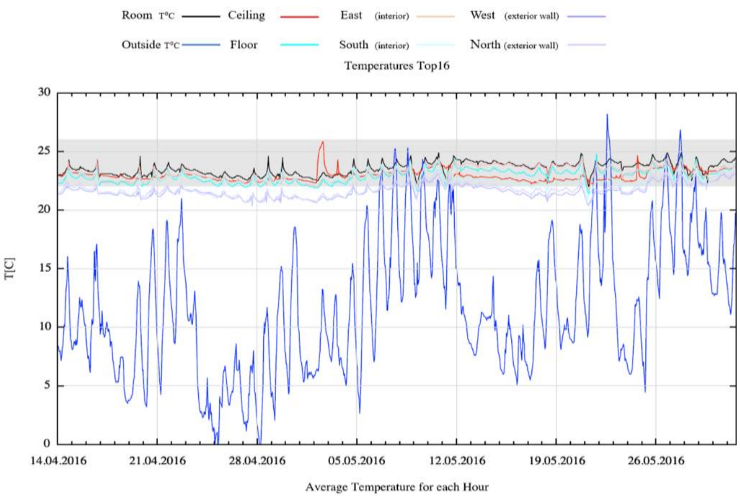


Fig.6
Air temperatures for indoor (black) and outdoor (blue) over 7 weeks.
Surface temperature for floor, ceiling, and four walls.
Δt [Air – ceiling] < 1°C
Δt [Air - wall] < 3°C
The three peaks in ceiling temperature mark times when artificial lightning was needed.

Minimal air temperature fluctuation (see whiskers in weekly boxplots in Fig. 4) and minimal radiant asymmetries (see Fig.6 above, Tab.1, below) combined with the ability of users to manually open the air vents ensure both optimal thermal comfort and high satisfaction among occupants.

Upper limits for uncomfortable radiant asymmetries are similar in the USA (ASHRAE 55-2013) and in Europe (EN ISO 7730:2005). The values for Building 2226, displayed in Fig.6 are well within these limits. Given the thermal stability of the wall, this is no surprise.

Tab. 1 Radian temperature asymmetry for PPD 6% (Predicted Persons Dissatisfied)

Δt (°C)	ASHRAE 55-2013	EN ISO 7730:2006	Grandjean* 1972	Building 2226
Air - warm ceiling	< 5	< 5	< 2-3	< 1
Air – cold wall	< 11	< 10	< 2-3	< 2

*Wohnphysiologie, Grundlagen gesunden Wohnens, Prof. Grandjean, Artemis Verlag, 1972

From a health perspective, the most beneficial feature of Building 2226 is the nearly perfect humidity range year-round! Even in winter, humidity remains in the range of 35 to 60 percent. This is particularly surprising since large independent surveys (SBiB study SECO, 2010; Swiss Energy department, 2016) have shown that particularly in low energy houses 30 to 50 percent of occupants complain about dryness. This is despite the fact that building standards are designed to keep PPD (Percentage Persons Dissatisfied) below 10 to (maximum) 20 percent (ASHRAE 55-2013, p.39).
Extremely low humidity in energy efficient houses is well documented (Frei und Reichmuth, 2004, FGK Status Report 8, 2015). Since almost all energy efficient buildings are airtight, air change is typically provided by mechanical or hybrid ventilation systems. In winter, any air change triggered by human-produced CO_2 which withdraws more moisture than that produced by the occupants results in a humidity drop and energy waste (FGK Status Report 8, 2015) and increases the percentage of people dissatisfied by dry air.

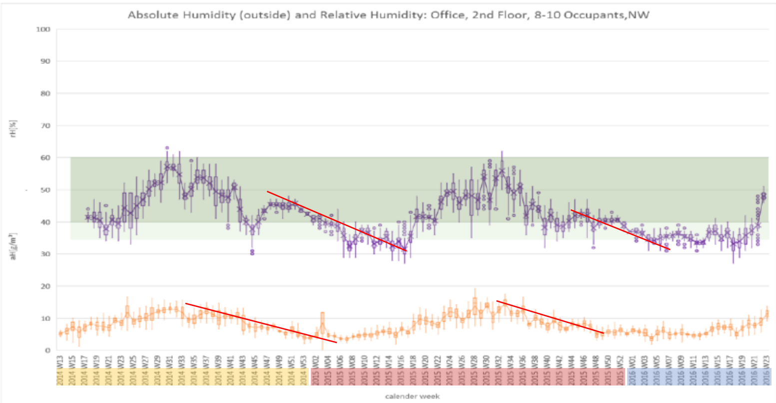


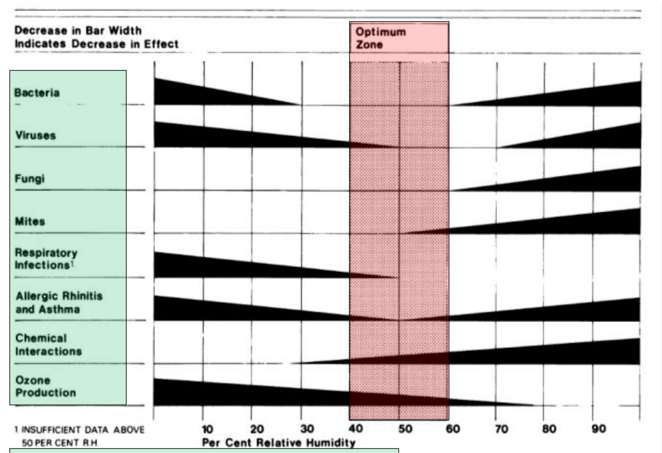
Fig.7
Relative indoor humidity (violet) and absolute exterior humidity (orange) displayed over 26 months.
Even in winter, relative humidity remains in the range of 35 to 60 percent.
Note the delayed slope (red) of humidity indoor - outdoor

The favorable humidity range in Building 2226 is achieved by a perfect balance between outdoor air ventilation (effecting moisture and heat loss in winter) and indoor human activity (moisture and heat input) regulated by CO_2 sensitive control technology. Most likely the significant moisture storage capacity of the massive clay brick walls (Klanatsky and Heschl, 2014) helps to maintain indoor humidity and delays it's decrease while moisture input from cold outdoor air is falling. In Fig.7 the delayed slope of indoor relative humidity, compared to outdoor absolute humidity, is displayed. An essential precondition for this water exchange between indoor air and the brick wall is the application of plasters with open pores for bi-directional water transport.

Is indoor humidity important for occupant health, or is it merely a comfort issue? Historically, until 1985, proper humidity levels were recognized as necessary for health because they helped modulate viral, bacterial and fungal growth, respiratory infections, allergic rhinitis, asthma and chemical interactions (Arundel and Sterling, 1986, see Fig.8). During the last thirty years of indoor climate research however, humidity has been managed as if it only impacted comfort and would not warrant further studies on disease and aerosol physics. Even the important 2007 literature review article by Wolkoff and Kjærgaard explicitly excluded some disease related terms and focused on comfort issues related to skin, eyes, mucous membranes and perceived IAQ. The authors of the review concluded that a humidity level of 40 percent was recommended for eyes and mucus membranes.
From the perspectives of physical laws of atmospheric air, humidity is both, a comfort and a health issue. Because temperature and humidity cannot be changed independently, humidity is inseparably linked to temperature which has limits for comfort. Moreover, basic physical laws make humidity an essential variable in health since water vapor, inseparable part of

atmospheric air, has a major role in properties and behavior of airborne particles (Hinds, 1999).

Fig. 8



Optimum relative humidity range for minimizing adverse health effects.

Processes like “hygroscopic growth”, “efflorescence”, “deliquescence” and “water adhesive forces” are humidity dependent and have decisive impact on sedimentation, re-suspension, float-time and aggregation of inorganic, organic and microbial airborne particles (Hinds, 1999). In contrast to indoor climate, indoor air quality (including particles and gases like CO_2 and water vapor!) is regarded incontrovertibly as a major health factor.

The humidity dependent processes shown above are well known to aerosol physicists. However, in the complex building environment, systematic research on the influence of moisture on airborne particles is missing. Even more alarming is that “Dryness” is considered to be one of the four principals needed to achieve good indoor air quality (Nazaroff W.W., 2013).

RLT Optimierung, a company managed by Ludwig Rüdisser (A-6840, Götzis), measured on three occasions (April 2014, March and December 2015) total microbial count (bacteria, mould and yeast) with a MAS 100 sampler (100 liters). Cultivation was done by böhler, Analytik GmbH, A-6800 Feldkirch. On all occasions outdoor air on two building facades and in two different office rooms were analyzed. To our surprise, all germ counts inside were between 10 to 80 percent lower than in outside air (results not displayed). We are pleased by these results but have no logic explanation. Interestingly, recent research using gene sequencing (Kembel et al., 2012) to analyze microbiomes showed that the diversity of airborne bacteria is greater in naturally ventilated rooms and the number of potentially dangerous bacteria is lower than in mechanically ventilated rooms.

4 DISCUSSION

“Do healthy buildings need technology?”, our introductory question, is answered by Building 2226 with a “no”. – Crucial elements of the “concept 2226” are the building envelope and the balanced natural ventilation. The main characteristics of the building envelope are “low pass filter for temperature fluctuations” and “high moisture storage capacity”, combined with porous plaster and uncovered walls for free heat and water transfer between air and wall.

Innovative automation of window movements allows optimal natural ventilation resulting in balanced indoor air hydration and prevention of the common and harmful condition of excessively dehydrated breathing air. The use of conventional, mechanical heating unavoidably results in dry indoor air which can only be balanced by humidification systems.

Like every prototype, minor improvements in the building control logic were needed. 1) The initially planned two ventilation openings per room for nighttime cooling were changed to five ventilation openings. (2) Several of the windows needed curtains to avoid radiation asymmetry in the summer.

5 CONCLUSIONS

The operation of an office building without mechanical heating, cooling and ventilation devices is possible. Thoughtful envelope construction and automation technology for balanced ventilation significantly reduce energy usage.

Next steps include 1) expand the “concept 2226” to multi-family dwellings 2) use of recently developed plasters with high sorption and desorption capacities in the range of 40 to 80 percent air humidity to further improve indoor humidity levels in dry winters. 3) Expand the algorithm for automated natural ventilation to include responses to internal humidity emissions from occupants and vapor producing activities. 4) Use predictive control strategies for renewable energy sources and sustainable grid energy.

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