Validation of a Digital Twin with Measurement Data

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ABSTRACT

The research objectives of this study are to develop and validate a detailed simulation model of a test cell which was used to measure heat balances for comfort evaluation.
The Research Centre on Zero Emission Buildings (ZEB) Test Cell Laboratory is a facility designed to carry out experiments on building envelope systems and their interaction with HVAC terminal units. Tests on the interaction between the building envelope, the building equipment, and indoor environmental quality analyses, with or without the presence of users in the test cell room, can be performed. The ZEB Test Cell Laboratory is constituted of two identical and fully independent test cells. Each test cell has one surface of the cell envelope exposed outside (a façade facing south), while the other five surfaces are surrounded by an environmentally-controlled volume. In order to be able to run numerical tests (in advance or with a large number of parameters) a simulation model of one test cell was developed in the programme IDA Indoor Climate and Energy (IDA ICE) v. 4.8.

The calibration of the model after setting it up according to the laboratory's technical data was carried out in two steps: In the first, no windows were opened so that all deviations could be attributed to the cell's envelope itself. Before also investigating the opening of windows in the second step, the discharge coefficient c_d which describes flow losses in natural ventilation had to be defined. By experiment, it was found to be $c_d = 0.75$ for the tilted window being used in the laboratory which is in accordance with the research by Heiselberg et al. (Heiselberg et al., 2001).

The simulation results of step 1 showed high accordance with the measurements. The simulated zone air temperature and envelope surface temperatures of step one were almost constantly within the measurement inaccuracy, except for the ceiling temperature. Here the deviation was higher compared to the other results. The evaluation of step 2, the test row with an open window, revealed issues with solar gains, which were greatly overestimated in the simulations. The too high solar gains led to a lower agreement of simulated and measured data in the second test row compared to the first. This deviation made it impossible to investigate the applicability of the previously determined *cd* value for the opened window.

KEYWORDS

Test Cell; Thermal simulation; Calibration; Discharge coefficient; Thermal comfort; Air flow.

1 INTRODUCTION

1.1 Background

With the application of mechanical heating and later cooling systems in buildings the weather outside the window faded into the background as all-year equal indoor climate was now possible on demand. This led to more and more maladjusted buildings and a more uniform building design all over the world, in every climate zone. Technology was meant to take over the work neglected by designers, causing large amounts of energy needed for heating and cooling in particular for the resulting “sealed boxes”.

It was common practice for decades, to keep indoor conditions within the proposed limits of P. O. Fanger’s PMV/PPD-model (Fanger, 1970) presented in many standards like the ASHRAE Standard 55-1992 (ASHRAE Standard 55-1992, 1992) or ISO 7730:1994 (ISO 7730:1994, 1994). Yet further research found that the PMV/PPD-model is not applicable for naturally ventilated buildings, where it became apparent that people are content with a wider range of temperatures than those in closed and air-conditioned ones (de Dear, Schiller Brager, 2001; de Dear, Brager, 1998).

While at the time of the early comfort studies technical capabilities were quite limited, today’s planning process is driven by digitalized optimization. And because environmental politics, shortage of fossil fuels and climate change force planners to exactly pre-consider every design step to meet expectations and more stringent regulations for the buildings’ performance, increasing effort is put in virtual models of buildings. In doing so, every possible response to indoor or outdoor conditions can be evaluated beforehand. But there is also an economic component since changes to be made during the planning process are much cheaper than during construction or after the building’s completion. Moreover, studies found that satisfied employees in offices tend to be more productive, which can save the company money (Huizenga C. et al., 2006). Still, new technologies and building materials as well as differing configurations from case to case make it necessary to continue research in indoor environmental comfort.

1.2 ZEB Test Cell Laboratory

For that reason, the Research Centre on Zero Emission Buildings (ZEB) recently established the ZEB Test Cell Laboratory for measuring indoor conditions for any desired façade types. This newly built test facility on the campus of the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway, is able to provide measurements for two fully independent test cells with different settings at the same time. The cells have one surface exposed to ambient conditions facing south, whereas the other five surfaces are adjacent to an approximately 210 m^3 guard volume, one for each cell. Both the cells and the guard volume are fully controllable with respect to their indoor air conditions. The cells have a volume of about 37 m^3 with internal dimensions (W x L x H) 2.50 m x 4.36 m x 3.39 m. The cells are suspended from the guard volume floor, leaving a gap of approximately 0.5 m between the structures. Cell floor, ceiling and walls, except for the façade to ambient, are made of prefabricated sandwich panels of 10 cm injected polyurethane foam between two 0.6 mm steel sheets, resulting in an U-value of 0.23 W/(m^2K) (Goia et al., 2017).

1.3 Aim of Work

The goal of the presented study is to set up a functional virtual simulation model of the Test Cell Laboratory with subsequent validation through measurement data. After the calibration, the model will be the basis for future test rows, such as material tests or comfort analyses as it helps to pre-assess promising test set ups and configurations. With the use of a calibrated model of a test cell initial investigations for work involving actual measurements can be executed fast and already in early project stages. Thus a lot of time and money can be saved by a thorough pre-selection of configurations to be tested.

2 SIMULATION MODEL

As mentioned, the main purpose of the ZEB Test Cell Laboratory is thermal comfort analysis. Mainly the following parameters are critical in the determination of thermal comfort: Air temperature, mean radiative temperature of surrounding surfaces, air velocity, relative humidity, the occupant’s metabolic rate and insulation of clothing (Fanger, 1970; ISO 7730:1994, 1994; ASHRAE Standard 55-2004, 2004). As ASHRAE Standard 55 allows a rather wide range for relative humidity it is assumed to have only minor influence on thermal comfort in the present case. The degree of activity and clothing of the user are generally dynamic and can be adjusted easily in the simulation programme IDA Indoor Climate and Energy (IDA ICE) (Bring et al., 1999), which is why focus is put on the first three aspects, namely air temperature, mean radiative temperature of surrounding surfaces and air velocity.

Like many thermal simulation programmes also IDA ICE simplifies air movements within a zone. The air speed within a zone is considered a constant at a predefined value of 0.1 m/s, but open to be chosen freely. Especially for comfort analyses involving natural ventilation, a constant value in this magnitude is not reasonable. The recently integrated Computational Fluid Dynamics (CFD)-plug-in in IDA ICE allows investigating local air velocities in the zone at a given point in time. An essential precondition for using this helpful plug-in is the correct determination of air flows to and from a zone by the analytical components – for windows namely CELVO (Climate and Energy Large Vertical Opening) – thus by an ordinary dynamic simulation (Bring et al., 1999). CELVO is bidirectional, thus allows calculating air flows in opposite directions simultaneously (see Eq. 1 and 2).

Governing equations in this component are

$$\dot{m}_{12} = \begin{cases} c_d\, w\, z_t \sqrt{2\,\rho_1\,(P_1 - P_2)} & for\ \ P_1 > P_2 \\ 0 & for\ \ P_1 < P_2 \end{cases} \tag{1}$$

$$\dot{m}_{21} = \begin{cases} 0 & for\ \ P_1 > P_2 \\ c_d\, w\, z_t \sqrt{2\,\rho_2\,(P_2 - P_1)} & for\ \ P_1 < P_2 \end{cases} \tag{2}$$

where $\dot{m}$ is the mass flow, c_d the discharge coefficient, w the opening width, z_t the opening height, ρ the density of air, and P the pressure at the respective reference level.

While pressure levels and air density are calculated by the program, discharge coefficient and opening area are self-defined. Especially when it comes to complicated opening forms such as pivoted windows, the determination of both can be very complex. The discharge coefficient hereby plays an important role as it is used as a factor to decrease an opening with the area A_{op} to an effective area A_{eff} (see Eq. 3), combining pressure and flow losses due to turbulences, friction etc. This is essential when using IDA ICE as the programme is not able to handle opening forms other than rectangular. But through choosing a different c_d, those window forms can be approximated.

$$A_{eff} = c_d\, A_{Op} \quad (3)$$

A general approach to determine the c_d value for any kinds of window shape, opening form and mounting situation does not exist. Many studies have been conducted but they all pointed out that for the determination of an accurate c_d very window and its mounting situation must be treated separately (Hall, 2004; Maas, 1995; Heiselberg et al., 2001). The opening to be further investigated in this study is a rectangular, vertical orientated window with the dimensions (width x height) 0.70 m x 1.21 m. To identify the c_d to be used for this specific, only tiltable window the study of Heiselberg et al. was used as a template for own measurements (Heiselberg et al., 2001). Like in the present case, Heiselberg used sort of a test cell or test room facility with two independently controllable room units. While in Heiselberg's laboratory set up the pressure difference was created by valves in the ventilation system and the experiments were non-isothermal, in the present, isothermal case blower door equipment was utilised to induce the pressure levels. The results described in another paper (Brozovsky et al., 2018) show a major coherence with Heiselberg's findings. The mean discharge coefficient for all opening angles of the tilted window was found to be c_d = 0.75.

Cattarin et al. (Cattarin et al., 2018) who investigated the parameters and inputs that are most influential on the thermal behavior of the particular test cell came to the result that following parameters are the most critical:

- Air temperature in the guard volume
- Initial temperature(s) of the test cell envelope
- Dimension of the window

This is why Cattarin et al. (Cattarin et al., 2018) recommend measuring the guard volume temperature very accurately, as well as measurements should run for at least a week in order to reduce the influence of the error through insecurity of the initial conditions. Because solar gains are one of the main drivers of the cell's thermal behaviour detailed knowledge about and modelling of the transparent envelope parts is necessary (Cattarin et al., 2018).

According to those recommendations, the measurements were taken for a 15-day period. Additionally, the properties of the windows are well known. Since the measurement period was done in the end of December and the beginning of January, even on clear days no direct sunlight hits the window because of the low elevation angle of the sun in this time of the year and a shadowing office building in front of the laboratory.

The measured boundary temperatures of the guard volume (air temperatures right at the surfaces of the test cell) and air flow volumes through the ventilation system to and from the zone have been fed into the simulation model to digitally recreate the exact same boundary conditions.

3 LABORATORY SETUP

The temperature sensors' and data acquisition's measuring accuracy for air and surface temperatures can be seen in Table 1. The measured temperature is referred to as *t*. Figure 2 shows the placement of the sensors whose measurements were used for the calibration. As the simulation program calculates only one value per surface, the mean measurement value of all sensors of a particular surface was used for the comparison.

Table 1: Measuring accuracy of sensors and data acquisition (DAQ)

Sensor Type	Measured variable	Accuracy
DAQ	All	± 0.37 °C
Resistance thermometer (RTD)	Air temperature	± (0.3+0.005|t|) °C
Thermocouples (type T)	Surface temperatures	± 1 °C or ± 0.0075 |t|

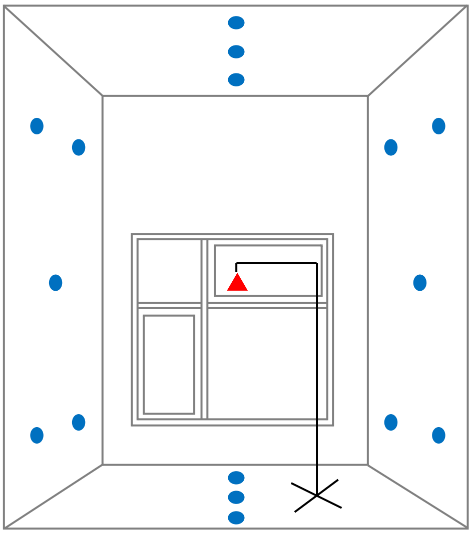

Figure 1: Placement of sensors in the cell: Resistance thermometer for air temperature (red triangle), thermocouples for surface temperatures (blue circles)

4 RESULTS OF THE CALIBRATION SIMULATION

For quantifying the accordance of measured and simulated temperatures some indicator parameters will be introduced. *q* will give indication about the percentage of time in which the simulation results are outside the measurement inaccuracy (Eq. 4 and 5) where s_i is the simulated value and m_i the measured value at time step *i* and *a* is the range of measuring inaccuracy, see Table 1. *CV(RMSD)* is the normalised value of the root-mean-square deviation (Eq. 6) and is used as a quality indicator. Generally, the lower the CV(RMSD) the better the fit of measured and simulated data.

$$q = \frac{\sum_{i=1}^{n} Q_i}{n} \cdot 100\ \% \tag{4}$$

$$Q_i = \begin{cases} 1 & , for\ |s_i - m_i| > |a| \\ 0 & , for\ |s_i - m_i| \leq |a| \end{cases} \tag{5}$$

$$CV(RMSD) = \frac{RMSD}{\overline{m}} \cdot 100\ \% = \frac{\sqrt{\sum_{i=1}^{n}(s_i - m_i)^2/n}}{\overline{m}} \cdot 100\ \% \tag{6}$$

4.1 Without opening the window

Following Figures 2 - 5 visualize the simulation results for the calibration step 1 where no windows were opened. *q* shows values from 0.0 to 3.3 %, the coefficient of variance of the root-mean-square deviation *CV(RMSD)* from 1.5 % to 4.0 %. Only the ceiling surface temperature shows a rather high deviation compared to the other surfaces or the air. The measured temperature appears to have a distinct dependency on the supply air temperature, while the simulated temperature is following the supply air temperature's path just to a limited extent.

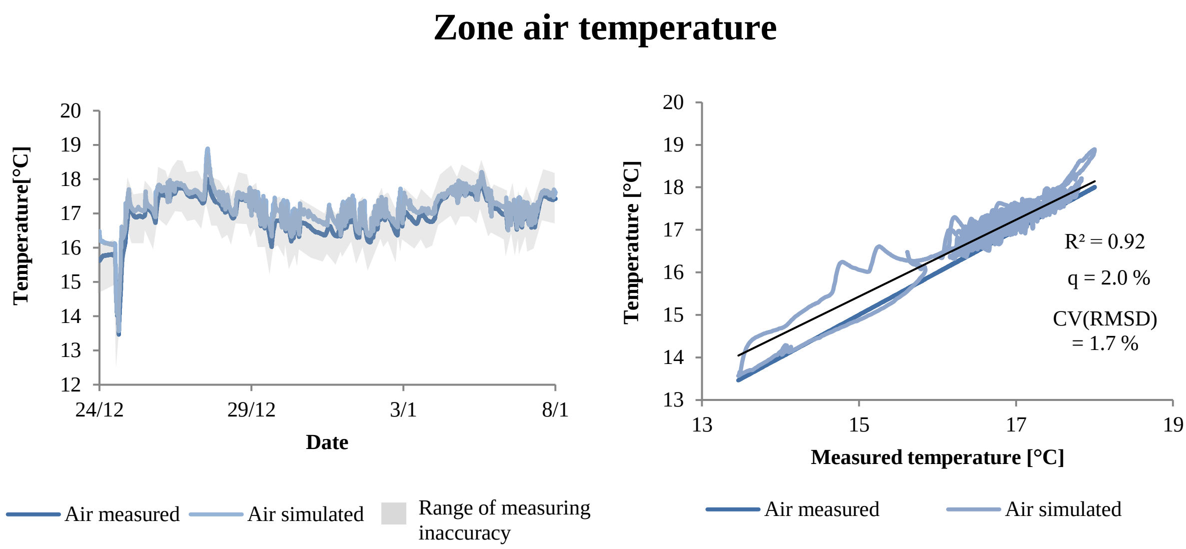

Figure 2: Measured and simulated zone air temperature in calibration step 1

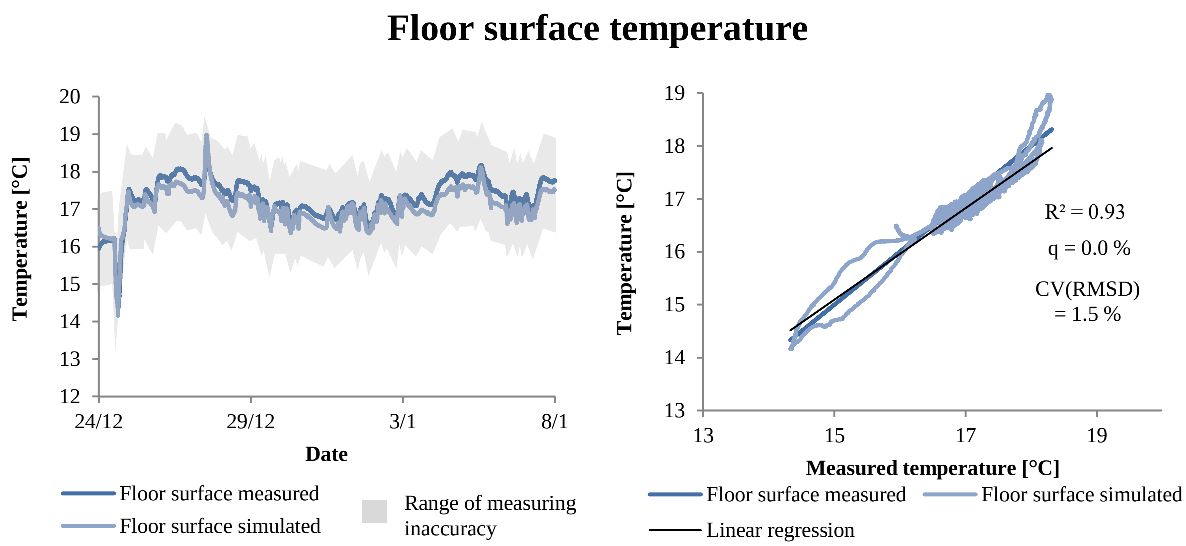

Figure 3: Measured and simulated floor surface temperature in calibration step 1

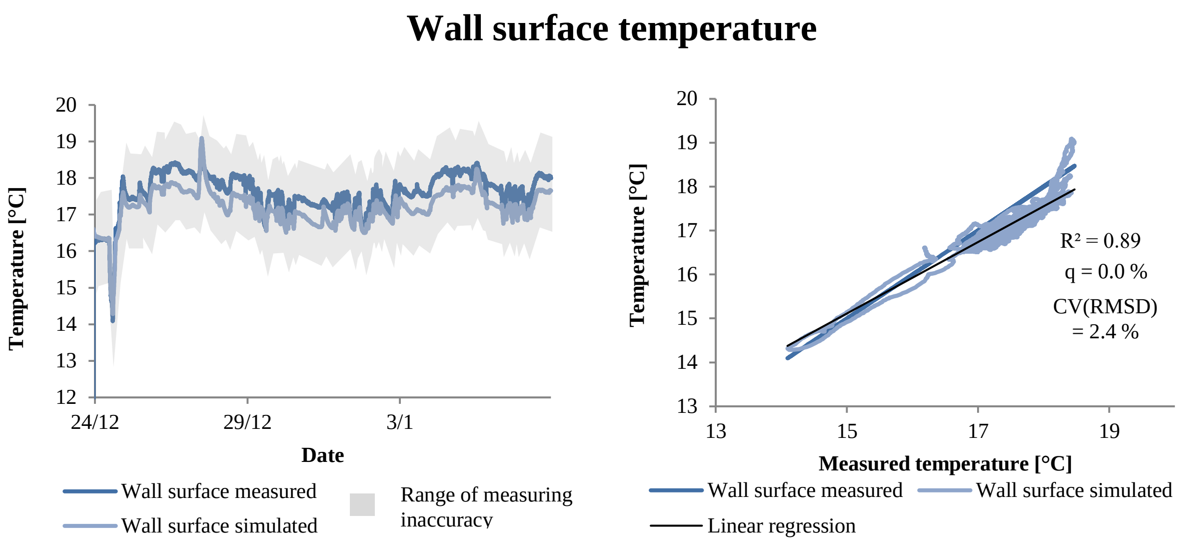

Figure 4: Measured and simulated surface temperature of the test cell wall(s) in calibration step 1

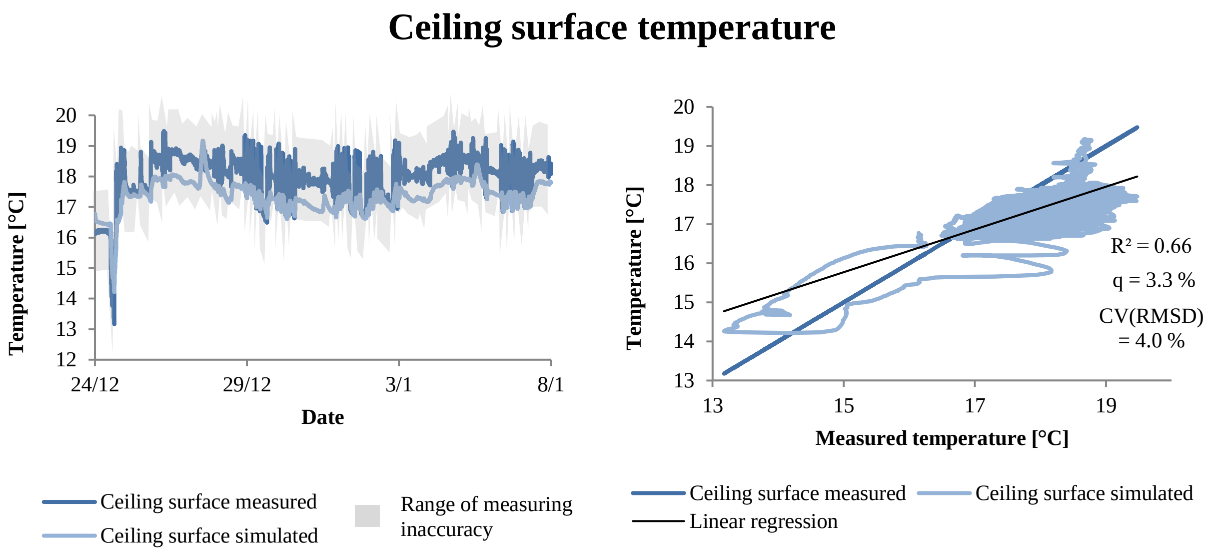

Figure 5: Measured and simulated ceiling surface temperature in calibration step 1

4.2 With opening the window

The test carried out for the second stage of the calibration process was shorter than the first one since the results from stage one indicated a 24 h start-up phase being long enough to evade the error through insecurity of the initial conditions. One weekend in February was used and the actual window opening was performed on the third day of the test. It was opened for 30 minutes in the afternoon. The analysis of the data revealed an error of 12.5 % up to 19.1 % during the times of high solar irradiation for the air temperature and the surface temperatures, which are not displayed. The weather on the respecting weekend was clear and sunny, with a quite constant ambient temperature around 0 °C. Clearly visible in Figure 6 is the overestimation of solar gains where the simulated zone air temperature rises well above the measured of 24 °C to a maximum value of 27 °C on February 10. During the time without solar irradiation, measured and simulated values were more similar.

The situation shown in Figure 6 is also occurring in the surface temperatures of the cell envelopes (see also Table 2) where the accordance of measured and simulated data is clearly worse than in simulation step 1. Further investigations have to be carried out to identify the error.

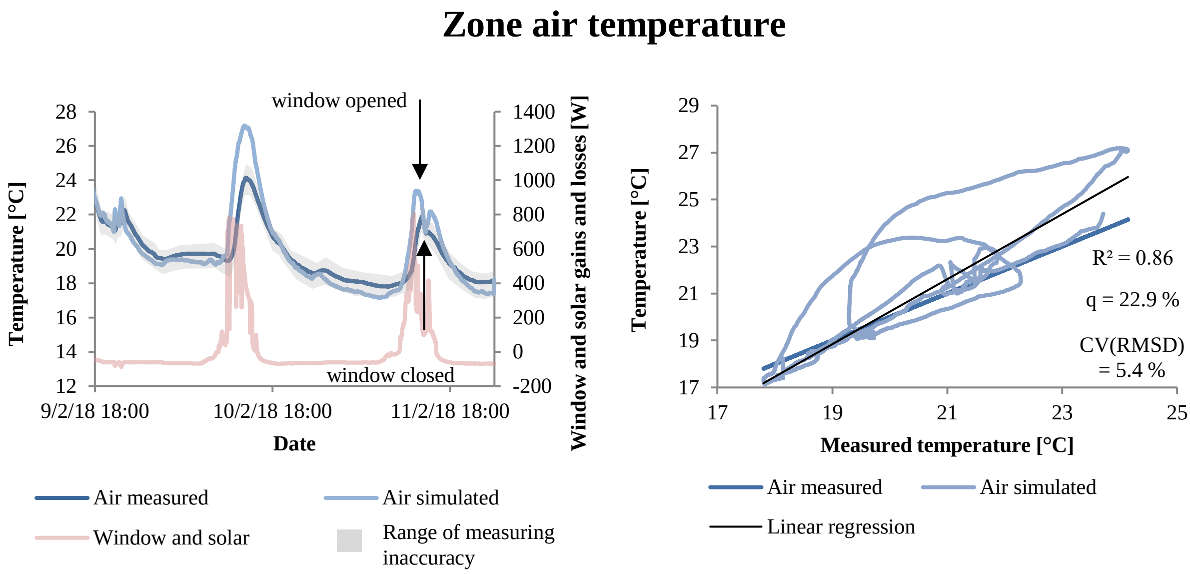

Figure 6: Measured and simulated zone air temperature in calibration step 2

Table 2: Quality parameters of calibration step 2 with opening windows

Temperature	R^2 [-]	q [%]	*CV(RMSD)* [%]
Air	0.86	22.9	5.4
Floor surface	0.94	16.1	6.4
Wall surface	0.88	20.2	7.7
Ceiling surface	0.66	25.1	9.2

5 CONCLUSIONS

This study shows the set up and the calibration of a simulation model of the ZEB Test Cell Laboratory in Trondheim, Norway. In the first step of the calibration no windows were opened. The results were up to 3.3 % of the time outside the measurement accuracy with a *CV(RMSD)* between 1.5 % to 4.0 %. The simulation model does not take into account that a supply air terminal was located near the ceiling since in the zone model the cell is an air node where incoming air is perfectly mixed with room air right away. The surface temperature is not dependent on the location of the supply air terminal, but just of the indoor air temperature, the thermal resistance of the construction and the temperature on the other side of the construction. Therefore, the results of the ceiling surface temperature deviate the most from the measurements.

Because in the second part of the calibration the cell's window was to be opened, first its discharge coefficient had to be determined. Isothermal measurements with blower door equipment found the discharge coefficient of the window to be c_d = 0.75 (Brozovsky et al., 2018) which is in accordance with the findings of Heiselberg et al. (Heiselberg et al., 2001).

As a consequence of the significant deviation evoked by overestimated solar gains during the time of opening of the window no conclusion about the quality of the window model or the accuracy of the determination of the discharge coefficient can be drawn. The simulated values were between 16.1 % and 25.1 % outside the measurement accuracy with a *CV(RMSD)* between 5.4 % to 9.2 %.

At times of low or zero solar irradiation the model reliably predicts the zone air and surface temperatures. However, further tests specifically on sunny days with two pyranometers (one of which with a shadow ring) installed on the façade right next to the window would enhance the quality of determination of direct and diffuse fraction of solar irradiation, which in this study was done by using the Skartveit-Olseth model (Skartveit, Olseth, 1987). The accuracy of this model is to be investigated especially for the winter period, when in locations of high latitudes sun angles in general are very low.

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