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The ZEB Test Cell Laboratory. A facility for characterization of building envelope systems under real outdoor conditions

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Abstract

The ZEB Test Cells Laboratory is an experimental facility at the Norwegian University of Science and Technology, designed to carry out different types of experiments. The primary use is for testing of building envelope systems, either in comparative or in calorimetric tests, but given the nature and the equipment of the test facility, the interaction between building envelope systems and HVAC terminal units can also be tested. Tests on the interaction between building envelope, building equipment, and building technologies in general can also be performed. Finally, indoor environmental quality analyses, with or without the presence of users in the test cell room, are also possible.
The paper gives a detailed report of the characteristics of the facility, including the equipment for climatic control, the monitoring system, and the control systems. Limitations, challenges and potentials improvements to fine tune the test rig are presented too.

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Keywords: Test Cell; Experimental facility; Outdoor facility; Experimental analysis; Façade; IEQ.

1. The ZEB Test Cell Laboratory in context

Some clear trends in the field of research and development of façade components can be seen in the last couple of decades. First of all, building envelope technologies, and façades in particular, are growingly designed to react to different boundary conditions (both inside and outside), and therefore their features need to be assessed under dynamic stress. Furthermore, building envelope components and building equipment are more and more integrated in term of

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function and management of indoor climate, and it becomes very complex to decouple the performance of one system from the one of the other, very often with non-linear relation (i.e. the two systems cannot be tested separately). In addition, a stronger focus has been placed on the interaction between systems and user because of unquestionable findings that show how user behavior is one of the main variables impacting on the performance of the building (and its components). Finally, the impact of façade components is now evaluated in relation to different domains of indoor environmental quality, and preferably such an assessment needs to be carried out simultaneously (and together with the measurement of the energy performance).

In short, the functions of façade systems to be tested are now many more (and more complex) than those traditionally assessed through conventional metrics (such as the U-value, or the g-value). This trend requires that new methodologies and facilities for research, development and testing of façade are developed. While conventional steady-state, single-domain performance parameters can be assessed through well established procedures and test rigs (e.g. guarded hot box) [1], a more comprehensive, dynamic assessment of façades is still missing common methodologies and facilities, though some clear tendencies can be also seen in new test facilities development.

In particular, tests are more and more carried out on full-scale prototype exposed to outdoor boundary conditions [2], following a trend initiated by the PASSYS Project in 1985 [2], and with the possibility to include user interaction (the user is in the same environment where the test is carried out). However, it is important to state that indoor test rigs, such as hot box or climate simulator, are still in use because they usually assure more accurate determination of conventional metrics of building components under steady-state conditions, something difficult to achieve with facilities (partially or fully) exposed to boundary conditions. In this context, the Research Centre on Zero Emission Buildings at NTNU has realized a new test facility, called ZEB Test Cell Laboratory, which complements the test rigs available in the Advanced Materials and Component Laboratories [3], and a full scale facility (ZEB Living Laboratory) that is occupied by real persons using the building as their home [4].

2. Anatomy of the test facility

The ZEB Test Cell Laboratory is constituted by two identical, fully independent test cells (Fig. 1). Each test cell has one surface of the cell envelope exposed to outdoor boundary conditions (a façade facing south), while the other five surfaces are surrounded by a guarded volume. The indoor air conditions of both the test cells and the guarded volumes can be controlled. The reason to use two independent cells, with two guarded volumes instead of a single surrounding volume, is to enable a higher flexibility for the experimental activities to be carried out with the test rig. For example, this layout allows parallel tests of the same building envelope technology/equipment with different indoor air temperature set-points, occupancy schedules or operations, to be carried out. Because of the guarded-volume feature, not only comparative tests are possible, but also absolute (calorimetric) tests can be carried out contemporarily on the two test cells (i.e. two different systems can be tested with different boundary conditions).

The facility has a footprint of approximately 135 m^2 and a volume of 900 m^3. The building is divided between the measurement area (that hosts the two test cells with the guarded volumes), and complementary spaces, where a control room and, services and HVAC equipment for the main building are placed. HVAC systems for the test cells and for the control volumes are instead installed right in the measurement area, together with the equipment for data acquisition and processing. The span-roof of the facility is also used for testing of PV, PV-T and solar thermal panes, which are installed on the roof slopes that faces south, with a tilt angle of approximately 42º.

Each test cells has a net volume of ca. 33 m^3, with the following internal dimensions (W x L x H): 2.4 m x 4.2 m x 3.3 m. The walls, ceiling and floor of each test cell are made of prefabricated sandwich panels (0.6 mm stainless steel sheets and 10 cm thick injected-polyurethane foam) with a U-value of 0.23 W/m^2 K. The cell is suspended from the floor of the main building by means of a supporting structure, leaving an air gap of approximately 0.5 m under the cell. The façade sample area has internal dimension (W x H) 2.4 m x 3.3 m, and is exposed to outdoor conditions facing south with a precision of ± 5º.

Each test cell has been assessed in terms of airtightness and thermal bridges, so that these values can be considered in the energy balance of the test cell. In particular, as far as airtightness is concerned, an ACH of under standard test conditions is in the range 1 to 1.5 1/h, while under normal operation an ACH of 0.3 1/h is obtained. As far as thermal bridges are concerned [5], it is worth mentioning that because of the very high value of the surface over volume ration, thermal bridges due to geometry are relatively high in this construction.

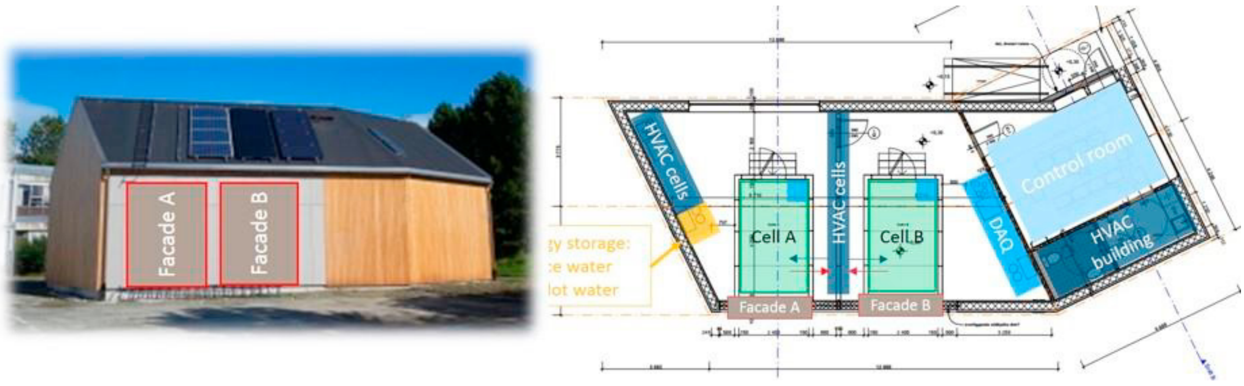

Figure 1. ZEB Test Cell Laboratory. (a) View from south. (b) Plan of the building

Each test cell has a surrounding volume that acts as a control guard of approx. 210 m^3. The airflow for temperature control of the surrounding volume is delivered through an air recirculation system as close as possible to the test cells, but measures have been taken to prevent draughts over the cell's surface that my impact on the heat transfer between the cell's surfaces and the control volume.

Thermal energy for temperature control of the two test cells and two surrounding volumes is managed by four independent heating and cooling equipment, installed in the two control volumes. A smaller, independent AHU provides fresh air intake to the guarded zones and to the auxiliary spaced of the test cell building.

3. Physiology of the test facility

3.1. Climatic and energy control

3.1.1. Cells

Thermal energy for climatic control is supplied to the two test cells via a main fresh air supply duct, which is split into two separated air conditioning sections, one for each cell. The air conditioning sections, based on a balanced mechanical ventilation layout. The supply section, assembled right at the ducts, consists of an adjustable fan, a water-based cooling coil with constant supply temperature, a PID controlled electric coil, followed by a silencer. The air conditioning section has been design to be able to supply 350 m^3/h, but under normal operation this value is usually set to 120 m^3/h (correspondent to approximately 4 ACH), within a temperature range of 12...40 °C. Accuracy in the supply temperature is ±0.2 °C. The PID for electric coil control is regulated by the plant management system based on the reading of a temperature sensor located downstream the silencer. Temperature is also measure in other sections of the plants with the scope of diagnostics and overall plant management.

The air flow temperature and the relative humidity are measured for monitoring purpose at the center of the supply duct right before it enters the test cell. A humidity-temperature probe equipped with Class A Pt100 and a temperature compensated capacitive sensor assures accuracy of ±0.3 °C and ± 1.5% for temperature and humidity, respectively. The supply air is then distributed by a 2 m long perforated fabric tube installed at the ceiling of the test room, along the north-south center line.

Monitoring of the airflow is performed through the measurement of the speed profile of the airflow in the duct, carried out by three transducers, installed at different positions (10%, 50%, and 90%) of the diameter of the supply duct. The measurement point is located approximately 7 diameters downstream the silencer and 2 diameters upstream a bend. The transducers incorporate a thin film sensor based on the hot wire principle. The accuracy of these probes depends on the airflow speed, and under normal operation, with a measured speed in the rang 1…2 m/s, the accuracy is 0.15 m/s ± 3 %, which translates in a total accuracy higher than 10%.

The measurement of temperature, humidity and airflow of the exhaust flow is performed with the same specifications on the extract duct. The measurement point for temperature and humidity is right where the duct leaves the cell, the airflow's speed profile is instead registered downstream a straight duct section of approximately 8 diameters, and 2 diameters upstream the silencer. Downstream the silencer, the adjustable fan that extracts the air from the cell is installed. The exhaust air of both cells is collected in a main exhaust duct and blown out.

Sensible and latent enthalpy flux of both the supply and the exhaust airflow can be thus calculated for calorimetric test purposes, though this calculation is presently affected by some inaccuracy primarily connected to the measurement of the speed profile. Control over the supply airflow temperature depends on the type of tests to be carried out, and can be so to obtain a stable value, or a time profile defined through schedules, or more in general based on any desired logic necessary to carry out the desired test.

3.1.2. Cell envelopes

The surfaces constituting the envelope of the test cell that are bordering with the control volume are equipped with thermocouples (T-type) for monitoring and control purpose. Both the inside (cell-side) and outside (guard-side) surface of the walls, the ceiling and the floor of the cell have a different numbers (from six to three each component, depending on the size) of thermocouples (accuracy ±0.5 °C) to monitor the temperature gradient between the two extremes of the components that separates the cell's air volume and the guard volume. The aim of this measurement is to monitor the heat transfer through these surfaces in order to take into account this phenomenon when solving the energy balance of the cell's air volume. A matrix of 18 T-type thermocouples (accuracy ±0.5 °C) is installed around the test cell's envelope, 5 cm from the guard-side surface of the test cell, and used for control purpose (see 3.1.3).

Differential pressure is recorded across the cell envelope, i.e. between each test cell and corresponding guard volume, through a piezo resistive differential pressure transmitter (0...100 Pa; accuracy ± 3 Pa.). This measurement is carried out in order to check for sensible increase in pressure difference between the two zones that might determine a significant increase in infiltration/exfiltration, phenomena that need to be considered in the cell's indoor air energy balance. The aim of this measurement is thus to detect period when energy balance could be more affected by heat loss/gain because of infiltration/exfiltration. For diagnostic purpose, the same type of measurement is also carried out between the guard volumes' air and the outdoor air.

Monitoring of the tested façade sample depends on the scope of the experiment and the system is design to host a wide range of sensors to fully characterize the building envelope technology under investigation.

3.1.3. Guard volumes

The two guard volumes surrounding the test cells are equipped with two independent air condition system. These systems follow the same scheme of the HVAC plants that climatise the test cells: each air condition system of the guard volume consists of a silence, an adjustable circulation fan, a water-based cooling coil, a PID controlled electric coil, and a second silencer. The airflow is made of fully recirculated air, which is first precooled by the cooling coil, run with constant flowrate and water set point temperature. The PID controlled electric coil conditions the recirculated air with a precision of ±0. 3 °C.

Up to 1700 m^3/h of conditioned air can be evenly distributed around the cell walls by six ducts diffusers placed around the cell (Fig. 2). The operation range or the air condition system is 12…40 °C. Temperature measurement is carried out in different parts of the plants for control purpose, with Class A Pt100 probes. No dedicated airflow measurement is implemented in these sections of the plants because not necessary. An assessment of the mass flow in the system can be done indirectly through information on the fans' speed.

The temperature of the airflow distributed around each test cell is set based on the reading of the group of 18 thermocouples, evenly distributed around the test cell's walls, ceiling and floor. The aim of this control strategy is to deliver air at the desired temperature (in normal operation, the same temperature of the indoor air of the test cell) close to the outer surfaces of the test cell's walls, ceiling and floor, so that (with the exclusion of phenomena due to heat accumulation in the enclosure of the test cell) heat transfer between the indoor air of the test cell and the air of the guarded zone is minimized.

3.1.4. Electric and waterborne thermal energy

Each test cell hosts a chassis for data acquisition and other installation to make the space of the cell similar to that of an office. This includes office pendant lighting and task lighting (both 230 V and 24 V), plugs for equipment (both 230 V and 24 V). The monitoring system is designed to record power delivered to the test cell through the 4 power lines that each test cell has, and the line that powers the local chassis for data acquisition. Power monitoring is carried out at the centralized DAQ controller through National Instruments C-modules NI-9225, NI-9227, and NI-9229. These assure high precision in power monitoring through simultaneous measurement of voltage and current.

Waterborne thermal energy for heating and cooling terminals in the test cells (not in use under normal operation) is assured by a common circuit to the two test cells. The hot water circuit is powered by a 15 kW electric heater mounted in a 300 l hot water storage tank, and can deliver hot water up to 80 °C. The cold water circuit is instead based on an air-to-water heat pump, delivering water at 7 °C and having a total capacity of 12 kW. These systems are also used to power the cooling coils of the cells' and control volumes' HVAC equipment.

The system is designed to allow full control over the water flow and water temperature of the circuits to be achieved for each cell, independently. Monitoring of the delivered thermal energy through the two circuits for each cell is performed through thermal energy meters equipped with ultrasonic flow meters and temperature sensors (Pt-500) installed on the flow and return. Energy calculation is performed directly by the thermal energy meter, with accuracy less than ±1.5%, and the value acquired by the centralized DAQ.

3.2. Environmental monitoring

Outdoor boundary conditions are monitored thorough an integrated weather station that records: a) dew point outdoor air temperature (Pt-100; range: -40…+60 °C; accuracy: ±0.15°C + 0,1 $\%_{measured}$); b) outdoor air relative humidity (thin film capacitive sensor; range: 0…100 $\%_{rh}$; accuracy: ±1,5$\%_{rh}$ +1,5 $\%_{measured}$); c) barometric pressure (piezoresistive sensor, 600…1100 hPa; accuracy: ±50 Pa); d) wind velocity (ultrasonic sensor, two axes; range speed: 0…60 m/s; range direction: 0…360 deg; accuracy speed: ±3%; accuracy direction: ±2 deg); e) global solar irradiance on the horizontal plane (thermopile; range: 0…2000 W/m_2; accuracy: II class pyranometer).

The weather station is complemented by two global solar irradiance sensors facing south (90° azimuth) tilted by 42 ° and 90 ° from the horizontal plane. Furthermore, a lux meter is installed to measure the global illuminance on the horizontal plane (thermopile, 0…150 klux; accuracy: ±5 %).

Five air temperature sensors are mounted on movable tripods and used to measure indoor air temperature in each test cell in different positions and at different heights in the cell. Sensors used are Pt 100, with range -5…+60 °C and accuracy: ±0.3 °C. The operative temperature in the test cell is determined using a globe sensor placed at the center of the cell, at 1,75 m height. The sensor is a Pt 100, with range -5…+60 °C and accuracy: ±0.3 °C. Temperatures of the walls, ceiling and floor can be obtained by the same sensors used to monitor heat transfer through the envelope.

A multi-sensor element mounted at 1,75 m at the side wall of the cells hosting a probe for indoor air relative humidity (range: 0…100 %; accuracy: ±5 %) and a temperature sensor is installed in the multi-sensor element (Si band-gap; range: 0…50 °C; accuracy: ±0.8 °C). This sensor is meant to represent a typical sensor for control in office buildings. CO_2 concentration is measured by a non-dispersive infrared sensor (range: 0…2000 ppm; accuracy: ±70 ppm + 5 $\%_{measured}$), one sensor in each room.

3.3. Data acquisition and post-processing

The ZEB Test Cell Laboratory is equipped with an integrated data acquisition and control system consisting of National Instruments Compact The acquisition of signals for both control and monitoring purpose, together with output for plant component's control, is managed centrally by one controller. A network of distributed chasses for data acquisition systems allows the total length of wires with analogue signals to be reduced to a minimum extent, still allowing a very robust management the entire installation, with just one controller. This combination provides the accuracy needed for sophisticated measurement and tests. The code for data acquisition and control of the HVAC components is developed in LabVIEW environment and allows a high degree of flexibility to be achieved.

The minimum logging interval is depending on the sensitivity of different sensors, varying from about 1 s for the velocity sensors in the ventilation ducts to about 1 min for the air temperature sensors in the cell. For a standard test the logging interval is set to 1 min to allowing a precise averaging of the about 520 sensor signals and set points in the data post processing. After conversion of the binary TDMS file to a text based file the post processing can be conducted with any software tool.

4. Current limitations and future improvements of the facility

The design of experimental facilities is never a straightforward process and continuous improvements always occur still when the facility is completed. The following issues will be addressed to increase the test rig's accuracy.

Infiltration/exfiltration losses are in line with those of a small building, but improvements are possible with a more airtight connection between the sandwich panels of the cell's envelope.

Thermal bridges can be reduced with some relatively simple modification, though a large part of them (due to geometry of the facility, cannot be easily reduced and should just then be considered in the energy balance.

The relatively high uncertainty of air speed measurements affects negatively the determination of the supplied/extracted enthalpy flow. More accurate measurement technique (standardized orifice plates) could be implemented. The supply ducts already incorporates a reduction in the diameter in line with the Venturi geometry, for measurement of airflow through pressure change. However, these changes in the pressure values are too small and the final accuracy of the system is similar to that obtained with hot wire principle. Calorimetric test could be carried out with full recirculation of air, monitoring heat loss and gain (i.e. coils, ducts, fans) along the airflow path.

The power control (pulse width modulation) need to be improved, because it induces temperature variation in the supply flow that affect the reading of the air speed sensor. The pulse width modulation cycle time needs to be reduced, or smaller electric heating coil installed to allow a lower variation in the temperature of the airflow.

Temperature stratification is seen in the test cell when heated, the lower part of the cell remaining colder. The installation of a alternative supply air diffuser may prevent stratification, however would lead to less uniform temperature distributions during cell cooling too. Alternatively, small fans for air recirculation inside the cell could be installed, still paying attention to avoid increased air speed inside the test cell.

The plant has not been designed to control latent loads, but a further development of the system may include a adiabatic humidifier in the supply duct to regulate water vapour content in the cell.

Future improvements are foreseen both in the automatic post processing of the data as well as in the selection of the channels and time period of interest. New user interfaces are also planned to be developed within this activity.

4. Conclusion

The ZEB Test Cell Laboratory is a facility for multipurpose characterization of building envelope systems under real outdoor conditions. Different building envelope technologies under same boundary conditions, or the same building envelope technology with different boundary conditions (e.g. ventilation flow, indoor set-point) can be tested, as well as different heating/cooling devices in combination with façade systems. Experiments on impact building envelope system on indoor environmental quality, with/without users in the cells are also possible.

After a period of commissioning, calibration and first experiments, the facility has proved its potentials and highlight limitations that are now under considerations. Future activities are now planned to overcome current limitations and improve the reliability and accuracy of the facility.

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