Ventilative cooling in a school building: evaluation of the measured performances

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ABSTRACT

The test lecture rooms of KU Leuven Ghent Technology Campus are one the demonstration cases of IEA EBC Annex 62: Ventilative Cooling. This nZEB school building is realised on top of an existing university building and contains 2 large lecture rooms for maximum 80 students with a floor area of 140m² each. An all air system with balanced mechanical ventilation is installed for ventilation, heating and cooling. The building is cooled by three techniques of ventilative cooling: (1) natural night ventilation (opening the windows at both sides of the building) (2) a modular bypass in the AHU and (3) indirect evaporative cooling (IEC).
This paper aims to evaluate thermal comfort in this nZEB school building and the performances of its ventilative cooling system. Therefore, long term measurements of internal temperatures, occupancy, opening of windows, operation of IEC, airflow of AHU, etc. were carried out from May to September 2017 (i.e. cooling season). In addition, the airflow rates through the windows in cross ventilation and single sided ventilation mode were measured on several days in March and April 2017. Both tracer gas concentration decay tests as air velocity measurements were used for this purpose.
The results show that a good thermal summer comfort was measured in the test lecture rooms at the Technology campus Ghent of KU Leuven (Belgium). Only during heat waves and/or periods with high occupancy rates, high indoor temperatures were monitored. Both nighttime ventilation and indirect evaporative cooling operate very well. IEC can lower the supply temperature by day significantly compared to the outdoor temperature. The ACR of the night ventilation depends a lot on wind direction and velocity. Furthermore, two key lessons learned from the operation phase are: (1) the data monitoring system was essential to optimize the performance of the ventilative cooling and (2) the users have to informed about the operation of automated systems.

KEYWORDS

Ventilative cooling, nZEB, school building, measurements, thermal comfort

1 INTRODUCTION

To reduce the energy consumption in buildings, the EPBD directive requires that from 2020 all new buildings in the European Union have to be nZEB buildings. One of the major new challenges in these highly insulated and airtight buildings is the increased need for cooling and risk on overheating not only during summer, but all year round. In addition, this cooling demand depends less on the outdoor temperature and more on the internal and solar heat gains (Heiselberg, 2018). A shift is noticed from reduction in heating to reduction in cooling demand. Therefore, conceptual and building technical measures as well as energy efficient cooling systems are needed in these nZEB buildings to guarantee a good thermal comfort. Ventilative cooling is an example of an energy efficient cooling method and was extensively and detailed studied within IEA EBC Annex 62. The test lecture rooms of KU Leuven Ghent Technology Campus were one the demonstration cases of IEA EBC Annex 62: Ventilative

Cooling (see O'Sullivan and O'Donovan, 2018). This paper aims to evaluate thermal comfort in this nZEB school building and the performances of its ventilative cooling system.

First, a description of the building, its systems and more specific the ventilative cooling and control strategy is presented. Afterwards, the measurement set up for the evaluation of air flow rates, operation of ventilative cooling and thermal comfort is shown. Section 4 presents the results of the measurements and finally the conclusions and lessons learned are presented.

2 BUILDING DESCRIPTION

2.1 Building and use

The nZEB school building is realized at the Technology campus Ghent of KU Leuven (Belgium) on top of an existing university building. The building contains 4 zones (see Figure 1): two large lecture rooms (1) and (2), a staircase (3) and a technical room (4). The lecture rooms have a floor area of 140 m^2, a volume of 380 m^3. The lecture rooms are designed as identical zones with a different thermal mass. The lower room has a brick external wall with exterior insulation while the upper room has a lightweight timber frame external wall with the same U-value. Both lecture rooms have a concrete slab floor. This results in a light (2^{nd} floor) and a medium (1^{st} floor) thermal mass according to EN ISO 13790.

Table 1 shows the building properties. The school building was constructed according to the Passive House standard. This means that the air tightness (@50 Pa) is lower than 0.6 h^{-1} and the U-values of the envelope parts are maximum 0.15 W/m^2K. The windows are constructed with triple glazing and have a g-value of 0.52. The window-to-wall ratio is 26.5% on both façades. The window-to-floor ratio is 13%. The windows are provided of internal and external solar shading. The external solar shading are moveable screens on the southwest façade which are controlled automatically and provided of manual overrule.

The occupancy level in the building is dependent on the academic year, which counts 124 days with courses and 63 days with exams (in January, June and August-September). Holiday periods are in April (2 weeks), July and the first half of August (6 weeks) and December-January (2 weeks). The lecture rooms are in use from Monday to Friday between 8h15 and 18h with a maximum occupancy of 80 persons or 1.78 m^2/pers. Figure 2 shows details of 1 typical week of occupancy.

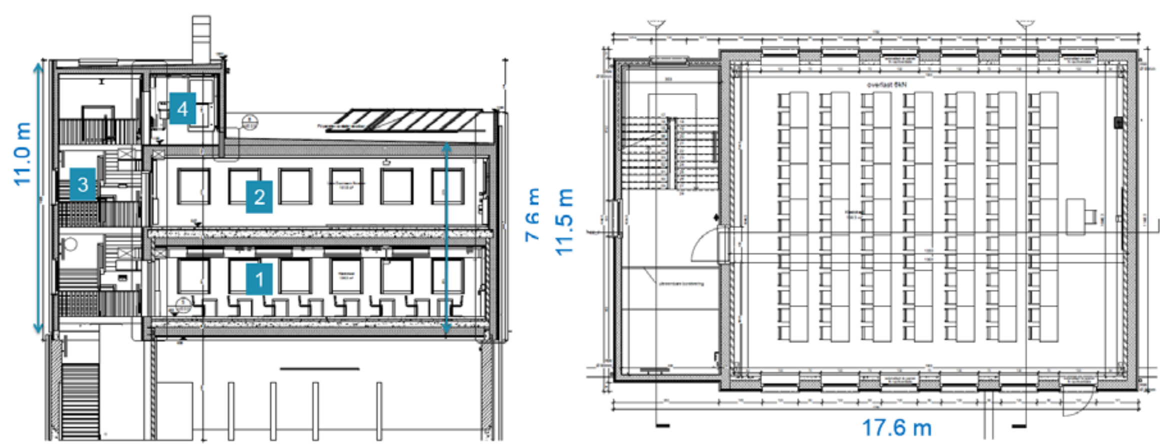


Figure 1: Section (left) and floor plan (right) of the test lecture rooms on KU Leuven Technology campus Ghent

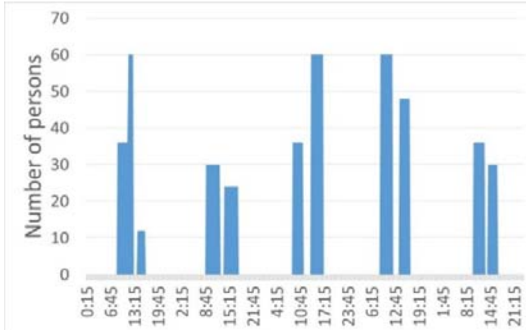


Figure 2: Typical occupancy profile in the lecture rooms during one course week (Monday to Friday)

Table 1: Building properties

Property	value	unit
U-value Wall	0.15	W/m^{2}K
U-value Roof	0.14	W/m^{2}K
U-value Floor	0.15	W/m^{2}K
U-value Window	0.65	W/m^{2}K
g-value Window	0.52	(-)
Air-tightness (@50 Pa) 1st floor	0.41	1/h
Air-tightness (@50 Pa) 2nd floor	0.29	1/h

2.2 Systems

The building is equipped with an all air system with balanced mechanical ventilation with a the total supply airflow of 4400 m³/h (see Figure 3). Demand controlled ventilation with 4 VAV boxes control the airflow based on CO_2-concentrations in the rooms.

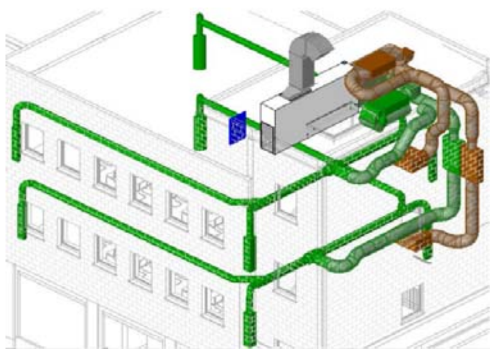


Figure 3: Visualisation of air distribution (supply in green, return in brown)

2.3 Ventilative cooling

Three different principles of ventilative cooling are implemented in this building: (1) natural night ventilation, (2) a modular bypass in the air handling unit and (3) indirect evaporative cooling (IEC). Design of the building and its ventilative cooling system is described in Breesch et al. (2016).

Night ventilation relies on cross ventilation through openable windows at both sides of the room (see Figure 4). The system includes 10 motorized bottom hung windows (1.29 x 1.38 m², maximum opening angle of 8.8°) with a chain actuator. There are 6 windows on the southwestern side and 4 on the northeastern side of the lecture room The total effective opening area of these windows is 4.0% of the floor area. The modular bypass and IEC are part of the AHU. The maximum airflow rate is 4400 m³/h. The maximum capacity of IEC at maximum airflow is 13.1 kW.

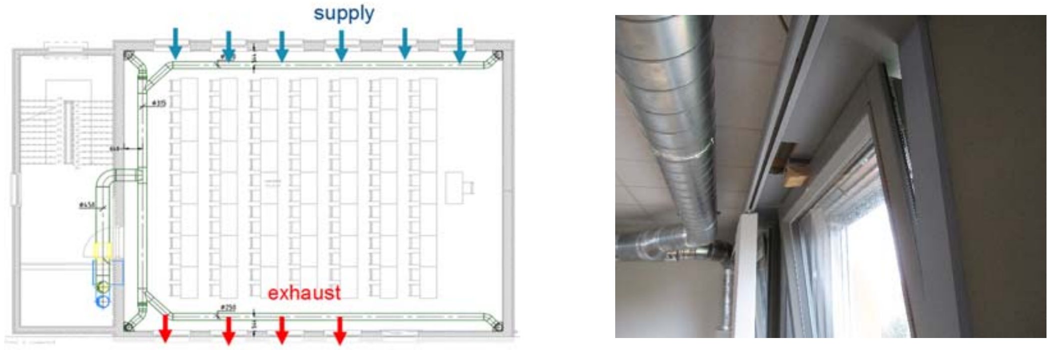


Figure 4: Principle of natural night ventilation (left) and detail of motorized window (right)

2.4 Control strategy

Control strategy of the systems consists of two parts. First, the control strategy of the mechanical ventilation system (operation of bypass and IEC) during occupancy is based on internal and external temperatures (see Figure 5 left). This strategy actuates the supply air temperature and the air flow rate. Second, control strategy at night that actuates the opening of the windows and is based on internal temperature and relative humidity and external weather conditions (temperature, rain) measured on site (see Figure 5 right).

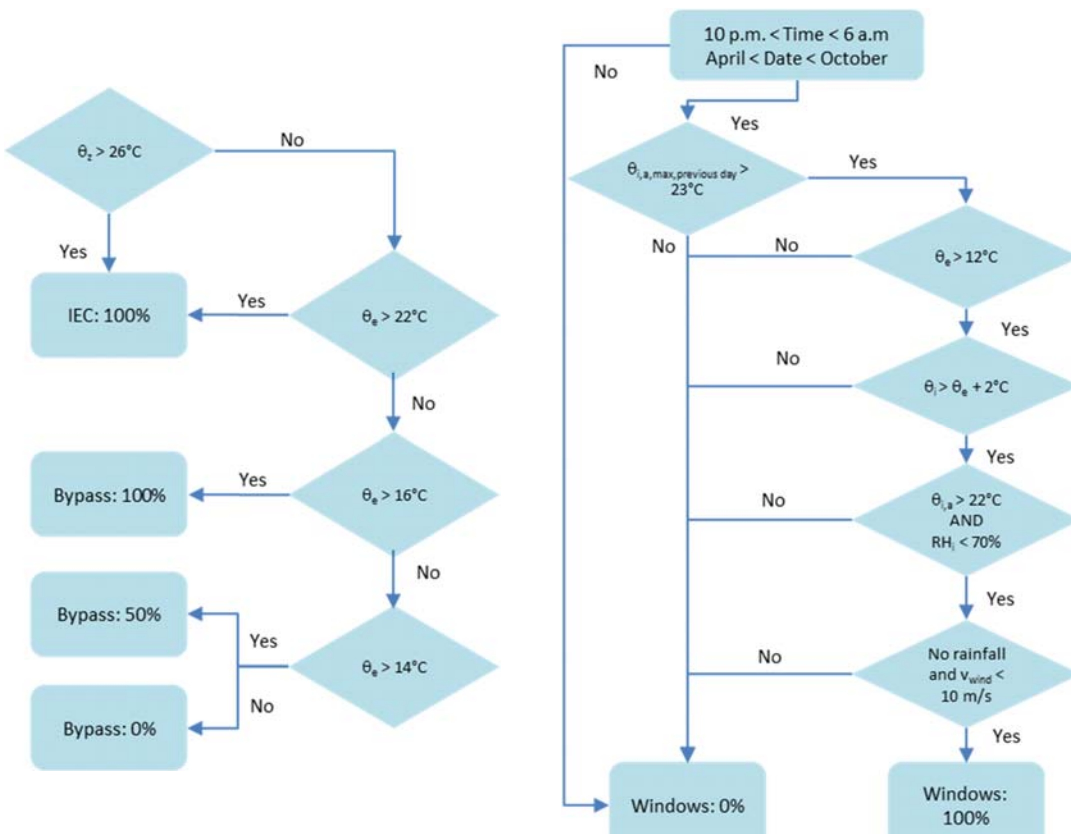


Figure 5: Control strategy flowchart of AHU during occupancy (left) and natural night ventilation (right)

3 MEASUREMENT SET UP

3.1 Airflow rate

Air Changes Rates (ACR) as result of the opening of the windows in the lecture rooms was measured using a tracer gas concentration decay test method in March and April 2017. The used gas is N_2O also known as laughing gas. Tests were completed in accordance with the procedures set out EN 12569. The measurements were carried out in a representative zone with two opposing windows with a width of 3,04m (see Figure 6, left). Tracer gas was injected and sampled in the middle of this small room. The concentration was increased in this sealed room to a constant value of 200 ppm. After reaching this goal, one or two opposing windows (depending on the test) were opened. The accuracy of the tracer gas equipment is 10% of the measured value.

ACR was also estimated from the air velocity measurements. Figure 6 (right) shows the test set up: the air velocity is measured every 10s during 30min on 4 locations with omnidirectional sensors. The effective area of the window is calculated 0.109 m². The airflow is determined as the effective area multiplied by the median of the air velocity.

Moreover, the air flow pattern is visualised by measuring air temperatures at different heights and positions (see Decrock and Vanvalckenborgh, 2017).

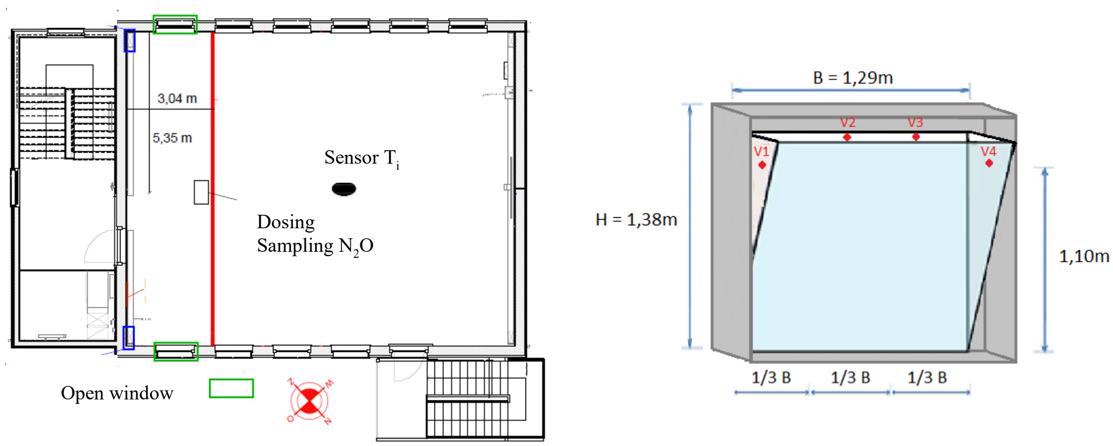


Figure 6: Test set up tracer gas measurement (left) and air velocity measurement (position of the sensors) (right)

Table 2: Properties of the sensors

Parameter	Type sensor	Accuracy
Air temperature	Omega PT100	± 0.10 °C
Air velocity	TSI 8475	3% of reading and 1% measurement range (0.05-2.50 m/s)
Room temperature	SE CSTHR PT1000	± 0.1 °C
Supply temperature	SE CSTHK HX	± 0.4 °C
Occupancy	Acurity Crosscan Camera	± 5%
Outdoor temperature	Vaisala HMS82	± 0.3 °C at 20°C
Wind velocity	Ultrasonic 2D Anemometer	± 0.1 m/s (0-5 m/s)
Wind direction	Ultrasonic 2D Anemometer	± 1 °

3.2 Indoor climate and operation ventilative cooling

A set of sensors has been installed to monitor continuously indoor and outdoor conditions and is described in Andriamamonjy and Klein (2015). The lecture rooms have their own weather station that monitors the main outdoor parameters: global horizontal solar radiation, outdoor temperature, relative humidity, wind speed and direction. For the indoor conditions, the temperature, CO_2 concentration and the humidity are continuously monitored. The occupancy of the lecture room is measured by using counting cameras which were installed in the lecture room. The operational data of the AHU, night ventilation, IEC, heating systems, etc. is also continuously monitored. The data from these sensors are displayed in real time and recorded within a computer based monitoring and control system. The time step is 1 minute. Table 2 shows type and accuracy of the sensors used in this study.

In this study, internal temperatures and operation of ventilative cooling are studied during the cooling season in 2017 in the lecture room on the first floor, i.e. from May 22th to September 30th 2017. As there was no occupancy in July and only limited in August, these months are excluded from the analysis.

4 RESULTS

4.1 Airflow rate and air temperature profile

Table 3 presents the results of the tracer gas decay tests for single sided and cross ventilation including the local weather conditions (wind velocity and direction) and the average indoor-outdoor temperature difference during the test. For cross and single-sided ventilation, the 95% confidence interval for ACR is respectively 1.21 to 2.12 and 2.17 to 4.64 h^{-1}.

Table 3: Measured ACR with tracer gas decay during spring 2017

Ventilation mode	ACR (h^{-1})	Wind velocity (m/s)	Wind direction	ΔT (°C)
Cross ventilation	4,18 ± 0,42	1,9	WNW	4,3
Cross ventilation	3,76 ± 0,38	2,1	ESE	1,6
Cross ventilation	3,04 ± 0,30	2,2	ESE	2,4
Single sided	2,05 ± 0,21	2,3	SSW	No data
Single sided	2,00 ± 0,20	2,68	S	No data
Single sided	1,17 ± 0,12	1,45	SSW	5,1
Single sided	1,56 ± 0,16	1,78	S	8,6

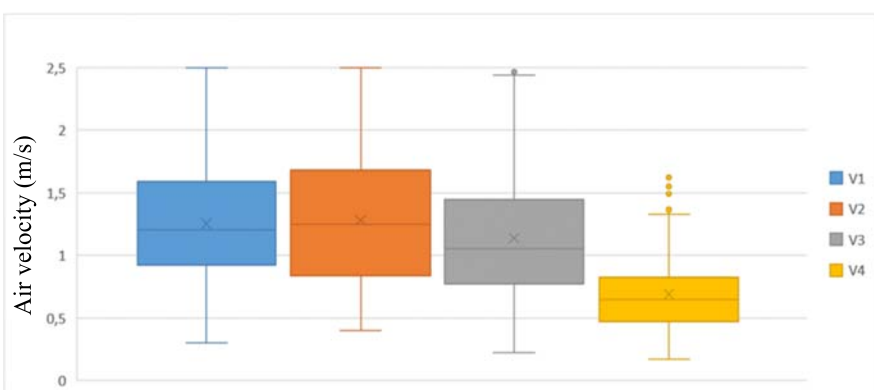
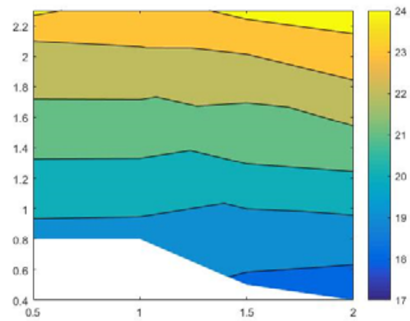


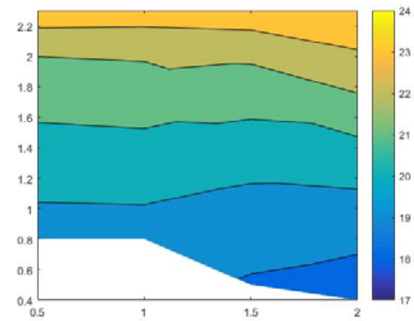
Figure 7: Boxplots of air velocity for cross ventilation (wind velocity = 1.9 m/s, wind direction = WNW and temperature difference = 4.3 °C)

Figure 7 shows the results of the air velocity measurements for cross ventilation executed at the same moment as the first tracer gas test in Table 3. The median value on the different positions equals 1.21 m/s, 1.25 m/s, 1.05 m/s and 0.65 m/s. Only the velocity at position V4 has a deviating value. This air velocity results in an ACR of 4,21 ± 0,13 h-1. A good agreement with the result from the tracer gas decay method was found (see line 1 in Table 3).

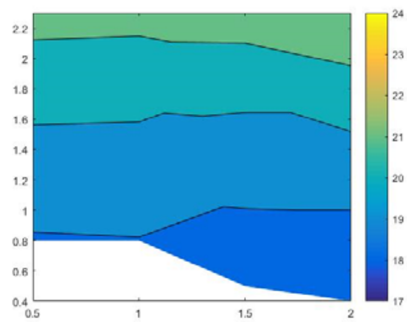
Figure 8 shows the air temperatures at the start and 10, 20 and 60 min after opening the window. The stratification at the start changes to a more uniform air distribution after 60 min. The air in the whole lecture room is cooled down.



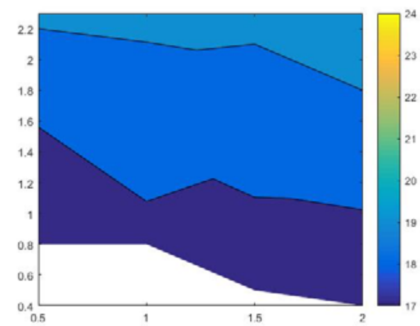
a) start



b) 10 min



c) 20 min



d) 60 min

Figure 8: Air temperature profile in the room at the start, after 10, 20 and 60 min for cross ventilation

4.2 Operation of ventilative cooling

Figure 9 presents the ratio of operation time of the windows to the possible total opening hours by night (22h tot 6h) and the ratio of the operation of the IEC to the operation hours of the AHU by day. IEC and nighttime ventilation are in use during 66% respectively 45% of the time.

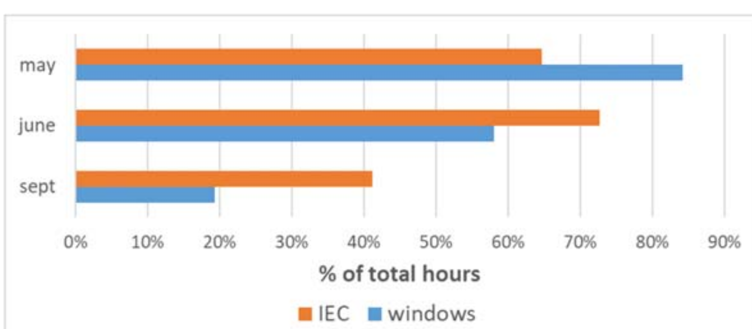
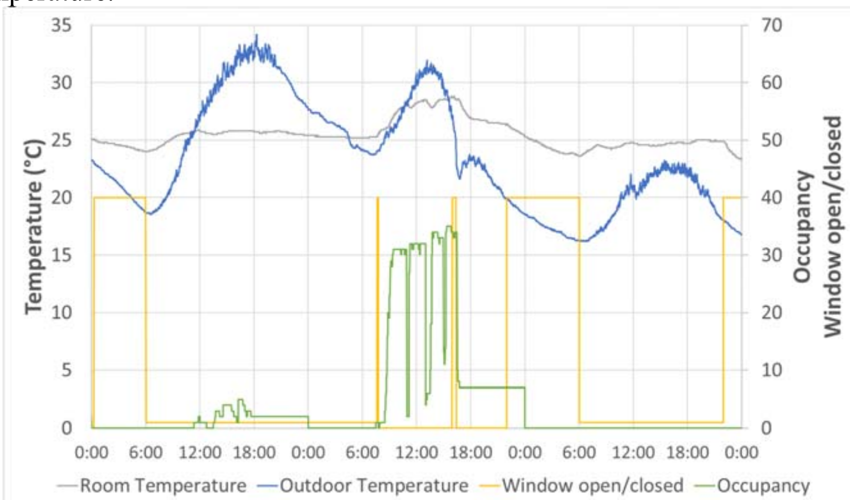


Figure 9: Percentage of hours of operation of windows by night and IEC by day from May to September 2017

In addition, Figure 10 shows the operation of the windows for night ventilation respectively indirect evaporative cooling during extremely warm days in June 2017. In that period, IEC operates the whole day and can lower the supply temperature significantly compared to the outdoor temperature.



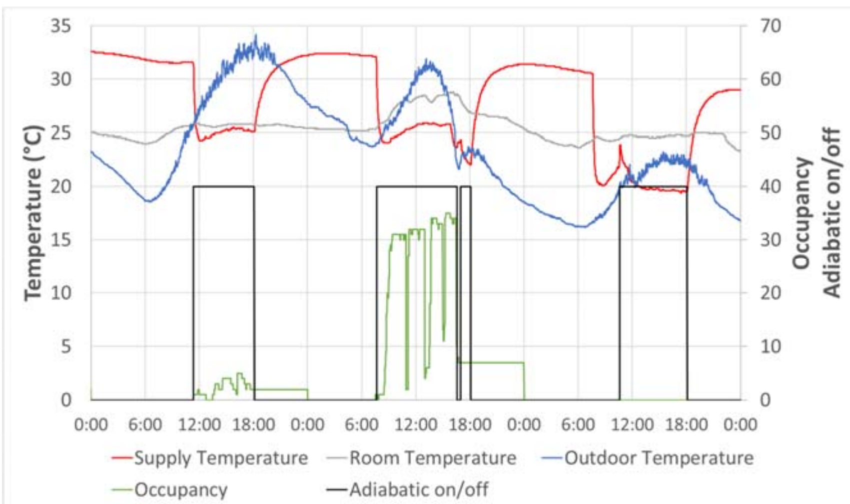


Figure 10: Operation of windows (above) and IEC (below) during an extremely warm period (21-23 June 2017)

4.3 Thermal comfort

Figure 11 presents hourly indoor operative temperature in this lecture room. The percentage of hours of exceedance per month above 23°C, 25°C and 28°C are shown. Furthermore, the number of occupied hours of exceedance of a particular indoor temperature above a threshold value is commonly taken as an overheating performance indicator. In this lecture room, during operation of the AHU, 5.1% and 0.3% of the hours in 2017 exceeded 25°C respectively 28°C. This means a good thermal comfort according to EN 15251.

Thermal comfort in this lecture rooms is also evaluated as a function of the running mean outdoor temperature as defined by the Dutch adaptive temperature limits indicator (van der

Linden et al., 2006) (see Figure 12). Overall, good thermal comfort is concluded. However, high temperatures are noticed during hot summer and/or periods with a high occupancy rate.

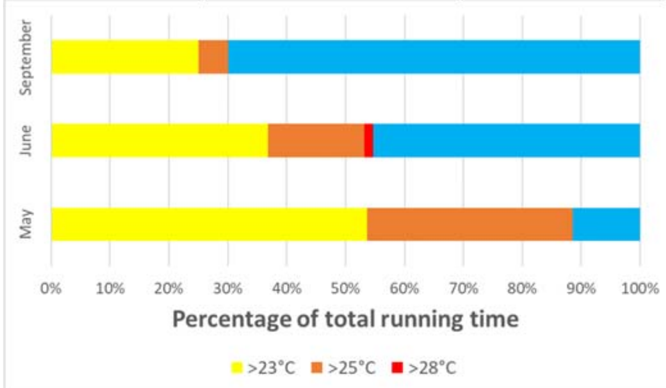


Figure 11 Percentage of hours above threshold values for internal temperatures in lecture room on 1st floor May-September 2017

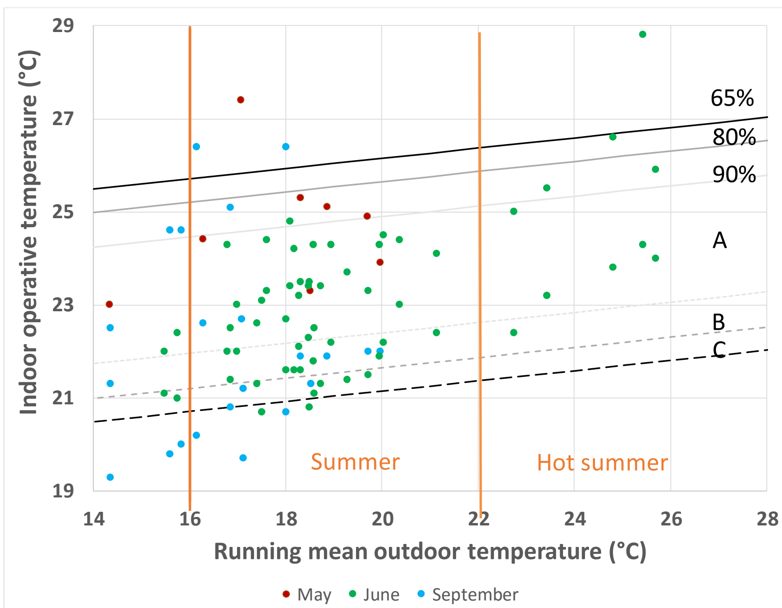


Figure 12 Thermal comfort evaluation according to the Adaptive Temperature Limits Method (van der Linden et al., 2006)

5 CONCLUSIONS AND LESSONS LEARNED

The test lecture rooms of KU Leuven Ghent Technology Campus are one the demonstration cases of IEA EBC Annex 62: Ventilative Cooling. Three different principles of ventilative cooling are implemented in this building: (1) natural night ventilation, (2) a modular bypass in the air handling unit and (3) indirect evaporative cooling (IEC). Thermal comfort in this nZEB school building and the performances of its ventilative cooling systems were evaluated.

A good thermal summer comfort was measured in the test lecture rooms at the Technology campus Ghent of KU Leuven (Belgium). Only during heat waves and/or periods with high occupancy rates, high indoor temperatures were monitored.

Both nighttime ventilation and indirect evaporative cooling operate very well. IEC can lower the supply temperature by day significantly compared to the outdoor temperature. The ACR of the nighttime ventilation (cross ventilation) depends a lot on wind direction and velocity. The ACR can be increased by adding mechanical extraction.

The extensive data monitoring system was of great value to detect malfunctions, to improve the control of the building systems and optimize the whole building performance. Monitoring showed e.g. that the windows for night ventilation opened and closed a lot at night during the first weeks. This was due to (1) bad translation of the signal of the rain sensor and (2) peaks in the wind velocity. These parameters are part of the control of the windows. This malfunctioning was discovered and solved by analysing the monitoring results.

Furthermore, attention has to be paid to the users. A lot of different teachers give classes in these lecture rooms. Most of them are not used to automated blinds, ventilation and ventilative cooling. They open the door to the corridor and the windows even when it is warm outside and consequently cause a decrease in thermal comfort. It is important to educate and inform the users about the operation of the automated system to come to a comfortable and energy efficient building.

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