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Building renovation with prefabricated ventilated façade element: a case study

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Abstract

This paper deals with the performance of a high school building renovated with prefabricated ventilated façade elements through a field experimental study under oceanic climate. Temperature, relative humidity and heat flux were measured at different points of the renovated façade, while temperature, relative humidity and CO₂ concentration were monitored within a classroom. The performance of the renovated building is discussed based on the analysis of two years of measurement data. The experimental results show that the measured *in situ* thermal resistance of prefabricated ventilated façade elements could be evaluated reliably only under winter period and that it is higher than the design one. Secondly, we note that the application of exterior thermal insulation does not lead to major moisture related pathology on retrofitted building envelope. Only small mold growth risks may exist close to hygroscopic material in relation with solar radiation. Last, we observe that hygrothermal comfort is achieved most of the teaching time, whereas CO₂ concentration exceed critical threshold levels every day.

Keywords

Exterior thermal insulation; In situ thermal resistance; ISO 9869; Heat and moisture transfer; Mold growth; Hygrothermal comfort; Indoor environmental quality

Highlights

- Performances of retrofitted educational building are evaluated.
- Thermal resistance, moisture-related risks and IEQ are investigated.
- Thermal resistance could be estimated reliably only under winter period.
- Overall safe behavior is observed despite ponctual mold growth risks.
- Hygrothermal comfort is mainly achieved in the classroom

1 Introduction

In a context of high energy consumption and large environmental impact of buildings, external thermal insulation is increasingly used for the retrofit of existing building envelopes.

There are basically two different systems:

- External Thermal Insulation Composite System (ETICS): an insulation layer is applied on outer side of existing façade and covered either by a thin finishing layer (usually of cement mortar) or with a cladding.
- Ventilated façade system: a ventilated cavity is created between insulation and cladding.

Whatever the system, external thermal insulation must meet three main requirements: improving building energy performance, avoiding moisture-related risks within the building envelope and improving indoor environmental quality (IEQ).

Regarding building energy performance, a building renovation including external thermal insulation is found to be an effective way to reduce building energy consumption of heating and cooling [1-4]. This is partly due to the reduction of thermal bridges and to the thermal improvement of the building envelope as confirmed by *in-situ* measurements of U-values [5-7].

Regarding moisture-related risks, pathologies can be encountered at different position, depending on the external thermal insulation system. At the exterior surface of ETICS, excessive moisture content due to wind-driven rain or vapor condensation may involve biological growth or mechanical damage [8-9]. These risks depend mainly on wetting–drying kinetics, render thickness and presence of external obstacles [10]. When external thermal insulation is added on wet walls, condensation risks may exist at the interface between existing wall and insulation. In the case of ETICS, low moisture diffusion properties of insulation material and finishing layer prevent the wall drying-out, leading to high moisture

content at the interface [11]. Such high initial moisture levels were observed experimentally by Capener and Sandin [12] for a south oriented renovated AAC wall in Sweden as well by Mandilaras et al. [7] for a north oriented renovated wall in Greece. On the other hand, Künzel [13] mentioned that these condensation risks can be avoided by using a ventilated façade system. Nevertheless, designing ventilated façade system is a critical task. By simulating the hygrothermal behavior of renovated massive walls, Pihelo et al. [14-15], Steeman et al. [16] and Coupillie et al. [17] recommend to install a vapor barrier and insulation with a good moisture buffering effect close to the existing wall. However, their simulation results are sensitive to initial moisture content of existing wall and to the vapor barrier resistance and should be compared to experimental data like those in [18]. Last, a risk of interstitial condensation can be encountered within insulation, particularly in presence of air infiltration/exfiltration. For instance, Langmans and Roels [19] predicted that adding an air barrier at outer side of insulation (in the view of meeting the severe airtightness requirements) is not suitable for moderate oceanic climates in Europe. Even if their model, which assumes cracks and air infiltration in the walls, was validated against laboratory experiments [20], there is still a need to collect further experimental data at building scale under real conditions.

Regarding indoor environmental quality (IEQ), an improvement is generally observed. For instance, Almeida and De Freitas [21,22] assessed the impact of retrofit on IEQ of school buildings in Portugal. They observed that hygrothermal comfort is improved compared to non-retrofitted schools, even if overheating was observed locally during the mid-season and summer. Median CO₂ concentration were found to be lower due to the use of mechanical ventilation; However, critical level remains frequently exceeded, particularly during winter when the opening of windows is not always possible. Similar observations were made for schools in Italy [23, 24] or in Denmark [25].

Since educational buildings are responsible for high energy consumption [26], a renovated high school building is investigated in this work. The main discussions concern the hygrothermal behavior of the renovated building envelope through the analysis of temperature and relative humidity measurements and the moisture-related risks after the retrofit. In addition, experimental data are analyzed in the view of evaluating the in-situ estimation of the envelope thermal resistance. Last, a short measurement campaign should give an overview of indoor environmental quality in the classroom.

2 Materials and methods

2.1 Description of the building

The studied building is a high school built in 1959 in the city of Lorient (west coast of France, characterized by an oceanic climate). The building is 150 m long, 12 m large and 15 m high and is mainly oriented in SW-NE direction. It was made of reinforced concrete skeleton, 16 cm precast concrete façade panels and single-glazed windows.

In 2015, the building was renovated by adding mechanical ventilation systems and prefabricated ventilated façade elements on exterior side of existing envelope. The use of prefabricated elements presents numerous advantages, such as standardizing and industrializing manufacturing processes, enhancing quality, reducing costs, renovation time and disturbance for occupants [27]. Here, each element is made of a timber frame structure with dimensions of 4 x 8 m and includes 5 double glazed windows (see Fig. 1). The opaque part of each element consists from interior to exterior of 12 cm glass wool, OSB board, 12 cm glass wool, rainscreen membrane (Delta-Maxx Plus from Doerken [28]), ventilated cavity and black metal cladding (see Fig. 2). These prefabricated elements must fulfil at least three requirements: thermal insulation, vapor diffusion resistance and airtightness. Regarding the

first two points, thermal conductivity and vapor diffusion resistance factor were measured in the lab according to ISO 12939 [29] and ISO 12572 [30]. Material properties, dry density and thicknesses are gathered in Table 1. The theoretical thermal resistance of the opaque part calculated according to ISO 6946 [31] ranges between 6.93 and 7.59 $\text{K}\cdot\text{W}^{-1}\cdot\text{m}^{-2}$, while vapor diffusion resistance is mainly fulfilled by OSB board. Airtightness of this building is controlled from outside due to the rainscreen membrane characteristic: for instance, blower door tests conducted by an external company showed that airtightness (n_{50}) was reduced from 5.15 h^{-1} before renovation to 1.58 h^{-1} .

Last, we noted that a 20 cm thick non-ventilated cavity is created between the prefabricated element and the concrete wall since the existing envelope is not flat (see Fig. 2).



Figure 1: Views of the building before retrofit and the prefabricated ventilated façade element.

Material	Density [kg m^{-3}]	Thermal conductivity [$\text{W m}^{-1} \text{K}^{-1}$]	Sd-value [m]	Thickness [mm]
Glass Wool	34	0.032 - 0.035	0.36	2 x 120
OSB	678	0.11	0.46	10
Rainscreen membrane	-	-	0.08	0.4

Table 1: Measured materials properties.

2.2 Description of the monitoring

The analysis was concentrated on one element located on the 2nd floor and on the central longitudinal body of the SE façade. This element faces a classroom. Its hygrothermal behavior is monitored by using K thermocouples, capacitive humidity sensors (Sensirion SHT 75, Staefa, Switzerland) and heat flux sensors (Captec, Lille, France). Uncertainties on temperature, relative humidity and heat flux were evaluated by the suppliers respectively at 0.5 °C, 2 % and 3 %. As illustrated in Fig. 2, sensors were placed at different interfaces in a representative part of the element (avoiding the vicinity of corners, junctions or window).

A weather station (Vantage PRO 2 by Davis Instruments, Hayward, CA) monitors outdoor condition near the building (air temperature and relative humidity, wind speed and direction, global horizontal irradiance). A capacitive humidity sensor and Netatmo weather station [32] provide measurements of indoor temperature and relative humidity, CO₂ concentration and noise in the classroom.

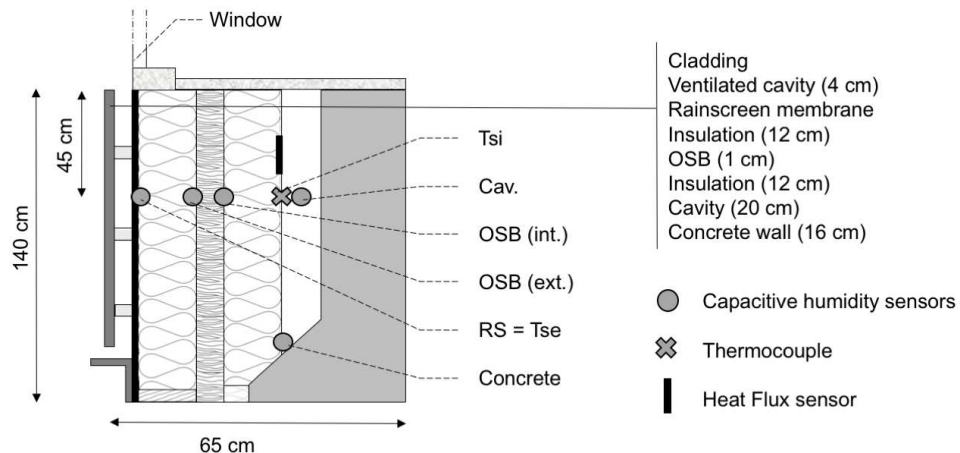


Figure 2: Overview of the design and the instrumentation of the prefabricated ventilated façade element.

All sensors are connected to different dataloggers, which records all the data at least every 10 minutes. The experimental campaign started at the end of renovation (in July 2015) and was carried for 2 years (until June 2017). As usual for long-term experiments, some measurement problems arise during the monitoring period and about 20 % of data are missing due data acquisition failure and power outage.

2.3 Determination of in-situ thermal resistance

Since the above instrumentation and the design of the monitoring process followed the guidelines of ISO 9869 [33], the thermal resistance of opaque building component can be evaluated according to this standard. In this work, three methods are used to analyze the data: average methods, average methods applied on night periods, dynamic method. The methodology for the calculation as well the convergence criteria are described in detail in the standard or in the literature [33-36] and are briefly sum-up hereafter.

Average methods consider one-dimensional quasi-steady state transfer through the wall. Basically, thermal resistance is evaluated as:

$$R = \frac{\sum_{j=1}^N (T_{sij} - T_{sej})}{\sum_{j=1}^N q_j} \quad (1)$$

where T_{sij} and T_{sej} are the internal and external surface temperature and q_j is the heat flux density. For light elements with a specific heat capacity lower than 20 kJ/(m² K) (which is the case here), the standard recommend to carry out the analysis only on data acquired at night [33]. In the dynamic method, thermal resistance is calculated by minimize the difference between the measured heat flux and the calculated one through a transient thermal model. A short description of the process for the data analysis is given in [33-34].

Since heating device can significantly affect the estimation of the thermal resistance [37], the methods are applied to the prefabricated element rather than to the retrofitted envelope: internal surface temperature and heat flux are measured at the insulation/cavity interface. On the other side, external surface temperature is measured on the rainscreen membrane because of data availability.

3 Hygrothermal behavior of prefabricated ventilated façade element

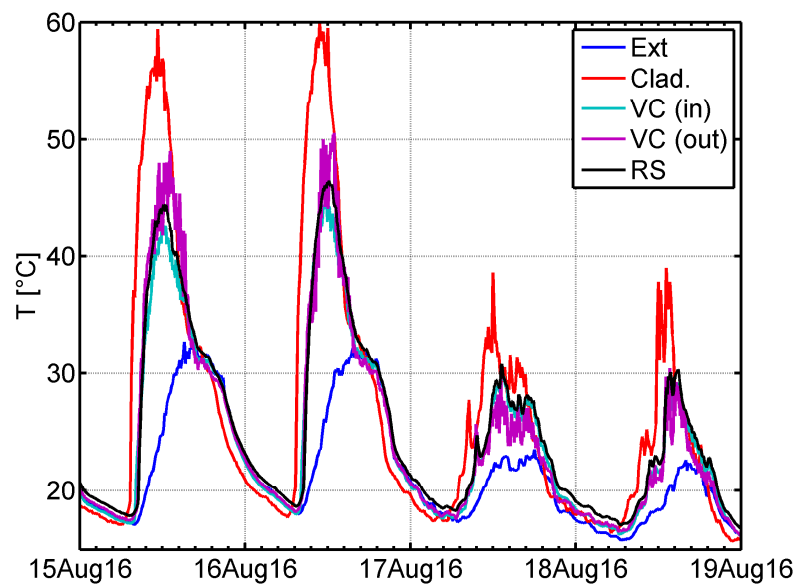
3.1 Focus on the cladding and the ventilated cavity during summer

A summer period (from 15th to 19th august 2016) including two sunny and two cloudy days is studied. Wind is oriented mainly in the west direction and its velocity does not exceed 2 m.s⁻¹. The measured cladding temperature and the ventilated cavity conditions regarding temperature, relative humidity and vapor pressure along the wall are shown in Fig. 3.

In general, temperatures follow a logical trend: cooling down at night and warming up during the day. On sunny days, cladding temperature increases from 8 a.m. and reaches a maximum of 60 °C at 11 a.m.. Due to thermal inertia, a phase shift of about 1.5 hours can be noticed between cladding and ventilated cavity maximum temperatures. Notably, maximum top ventilated cavity temperature is higher of 5 °C than maximum bottom one: air flow due to thermal buoyancy is upwards when outside temperature is lower than cavity temperature. A part of solar energy is transferred outside by air flowing in the ventilated cavity and the thermal load on the insulation is thus limited. In absence of direct solar radiation, both cladding and ventilated cavity temperatures tend to exterior temperature. During nights after, it should be noted that cladding temperature drops below exterior temperature due to long-wave radiation exchange with the sky. On cloudy days, cladding and ventilated cavity

temperature do not exceed 40 °C and no significant differences are observed between the top and bottom cavity temperatures.

During this experiment, bottom ventilated cavity vapor pressure closely follows exterior vapor pressure. During sunny days, bottom ventilated cavity relative humidity strongly decreases and reaches levels of 30 % due to temperature increase. On the other hand, top ventilated cavity vapor pressure is much higher than the bottom one: because of solar radiation, wet wall starts to dry out, causing high amounts of vapor to be transported upwards to the ventilated cavity. During nights and cloudy days, no significant differences are observed between bottom and top ventilated cavity relative humidity and their levels are closed to the exterior ones. This behavior is similar as the one observed by Vanpachtenbeke et al. [38] for brick veneer cladding.



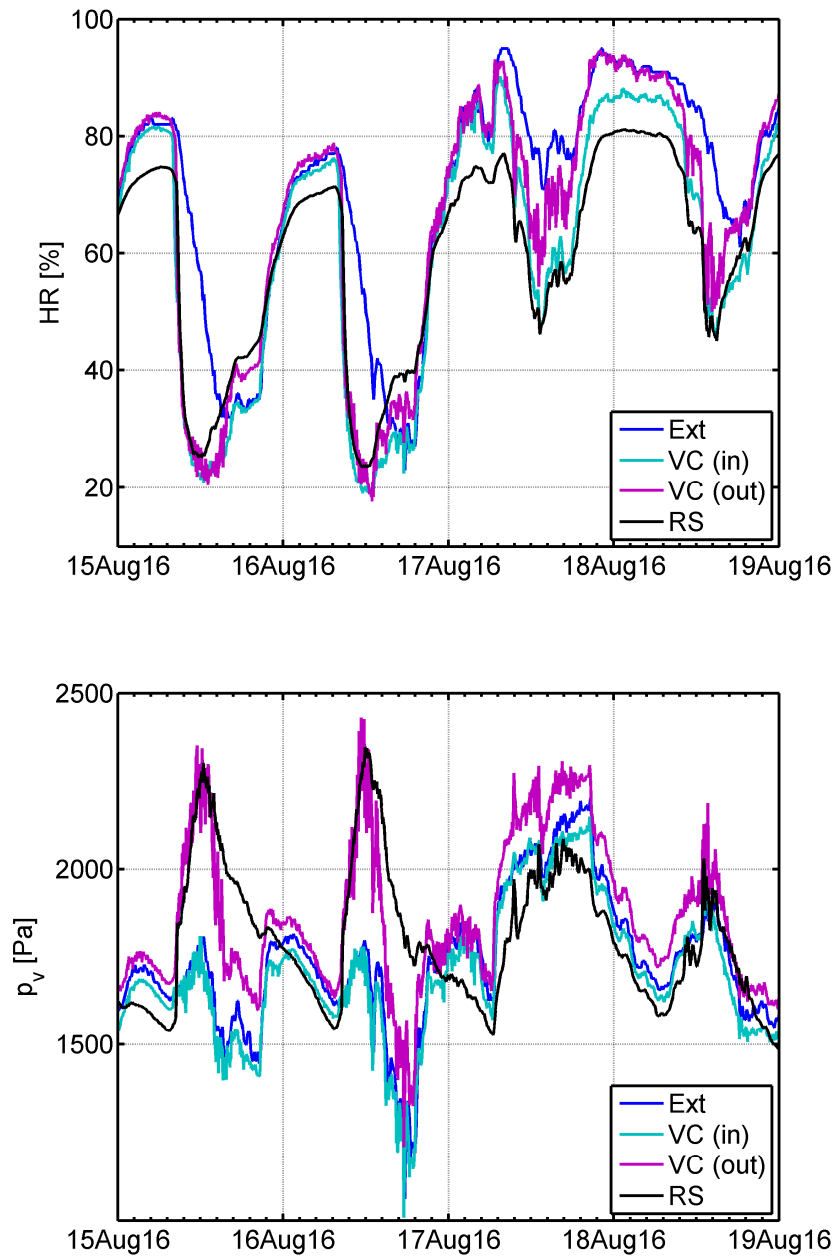


Figure 3: Measured and simulated temperatures, relative humidity and vapor pressure closed to the ventilated cavity during a summer period.

3.2 Focus on prefabricated ventilated façade element during winter

The hygrothermal of prefabricated ventilated façade element is analyzed from 23rd to 27th December 2016. During this period, the school is neither occupied, nor heated. Outdoor temperature and relative humidity show levels respectively between 6 and 12 °C and between 70 and 100 %. It should be noted that outdoor temperature remains almost constant and equal to 11 °C for 48 hours. Daily solar radiation levels are comprised between 100 and 370 W.m⁻². Wind is oriented in the SW-NE direction and its velocity does not exceed 2 m.s⁻¹.

Fig. 4 shows measured temperatures at different positions and heat flux at the interface between insulation and cavity. During a sunny day, air warms up in the ventilated cavity due to solar radiation and the deeper within the wall, the higher the decrement and the time shift of solar heat wave. Consequently, measured heat flux is reduced and even can be slightly positive. Nevertheless, temperature within the cavity seems not to be impacted by outdoor solicitations, but rather by the interior one since high thermal inertia of concrete may regulate this temperature. During cloudy days and nights, temperature measured in the ventilated cavity tends towards the exterior ones. Furthermore, we notice a slight decrease of temperatures within the wall and the cavity because of heat loss.

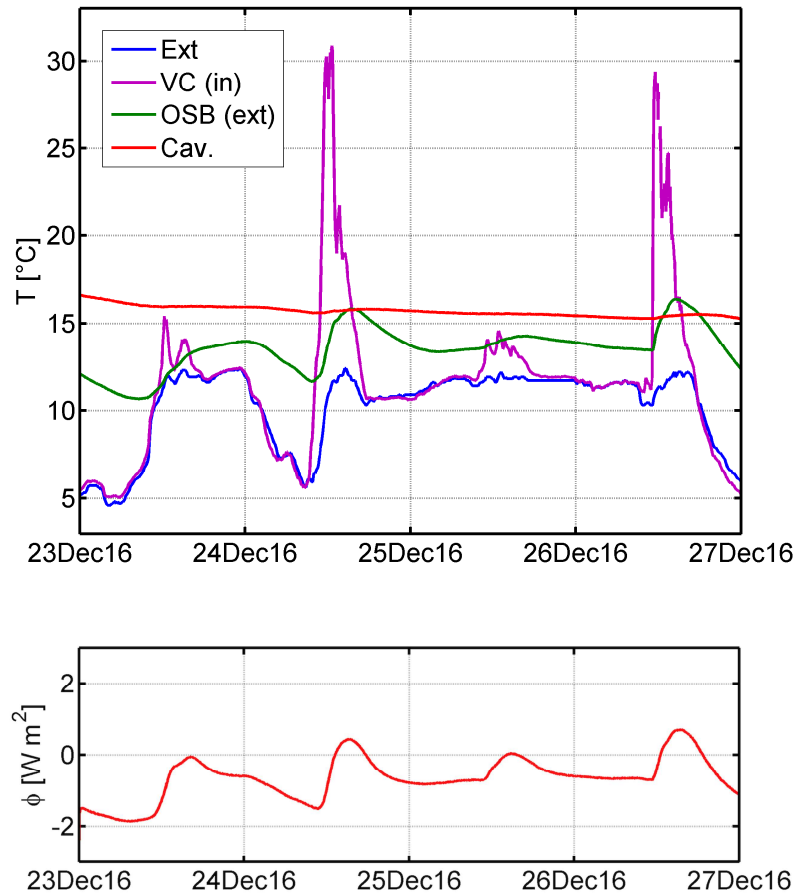


Figure 4: Comparison between measured and simulated temperatures and heat flux during a winter period.

Fig. 5 shows measured relative humidity and vapor pressure at different positions within the prefabricated ventilated façade element. In the presence of solar radiation, relative humidity decreases and vapor pressure increases behind the rainscreen membrane as in the ventilated cavity. This hygric load is dampened within the wall and delayed, but much slowly compared to thermal transfer. For instance, vapor pressure variations are dampened by 50 % and delayed by 4 h across the OSB board. However, we note sudden, quick (a mean of 1 hour and a half) and significant (about 10%) increase of relative humidity closed to OSB board, correlated with temperature variations. A possible explanation of these observations relies on

the fact that OSB board is an hygroscopic material for which sorption isotherm may depends on temperature: contrary to humid air, an increase of temperature leads to an increase of relative humidity assuming a constant moisture content [39]. The released moisture can be either transferred if temperature remains constant or re-condensed if temperature decreases again. Finally, this phenomenon induces a sudden increase of relative humidity above critical levels without changing the moisture content level within the materials [40]. Last, decrease of vapor pressure in the cavity is correlated to the one observed within the wall and not to the indoor one: this indicates the absence of any infiltration of indoor air into the cavity wall.

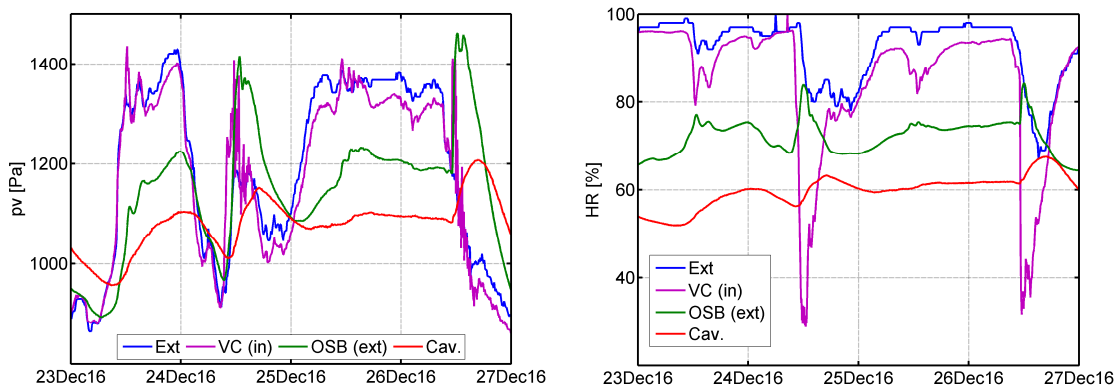


Figure 5: Comparison between measured and simulated relative humidity and vapor pressure during a winter period.

3.3 Annual behavior and moisture-related risks

Fig. 6 presents daily averaged temperature, relative humidity and vapor pressure measured outdoor and at different positions of the prefabricated element from June 2016 to July 2017.

The annual average effective outdoor temperature and relative humidity were 12 °C and 80 %, varying respectively between -2 °C and 28 °C and between 45 % and 95 %. Solar radiation may reach maximum values of 1250 W/m² (sunny summer days). Wind have a mean velocity of 2.5 m s⁻¹ and is mainly oriented in the SW-NE direction, indicating that the investigated element is not facing directly to the wind.

The annual hygrothermal behavior within the element is governed by external temperature and vapor pressure. In the ventilated cavity, temperature and relative humidity shows large variations due to solar radiation, while vapor pressure follows external variations. Even if there are large variations in the ventilated cavity, mean daily temperature and relative humidity variations are quite limited within the element. For instance, temperature in the closed cavity do not exceed 23 °C during summer and do not drop below 19 °C, excepted a decrease to 10 °C during Christmas holidays, when the building is not heated. In addition, relative humidity varies slightly around 50 %. Finally, the above results indicate that thermal and hygric insulation is well fulfilled by the prefabricated ventilated façade element and that the hygrothermal solicitation on the concrete wall is limited.

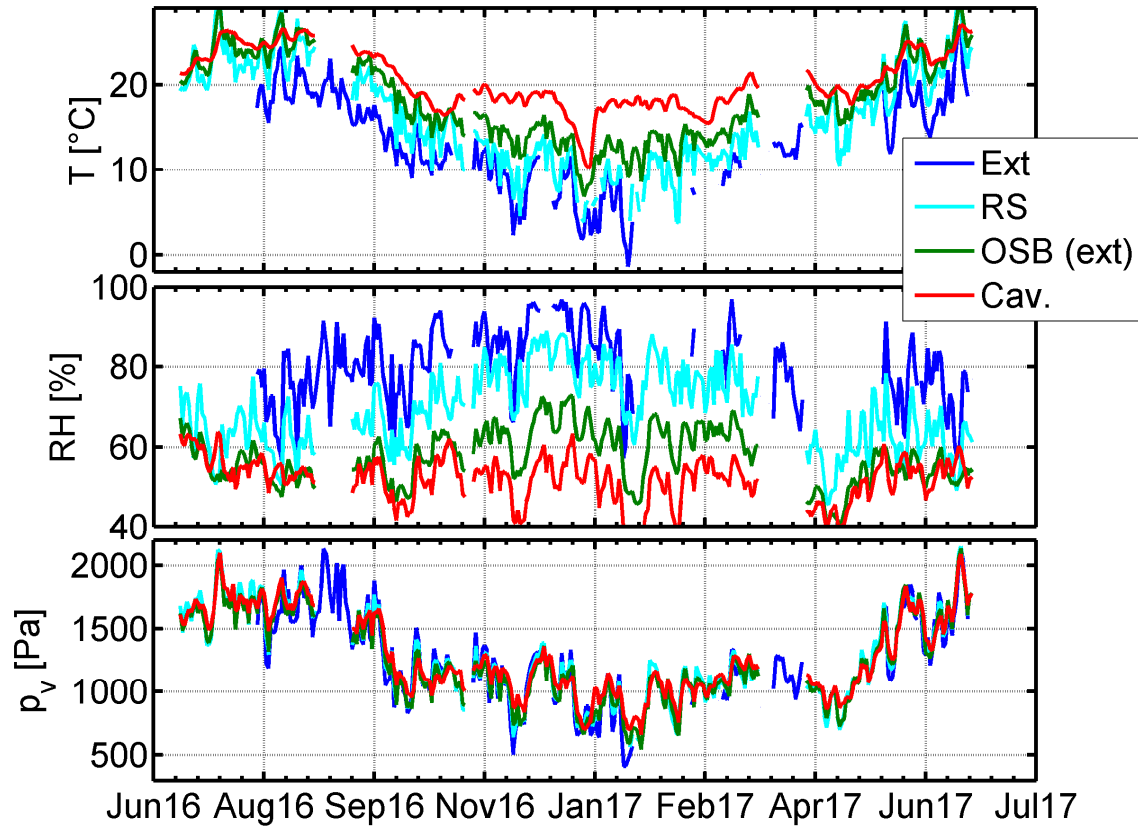


Figure 6: Daily averaged temperature, relative humidity and vapor pressure measured outdoor and at different points of the prefabricated ventilated façade element.

A similar behavior was also observed from June 2015 to July 2016. In order to compare the 2 first years of service, Fig. 7 evaluates the mean relative humidity measured at different positions. Here, the comparison is performed during winter, i.e. from December to February, since relative humidity show its highest level during this period (see Fig. 6). At each position, relative humidity, and thus moisture content, is lower the second year than the first one. Even if moisture was accumulated in the concrete wall before retrofit, it is slowly transferred outside without inducing any interstitial condensation in the element. The retrofit of this envelope is therefore safe.

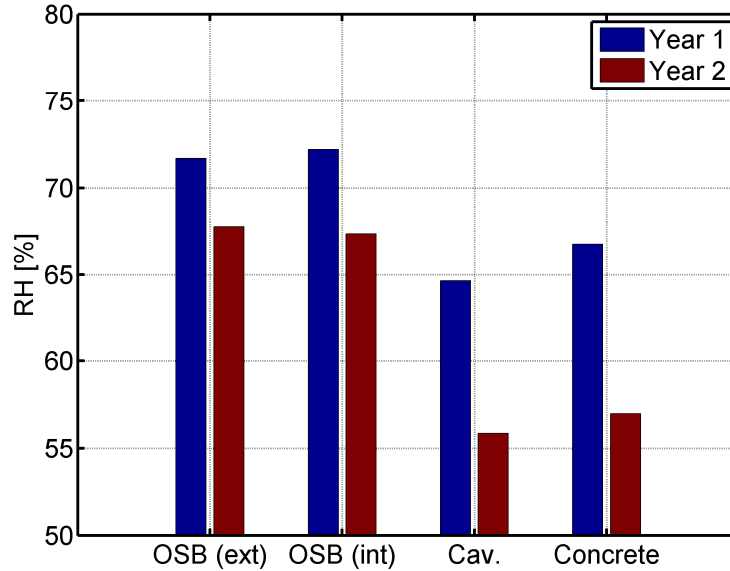


Fig. 7: Comparison of mean relative humidity evaluated during winter at different positions.

Risk of mold growth is broadly evaluated in Fig. 8 by comparing temperature and relative humidity measured for rainscreen membrane and OSB to Isopleth defining critical conditions for mold growth [41]. In addition, Table 2 gathers the frequency and the cumulated time (i.e. the time of wetness TOW) when critical conditions are exceeded. For the rainscreen membrane, risks of mold growth occur frequently and significantly. Critical relative humidity is exceeded mainly during night periods: this is due to a temperature decrease combined to the fact that moisture transfer is slower than thermal transfer. On the other hand, measured relative humidity may drop significantly below critical level during daytime because of solar radiation. For the OSB, the frequency and the magnitude of risks are significantly lower and are due to the relative humidity increase related to solar radiation (see Section 3.2). Nevertheless, as highlighted by Viitanen et al. [42] or by Johanson et al. [43], mold growth occurs after an incubation time that is much larger than the duration of the above-mentioned RH increase. Therefore, no moisture-related risks are expected around the OSB board.

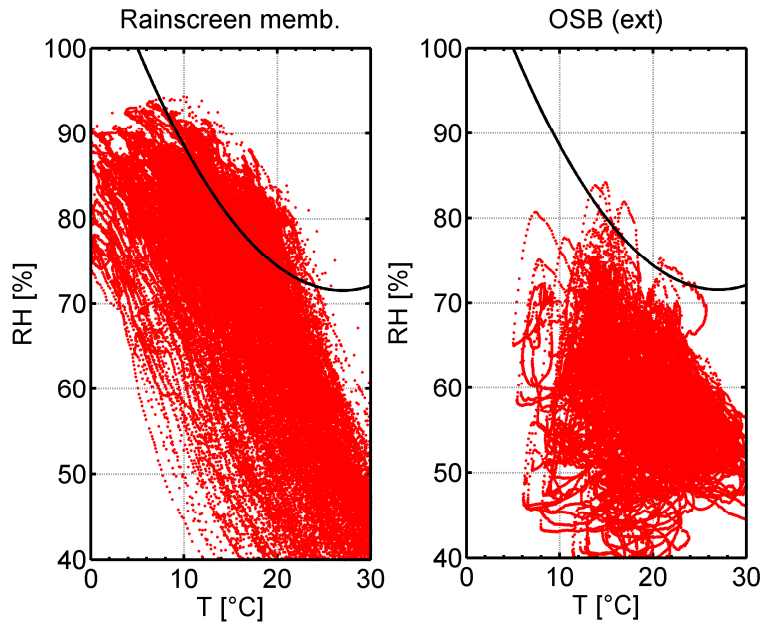


Figure 8: Mold growth risk from May 2016 to June 2017.

	Rainscreen membrane	OSB
Frequency of risk [-]	1613	73
TOW [h]	2080,3	28

Table 2: Frequency of mold growth risk and TOW from May 2016 to June 2017.

4 Building performance and indoor environmental quality after renovation

4.1 Thermal resistance of prefabricated ventilated façade element and building performance

In the view to evaluate the in-situ thermal resistance of the prefabricated ventilated façade element, a measurement period must be defined carefully accounting for the following considerations. Previous studies showed that the higher the mean temperature difference

between the internal and external surface, the faster and the more accurate convergence of the average methods [35, 44, 45]. In addition, it should be checked that thermal mass effects are negligible on average [33]. Last, change to the direction of heat flux should be avoided since the assumption of steady-state behavior is no more valid. Whereas this change is scarce for heavyweight walls, it may occur more frequently for lightweight walls. Therefore, the average method is typically only used during the winter heating season. The application of the dynamic method is broader, even if some difficulties were observed in the estimation for very fluctuating outdoor conditions [35].

Here, the analysis is performed from 15/01/2017 till 15/02/2017. The measurement data are plotted in Fig. 9: internal surface temperature ranges from 16.3 °C to 19.2 °C with an average of 17.5 °C, external surface temperature varies between -3.5 °C and 33.4 °C with an average value of 8.1 °C, and heat flux density fluctuates between -0.39 and -2.41 W/m² with a mean value of -1.21 W/m². Prior to this period, sunny and cloudy days alternates.

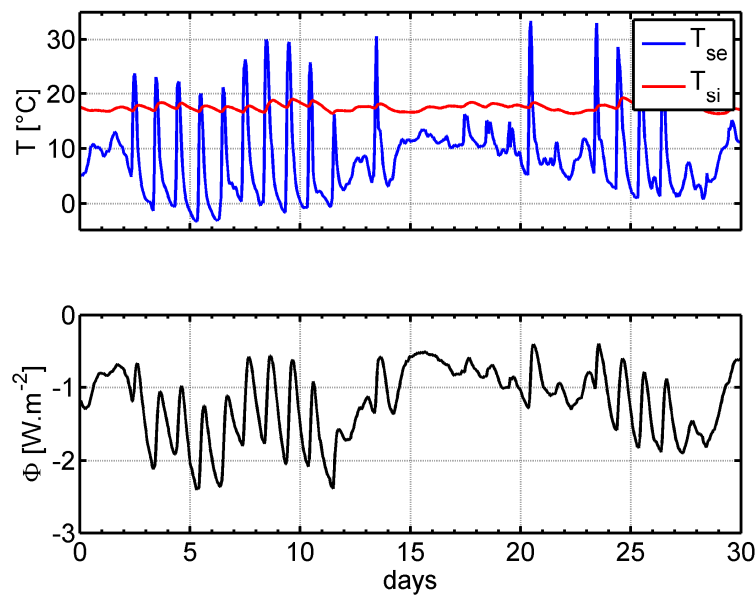


Figure 9: internal and external surface temperatures and heat flux density measured on the prefabricated ventilated façade element.

The thermal resistance estimates resulting from the different analysis methods are represented in Fig. 10 in function of the length of the data sets, i.e. the number of days included in the analyzed measurement data. First, let note that first results appear in day 3 since a 3 days minimum measuring period is required in the standard [33]. Second, we observe that all methods converge to a single value. The convergence criteria defined in the standard are satisfied after 10 days for the average methods and after 6 days for the dynamic method. Mean estimated thermal resistance and standard deviation are sum up in Table 3.

In addition, two uncertainty analysis are done: the first aims to quantify how the measurement uncertainty defined in Section 2.2 propagates to the estimated thermal resistance; the second concerns the influence of weather conditions prior to the analysis: either 5 consecutive sunny days or 5 consecutive cloudy days. The resulting uncertainties are also gathered in Table 3.

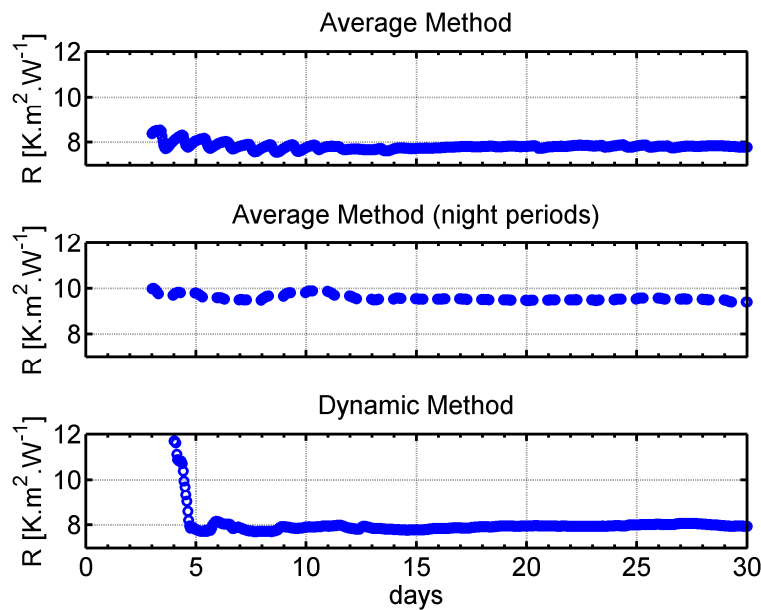


Figure 10: Comparison of the different analysis methods for estimation of thermal resistance.

Average and dynamic methods estimate similar thermal resistances that are up to 7 % higher than the theoretical one. A gap between calculated and measured thermal resistances of renovated building envelopes was also previously observed in the literature [7,46]. Experimental uncertainties may be one reason: uncertainty due to measurement errors is up to 5.3 %, whereas the influence of weather conditions prior to the analysis is less. Other reason may be due to the limit of modeling assumptions (influence of boundary conditions, of thermal bridge, of ventilated cavity, of moisture, etc.) [45]. Nevertheless, the differences remain in the overall uncertainty bounds defined in the standard.

On the other hand, thermal resistance evaluated with night data differs by 37 % compared to the theoretical one and is sensitive to experimental uncertainties. Even if the prefabricated element is lightweight, its dynamic behavior is not completely cancelled out. Therefore, the average method applied on night periods seems not to be suitable in this case.

	Mean value [K.m ² /W]	Standard deviation [K.m ² /W]	Uncertainty due to measurement uncertainty	Uncertainty due to weather conditions prior to the analysis
Average Method	7.815	0.034	Up to 5.3 %	Up to 1.3 %
Average Method (night periods)	9.503	0.037	Up to 4 %	Up to 5 %
Dynamic method	7.954	0.064	Up to 4.5 %	Up to 0.4 %

Table 3: mean estimated thermal resistance, standard deviation and uncertainties.

4.2 Indoor environmental quality

In educational buildings, hygrothermal comfort and indoor air quality (IAQ) interacts with students' health, attitude and performance [47]. Hygrothermal comfort within the

classroom is evaluated here through the measurement of temperature and relative humidity in the center of classroom. In terms of IAQ, CO₂ concentration is measured since it is the most common indicator and a critical parameter in school classrooms where occupant density is high. Here, CO₂ measurement could be done on teacher's desk only for two weeks during autumn 2016. Their variations are plotted in Fig. 11 for 2 representative days. In addition, Fig. 11 includes teaching periods defined when sound level exceeds a threshold value of 45 dB.

Indoor temperature and CO₂ concentration vary significantly in relation with classroom occupancy, while relative humidity fluctuations are rather limited. After student's arrival (in the morning or after lunch break), indoor temperature increases up to 2 °C due to internal heat gain by metabolism and electric devices (computers). Simultaneously, CO₂ level rises sharply and continues rising towards 1500 ppm due to classroom occupancy. In return, temperature and CO₂ concentration drops slightly during short breaks (morning of the first day) or after expected window opening (afternoon of the second day) and more significantly during longer breaks (lunch time of the 2 days). Last, we note that indoor CO₂ concentration tends toward outdoor concentration in less than 4h, whereas temperature decrease is much slower due to the thermal inertia of building envelope.

During unoccupied periods, CO₂ concentration measurement can be used to evaluate the air change rate ACH in the class room through a gas tracer analysis explained in the standards ISO 12569 [48]. Here, ACH of $1 \pm 0,15 \text{ vol.h}^{-1}$ is evaluated during lunch times. Such values are rather low to offer adequate indoor air quality during teaching periods. Indeed, during the 15 days of CO₂ concentration measurement campaign, the recommended limit for school classrooms of 1000 ppm [49] was always exceeded within 30 minutes from student's arrival and for 30 % of all teaching time. These observations agree with previous results of large study on indoor air quality in French school [50]. Nevertheless, measured CO₂

concentrations remain much lower than the ones measured in non-retrofitted schools, as highlighted in [21].

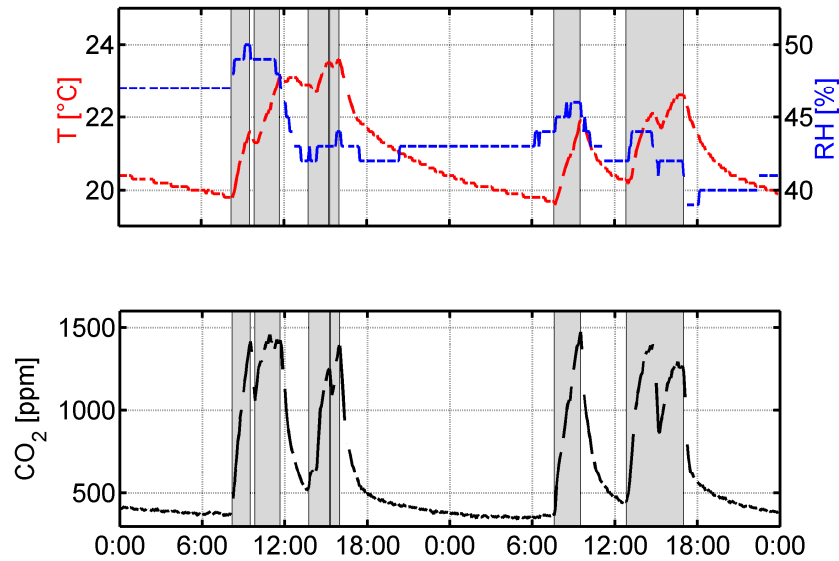


Figure 11: Temperature, relative humidity, CO₂ concentration and teaching period for two representative school days during autumn.

Fig. 12 gives an overview of hygrothermal comfort by comparing temperature and relative humidity measured during winter, mid-season or summer with Givoni bioclimatic chart. Here, only the data measured during the theoretical period of occupied classrooms (defined from 8:00 am to 6:00 pm, from Mondays to Fridays) were considered in the analysis. In addition, percent of discomfort are mentioned. Hygrothermal comfort is mostly acceptable except for the following cases: during winter, indoor temperatures lower than 19 °C were measured early in the morning, particularly after week-ends and holidays, since building heating is started at the same time than class period; from April to October, solar gain combined to other internal heat load may lead to significant overheating. This leads to particularly high theoretical percentage of discomfort during summer. In practice, the

classrooms are rarely occupied during this period particularly due to secondary school leaving examination in June.

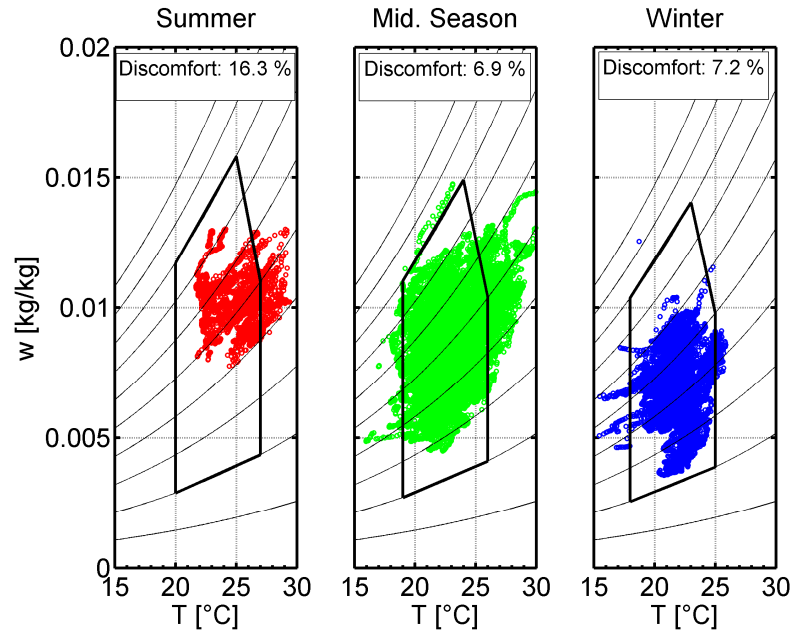


Figure 12: Hygrothermal comfort chart in the classroom during class period.

5 Conclusions

This work presented the two years monitoring of high school building renovated with prefabricated ventilated façade elements. The analysis focused on three points: the thermal performance of the envelope, the short-term moisture related durability and the indoor environmental quality (IEQ).

First, the thermal resistance of the opaque part of the envelope was estimated following the ISO 9869 standard. Its application leads to estimated values higher than the design one, particularly when only night periods were considered in the analysis.

Second, we noted that this retrofitting solution is suitable in terms of moisture-related risks: the envelope dried during the two years investigated and no interstitial condensation was observed in the envelope. Occasionally, critical conditions were exceeded close to hygroscopic material due to solar radiation. Nevertheless, the analysis revealed that moisture content is expected not to vary significantly and, thus, the risk of mold growth should be rather limited. This point should be however investigated more in detail.

Last, the investigation on IEQ underlined that hygrothermal comfort and indoor air quality are fulfilled most of the teaching time. However, unfavorable conditions were observed either early in the morning or after long occupation. Therefore, the comfort of the student and, thus, their health, attitude and performance can be improved by reconsidering and adjusting the operation of energy systems in a retrofitted building.

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