On the drying potential of cavity ventilation behind brick veneer cladding: a detailed field study

Michiel Vanpachtenbeke[a,b*], Jelle Langmans[a], Jan Van den Bulcke[b],
Joris Van Acker[b] , Staf Roels[a]
[a]*KU Leuven – University of Leuven, Department of Civil Engineering, Building Physics Section,*
Kasteelpark Arenberg 40 – bus 02477, BE-3001 Heverlee (Leuven), Belgium
[b]*UGent – Ghent University, Department of Forest and Water Management, Laboratory of Wood*
Technology – Woodlab, Coupure Links 653, BE-9000 Ghent, Belgium

**Corresponding author. Tel.: +32 16 37 63 16; fax: +32 16 32 19 80.*
E-mail address: michiel.vanpachtenbeke@kuleuven.be

Abstract

A qualitative and durable built environment requires an effective moisture control strategy. Moisture related problems can have an impact on the health of inhabitants or even jeopardize the building's structural integrity. Knowledge of the hygrothermal response and the drying potential of the current building enclosures under environmental loads is therefore crucial. In the current study detailed field experiments have been conducted in Belgium to study cavity ventilation behind brick veneer cladding. A simplified version of a South-West oriented cavity wall finished with brick veneer cladding has been analysed regarding the airflow pattern inside the cavity and the cavity's hygrothermal conditions. In this way, the drying potential of cavity ventilation behind brick veneer cladding can be assessed. For the dataset considered in the present article, the study showed that buoyancy induced cavity ventilation leads to a higher effective air change rate compared to cavity ventilation due to wind pressure. Furthermore, it was found that cavity ventilation is not of great help to dry out the whole outer leaf. However, it proved to lower the moisture levels inside the cavity, which – if e.g. the brick veneer is combined with a wooden loadbearing wall – might be important to avoid mould growth problems. The study also showed that climatic conditions play an important role in the drying potential: sunny but windless days have larger drying potential than cloudy but windy days.

***Keywords**: Cavity ventilation, brick veneer cladding, air change rate, hygrothermal conditions, drying potential*

1. Introduction

Moisture control is an essential aspect of a qualitative and durable built environment. Especially in case of timber frame constructions, increasingly popular in times of environmental awareness, it is appropriate to keep the moisture levels low. Moisture related problems can result in mould growth and/or wood decay in those moisture sensitive constructions, leading to an increased health risk for inhabitants or potential structurally unsound buildings. Therefore, it is important to investigate the hygrothermal response and the drying potential of the current building enclosures under environmental loads. Nowadays, a ventilated cavity wall, consisting of an outer leaf, a cavity and an inner leaf, is a widespread building system expected to keep the moisture level in the building's envelope to an

Nomenclature		*Greek*	
Roman		β	Vapour transfer coefficient (s/m)
A	Surface area (m^2)	ρ	Density (kg/m^3)
ACH	Air change rate (1/h)	*Subscripts*	
C	Air flow coefficient (ACH/Pa^n)	a	dry air
g	Mass flow (kg/s)	atm	atmospheric
g	Gravitational acceleration (m/s^2)	bottom	bottom
h	Height (m)	b	buoyancy
n	Flow exponent (-)	cav	cavity
P	Total pressure (Pa)	ext	exterior
ΔP	Pressure difference (Pa)	i	variable index
p	Partial pressure (Pa)	in	incoming flux
R	Specific gas constant (J/kg/K)	int	interior
RH	Relative Humidity (%)	out	outgoing flux
T	Temperature (K)	meas	measured
V	Volume (m^3)	middle	middle
Abbreviations		se	exterior surface
CFD	Computational Fluid Dynamics	top	top
HAM	Heat, Air and Moisture	tot	total
OHJ	Open Head Joint	v	vapour
SW	South-West	w	wind

acceptable level. Compared to monolithic walls, cavity walls are an improvement in terms of rain tightness. The outer leaf serves as a rain screen, while the cavity acts as a capillary break to avoid rain water penetration into the inner wall. To further improve the drying performance of cavity walls, cavity ventilation has been suggested. Cavity ventilation is created by providing openings at the top and/or bottom of the cladding, either over the full width or only at fixed distances from each other. The driving potential for cavity ventilation is a combination of wind and buoyancy force. The three main functions of cavity ventilation are [1,2]: 1) Convective drying of both the inside surface of the cladding and the outside surface of the inner leaf, 2) Facilitating vapour transport to the outside as a bypass of the claddings' vapour diffusion resistance, and 3) Avoiding/Reducing inward vapour transport (solar driven moisture transport). Although cavity ventilation is widely applied, past research resulted in contradictory findings regarding its benefits [3,4]. As stated by Karagiozis and Künzel [2], whether a ventilated cavity is beneficial or not depends on the composition and orientation of the wall, on the indoor and outdoor climate conditions and on the use of moisture sensitive building materials. Künzel et al. [4] also addressed the contradictory findings to a difference in the applied materials: traditional masonry cavity walls generally don’t need cavity ventilation [5,6], whereas timber framed walls do benefit from a ventilated cavity [7,8].

Timber frame constructions are most common in North-America, Scandinavia, Russia, Australia, New Zealand and Japan, whereas in Europe a masonry tradition prevails [6]. However, due to the increasing energy efficiency requirements, timber frame houses are becoming more and more popular across Europe. In order to preserve the buildings’ view though, masonry leafs are often still used as cladding system in countries with a masonry tradition. Masonry leafs have a high buffer capacity for wind driven rain but are poorly ventilated compared to sidings or rendered systems [9], which are typically used in countries with a timber frame tradition. As a consequence, a high relative humidity can be expected in the cavity. In combination with a moisture sensitive inner part of the wall, this could result in an increased risk of early failing by mould growth and wood rot.

The aim of the present paper is to study the cavity moisture conditions behind a brick veneer cladding and how they are influenced by cavity ventilation. In this way, the drying potential of cavity ventilation can be assessed. After a brief literature review, the main part of the paper describes a detailed study about the contribution of the different driving forces of cavity ventilation to the total cavity air change rate. Therefore, specific field experiments have been conducted at the Building Physics Section of KU Leuven, Belgium.

2. Literature review

In this section, a brief literature review is carried out. First, previous work by different researchers on the size and pattern of the airflow in the cavity is surveyed. Thereafter, on the basis of a simple example, the literature about the drying potential of cavity ventilation is discussed. Finally, hygrothermal conditions inside the cavity are discussed.

2.1. Air change rate behind brick veneer cladding

The magnitude and pattern of the air change rate behind rain screen claddings depend on two factors: 1) the driving forces on the one hand and 2) the configuration of the cladding and its vents on the other hand. The driving forces are a combination of thermal and moisture buoyancy and wind pressure. These forces cause a pressure differential along the height of the cavity, and consequently an airflow through the cavity will be created. In addition, the magnitude of this airflow also depends on the type of cladding, and how the vents are constructed in the cladding. In case of a brick veneer cladding, vents are created by leaving a certain number of head joints open.

The literature makes a distinction between a ventilated and vented cavity wall [2,8]: a ventilated cavity wall is provided with vent openings at the top and bottom of the cavity, whereas a vented wall only has vent openings at the bottom of the cavity. The former technique is used in order to stimulate air circulation while the latter is usually provided for drainage only. Consequently, the air exchange rate between exterior and cavity will be much higher in case of a ventilated wall compared to a vented wall. This means, strictly speaking, that a European brick cavity wall with open head joints at both top and bottom is considered as a ventilated wall. However, a measurement study of Langmans et al. [9] showed that the air change rate of a ventilated brick cavity wall is two orders of magnitude smaller than the air change rate of a ventilated wall with sidings. Therefore, regarding the size of the air exchange rate, a brick cavity wall with top and bottom open head joints corresponds more to the description of a vented wall.

In order to estimate the drying potential of cavity ventilation and the impact on the hygrothermal conditions inside the cavity, the size and pattern of the ventilation flow need to be studied. The focus of the present study is on brick veneer cladding. An extensive amount of studies have already been conducted on other types of rain screen claddings [e.g. 10–12], but will not be discussed here. When it comes to brick veneer claddings, Straube and Burnett [1] measured the flow characteristics of an open head joint (vent area 6.5 x 1.0 cm) with or without inserts. In this way, they experimentally derived the relationship between pressure difference over and airflow through masonry vents. Furthermore, Straube and Finch [8] conducted field measurements to determine the air change rate behind rain screen claddings. For brick veneer claddings with plastic bug screen inserts, they found an air change rate in the range of 0-10 air changes per hour (ACH). They also showed that solar radiation on the wall surface has an important influence on the cavity air change rate. In a study carried out by Sandin [13], smoke visualisation tests were performed in order to estimate the air change rate behind brick veneer cladding, with and without open head joints. For a cavity depth of 20 mm and one open head joint per 1.25 m, the author also found an air change rate approximately in the range of 0-10 ACH. This study also showed that the airflow direction in the cavity can highly change. Bassett and McNeil [14,15], however, reported higher values of ventilation rates behind brick veneer claddings based on tracer gas measurements. For a cavity depth of 40 mm and designed ventilation openings of 1200 mm² at the top and bottom of the cavity, they measured cavity air flows in a range of 0.5 to 2 L/sm, which conversed to air change rates corresponds to approximately 10-100 ACH. An extensive field study was conducted in Belgium by Langmans and Roels [16] in which they investigated the applicability of different measuring techniques to quantify cavity ventilation, including: tracer gas measurements, air velocity measurements with hot bead anemometry, pressure differential measurements along the height of the wall combined with a hydraulic network and a novel technique based on the measured temperatures and relative humidity. Measurements were performed on eight test walls with different orientation and cladding material. They concluded that the best technique to quantify the ventilation rate behind a brick veneer cladding was an indirect method based on the measured pressure differentials. The air velocities behind brick veneer cladding were too low to measure directly using anemometers. For walls cladded with sidings, on the other hand, the researchers concluded that both the indirect and the method with anemometers were applicable. Furthermore, they stated that the air was not always removed from the cavity due to the high frequency in direction changes. This corresponded to a reduction factor of the air change rate of 5-40%, in line with a study by Falk and Sandin (see further) [17]. In a second paper, Langmans et al. [9] focussed on the impact of three main parameters on the overall air change rate: the cladding system (brick veneer and sidings), the wall's orientation (South-West and North-East) and the area of ventilation openings. The study showed that cavity ventilation behind brick veneer cladding is two orders of magnitude lower than behind sidings, respectively 1-10 ACH and 100-1000 ACH. These numbers are in accordance with the findings of Straube and Finch [8] and Sandin [13]. Furthermore, the cavity ventilation rate on the leeward side was 25-40% lower than on the windward side. In addition, the wind driven pressure differential was found to be higher on the South-West façade (windward side) when it comes to downward flow, and higher on the North-East façade (leeward side) for upward flow.

For both the South-West and North-East oriented walls, an increased counter pressure was observed due to buoyancy because of solar radiation on the wall, however different in size and at a different moment during the day. The order of magnitude of the air pressure differential induced by thermal buoyancy and wind were found to be in the same order of magnitude. Finally, regarding the area of ventilation openings, they observed that two open head joints per meter instead of one doubled the air change rate in the cavity behind brick veneer. As was mentioned earlier by the studies of Sandin [13] and Langmans and Roels [16], the airflow direction in the cavity frequently changes. Although they did measurements with rendered walls and not with brick veneer cladding, Falk and Sandin [17] also recognized this phenomenon and concluded that the efficiency of the air exchange was significantly reduced hereby. They found that the effective ACH was reduced with 5 to 40% compared to the measured ACH based on anemometry. Furthermore, the authors concluded that there was no clear correlation between wind angle and the magnitude of wind-induced airflow in the cavity. Although Langmans et al. [9] found a difference of 25 to 40% in air change rate between wind- and leeward side of the building, these findings are in accordance because based on static pressure tests, the ventilation rate on the leeward side of the building would be much lower. Therefore, dynamic wind loads causes significant higher air change rates at the leeward side of the building.

2.2. Drying potential of cavity ventilation behind brick veneer cladding

In order to get an idea of the drying potential of cavity ventilation, first a simple calculation is performed for the experimental set-up used in this study. This example will be applied thereafter to discuss and put previous research findings about the drying potential of cavity ventilation in perspective. A wall with a height of 2.7 m and cavity of 4 cm is considered (see Figure 2). In order to estimate the maximum drying capacity of cavity ventilation, following assumptions are made, which were also considered and justified by Straube et al. [1]:

- The drying rate is controlled by the rate of ventilation flow and not the rate of evaporation from the brick veneer surface to the cavity air (saturated brick veneer).
- Moisture conditions are constant along the height of the cavity (single node model).

- The drying process has no influence on the temperature conditions inside the cavity.

To come to a maximum drying rate, the relative humidity of the air leaving the cavity is set to 100%. The temperature of the cavity air as well as the outside conditions are based on measured daily averaged values (see further). These values are listed in Table 1 for two different climatic conditions: a warm and sunny day and a cold and cloudy day. The following simple mass balance is used to calculate the drying rate of cavity ventilation in function of the air change rate per hour:

$$(1) \qquad g_v = \left(\frac{p_{v,cav}}{T_{cav}} - \frac{p_{v,ext}}{T_{ext}}\right) \cdot \frac{ACH \cdot V}{3600 \cdot R_v}$$

in which g_v (kg/s) is the vapour transported by cavity ventilation, V (m³) the cavity volume (2.7 x 0.04 x 1 m³), R_v the gas constant of water vapour (462 J/(kg K)), p_v (Pa) the partial vapour pressure of the cavity/exterior air, T (K) the temperature of the cavity/exterior air and ACH (1/h) the air change rate per hour.

The drying potential of cavity ventilation for the considered two days is compared to the drying of the brick veneer to the outside. As the two days are at the end of a period with a lot of rainfall, the brick veneer is considered wet. Therefore, the vapour pressure of the brick veneer surface is assumed to be equal to the saturated vapour pressure. As already stated by Langmans et al. [9], this is a reasonable assumption since the sorption isotherm of the applied brick only starts to peak at humidity levels higher than 99%, whereas it is quasi constant at lower humidity levels. The drying rate of the brick veneer's exterior surface is calculated by the following equation:

$$(2) \qquad g_v = A \cdot \beta \cdot (p_{v,se} - p_{v,ext})$$

in which g_v (kg/s) is the convective vapour flux from the brick veneer surface to the outside, A the brick veneer surface (2.7 x 1 m²), β the vapour transfer coefficient ($1.5 \cdot 10^{-7}$ s/m) and p_v (Pa) the partial vapour pressure of the brick veneer surface/exterior air.

In Figure 1, both drying rates are plotted against the number of cavity air changes per hour (ACH). From this simple example, it can be seen that drying to the outside dominates cavity ventilation drying, especially in the typical range of air change rates behind brick veneer cladding. Consequently, the contribution of cavity ventilation to the drying of the outer leaf is negligible. This was also concluded by Hens et al. [5] and Hens and Mohamed [6] based on field and laboratory measurements, and by Van Belleghem et al. [18] based on coupled CFD-HAM simulations. Also Sandin [19] came to this conclusion based on field measurements in the Swedish climate. He estimated the maximum daily drying out through the air gap at 0-0.1 kg/m². Compared to monthly driving rain of about 20-50 kg/m², he concluded that cavity ventilation was not sufficient to significantly affect the moisture content of the brick veneer wall.

Furthermore, Figure 1 shows that the drying potential of cavity ventilation is highly dependent on the climatic conditions. For climate 1 (the warm and sunny day), in the considered range of 0-1000 ACH, the outside drying rate is higher than the drying rate due to cavity ventilation. In contrast, for climate 2 (the cold and cloudy day), in case of high ventilation rates, cavity ventilation is as efficient as outside drying. Salonvarra et al. [3] reported that German field studies [20] indicated a higher drying rate at the cavity side than at the exterior side of the cladding, which is contradictory to the findings of Hens et al. [5] and Hens and Mohamed [6]. The simple example shows that this indeed might be the case in some situations, but very unlikely in case of a brick veneer cladding without measures to increase the ventilation rate. Moreover, overall, outside and cavity ventilation drying on a warm and sunny day is far more beneficial than on a cold and cloudy day.

Table 1: Conditions of the cavity, outside and brick veneer surface for two different climates

	Climate 1 (warm and sunny day)		**Climate 2 (cold and cloudy day)**	
	Temperature [°C]	RH [%]	Temperature [°C]	RH [%]
Cavity	21.5	100	6	100
Outside	19.0	81.0	7.7	83.2
Surface brick-outside	21.6	100	5.4	100

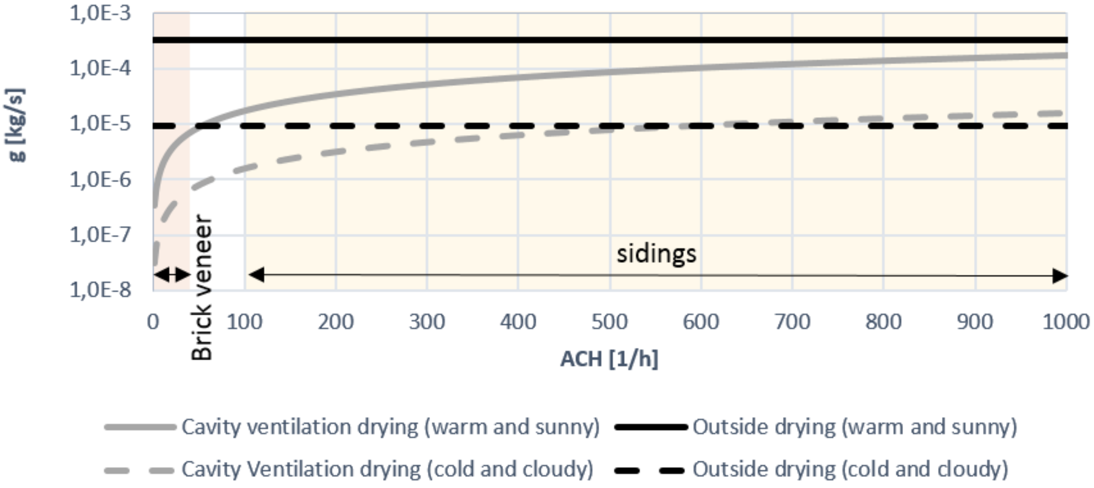

Figure 1: The drying potential of cavity ventilation as a function of the ventilation rate (ACH) compared to outside drying of a wet brick veneer cladding. (The drying potential is presented with logarithmic scale on the vertical axis)

Although cavity ventilation is not of great help to dry out the entire outer leaf, it can be a crucial process to dry out the cavity surface of the brick veneer as this layer determines the cavity conditions. Thus cavity ventilation may still have a significant influence on the cavity conditions.

Furthermore, various researchers stated that cavity ventilation certainly was beneficial or even important for the drying of the inside leaf [7,8,18]. Also in case of in- or outwards vapour driven moisture, cavity ventilation can play a major role [1,8]. According to Straube and Burnett [1], previously noted inward vapour driven problems could even be addressed to a lack of cavity ventilation.

2.3. Moisture/Hygrothermal conditions inside the cavity

Besides the drying potential of cavity ventilation, it’s also interesting to study the cavity conditions behind the brick veneer cladding. When dealing with a moisture sensitive inner part of the wall, these conditions will determine the moisture content of the different materials and will be decisive for the eventual development of mould growth or wood decay.

Many researchers studied the drying potential of cavity ventilation, but – to the authors’ knowledge – little research is done regarding the moisture conditions inside the cavity. Field measurements executed by Straube and Burnett [1] showed that the moisture content of the cavity air in a well vented brick veneer cavity wall was 14% higher than that of the exterior air. In contrast, in case of an unvented cavity wall, it increased to 44%. Furthermore, Straube et al. [7] conducted field experiments in which the relative humidity of the cavity was measured. They found that the humidity conditions behind vinyl sidings clad walls were lower than behind walls with a brick veneer cladding. The humidity level behind the brick veneer cladding was in 40 to 60% of the time above 90% RH. However, these field tests were conducted as a drying experiment, and at regular time intervals, the wall was artificially wetted to simulate accidental wetting.

Finally, Langmans et al. [9] measured the hygrothermal conditions in the cavity of a brick veneer cladded wall. They found that lower ventilation rates, as a consequence of less open head joints, resulted in higher humidity conditions behind the cladding. This was especially the case for those walls exposed to wind driven rain and solar radiation. In addition, they stated that the temperature behind the claddings was not influenced by the number of open head joints.

2.4. Aim of the present study

Calculation and evaluation of the air change rate behind brick veneer claddings has been studied intensively [8,9,16]. Also the efficiency of cavity ventilation has been discussed [16,17]. The first objective of this paper is to study in more detail the changing directions of the airflow in the cavity under influence of buoyancy and wind pressures. This will be done for different weather conditions and the impact on the air change rate and the airflow pattern will be discussed. Furthermore, the impact of the airflow on the hygrothermal conditions in the cavity will be studied. Most studies consider the cavity as a single zone, assuming the hygrothermal conditions constant for the entire cavity. In this study, the temperature and humidity profiles along the height of the cavity will be analysed. Finally, the drying out potential of cavity ventilation behind brick veneer cladding will be assessed. To do so, a specific full-scale set-up was built at the Building Physics section of KU Leuven. This will be explained in the next section.

3. Experimental set-up

Four simplified versions of a cavity wall finished with brick veneer cladding were constructed in the VLIET test building belonging to the Building Physics Section of KU Leuven (Belgium) [21,22]. The

VLIET building is a single storey test building which has the possibility to study building envelope parts exposed to real weather conditions and to evaluate their energy efficiency, hygric behaviour and durability. The building has a pitched roof and a flat roof module. In both modules, test walls can be installed at the South-West wall - in Belgium the dominant direction of winds, wind driven rains and solar irradiation - or the North-East wall of the building. All brick veneer cladded walls tested in this study were constructed in the flat roof part of the building (see Figure 2), two of them South-West oriented, the other two oriented North-Eastwards. The walls all had a 9 cm thick brick veneer cladding with a cavity depth of 4 cm and an inner structure consisting of a 12 cm thick extruded polysterene board. This polysterene board mimics the traditional insulation and inner structure and acts as a vapour tight and airtight break. The height of the walls was 2.7 m and the width between 0.8-0.9 m. The top and bottom of the brick veneer was provided with a grid system allowing for a variation in the number of open head joints. The dimensions of each open head joint were 3.5 x 1.5 x 9 cm^3. Since in this paper only the South-West oriented walls will be considered (see further), Table 2 summarizes the number of open head joints in the brick veneer cladding of these two walls for different measuring periods.

Table 2: Number of open head joints (OHJ) in the brick veneer cladding of the two South-West walls

	2 OHJ	**1 OHJ**	**no OHJ**
Wall 1 (South-West)	07/02/2014 – end	30/01/2014 – 06/02/2014	/
Wall 2 (South-West)	/	30/01/2014 – 06/03/2014	07/03/2014 - end

Furthermore, a grid of sensors measured the temperature, relative humidity and air pressure at specific locations in the walls, as shown in Figure 2. All sensors were placed in the middle of the walls' width. Temperatures were measured at each material surface within the wall and in the middle of the cavity at three different heights: 20 cm from the top, at middle height and 20 cm from the bottom. Also relative humidity sensors were placed in the middle of the cavity at the top, middle and bottom, and at the interior surface at middle height. The measurement interval of these sensors was 10 minutes. The thermocouples and relative humidity sensors were calibrated in advance with an optical dew-point transmitter [23] in order to increase the global sensor accuracy provided by the manufacturer. The thermocouples were calibrated at four different temperatures (1, 10, 20 and 25°C) and the relative humidity sensors at three humidity levels (30, 80, 99% RH). In Table 3, the resulting accuracy of the sensors are summarized [16]. The air change rate in the cavity will be determined with an indirect method based on the measured pressure differentials, as this was found to be the most reliable method in case of brick veneer cladding [16]. Each test wall was equipped with a pressure gauge (differential pressure transmitters [24]) to measure the pressure drop across the top and bottom open head joint. Pressure taps connected the top and bottom open head joints with the pressure gauge (see Figure 2). The measurement interval was 10 seconds.

In addition, the outside climatic conditions were recorded by the building's weather stations: one located above the test building and one in the nearby open field, both at 10 m above ground level. The measurements included temperature, relative humidity, solar radiation, rain, wind speed and wind direction, all on a 10-min basis.

Table 3: The different types of sensors used with corresponding accuracy and measuring range [16]

Sensor	Manufacturer	Type	Accuracy	Range
Thermocouple	Thermo Electric	Type TT	±0.1 °C	-20/60 °C
RH-sensor	Honeywell	HIH-4000/21	±2%	0/100%
Pressure gauge	Halstrup Walcher	P26 and P92	±0.3 Pa	±50 Pa

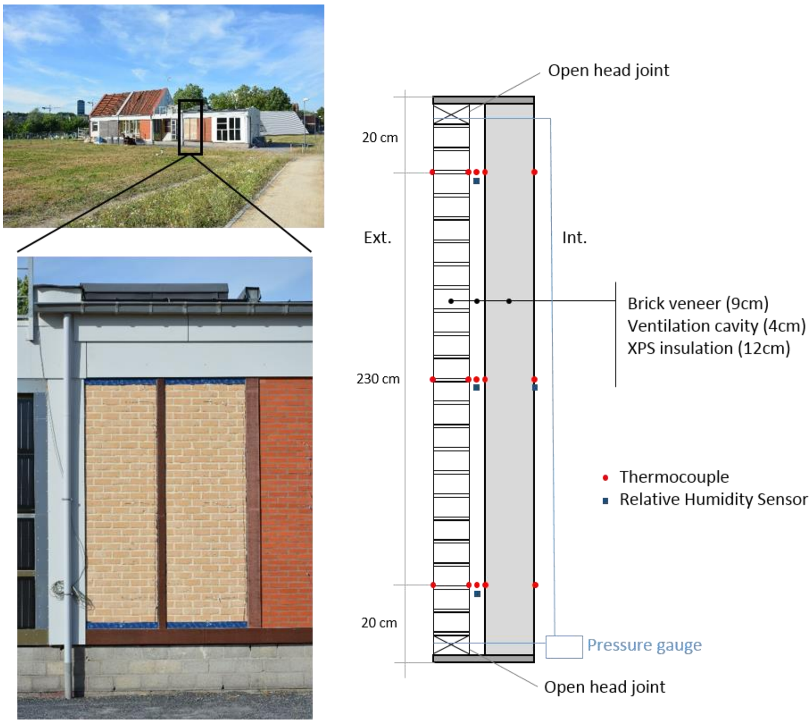

Figure 2: South-West wall of the VLIET building and measuring set-up (based on [16]*)*

4. In-depth analysis of buoyancy and wind driven cavity airflow

As mentioned before, the magnitude of the airflow behind rain screen claddings depends on two aspects: the configuration of the cladding and vents on the one hand and the driving forces on the other hand. The relation between the total air pressure differential across the cavity (ΔP) and the resulting air change rate per hour (ACH) is mostly fitted with a power law function:

(3) $$ACH = C\Delta P^n$$

Langmans and Roels [16] determined this relationship experimentally (adjusted pressurization test) and theoretically (hydraulic network methodology) for this specific configuration. For the latter, the friction loss of the open head joints was measured in the laboratory and the air permeability of the brickwork was adopted from Hens [25]. Exponent n equals 0.51 and coefficient C 7.4 and 14.8 ACH/Pa^n in case of one respectively two OHJ per meter both at the top and bottom of the cladding. The cladding consists of new brickwork, which typically has a higher airtightness compared to older brickwork.

The driving forces for cavity ventilation are wind pressure and thermal and moisture buoyancy. The wind-induced pressure differences across the height of the wall can be derived from Bernouilli’s equation [9], using the difference in local wind pressure coefficient at the top and bottom open head joint. However, various researchers have already pointed out that the local wind pressure coefficient in static and dynamic wind conditions can be very different [9,10,17]. Therefore, a pressure gauge was installed at each wall to record the wind pressure differential across the height of the wall. Due to the specific set-up of the pressure measurement system, the measured pressure differentials must be compensated for temperature differences between inside and outside: since the pressure gauge is located indoors at the floor level and the upper pressure tap runs indoors to the pressure gauge (see Figure 2), a static air pressure differential is created because of the difference in interior and exterior air temperature. The wind induced air pressure differential (ΔP_w) then becomes:

(4) $$\Delta P_w = \Delta P_{meas} - (\rho_{int} - \rho_{ext}) \cdot g \cdot h$$

in which ΔP_{meas} the measured air pressure differential, ρ (kg/m^3) the air density of the interior/exterior air, g the gravitational acceleration (9.81 m/s^2) and h the height of the cavity wall (2.7 m).

Furthermore, the induced pressure differentials due to thermal and moisture buoyancy (ΔP_{buoy}) are calculated based on the measured cavity and outdoor temperature and relative humidity:

(5) $$\Delta P_b = P_{atm} \cdot g \cdot h \cdot \left(\frac{1}{R_{cav} T_{cav}} - \frac{1}{R_{ext} T_{ext}}\right)$$

in which P_{atm} the atmospheric air pressure (101325 Pa), g the gravitational acceleration (9.81 m/s^2), h the height of the cavity wall (2.7 m), T (K) the cavity/exterior air temperature and R (J/(kg K)) the gas constant of the cavity/exterior air. Temperature and relative humidity values at intervals of 10 seconds are achieved by interpolation of the 10 min-data. Since the cavity/exterior air is a combination of dry air and water vapour, R will be a value between R_a=287 J/kgK and R_v=467 J/kgK:

(6) $$\rho_i = \rho_{a_i} + \rho_{v_i} \Rightarrow \frac{P_i}{R_i T_i} = \frac{p_{a_i}}{R_a T_{a_i}} + \frac{p_{v_i}}{R_v T_{v_i}} \xrightarrow{T_i = T_{a_i} = T_{v_i}} R_i = \frac{P_{atm}}{\frac{P_{atm} - p_{v_i}}{R_a} + \frac{p_{v_i}}{R_v}}$$

in which R_i (J/kgK) the gas constant of the cavity/exterior air and p_{v_i} (Pa) the partial vapour pressure of the cavity/exterior air. In equations (5) and (6), the overall cavity temperature and partial vapour pressure are assumed to be a surface weighted average of the different temperatures/vapour pressures along the height of the cavity:

(7) $$T_{cav} = 0.29 \cdot T_{top} + 0.42 \cdot T_{middle} + 0.29 \cdot T_{bottom}$$

(8) $$p_{v_{cav}} = 0.29 \cdot p_{v_{top}} + 0.42 \cdot p_{v_{middle}} + 0.29 \cdot p_{v_{bottom}}$$

The total pressure difference then becomes:

(9) $$\Delta P_{tot} = \Delta P_w + \Delta P_b$$

To convert these total pressure differences into a total air change rate ($\mathrm{ACH_{total}}$) in the cavity, equation (3) is used. The total air change rate can further be divided into a buoyancy and wind share. Since the air change rate is linked to the pressure differentials by an exponential relation, it is not correct to use equation (3) separately for the wind pressure and the thermal and moisture buoyancy. The sum of these two air change rates would not equal the total air change rate. Therefore, in accordance with [17], the more stable pressure difference due to buoyancy is always used as basis pressure difference:

(10) $\mathrm{ACH_b} = \mathrm{C} \cdot \Delta \mathrm{P_b^{0.51}}$

(11) $\mathrm{ACH_w} = \mathrm{ACH_{tot}} - \mathrm{ACH_b}$

Most researchers neglect the influence of moisture buoyancy. However, in a cavity of a brick veneer cladded wall, moisture levels may reach high values. Therefore, in this paper the error made by not taking into account moisture buoyancy will be discussed. The air change rate by only considering thermal buoyancy (thus with $\mathrm{R} = \mathrm{R_a} = \mathrm{constant}$) and by considering a combination of thermal and moisture buoyancy ($\mathrm{R} = \mathrm{variable}$) will be compared.

4.1. ACH behind brick veneer for a cloudy windy day, and a sunny windless day

In this paragraph, two characteristic days are chosen to analyse the impact of the different driving forces on cavity ventilation: a cloudy, windy day (27th February 2014) and a sunny, windless day (5th March 2014). Both considered days are situated at the end of a period with high amounts of rainfall (see Figure 8), which makes them ideal for the analysis of the drying potential of cavity ventilation. Since in Belgium South-West is the direction of prevailing wind driven rains and solar irradiation, the analysis will only be done for the South-West oriented walls.

The first two graphs in Figure 3 and Figure 4 give information about the climatic conditions on the cloudy windy day and sunny windless day respectively, whereas the third graph shows the total air change rate in the cavity of the South-West oriented wall with two open head joints. Positive values of ACH correspond to a downward airflow in the cavity, negative values to an upward airflow. The average wind velocity measured at a height of 10m at the test location in 2014 was 1.91 m/s, with a standard deviation of 1.19 m/s. Cavity ventilation on the cloudy, windy day (Figure 3) can reach relative high levels of ACH, up to 40 ACH. However, the direction of the airflow continuously changes. The hourly averaged values for the air change rate in the cavity (black line) are consequently much lower and range from -10 to +10 ACH. The total air change rate is divided into a buoyancy share and a wind share in the last two graphs of Figure 3. It can be noticed that the wind pressure is responsible for the fluctuating character of the air change rate in the cavity. In contrast, cavity ventilation due to buoyancy is flowing for a longer period of time in one direction: when the temperature outside is colder than inside the cavity, the airflow is upwards, and vice versa. Since wind pressures were not high all day, the total air change rate is dominated by a buoyancy induced flow until 12 p.m.. From 12 p.m. onwards, cavity ventilation is dominated by a wind induced airflow. Between 6 a.m. and 12 p.m., significant wind pressures are registered as well. However, since the wind direction during this period is not clearly South-West, the air change rate fluctuates around 0 ACH. In the second half of the day, a general downward flow is observed due to wind pressures, yet still highly fluctuating. Finally, in Figure 3, also a comparison is made between thermal and moisture buoyancy in the graph on the fourth row. Although most of the time negligible, (not) accounting for moisture buoyancy can lead to differences of up to 2 ACH.

On the sunny and windless day (Figure 4), the peaks in ACH are lower, up to 20 ACH. The hourly averaged ACH ranges approximately from -14 to +12 ACH, which is slightly more than on the cloudy, windy day. On the other hand, the air flows in one direction for a longer time period. Since there is little wind, the buoyancy induced airflow dominates the air change rate. Regarding thermal buoyancy, at night and in the morning, the outdoor air is colder than the cavity air and therefore the airflow in the cavity due to thermal buoyancy is upwards. Around noon, when the sun is rising and the outdoor temperature increases, the cavity air is colder than the outside air due to the brickwork’s capacity. Consequently, the cavity ventilation induced by thermal buoyancy is downwards at that moment. Furthermore, also in this situation, the moisture induced buoyancy is not always negligible. At moments when thermal buoyancy is/approaches zero, differences between the curve that takes into account moisture buoyancy and the curve that doesn’t can reach values up to 4 ACH. During the afternoon, the difference is approximately 1 ACH. The reason why this curve peaks at moments when thermal buoyancy reaches zero and is almost zero during the rest of the day, is because of the non-linear character of equation (10). Extra pressures due to moisture buoyancy will contribute less to the total air change rate if there is already a considerable pressure difference due to temperature differences than if the temperature differences are small. Only during the afternoon, when moisture levels are probably high inside the cavity, the difference reaches 1 ACH for a longer period in the presence of a significant thermal buoyancy induced airflow. This corresponds to 10% and more of the total air change rate during two to three hours. When considering only the pressure differences in equation (10) instead of the non-linear air change rate, not taking into account moisture buoyancy will be far less negligible. The error made by not taking into account moisture buoyancy will be 10% or more of the total pressure differential during an even more significant period of the day.

To summarise: buoyancy driven cavity ventilation ensures air flowing in one direction in the cavity for a longer time period, but does not reach high levels of ACH. While wind driven ventilation reaches high levels of ACH, but continuously changes in direction. As a result, since the velocity of the airflow in the cavity behind a brick veneer cladding is not very high, the cavity air volume will not always be entirely refreshed before the flow direction is changed. In contrast, it can be assumed that this issue is less critical for claddings with higher ventilation rates (e.g. sidings, rendered systems). In order to assess which driving force is more beneficial to ventilate the cavity, an effective air change rate is calculated in the next paragraph.

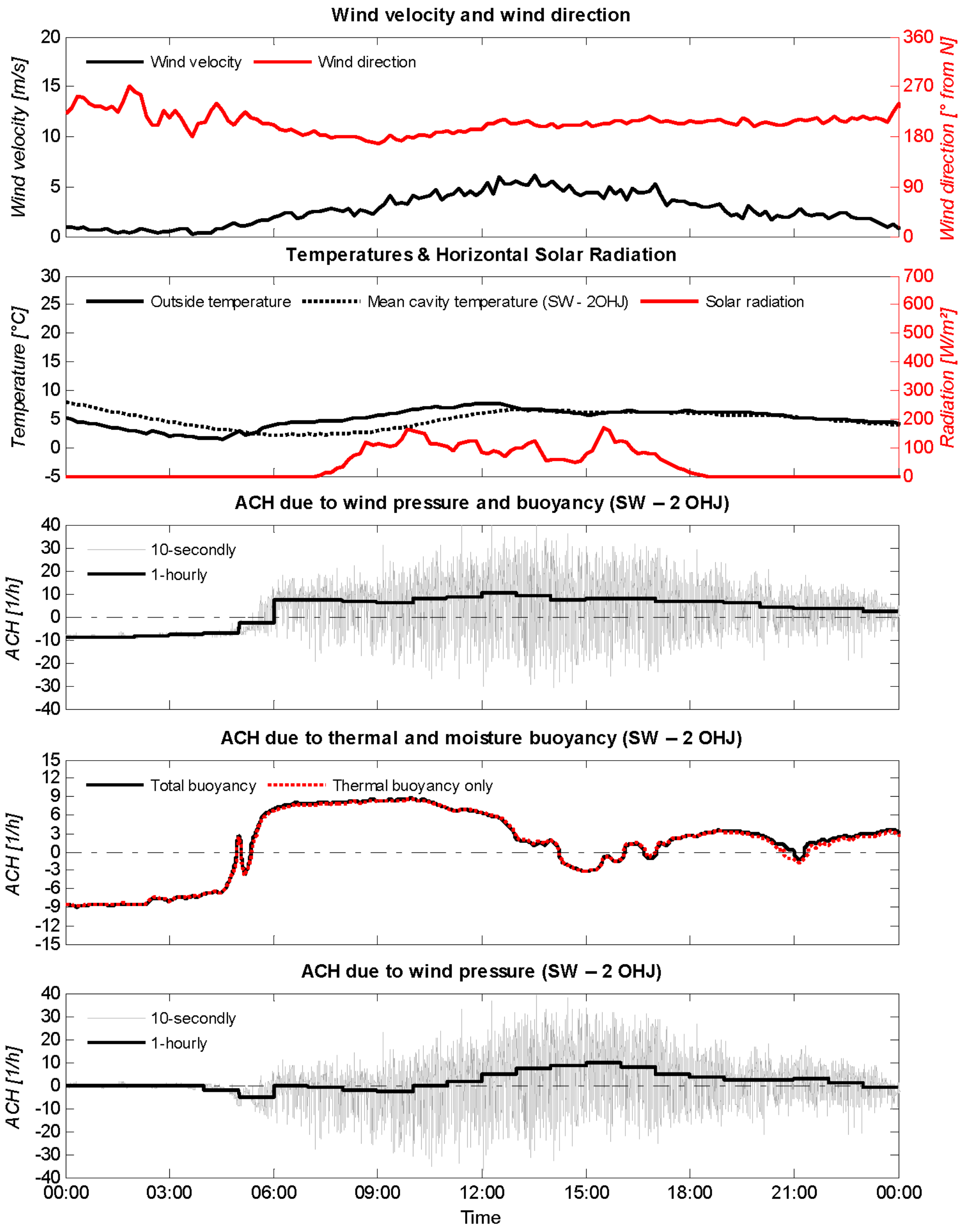

Figure 3: Cavity ventilation on a cloudy, windy day (February 27th 2014)

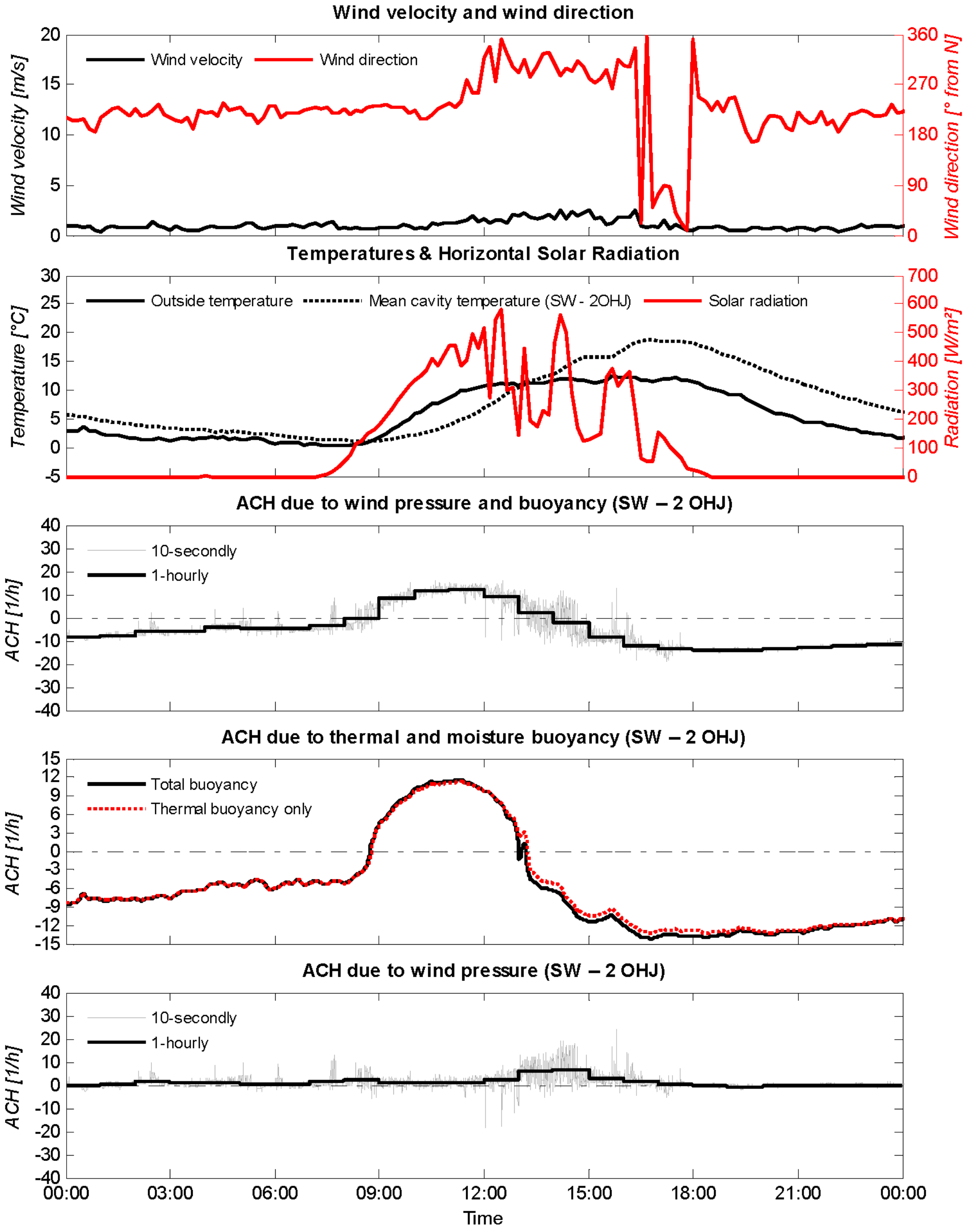

Figure 4: Cavity ventilation on a sunny, windless day (March 5th 2014)

4.2. Effective air change rate

In the previous paragraph, the air change rate per hour was calculated at discrete time intervals of 10 seconds. However, due to the fluctuating character of the ventilation flow through the cavity, no information is given on how many times the cavity air is actually refreshed. Therefore, in this paragraph, an effective air change rate per hour is calculated, averaged over one day.

In a first step, the number of times that the total cavity air volume is replaced with fresh outside air during the considered day is counted. This is achieved by converting the calculated ACH to a refreshed air volume for every time interval of 10 seconds. When the cumulated refreshed volume equals the total cavity volume, the cavity air volume is refreshed with outdoor air once. The first two rows of Table 4 show the results for the windy and sunny day. The second column contains the total air changes during one day, whereas the third and fourth column subdivide this number in air changes by upward respectively downward flow. Then, the total air changes are divided by 24 hours to obtain the effective ACH for that day, shown in column five. To compare this value with the findings of Falk and Sandin [17], who deduced a reduction factor between the measured air change rate, based on anemometry, and the actual air change rate, also the daily air change rate calculated from the absolute values of the pressure differences along the cavity wall together with the corresponding reduction factor are presented in the last two columns. The latter is calculated as the ratio of the difference of the absolute and effective ACH to the absolute ACH. The obtained values are approximately in line with the values reported by Falk and Sandin [17]: 5-40%. The reduction factor for the sunny and windless day is slightly lower: 3.6%.

Table 4: Calculation of the effective air change rate

Day	**Total air changes**	**Air changes by upward flow**	**Air changes by downward flow**	**Effective absolute daily ACH**	**Daily absolute ACH**	**Reduction factor (based on Falk & Sandin [17])**
Windy day	161	44 (27%)	117 (73%)	6.7	9.2	27.2%
Sunny day	206	160 (78%)	46 (22%)	8.6	8.9	3.6%
Windy average	172	1.3 (1%)	170.7 (99%)	7.2	11.2	35.6%
Sunny average	253.7	200.7 (79%)	53 (21%)	10.6	10.8	2.2%

On the cloudy and windy day, the majority of air changes is created by a downward airflow. This is caused by a dominant buoyancy driven airflow in the morning and mainly by the Southwestern wind in the afternoon. The air changes by upward flow, on the other hand, are mainly caused by buoyancy effects during the windless night. In contrast, on the sunny and windless day, air changes are predominantly created due to an upward airflow. In this case, both the upward and downward air changes are practically only caused by buoyancy effects. Furthermore, it can be noticed that in this case, buoyancy induced airflow will lead to more total air changes than wind induced airflow. Cavity ventilation induced by wind suffers from the counteracting effect resulting from the highly fluctuating character of the wind pressures. As a result, the effective air change rate on the cloudy, windy day is around 2 ACH lower than the air change rate on the sunny, windless day. This is also the reason why the reduction factor is much higher for the windy day compared to the sunny day. Based on the absolute pressure differentials along the cavity height, both driving forces are able to create around 9 air changes per hour in the cavity. However, since wind pressure alternates between positive and negative values on a short time basis, it takes longer to entirely refresh the cavity air volume.

This is illustrated by Figure 5, in which the fresh air front entering the cavity is presented. The incoming air front due to buoyancy (grey curve) occurs in a period between 18h and 19h on the sunny day, when wind effects are negligible and temperature differences relatively high. The incoming air front due to wind (black curve) occurs in a period between 13h and 14h on the windy day, when buoyancy effects are negligible and wind speeds high. In this way, it is possible to directly compare wind induced airflow and buoyancy induced airflow. Wind induced airflow reaches values up to 40 ACH in this period, buoyancy induced airflow up to 15 ACH. In case of buoyancy induced flow, the air flows continuously in one direction, upwards in the present case. Wind induced airflow often changes direction, but is mainly downwards. Although wind induced airflow can reach higher levels of air change rates, more time is needed to completely refresh the cavity volume once. The fluctuating character and the resulting counteracting effect of the wind pressures slow down the air change process.

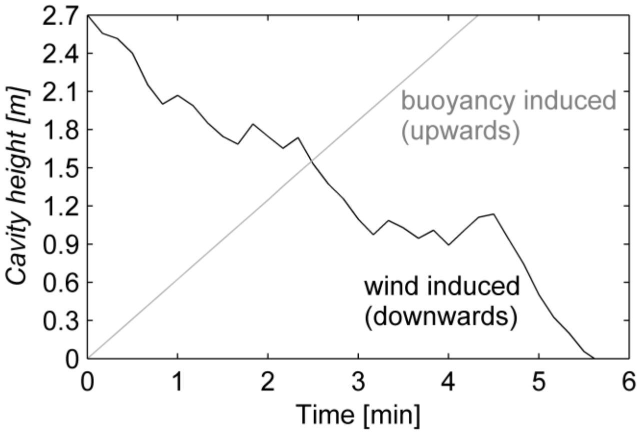

Figure 5: Fresh air front inside the cavity due to buoyancy (grey) and wind (black)

The parameters in Table 4 are also checked for three additional windy and cloudy days (February 8th, February 9th and February 13th of 2014) and three additional sunny and windless days (March 14th, April 1st and June 21st of 2014). Following criterion is used: a minimum wind velocity of 2.5 m/s and a maximum horizontal solar radiation of 50 W/m² on average for the windy and cloudy day, and a minimum horizontal solar radiation of 110 W/m² and a maximum wind velocity of 1.2 m/s on average for the sunny and windless day. The averaged values for both sets of three days are presented in the last two rows in Table 4. These averaged values confirm the conclusions resulting from the two particular days. However, it is remarkable that there are practically no upward air changes on the three windy days, while on the particular windy day (27th of February) upward air changes are 27% of total air changes. This is caused by a combination of a relatively sunny day preceding the 27th of February and a cold night on the 27th of February. Due to the thermal capacity of the brick veneer cladding, the cavity temperature during the windless night is higher than the outside temperature, resulting in an upward flow. In the period of the three other windy days, solar radiation is limited and generally doesn't increase cavity temperatures such that they are higher than the outside temperature. On the contrary, cavity temperatures are most of the time even lower than the outside temperature. And when the temperature in the cavity is (slightly) higher, the buoyancy effect is often overruled by a dominant wind pressure during that windy day. As a result, the downward airflow during the cloudy and windy days is caused by both buoyancy and wind pressure.

The results in Table 4 suggest that, based on air change rates, buoyancy driven cavity ventilation is far more beneficial for drying purposes than wind driven cavity ventilation. Moreover, an extra advantage of buoyancy driven cavity ventilation is that the air in the cavity is typically warmer than the outside air. In this way, the air in the cavity can evacuate more vapour to the outside. This will be further investigated in the next section.

5. Impact on moisture/hygrothermal conditions inside the cavity

In this section, first the hygrothermal cavity conditions will be studied. Therefore, the walls were equipped with sensors to measure temperature and relative humidity inside the cavity. In a second part, the drying potential of cavity ventilation will be discussed. The analysis is done based on the two characteristic days: the cloudy and windy day and the sunny and windless day. Again, only the South-West oriented walls will be considered.

5.1. Hygrothermal conditions inside cavity

In Figure 6 and Figure 7, the cavity conditions regarding temperature, relative humidity and vapour pressure along the height of the South-West wall with two open head joints are shown for respectively the cloudy and windy day and the sunny and windless day. The vapour pressure is derived from the measured temperature and relative humidity via the following formula [26]:

$$(12) \qquad \mathrm{p_v} = \mathrm{RH} \cdot \exp\left(65.8094 - \frac{7066.27}{\mathrm{T}} - 5.976 \cdot \log(\mathrm{T})\right) \qquad [\mathrm{Pa}]$$

In general, for both days, the cavity temperature follows a logical trend: cooling down at night and warming up during the day. A phase shift can be noticed between cavity and outside temperature due to the brickwork’s capacity. On the cloudy day, Figure 6 shows that the cavity and outside temperature are in the same range, mainly caused by the high thermal conductivity of the brickwork. During the windy part of the day, the top, middle and bottom cavity temperature hardly differ, and follow the outside temperature well. Since air has a low heat capacity compared to brick, the air will quickly take over the temperature of the brick, especially when dealing with low airflow velocity. Therefore, the temperature of the brickwork probably approximately equals the outdoor temperature. As a result, the brickwork hardly heats up or cools down the airflow. In contrast, on the sunny day (Figure 7), the cavity temperature is much higher than the outside temperature due to solar radiation on the wall. Notably, the top cavity temperature is always highest in case of a windless day. If the outside temperature is lower than the cavity temperature, the cavity ventilation direction is upwards due to thermal stack: cold outside air enters the cavity bottom, making it the coldest spot. Inversely, if the outside temperature is higher than the cavity temperature, the ventilation direction is downwards. This downstream causes the warm outside air to enter the top of the cavity, which becomes the warmest spot. This is illustrated in Figure 7. The temperature in the middle of the cavity is situated between the top and bottom temperature and is highly influenced by the thermal mass of the brick veneer. It is closer to the bottom temperature when warm outside air enters the cavity at the top while the brickwork is still cold. However, after a sunny afternoon, the cavity temperature at mid-height is closer to the top temperature when cold outside air enters the cavity at the bottom.

Regarding moisture conditions inside the cavity, there is a great difference between the two considered days as well. On the cloudy and windy day, Figure 6 shows that the relative humidity in the cavity generally stays higher than 80%. Only at noon, the top of the cavity starts to dry out a little bit due to cavity ventilation. Cavity vapour pressures are quite low all day and closely follow the outside vapour pressure. On the sunny and windless day, however, a great difference along the cavity height can be noticed in Figure 7. First, around 9 a.m., when cavity ventilation starts to go downwards due to thermal stack, the relative humidity of outside air is 100%. The more humid outside air enters the top of the cavity and causes locally a sudden increase in relative humidity and vapour pressure. At the bottom of the cavity, a smoother and delayed increase is observed. When around 10 a.m. the relative humidity of the outside air drastically decreases, the relative humidity at the top of the cavity decreases as well. In contrast, the relative humidity at the bottom is still increasing at that moment. It is due to the downward direction of cavity ventilation that the cavity top begins to dry out. In the afternoon, the wall is exposed to solar radiation and consequently the temperature in the cavity rises above the exterior air temperature. As a result, the cavity ventilation direction again is upwards. The solar radiation on the wet brick veneer causes high amounts of vapour to be transported to the cavity. As the ventilation rate behind brick veneer cladding is low, the vapour cannot be completely removed by cavity ventilation. As a result, cavity vapour pressures are becoming very high compared to the outdoor vapour pressure. Notwithstanding an increase in cavity temperature, the relative humidity at the top of the cavity stays high and increases even more. In contrast, due to the upward cavity ventilation, the wall is able to dry out at the bottom: the relative humidity strongly decreases, and reaches levels of 40%. After a certain time, also the relative humidity in the middle of the cavity starts to decrease. Only when there is little rainfall and enough sun during a certain period, the entire cavity can dry out. In this way, the relative humidity in the cavity will gradually decrease. This is shown in Figure 8 (black and grey curve). During periods with a lot of rainfall (January-February & May-June), the bricks will absorb more and more moisture and consequently the relative humidity inside the cavity increases, even after providing an extra open head joint at the top and bottom on February 7th (first vertical black line). When a period with less rainfall follows (March-May), both the top and bottom relative humidity decreases to lower humidity levels with maxima between 50% and 60%. In Figure 8 also the cavity relative humidity for a wall with the same build-up and orientation, but one open head joint before and no open head joints after March 7th is shown (red and light red curve). After the rainy period and after closing all the open head joints, the relative humidity in the cavity remains very high for a longer period of time compared to the ventilated wall. This illustrates again that cavity ventilation has an important influence on the cavity conditions.

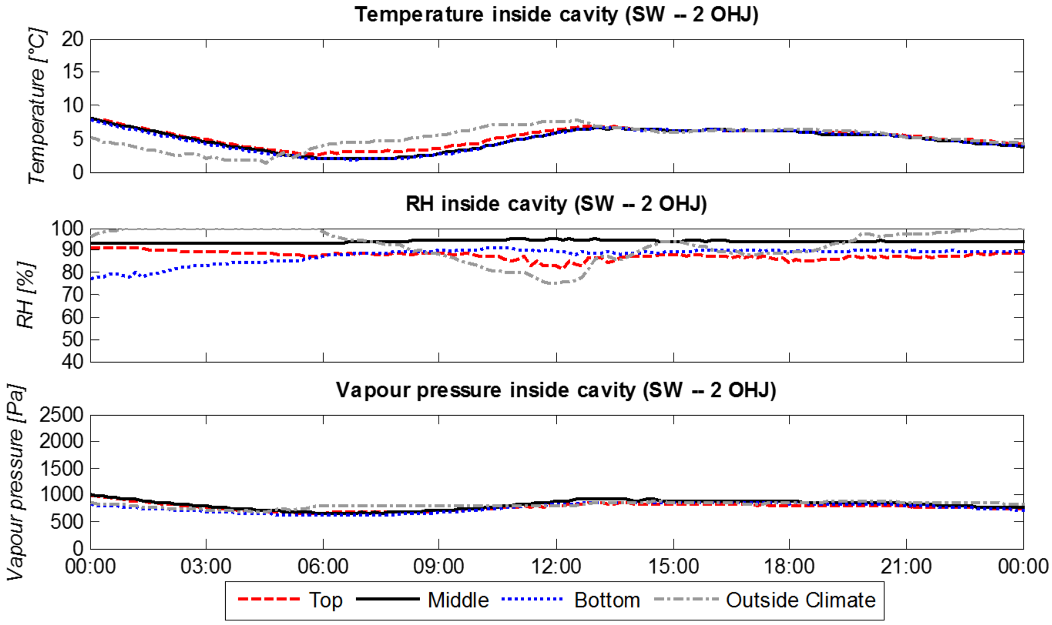

Figure 6: The temperature, relative humidity and the derived vapour pressure inside the cavity of the South-West wall with two OHJ on a cloudy and windy day (February 27th 2014)

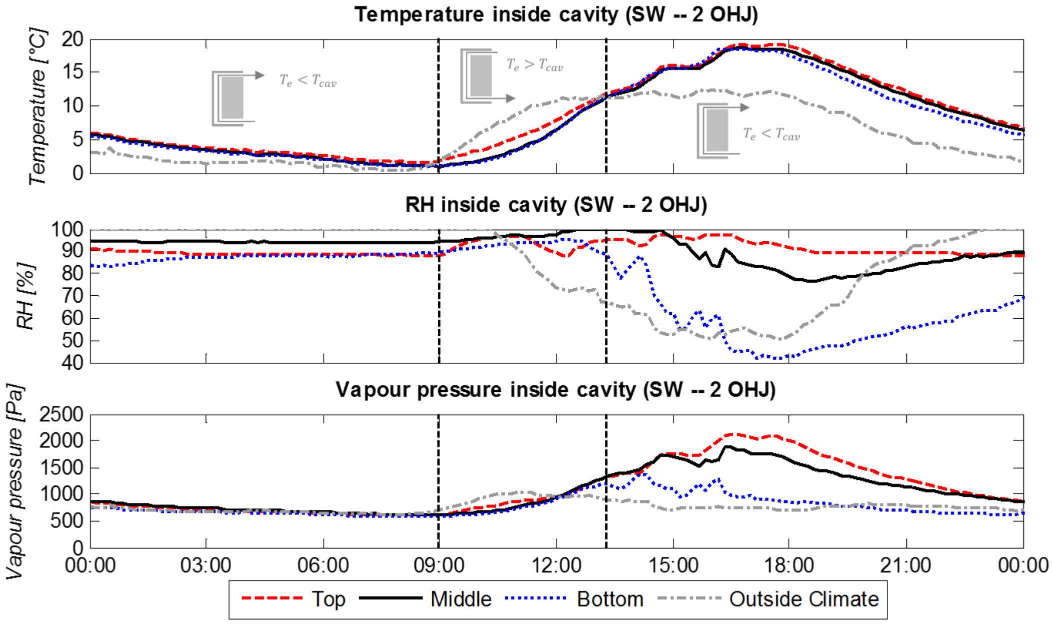

Figure 7: The temperature, relative humidity and the derived vapour pressure inside the cavity of the South-West wall with two OHJ on a sunny and windless day (March 5th 2014)

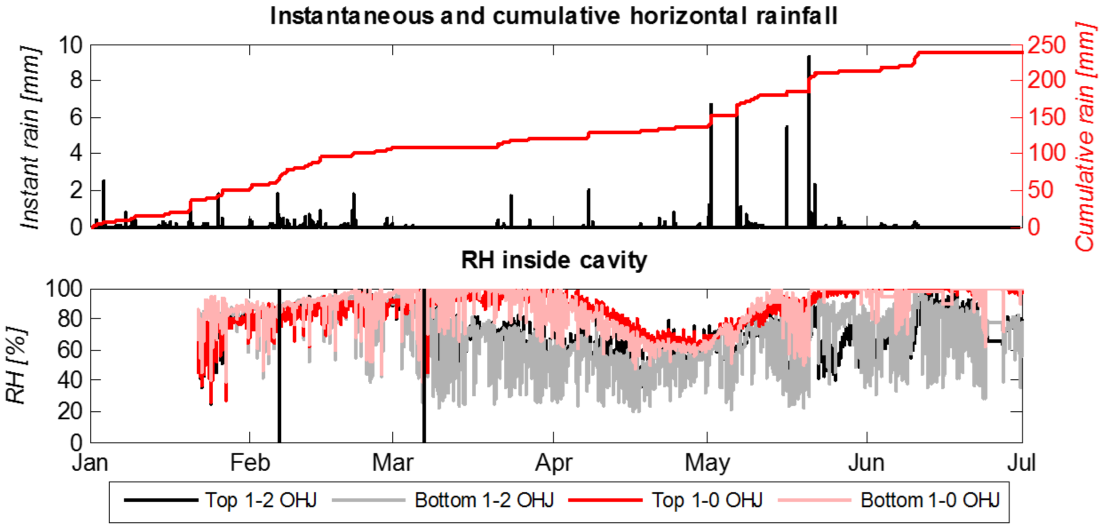

Figure 8: Relation between the amount of rainfall and the relative humidity inside the cavity of the South-West wall

5.2. Drying potential of cavity ventilation behind brick veneer cladding

In order to assess the drying potential of cavity ventilation, in this section the total net amount of vapour removed from the cavity is calculated. The influence of the climatic conditions are studied by considering the same two characteristic days as before.

Every 10 seconds, a drying rate is calculated via the following formula:

$$g_v = g_{v_{out}} - g_{v_{in}} = \left(\frac{p_{vcav}}{R_v \cdot T_{cav}} - \frac{p_{v,ext}}{R_v \cdot T_{ext}}\right) \cdot \frac{abs(ACH)}{3600} \cdot V_{cav} \quad (13)$$

in which g_v (kg/s) the vapour flux, $p_{v,cav}$ (Pa) the vapour pressure of the air leaving the cavity, T_{cav} (K) the temperature of the air leaving the cavity, R_v the gas constant of water vapour (462 J/(kg K)), ACH (1/h) the air change rate per hour during the 10 seconds time interval, V_{cav} the cavity volume (2.7 x 1 x 0.04 m³), $p_{v,ext}$ (Pa) the vapour pressure of the outdoor air and T_{ext} (K) the temperature of the outdoor air. Temperature and relative humidity values at intervals of 10 seconds are achieved by interpolation of the 10 min-data. If the air change rate is upwards, the cavity conditions measured by the top sensors are used in equation (13) to determine the amount of moisture that is transported to the outside, and vice versa.

In Figure 9, the cumulative drying of the wall is presented for both the cloudy and windy day and the sunny and windless day. On the cloudy and windy day, the total net amount of vapour removed by cavity ventilation is approximately zero. Moreover, the amount of moisture that entered the cavity by cavity ventilation was slightly higher than the amount of moisture removed from the cavity. It can be concluded that in these weather conditions, cavity ventilation is not beneficial for drying out purposes of the wall, as was already presumed in paragraph 2.2. On the contrary, cavity ventilation can even increase the structure’s moisture content, which was also mentioned by Gudum [10]. Also the exterior surface was not able to dry out. On the sunny and windless day, clearly more moisture is removed from the cavity compared to the moisture that has entered the cavity. The difference is approximately 0.07 kg. This difference is only created in the afternoon, when temperatures inside the cavity were high compared to the outside temperatures. A higher cavity temperature results in a higher saturated vapour pressure. In this way, the air in the cavity can evacuate more vapour to the outside. Compared to the drying of the exterior surface, however, this is two orders of magnitude less. It has to be stressed that the calculation of the exterior surface drying was based on the assumption of a surface relative humidity of 100%. Realistic values for the capillary saturation moisture content of bricks are approximately between 140 kg/m³ and 300 kg/m³ [27]. For this case, it means that the vapour removed by cavity ventilation that day accounts for less than 1% of the total moisture content of a capillary saturated brickwork. Thus it can be concluded that cavity ventilation is not beneficial to dry out the entire outer leaf. However, drying of the inside surface of the brick veneer cladding by cavity ventilation still is important to lower the moisture levels inside the cavity, as was shown in the previous section. This might be essential to avoid mould growth problems in case the brick veneer is combined with a wooden loadbearing wall.

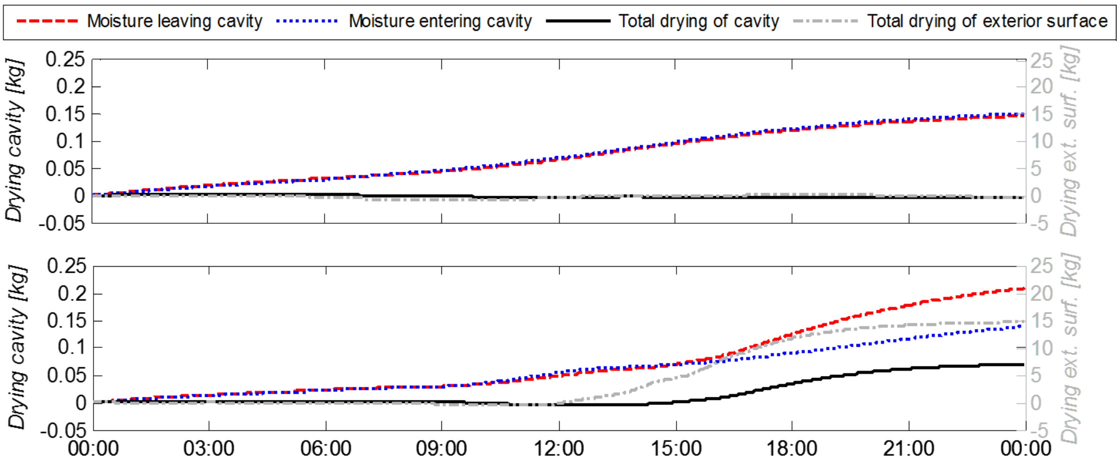

Figure 9: Cumulative drying of the cavity (left axis) and the exterior surface (right axis) for the cloudy and windy day (top) and the sunny and windless day (bottom)

6. Discussion and conclusion

The present article studied cavity ventilation behind brick veneer cladding. Four test walls finished with brick veneer cladding were constructed in the outdoor test building of the Building Physics Section of KU Leuven (Belgium). The focus of the present article is on the South-West oriented walls which correspond to the highest wind-driven rain and solar loads. The study showed that the wind induced air change rates can reach high peak values, but both its absolute values and its flow direction are highly fluctuating. In contrast, buoyancy induced air change rates are lower, but more stable. The research results prove that the latter, thermal buoyancy-induced cavity ventilation, leads to the highest effective air change rate. Furthermore the study shows that moisture-induced buoyancy forces in the cavity are most of the time negligible. Only at specific circumstances - when thermal buoyancy effects are small, or when cavity vapour pressures are very high - moisture buoyancy can contribute to the total air change rate in the cavity for more than 10% during multiple hours. However, when cavity vapour pressure is high, drying is more important and consequently a higher contribution of moisture buoyancy to the total air change rate is beneficial.

On a cloudy and windy day, the temperature and relative humidity distribution along the height of the cavity is very small. Although the cavity's vapour pressures are relatively low for these circumstances, the relative humidity inside the cavity is typically high at low outdoor temperatures. Under the circumstances mentioned, the cavity temperatures are in the same range as the outdoor temperature. On a sunny and windless day, however, cavity temperatures can rise much higher than the outdoor temperature. Since the heat capacity of air is low, the temperatures inside the cavity are mainly affected by the brick veneer cladding. In addition, the thermal stack effect makes the cavity top always warmer for these conditions, irrespective of the airflow direction inside the cavity. When a wet brick veneer cladding is exposed to solar radiation, cavity ventilation greatly affects the moisture conditions inside the cavity. The wall is able to dry out locally under these conditions as drier air is entering the cavity. Only when there is little rainfall and enough sun during a longer period, the entire cavity will show decreasing humidity levels. In case of an unventilated cavity wall, this process takes much longer.

From this study it is clear that cavity ventilation drying on a cloudy and windy day is not beneficial. The results illustrate that the highest drying potential is obtained by solar driven cavity ventilation. The air in the cavity is typically warmer than the outside air and thus is able to evacuate more vapour to the outside. But overall, the moisture removed by cavity ventilation is negligible compared to the moisture content of the brick. Drying out at the outside surface is far more important in order to dry out the whole outer leaf, confirming the numerical simulations of Van Belleghem et al. [18]. However, drying of the inside surface of the brick veneer cladding by cavity ventilation is important to lower the moisture levels inside the cavity. If e.g. the brick veneer is combined with a wooden loadbearing wall, this might be essential to avoid mould growth problems.

Finally, future work could consider some further aspects to contribute to this research. The studied cavity wall has a simplified inner leaf consisting of a polystyrene panel, which is a highly thermally insulating and vapour tight layer. In this way, the effect and drying potential of cavity ventilation behind brick veneer cladding can be isolated. However, in reality, more vapour open and hygroscopic materials are commonly used as inner leaf. It would be interesting to study how this affects the hygrothermal behaviour of the building component. Similarly, the influence on the cavity temperature by the outward heat flux in case of an uninsulated cavity wall can be considered. Furthermore, the height of the cavity will strongly affect the calculation of the effective air change rate. And in the current study, the airflow inside the cavity is considered as one-dimensional, yet in reality air movements in three dimensions may be expected in the cavity. In addition, it must be stated that only air flowing across the height of a perfectly compartmentalized single wall assembly is considered. Air flows due to a possible interconnection between windward and leeward part of the building envelope have not been accounted for. At last, care has to be taken with the use of the unit '(effective) air changes per hour (ACH)'. Moisture removal from the cavity is caused by a flow rate per unit area through the vents. As a consequence, a wall with a different cavity depth may have a different (effective) air change rate, but a similar moisture removal rate.

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