Ventilation Effectiveness of Alternating Façade-integrated Ventilation Devices in a Dwelling

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Abstract

Ventilation systems are designed based on the air flow volume required to ventilate the room, the same applies to façade-integrated ventilation devices operating in alternating mode, also referred to as push-pull devices. Those rather small devices represent a simple way to provide fresh air and air-to-air heat recovery for residential dwellings. The present research aims to analyse the ventilation effectiveness of push-pull devices experimentally. Hence, a tracer gas analysis is performed in a residential building. The experimental object is a storey of a residential building consisting of four rooms each equipped with one façade-integrated ventilation device. Three of these operate in alternating mode performing a regenerative heat recovery, while the fourth is an exhaust only device. The measurements are carried out during summer and winter to investigate the influence of the varying climate boundary conditions. In order to evaluate the ventilation effectiveness, the age of air is determined based on the concentration decay method applying CO_2 *as a tracer gas. For the evaluation the air exchange efficiency* ε^a *in the breathing zone at 1.7 m height was applied. As a conclusion it was found that push-pull devices can provide a mixed ventilation characteristic although there are trends for a vulnerability to pressure and temperature differences between the in- and outdoor surroundings, which lead to ventilation short circuits.*

INTRODUCTION

Construction tasks in Europe are increasingly focusing on the maintenance and refurbishment of existing buildings. Due to improved airtightness and energy efficiency regulations, the installation of mechanical ventilation systems is becoming a more common practice in residential buildings. Facade-integrated ventilation units are both interesting for new buildings as well as for renovation, since no ductwork is required, and their installation is simple. Within the scope of the present work, experimental investigations are carried out on their performance regarding their main objective: ventilation efficiency (Sandberg 1981). For this purpose, a proof of the measurement concept was carried out before in a climate chamber test facility (Auerswald et al. 2020). This small study led to the conclusion that façade-integrated regenerative and decentralised **v**entilation devices (push-pull devices) operating in alternating mode do not necessarily provide a mixing ventilation pattern. Furthermore, another hypothesis came up during this previous laboratory investigation: "Push-Pull device systems can lead to a stratification caused by the temperature differences. Also ventilation short cuts where indicated due to apperatures positioned to close to each other.

In contrast to this, a recent study concludes that building zones equipped with push-pull devices do always provide a mixing ventilation characteristic without significant short-circuiting (FGK 2019). This is a noticeable statement since their results include values $\varepsilon^a < 0.5$. To neglect even minor differences in the ventilation efficiency is problematic, since in case of a mechanical ventilation systems air change rates correspond to an exergy consumption.

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For a simplified approximation the relation of two air change rates is connected to the ratio of the correspond- ing power supply by a power of three due to the fan laws. Furthermore, it is important to not only exchange air, but ensure air is exchanged where it is most needed, which is mainly the breathing zone of occupants in order to meet the WHO-guidelines for healthy indoor air (WHO 2006, 2009).

Further studies have been summarised in Auerswald et al. 2020 and do not show that push-pull devices always meet the flat assumption of providing mixing ventilation. There is rather a need to find out under which circumstances push-pull devices can provide such a ventilation characteristic. Possible effects found worth to investigate are the impact of climate conditions, pressure difference relative to the building environment as well as varying ventilation levels (Merzkirch 2015; FGK 2019; Auerswald et al. 2020).

To find improvement potential for push-pull devices is of importance as they will play an increasingly important role in residential buildings, especially as a retrofit element (van Holsteijn et al. 2020).

VENTILATION EFFECTIVENESS

The primary objective of ventilation is to provide fresh air, while simultaneously removing pollutant loads. The indicators for assessing ventilation effectiveness can be divided into the two categories contaminant removal indicators and air renewal indicators. The present work focuses on air renewal indicators.

Age of air

The age of air τ introduced by Sandberg (1981) is a common measure to analyse ventilation efficiency. It defines the time that has elapsed between the entry of fresh air into a building zone until its reaching of a specific point i in that same zone. For an ideal piston flow the local age of air $\bar{\alpha}_i$ (in h) may be interpreted as the time it takes an imaginary piston starting from one end of the room to a certain point. As only the piston flow crosses the space in the most direct way, the $\bar{\alpha}_i = \tau_f$ at the outlet simultaneously represents the shortest possible residence time or nominal time constant τ (in h), which is the reciprocal nominal air-exchange rate n (in h^{-1}).

$$\tau = \frac{V}{\dot{V}} = \frac{1}{n} \tag{1}$$

Furthermore, Skåret (1986) shows that the spatial average of the air age $\langle\alpha\rangle = \tau/2$ in case of piston flow. In this study the equation for $\langle\alpha\rangle$ is given by equation (2).

$$\langle\alpha\rangle = \frac{\sum_{i=1}^{N} \bar{\alpha}_i}{N} = \frac{1}{\langle n\rangle} \tag{2}$$

In most real application cases, the air flow cannot be treated as a piston flow. The local air age of each coordinate in a room can be evaluated by the methods described by Sandberg (1981) and DIN ISO 16000-8 (2008). All of these methods are based on time dependent concentration measurements of a specific tracer gas concentration C(t) at a specific spatial coordinate in the room (P,i). The most popular method, which has been applied during this project as well, is the concentration decay method. For this method the air age of a specific coordinate i is calculated based on the local CO_2 concentration decay according to Mundt et al. (2004). In addition the outdoor concentration of CO_2 was considered through the mass balance of CO_2 as an averaged constant baseline concentration (Cui & Cohen 2015). Furthermore, constant density and molar mass of unsaturated moist air as well as constant volume flow ($\dot{V}_{av}(t) = \dot{V}_{sup}(t) = \dot{V}_{exh}(t) =$ const.) was assumed. The theoretical foundation for the integral is the decay curve approach described by Lidwell (1960). The concentrations $\Delta\bar{C}_{P,i}(t)\ \forall t \in [t_0, t_f]$ used for equation (3) in this study are simple moving average values of the intentionally accumulated CO_2-concentration added to C_{out}, covering a time interval of the period time $\Theta = 120$ s $\ll |t_0 - t_f| \approx [2, 8]$ h(1 of the ventilation devices and assigned to the last time stamp of each interval. This way each concentration value for the decay curve represents a full ventilation cycle (supply & exhaust phase) of the alternating devices. The numerical approximation of the improper integral in equation (3) is then realised through the trapezoidal rule according to DIN ISO 16000-8 (2008). This approach requires a termination criterion in order to approximate the residual tail of the decay curve between t_f and ∞ by $+\overline{\Delta C}_{P,i}(t_f) / \bar{\lambda}_{tail}$, with $\bar{\lambda}_{tail}$ according to equation (4). As termination criterion for the decay curve measurements serves $\overline{\Delta C}_{P,i}(t_f) < 37\ \% \cdot \overline{\Delta C}_{P,i}(t_0)$ (Maas 1995). The standard deviation of $\bar{\lambda}_{tail}$ can be used as measure for the quality of the measurement data, since a constant $\lambda_{tail}(t), \forall t \in [t_0, t_f[$ represents an ideal exponential decay.

$$\bar{\alpha} = \frac{1}{\overline{\Delta C}_{P,i}(t_0)} \cdot \int_{t_0}^{\infty} \overline{\Delta C}_{P,i}(t)\, dt, \quad \text{with } \overline{\Delta C}_{P,i}(t) = \frac{1}{\Theta} \cdot \sum_{t-\Theta}^{t} \left(C_{P,i}(t) - \bar{C}_{out}\right) \tag{3}$$

$$\bar{\lambda}_{tail} = \text{mean}\left(\ln\left(\frac{\overline{\Delta C}_{P,i}(t_f)}{\overline{\Delta C}_{P,i}(t)}\right) \cdot \frac{1}{t - t_f}\right), \forall t \in [t_0, t_f[\tag{4}$$

To evaluate the (relative) air exchange efficiency ε^a the definition by Skåret (1986) will be applied. The equation (5) following this definition is widely accepted. The room average age of air $\langle\bar{\tau}\rangle$ reaches its lowest value $0.5 \cdot \tau$ in case of ideal piston flow. For ideal mixing ventilation, a homogeneous age of air $\bar{\tau}_{P,i} = \text{const.}\ \forall i \in \mathbb{N}$ is assumed throughout the room, which results in $\varepsilon^a = 50\ \%$. Real ventilation systems should be located between $\varepsilon^a = 50\ \%$ and $\varepsilon^a = 100\ \%$. Lower efficiencies indicate short-circuit currents and stagnating areas. As a result $\langle n \rangle$ has to be larger than n_{nom} and reaches its maximum at $\langle n \rangle = 2 \cdot n$.

$$\varepsilon^a = \frac{\tau}{2} \cdot \frac{1}{\langle\bar{\tau}\rangle} = \frac{1}{2} \cdot \frac{\langle n \rangle}{n} = \frac{\langle n \rangle}{2} \cdot \frac{V}{\dot{V}} \tag{5}$$

EXPERIMENTAL SETUP

The measurements have taken place in the garden floor of a semi-detached residential hillside building. The building is located in a single-family and small multi-family houses neighbourhood on a hillside facing to the west in Freiburg (BW, Germany). Approximately 1.5 m of the east façade is below the ground level. About 8 m in front of the west façade there is a large tree. Between the considered house and the next building to the north there is a gap of about 20 m. The investigated living space is in the garden floor of the house and is equipped with decentral- ised façade integrated ventilation devices. The dimensions of the investigated living space, as well as the positions of the push-pull devices are depicted in Figure 2 (see appendix). The three small technical rooms on the bathroom side of the corridor do not belong to the living space. The doors of these rooms were sealed for the investigation. The considered living space has an area of 88.7 m² and a total volume of 195.1 m³ with a ceiling height of 2.21 m. The sleeping space in this part is composed out of the bedroom (BR) and the room "Child 2" (C2) with an area of 45.5 m². The occupancy of the flat is considered to be 3 adults which corresponds to a low occupancy rate. The building has recently been renovated (windows, thermal insulation, ventilation & heating system), which is why it is assumed that it is in full accordance with BBSR (1994) and has low heat losses.

Table 1. Calculated ventilation levels acc. to DIN 1946-6

#	Ventilation level		Acc. 05-2009 in $m^3 \cdot h^{-1}$	Acc. 12-2019 in $m^3 \cdot h^{-1}$
1	Moisture protection, low	$\dot{V}_{vs,mp} + \dot{V}_{w,mp}$	20.9	6.01
3	Reduced ventilation	$\dot{V}_{vs,rv} + \dot{V}_{w,rv}$	62.5	50.5
4	Nominal ventilation	$\dot{V}_{vs,nv} + \dot{V}_{w,nv}$	93.7	77.1
5	Intensive ventilation	$\dot{V}_{vs,iv} + \dot{V}_{w,iv}$	125	104

According to DIN EN 16798-1 (2021) a renovated building should by default fulfil the characteristics of a category 2 space and has to provide a nominal air change rate of $n = 0.6\ h^{-1}$ and $0.42\ l \cdot s^{-1} \cdot m^{-2}$ in the bedrooms. This results in this case in a fresh air flow of $\dot{V}_{total} = 117\ m^3 \cdot h^{-1}$. The German regulation DIN 1946-6 (2009) or DIN 1946-6 (2019)[2] respectively defines different ventilation levels which consider the occupancy, the humidity, the thermal insulation and the type of the building. This regulation allows to provide the total ventilation volume flow through infiltrations, ventilation system $\dot{V}_{vs}$ and window opening $\dot{V}_{w}$. The infiltration rate $\dot{V}_{inf}$ was empirically calculated as 10.3 $m^3 \cdot h^{-1}$[3] or 11.8 $m^3 \cdot h^{-1}$[4] respectively. The ventilation system itself consists out of three equal and synchronised push-pull devices and an exhaust only unit in the bathroom. To balance the supply and exhaust airflows, it is assumed that the devices operating in supply air mode compensate the air flow of devices operating in exhaust air mode, which is expressed by the equations (6) till (7). Exhaust-only devices are usually not compensated since they operate mostly for short time intervals. This simplification was applied here as well for the bathroom exhaust fan by an additional infiltration $\dot{V}_{inf,bath} = -\dot{V}_{bath}$.

2 Both versions are relevant here since the older was valid during the renovation, however the later one is relevant now.

$$ {}_{BR,sup} \quad {}_{C1,exh} \quad {}_{C2,exh} \quad {}_{bath} \quad {}_{inf} \quad {}_{inf\,bath} \quad {}_{inf} \tag{6}$$

$$0 = V_{BR,exh} + V_{bath} - V_{C1,sup} + V_{C1,sup} \quad V_{inf} \quad V_{inf\,bath} \quad V_{inf} \tag{7}$$

$$0.5\, V_{BR,sup} = V_{C1,sup} = V_{C2,sup} = -0.5\, V_{BR,exh} = -V_{C1,exh} = -V_{C2,exh} \tag{8}$$

$$V_{av} = \text{mean} \;\; \max\; V_{BR,sup}, V_{C1,exh} + V_{C2,exh} \;,\; \max\; V_{BR,exh}, V_{C1,sup} + V_{C1,sup} \tag{9}$$

$$V_{av,exh} = \text{mean} \;\; \max\; V_{BR,sup}, V_{C1,exh} + V_{C2,exh} + V_{bath} \;,\; \max\; V_{BR,exh} + V_{bath}, V_{C1,sup} + V_{C1,sup} \tag{10}$$

In order to evaluate the ventilation effectiveness CO_2 was used as tracer gas. The CO_2-sensors[5] have been installed in a horizontal plane at 1.7 m above floor level according to DIN EN 16798-3 (2017), S. 21 and DIN EN ISO 7726 (2002), S.16 as well as in each indoor aperture of the ventilation devices and in the outdoor vicinity. The sensor positions are marked in Figure 2. Furthermore a weather station[6] was installed at a distance of 5 m to the southern façade of the building. Each setup was evaluated during summer and winter weather conditions. Before the initialisation of each concentration decay measurement, CO_2 has been accumulated to ~2 000 ppm. During the accumulation phase, several circulation fans were used to homogenise the distribution of the CO_2.

RESULTS

To check whether the devices meet the volume flow criteria's according to equation (6) till (8) with $\dot{V}_{bath} = 0$ their controller was set to the manufacturer's specifications and the flows were measured applying a rotating vane anemometer[7] with a diameter of 100 mm. Afterwards the effective volume flow was calculated as integral over time. For the flow measurements themselves several sources of uncertainty need to be considered especially during the approximately 6 s of the flow direction change. The resulting volume flows for each case with and without infiltration are summarised in Table 2. Since not differential pressure measurements where possible the infiltration was approximated by the static procedure of DIN 1946-6 (2019)

Table 2. Time average volume flow in $m^3 \cdot h^{-1}$ [8]

level	$\Delta\dot{V}_{sup,exh}$	$\dot{V}_{av}$	$\dot{V}_{av,exh}$	$\dot{V}_{av}+\dot{V}_{inf}$	$\dot{V}_{av,exh}+\dot{V}_{inf}$
3	-4.0 ± 7.8	32.0 ± 8.3	79 ± 11	44 ± 11	91 ± 13
4	0.3 ± 8.6	39.4 ± 8.6	84 ± 10	39.4 ± 8.6	96 ± 12
5	-4.0 ± 9.8	48 ± 12	93 ± 16	48 ± 12	105 ± 17

The results according to Table 2 indicate there are some imbalances $\Delta\dot{V}_{sup,exh}$ regarding the volume flow even without the exhaust only device switched on. The reason for this was probably that the absolute volume flow of room child 2 $|\dot{V}_{C2}|$ was always higher than in room child 1 $|\dot{V}_{C1}|$. However, these imbalances are fairly low compared to both their associated uncertainties and to the aforementioned infiltrations.

The bathroom device has a volume flow of $\dot{V}_{bath} = (47.4 \pm 3.8)$ $m^3 \cdot h^{-1}$. This volume flow has been measured with closed windows and doors, while the other alternating devices have been switched off. $\dot{V}_{av}$ and $\dot{V}_{av,exh}$ are the ventilation airflow provided mechanically by the system. Adding the approximation for the expected infiltrations delivered the effective volume flows $\dot{V}_{av}+\dot{V}_{inf}$ and $\dot{V}_{av,exh}+\dot{V}_{inf}$ to calculate τ by equation (1).

Comparing Table 1 and Table 2 yields that the ventilation system installed is designed too small to comply with DIN 1946-6 (2019), DIN 1946-6 (2009) nor DIN EN 16798-1 (2021)by itself. Even at the level plus exhaust only device switched on, the provide effective volume flow would be below the "Nominal ventilation" level.

Therefore, and since the influence of different volume flows shall be considered as well, only the ventilation levels 4 and 5 are investigated in this study. In total this leads to the following parameters varied for the evaluation:

1.) Season: summer (S), winter (W) 2.) Ventilation level: L4, L5
3.) Exhaust only device: on (e1), off (e0)

During both parts of the measurement campaign in August 2019 and February 2020 the weather station and the outdoor CO_2-sensors measured the outdoor conditions. Table 3 lists the mean outdoor conditions (outdoor temperature $\bar{\vartheta}_{out}$, relative humidity $\bar{\varphi}_{out}$, CO_2-concentration $\bar{C}_{out}$, wind speed $\bar{v}_{wind}$, gust speed $\bar{v}_{gust}$ & wind direction $\bar{\alpha}$ during the decay curve measurements. These data are necessary since the conditions around the building effect the temperature and the pressure differences as well as the infiltrations between indoor and outdoor. For the tracer gas measurement with CO_2, it is necessary to record the outdoor concentration.

Table 3. Mean outdoor conditions ± s² during the decay curve measurements

case	$\bar{\vartheta}_{out}$ in °C		$\bar{\varphi}_{out}$ in %rh		$\bar{C}_{out}$ in ppm		$\bar{v}_{wind}$ in $m \cdot s^{-1}$		$\bar{v}_{gust}$ in $m \cdot s^{-1}$		$\bar{\alpha}$ in °	
S L5 e0	20.9	± 2.0	67	± 9	499(9	± 97	0.51	± 0.56	2.1	± 1.5	215	± 68
S L4 e0	23.6	± 1.5	60	± 6	394	± 27	0.16	± 0.29	1.00	± 0.73	226	± 80
W L5 e0	10.1	± 0.6	53	± 7	381	± 8	0.59	± 0.63	1.8	± 1.2	195	± 27
W L4 e0	6.5	± 0.2	78	± 3	423	± 6	0.56	± 0.51	1.90	± 0.86	199	± 21
S L5 e1	19.7	± 0.7	59	± 3	499(6	± 97	0.12	± 0.25	1.17	± 0.72	275	± 91
S L4 e1	18.8	± 0.1	81	± 0	592	± 17	0.01	± 0.06	0.20	± 0.42	233	± 134
W L5 e1	5.0	± 0.0	74	± 1	461	± 6	0.93	± 0.56	2.6	± 1.0	187	± 24
W L4 e1	13.0	± 0.3	83	± 1	368	± 7	1.24	± 0.62	3.1	± 1.0	195	± 16

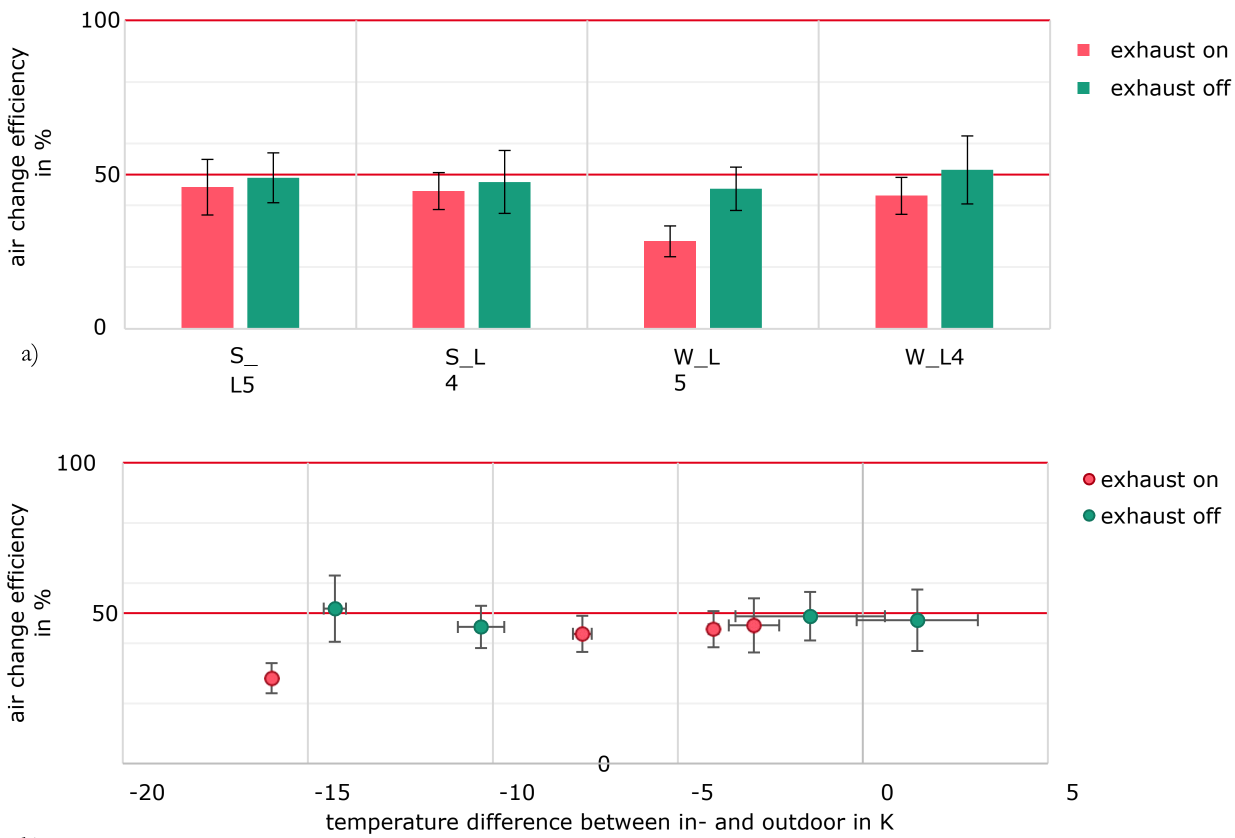
The building is situated in an area with a fairly low annually average wind speeds of < 1.7 $m \cdot s^{-1}$ according to DWD (2004). Accordingly, low wind speeds are recorded during the measurements (Table 3). Due to the wind protected location of the building no clear correlation to the wind speed can be drawn. However, a combined operation of the push-pull with an additional exhaust-only device leads to pressure difference between in- and outdoor as well and here the results depicted in Figure 1a indicate an impact, namely a reduction of the air change efficiency.

No clear trend can be found as well for a dependence on the effective volume flow. However, it needs to be considered that this system has very low air change rates. Furthermore, infiltrations are approximated as a considerable source for additional air exchange but with a vague uncertainty estimation. For higher air change rates the air change efficiency is expected to decrease (Sandberg 1981).

Also, no trend can be found for the temperature differences between in- and outdoors (Figure 1 b). This is particularly noticable since there are several studies which found that the ventilation efficiency depends on temperature gradients making it an important design parameter for positioning the ducts (Skåret & Mathisen 1983; Olesen et al. 2011; Tomasi 2012; Tomasi et al. 2013). On the other hand, studies which concerned push-pull devices found similar results (Manz et al. 2000; FGK 2019). Possible explanations for this finding maybe that the climate conditions during the campaigns were rather mild, that the heat recovery system has a high performance and/or that the low ventilation flow does not penetrate the indoor space far enough.

Table 4. Mean indoor conditions ± s² during the decay curve measurements & results of the ventilation efficiency measurements

case	$\bar{\vartheta}_{in}$ in °C		$\overline{\Delta T_{ls}}$ in K		$\bar{\varphi}_{in}$ in %rh		$\langle C_0 \rangle$ in ppm		$\langle C_f \rangle$ in ppm		ε^a in %		$\langle n \rangle$ in h^{-1}	
S L5 e0	22.3	± 0.1	1.2	± 0.1	57	± 0	1865	± 124	686	± 77	**49.0**	±8.1	0.31	±0.01
S L4 e0	22.2	± 0.6	1.3	± 0.0	60	± 1	2307	± 110	850	± 72	**48**	±10	0.24	±0.01
W L5 e0	20.4	± 0.1	1.4	± 0.1	40	± 1	2082	± 160	728	± 105	**45.4**	±7.0	0.27	±0.01
W L4 e0	20.8	± 0.2	1.1	± 0.0	41	± 1	1714	± 197	604	± 112	**52**	±11	0.26	±0.01
S L5 e1	22.7	± 0.1	1.5	± 0.1	55	± 0	1794	± 142	658	± 141	**45.9**	±9.0	0.47	±0.01
S L4 e1	22.9	± 0.0	1.4	± 0.0	66	± 0	2931	± 433	1067	± 190	**44.7**	±6.0	0.1	±0.01
W L5 e1	21.0	± 0.1	1.5	± 0.0	43	± 0	1663	± 123	590	± 77	**28.4**	±5.0	0.28	±0.01
W L4 e1	20.6	± 0.1	1.1	± 0.0	46	± 0	1868	± 155	645	± 89	**43.1**	±6.0	0.38	±0.01



b)

Figure 1 Relative air change efficiencies ε^a at breathing level 1.7 m above ground in the occupied zone: a) a balanced or imbalanced ventilation setting in summer and winter and b) the time average temperature difference between indoor and outdoor air $\overline{\Delta_{int} T}$

CONCLUSION

In this study façade-integrated regenerative and decentralised ventilation (push-pull) devices operating in alternating mode have been investigated experimentally in a real dwelling in Freiburg, Germany. First, it has been shown that for the given implementation the ventilation concept for the dwelling has to combine the mechanical ventilation system with window ventilation since the system itself is not able to provide a sufficient air change rate according to the German DIN 1946-6 (2019), DIN 1946-6 (2009) nor the European standards DIN EN 16798-1 (2021).

The measurements themselves took place for winter and summer conditions and fairly low wind conditions. For these conditions the push-pull ventilation system partly reached satisfying air change efficiencies of about $\varepsilon^a = 0.48$ for the main use case of a balanced system without the exhaust only device switched on. When the exhaust only device was used in parallel the air change efficiency dropped below the mixing ventilation level of $\varepsilon^a = 0.39$ which means short-circuiting occurs. Even though it was expected this study could not find a correlation between the air change efficiency and the wind speed or the temperature differences between in- and outdoors. A key factors for this could be that the climate conditions for both the winter and the summer campaign were rather mild and that the already installed system provided to low air change rates. Further studies should perform similar measurements for push-pull systems designed according to DIN EN 16798-1 (2021) and include infiltration tests.

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NOMENCLATURE

C	=	CO_2 concentration in the air	ppm	α	=	air age	s
Δ	=	difference	(various)	τ	=	nominal time constant	s
ε^a	=	air exchange efficiency	-	Θ	=	period time of the ZAS-D	s
$\in$	=	“element in a set of sth.”	-	U	=	uncertainty ($k_p = 2$)	(various)
n	=	air exchange rate	-	v	=	velocity	$m \cdot s^{-1}$
t	=	time	s	$\dot{V}$	=	volume flow	$m^3 \cdot h^{-1}$
T	=	temperature	K	$\forall$	=	“for all”	-
ϑ	=	temperature	°C				

SUBSCRIPTS

0 = initial

exh = exhaust air f = final

fs = floor to sealing

i = local point i in space iv = intensive

ventilation j = local point j in space ma =

moist air

mp = moist protection

nv = nominal ventilation P

= probe

rv = reduced ventilation

sup = supply air

vs = ventilation system w

= window opening

$\bar{\cdot}$ = time average

$\langle \cdot \rangle$ = spacial average

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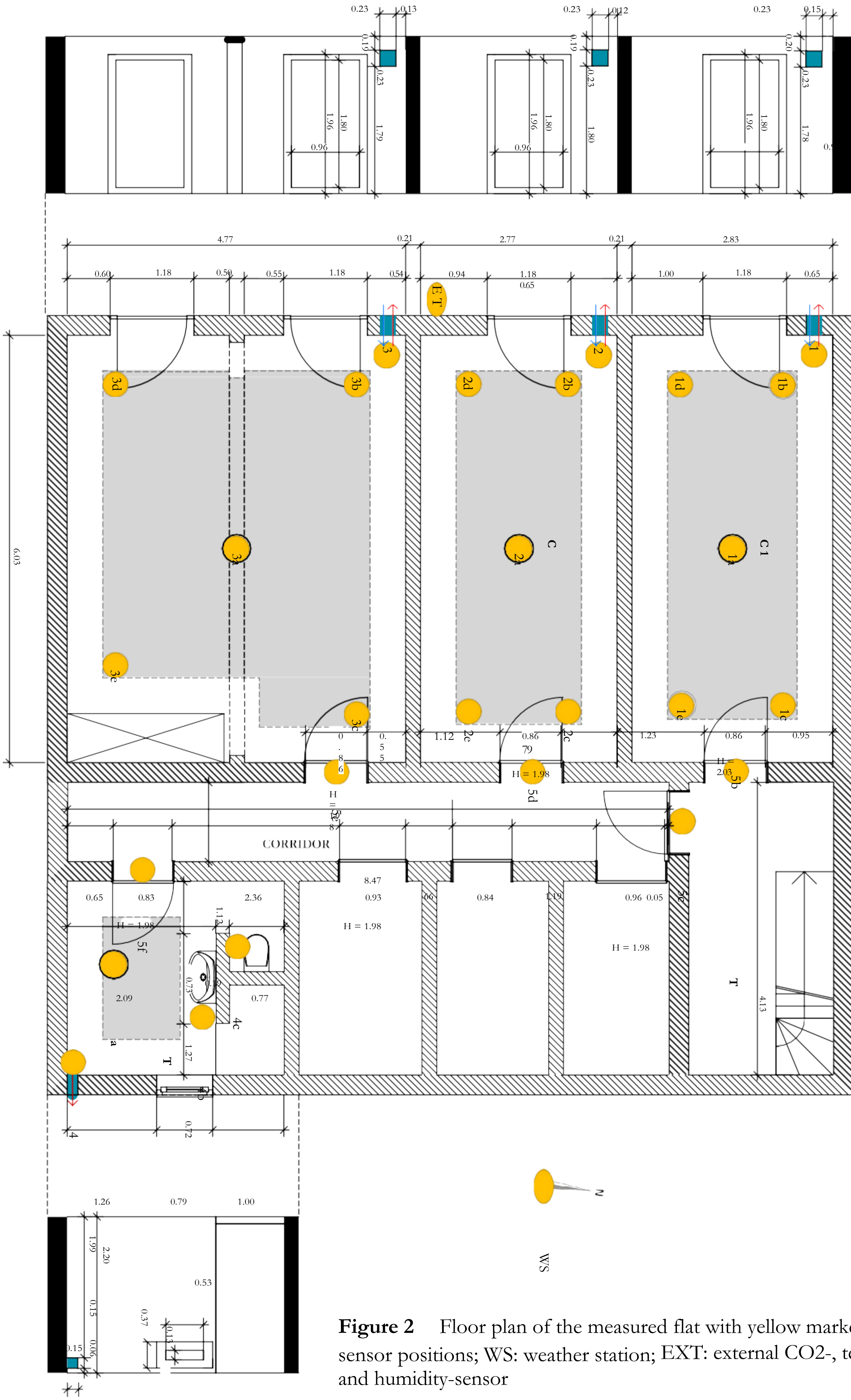

Figure 2 Floor plan of the measured flat with yellow markers for the sensor positions; WS: weather station; EXT: external CO2-, temperature- and humidity-sensor