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Non-Intrusive Measurements to Incorporate the Air Renovations in Dynamic Models Assessing the In-Situ Thermal Performance of Buildings

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Abstract: This paper reports the analysis of the feasibility to characterise the air leakage and the mechanical ventilation avoiding the intrusiveness of the traditional measurement techniques of the corresponding indicators in buildings. The viability of obtaining the air renovation rate itself from measurements of the concentration of the metabolic CO_2, and the possibilities to express this rate as function of other climatic variables, are studied. N_2O tracer gas measurements have been taken as reference. A Test Cell and two full size buildings, with and without mechanical ventilation and with different levels of air leakage, are considered as case studies. One-month test campaigns have been used for the reference N_2O tracer gas experiments. Longer periods are available for the analysis based on CO_2 concentration. When the mechanical ventilation is not active, the results indicate significant correlation between the air renovation rate and the wind speed. The agreement between the N_2O reference values and the evolution of the metabolic CO_2 is larger for larger initial values of the CO_2 concentration. When the mechanical ventilation is active, relevant variations have been observed among the N_2O reference values along the test campaigns, without evidencing any correlation with the considered boundary variables.

Keywords: building energy; building envelope; performance assessment; air renovation; non-intrusive measurements; on-board monitoring

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1. Introduction

Buildings use about 40% of the total energy produced globally and have a relevant potential in terms of energy savings and reducing the pollutant emissions to the atmosphere [1]. These issues are driving an increasing interest to foster the energy efficiency in buildings leading to the elaboration and incorporation of related regulations, stressing the demand to broaden the knowledge related to the energy performance of the buildings, and motivating many research initiatives in this area. Presently, the majority of the checks of compliance and energy performance labelling of buildings rely on design values and theoretical assessments or simulations. Nevertheless, many researches have demonstrated that the actual performance of a building can be very different from the one theoretically evaluated [2,3]. The readiness of reliable enough test procedures applicable to as built buildings for assessing their thermal performance, would contribute to eliminate the problems related to the performance gap. The need for tools identifying the sources of the performance gaps, and providing feedback to different stakeholders, is included among the research themes considered by the Energy in Buildings and Communities (EBC) Technology Collaboration Programme (TCP) of the International Energy Agency (IEA) [1]. One of the elements having a significant influence on the energy behaviour of the buildings is the building envelope. The identification of the intrinsic thermal properties characterising the as built building envelope from on board monitoring system is recently attracting the attention of many research groups in the context of international collaboration initiatives [4]. In this context, those monitoring systems with a limited set of non-intrusive measurement devices, embedded in the building, as those typically used for billing or for controlling the Heating, Ventilating and Air Conditioning (HVAC) systems are considered as on board monitoring systems. The energy performance assessment of the building envelope can be carried out through data analysis techniques that require the measurement (that can be direct or indirect) of all the effects that contribute to the energy balance in the space that is confined by the building envelope being characterised [5]. One of the contributions to this energy balance is the one from air renovations, either by mechanical or natural ventilation, or by infiltrations as consequence of cracks or material porosity [6].

There are several procedures for the experimental assessment of the air renovation rate in rooms. Some of these procedures are based on pressurisation and others are based on tracer gas techniques [7]. These traditionally applied methods that could give precise results are complex, expensive and highly intrusive for the building users and inhabitants. Additionally, these traditional techniques characterise the air renovations by a constant parameter. Some standardised procedures obtain this parameter under a pressure that is raised regarding the pressure of the building in use [8]. These constant values can introduce some degree of uncertainty on the data based dynamic modelling techniques that are applied for the thermal performance assessment of the building envelope from on-board monitoring systems [5,9,10]. Part of this uncertainty can be driven by the use of the air renovation rate as a constant parameter when actually it is a variable. A review paper that has been recently published identifies the dynamic behaviour of the air renovation rate as an issue contributing to the uncertainty in tracer gas-based methods [11]. Other authors have analysed the uncertainties due to wind in building pressurisation tests [12]. They identified errors in the rage 6–12% for wind speed in the range 6–10 ms^{-1} for test carried out under a standard pressure of 50 Pa, while the errors raised up to 35% and 60% for wind speeds of 6 ms^{-1} and 10 ms^{-1}, respectively under a pressure of 10 Pa. When the air renovation rate is obtained according the standardised building pressurisation tests, the transformation of the pressurised value to the non-pressurised one, can introduce also certain degree of uncertainty in the dynamic models that are used for the energy performance assessment of in-use buildings. The presence of some uncertainty and variability in the air renovation rate due to infiltrations as well as mechanical ventilation, can contribute to understand and explain the behaviour of the Heat Loss Coefficient (HLC) experimentally assessed and its uncertainties [13,14].

The work reported in this paper is focused on the experimental assessment of the air renovation rate analysing the reliability of cheaper and more cost effective techniques regarding the traditional techniques based on tracer gas. The feasibility to characterise air leakage and mechanical ventilation avoiding the intrusiveness of the traditional measurement techniques is analysed. The viability to obtain the air renovation rate itself, as well as the possibilities to express it as function of other variables (such as wind speed, atmospheric pressure, etc.), are studied extending some preliminary studies [15]. Tracer gas measurements based on N_2O have been used as reference. Experimental relations between the air renovations and the wind speed, the indoor-outdoor air temperature difference, and the atmospheric pressure have been analysed. The reliability of an alternative method based on the evolution of the metabolic CO_2 using wall mounted sensors of CO_2 concentration is evaluated. A PASLINK Test Cell [16,17] and two full size buildings are considered as case studies. First the Test Cell and a very simple single zone building, without mechanical ventilation, are considered. Afterwards, a room in an office building has been studied with and without mechanical ventilation. One-month test campaigns have been used for the reference study based on tracer gas measurements using N_2O, in both buildings and the Test Cell. Longer periods are available for the analysis based on CO_2 concentration.

The next sections are organised as follows: Section 2 presents the considered case studies, and briefly describes the experiment set up and the methodology applied for data analysis, Section 3 presents and discusses the results that have been obtained for the different case studies, and finally Section 4 summarises the conclusions regarding the behaviour of the air renovation rate, discusses the effect of this behaviour on the Heat Loss Coefficient (HLC) and suggest further research on this issue.

2. Materials and Methods

The next subsections included under this section describe the three considered case studies, the experiment set up, the tests carried out, and finally the methodology applied for data analysis.

2.1. Case Studies

A PASLINK Test Cell and two full size extensively monitored buildings are considered as case studies [16,17]. These buildings and the Test Cell, briefly described in Section 2.1.1, Section 2.1.2, Section 2.1.3 are at the CIEMAT's Plataforma Solar de Almeria (PSA), in Tabernas (37.1° N, 2.4° W), Almería (Spain). They are in a rural area where the climate is semi-arid, with large day-night temperature variations.

2.1.1. PASLINK Test Cell

The PASLINK Test Cell consists in a test facility with a high-thermal-insulation test room and an auxiliary room (Figure 1a). The test room has a surface of 4.825 × 2.48 m^2 and its high is 2.47 m. The Test Cell is placed in a large open area without any shading. It has an air conditioning system and measurement devices for testing full-scale building components. Its test room envelope is highly insulated by 40 cm of polystyrene and it is equipped with the Pseudo-Adiabatic Shell (PAS) Concept. This system is based on a thermopile that detects if there is heat flux through the envelope of the test room, and cancels it by means of a heating foil. The interior surface of the test room is finished with an aluminium sheet giving it thermal uniformity. The Test Cell is over a rotating device that enables it for testing in any orientation.

(**a**) (**b**) (**c**)

Figure 1. Buildings considered as case studies: (**a**) PASLINK Test Cell; (**b**) Single-zone building; (**c**) Office building.

The south wall and the roof of the test chamber are interchangeable, which permits any vertical or horizontal building component to be installed for testing. The tests of air renovations considered in this work correspond to a reference experiment. In this case, the Test Cell incorporates a homogeneous and opaque wall in its replaceable façade.

This test was conducted in the framework of a series of tests that included several photovoltaic modules and electrocromic windows replacing a piece of the component taken as reference. The Heat Loss Coefficients of these components are obtained by subtracting the Heat Loss Coefficient obtained with the photovoltaic modules or the electrocromic windows, from the Heat Loss Coefficient obtained from the reference component. The Test Cell is designed to be very airtight. Typical air renovation rates during testing are between 0.02 and 0.05 renovations per hour [18]. The assessment of its air renovation rate is important in order to check the achieved level of air tightness and to assess the deviations from this level due to the climatic variables.

2.1.2. Single-Zone Building

This building is a small workshop with just one room, and its area is 31.83 m^2 (Figure 1b) [17]. It can give experimental support to diverse research activities maintaining it empty or with low occupancy rates. It was built in 2002. It is near another twin building that is placed 2 m from its east wall. Both are built in an open area without any other obstacles around that could shade them.

This building was designed to reduce the energy demand incorporating the following passive strategies: South orientation, shading elements avoiding the solar gains in summer and maximising them in winter, the windows are double-glazed to reduce heat losses, and diagonally aligned (north-south) to facilitate the natural ventilation, thermal mass incorporated in the building envelope, external insulation and high ceilings.

2.1.3. Office Building Prototype

The so called C-DdI ARFRISOL at PSA is a one floor building with most of the regularly occupied offices facing south (Figure 1c). Its net floor area is 1007.40 m^2. It was constructed in 2007 in the framework of the PSE-ARFRISOL project [19]. It is a prototype of a new plant, built on one floor longitudinal plan.

A double-wing structure, that is installed on the roof along the main axis of the building, protects it from the solar radiation. This structure integrates two different types of solar collectors. Uncovered collectors which are designed to operate as radiant coolers by night are over the wing facing north. Flat plate collectors that are designed to supply hot water for the heating, cooling and DHW systems are over the south facing wing. Small solar chimneys that provide night ventilation of the offices are constructed on the central part of this structure. The south windows are protected by an overhang that provides shade during the summertime and facilitates passive heating in winter.

This building is in use, but it must be taken into account that the experiments used for this work were carried out when the considered room was positively empty; at lunch time and also once the working day is finalised (identified every day as test 1, and test 2, respectively).

2.2. Experiment Set Up

A tracer gas device combined with a gas analyser have been used to carry out Decay experiments based on the evolution of N_2O concentration in both buildings and the Test Cell.

The Test Cell and the two buildings are extensively monitored. The monitoring system records minutely read measurements of the following variables:

- N_2O concentration when the Decay experiments are being conducted.
- Indoor and outdoor air temperatures, relative humidity, and concentration of CO_2. Two sensors are installed to measure this variable. An accurate and expensive sensor used as reference, and a cheaper and less accurate sensor (Identified as CO_{2_ref} and CO_2 respectively in this document).
- Temperature of walls, floor and glass surfaces.
- Energy delivered by the heating system (radiant floor).
- Electric consumption due to computers and lighting
- Whether doors and windows are closed or "not closed".
- Ground temperature.
- Beam, diffuse, global horizontal, global vertical south and global vertical north solar irradiance.
- Longwave radiation.

One-month test campaigns for each building were considered for the analysis. These campaigns were conducted under different conditions: Dynamic heating sequence in the Test Cell maintaining a large indoor to outdoor air temperature difference, free running test in the single-zone building, and space heating maintaining the indoor air temperature in a comfort range in the office building.

2.3. Methodology

2.3.1. Analysis of the Relations between the Air Renovation Rate and Climate Variables

- For both buildings and the Test Cell, for infiltrations and mechanical ventilation, tracer gas measurements based on N_2O have been used as reference. The air renovation rate has been obtained using the Decay method [7]. Experimental relations between the air renovation rate and the following variables have been analysed.
- The difference between the indoor and outdoor air temperatures ($T_i - T_e$).
- The wind speed (W).
- The product of the wind speed and the difference between the indoor and outdoor air temperatures ($W(T_i - T_e)$).
- The product of the wind speed raised to two and the difference between the indoor and outdoor air temperatures ($W^2(T_i - T_e)$).
- The atmospheric pressure (P_{atm}).
- The absolute value of the variation of wind speed per unit of time($|dW/dt|$).

2.3.2. Analysis of Feasibility to Obtain Air Renovation Rate from Wall Mounted CO_2 Sensors

Additionally, the reliability of an alternative method based on the evolution of the metabolic CO_2 using wall mounted sensors of CO_2 concentration is evaluated in a room of the office building. A reference value ($CO_{2infinite}$) has been used, such that the variable used for the Decay method is the CO_2-$CO_{2infinite}$. This value was obtained as the average of the CO_2 concentration in a period when the room is positively non-occupied (from 9 pm to 7 am), starting when the Decay curve has reached its asymptotic value. An error obtained as the percentage of deviation regarding the reference value (based on N_2O), has been represented as function of the maximum value of the CO_2 concentration at the beginning of the decay method curve.

3. Results and Discussion

A reference value has been obtained for each of the considered case studies. These reference values have been obtained using a N_2O tracer gas applying the Decay method. The measurements carried out for the different case studies, presented in Figure 2, evidence that the air renovation rates are different for the different case studies.

The air renovation rates obtained from these tests are:

- PASLINK Test Cell: 0.056 renovations/hour.
- Single-zone building: 0.308 renovations/hour.
- Office building without mechanical ventilation: 0.825 renovations/hour.
- Office building with the mechanical ventilation active: 2.12 renovations/hour.

The dependence of these infiltration rates on the considered climate variables, and the feasibility to obtain them from the concentration of the metabolic CO_2, is discussed in the next subsections.

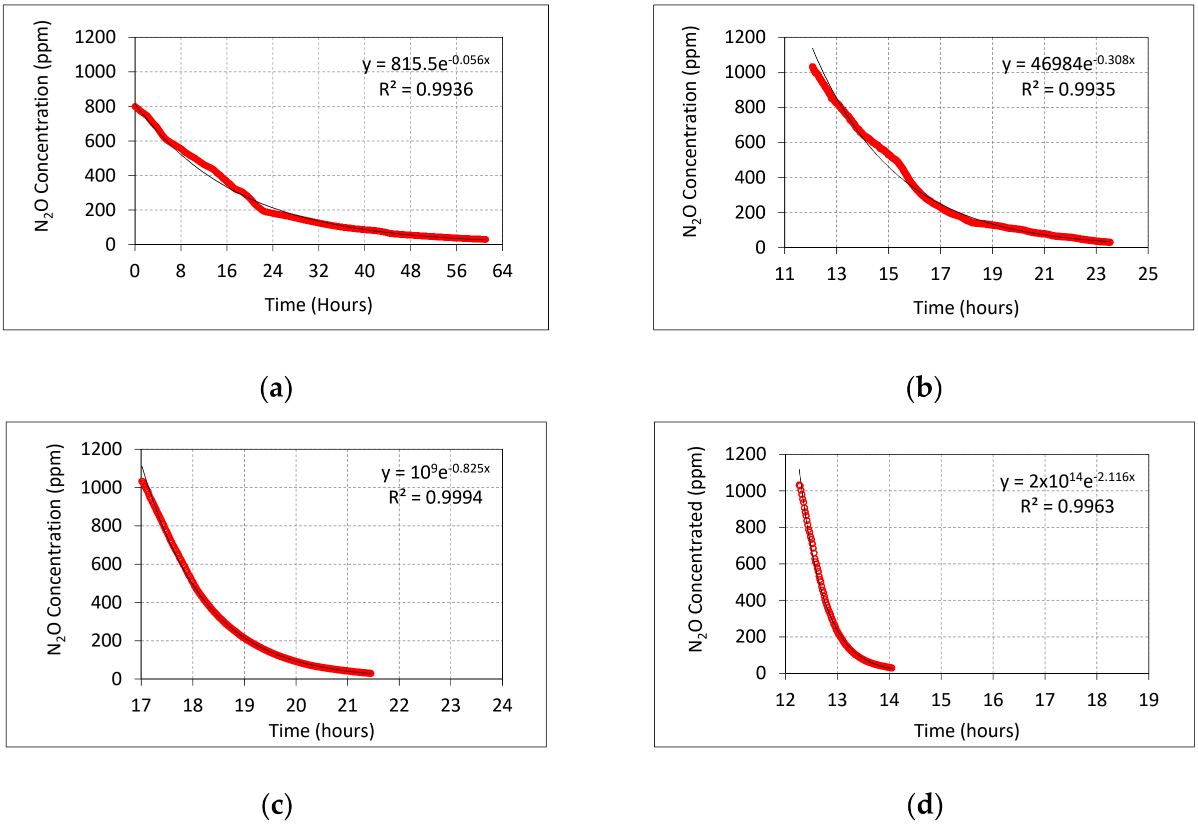


Figure 2. Decay method based on N_2O as tracer gas, applied to the three case studies: (**a**) PASLINK Test Cell (08/10/2018–11/10/2018); (**b**) Single-zone building 24/02/2016; (**c**) Office building without mechanical ventilation (10/02/2017); (**d**) Office building with mechanical ventilation (02/02/2017).

3.1. PASLINK Test Cell. Infiltrations

As expected, very low infiltration rates have been obtained for all the tests carried out in the PASLINK Test Cell. These results are shown in Figure 3 and Table 1. In this case, the infiltration rate does not show any relevant correlation with the indoor to outdoor air temperature difference (Figure 3a). This correlation also is not relevant with the atmospheric pressure (Figure 3d). However, the air infiltration rate presents some correlation with other considered variables. It shows significant linear dependency on the wind speed (Figure 3e), and the dependency is remarkable on the absolute value of the variation of the wind speed per unit of time (Figure 3f).

3.2. Single-Zone Building. Infiltrations

The results obtained for the single zone building are summarised in Table 2. This table shows that the air renovation rate (n) presents a large variation in the range 0.16–0.97 renov/hour. Its average is 0.37 renov/hour, and its standard deviation is 0.26 renov/hour. Figure 4a,c,e,g,i) shows that the n value has evident correlation with all the considered boundary variables except the atmospheric pressure (Figure 4g). The most relevant correlation detected is regarding the wind speed (Figure 4c). The absolute value of the variation of the wind speed per unit of time is also relevant (Figure 4i).

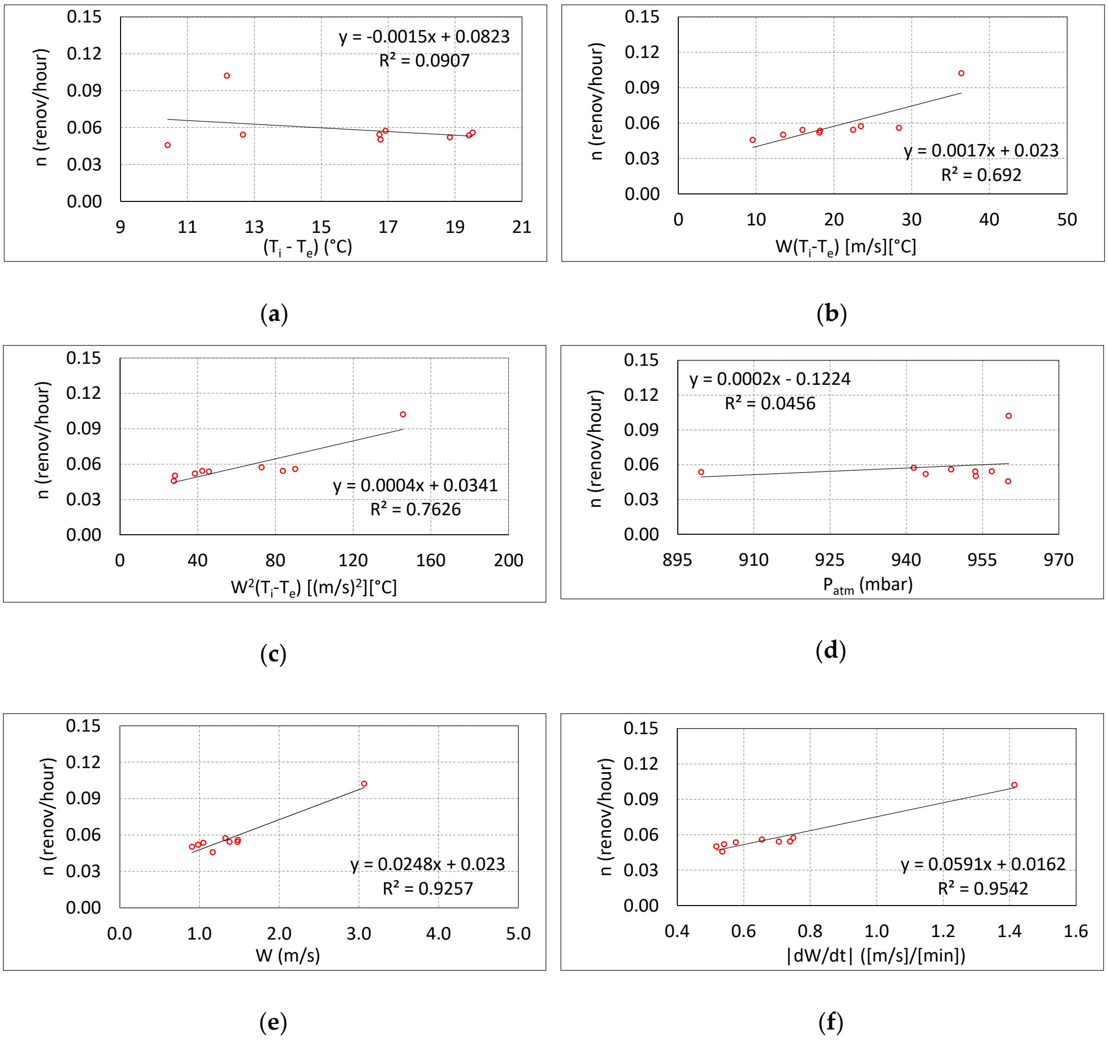


Figure 3. PASLINK Test Cell. Relations between the air renovation rate and the climatic variables. N_2O tracer gas measurement taken as reference. (**a**) Indoor to outdoor air temperature difference; (**b**) product of the indoor to outdoor air temperature difference and the wind speed; (**c**) product of the indoor to outdoor air temperature difference and the wind speed raised to two; (**d**) atmospheric pressure; (**e**) wind speed; (**f**) absolute value of the variation of wind sped per unit of time.

Table 1. PASLINK Test Cell. Experimentally determined air infiltration rates and climate variables.

Days In 2018	*n* (N_2O) [1] (ren/h)	r^2 (N_2O) [1] (·)	$T_i - T_e$ (°C)	W (m/s)	$W(T_i - T_e)$ [m/s] [°C]	$W^2(T_i - T_e)$ [(m/s)^2] [°C]	P_{atm} (mbar)
24/09–26/09	0.1022	0.9834	12.2	3.07	36.39	145.7	960
27/09–29/09	0.0543	0.9778	16.7	1.48	22.46	83.9	957
02/10–04/10	0.0536	0.9917	19.4	1.05	18.20	45.9	900
05/10–07/10	0.0503	0.9983	16.8	0.91	13.45	28.3	954
08/10–11/10	0.0560	0.9936	19.5	1.48	28.35	90.3	949
12/10–14/10	0.0543	0.9829	12.7	1.38	15.94	42.4	954
23/10–25/10	0.0458	0.9367	10.4	1.17	9.52	27.8	960
26/10–29/10	0.0574	0.9882	16.9	1.33	23.45	72.9	941
29/10–01/11	0.0520	0.9979	18.8	0.98	18.11	38.6	944

[1] The (N_2O) indicates that the values included in the column were obtained using the N_2O tracer gas.

3.3. Office Building Prototype

3.3.1. Infiltrations

The results obtained for the studied room are summarised in Figure 4b,d,f,h,j and Table 3. Considering the analysis based on N_2O, the air renovation rate (n) presents some variation. However, the observed variation is not so large as in the single-zone building. The n value is between 0.61 and 0.75 renov/hour. Its average is 0.67 renov/hour, and it standard deviation is 0.05 renov/hour. Figure 4b,d,f,h,j shows that the n value has relevant correlation with all the considered boundary variables except the indoor to outdoor air temperature difference and the atmospheric pressure. The most relevant correlation detected is regarding the wind speed (Figure 4d).

It is noticeable the different behaviour observed for the dependence of the n value with the indoor-outdoor temperature difference in this heated room regarding the single zone free running building. The n value for the heated office does not show relevant dependence with this variable (Figure 4b). This behaviour is also observed in the Test Cell, also heated during the test campaign, that does not show relevant dependence with this variable (Figure 3a). However, a linear tendency is seen for the free running single-zone building (Figure 4a). This different behaviour could be explained by the different ranges of indoor-outdoor air temperature differences in the case studies (Figures 3a and 4a,b).

Acceptable agreement is observed for the values obtained using the metabolic $CO_{2\,ref}$ concentration, measured with the wall-mounted sensors, regarding the reference n values based on N_2O (Table 3 and Figure 5a). The agreement is very poor when the less accurate CO_2 sensor is used (Table 3 and Figure 5a). This behaviour is explained by taking into account that the office has just one user, and consequently, the level of CO_2 concentration produced by the metabolic activity is very low, which is leading to relevant uncertainties in the estimations of the n values if the used sensor does not have enough resolution. These uncertainties show a decreasing tendency when the CO_2 concentration increases (Figure 5b). Taking into account this behaviour a better performance of this sensor is foreseen for larger CO_2 concentrations that would be present in rooms with more occupants. This issue will be further investigated.

Table 2. Single-zone building. Experimentally determined air infiltration rates and climate variables.

Day	n (N_2O) [1] (ren/h)	r^2 (N_2O) [1] (·)	$T_i - T_e$ (°C)	W (m/s)	$W(T_i - T_e)$ [m/s] [°C]	$W^2(T_i - T_e)$ [(m/s)^2] [°C]	P_{atm} (mbar)
09/02/2016	0.74	0.9756	−2.49	9.20	−21.88	−214.9	956
10/02/2016	0.60	0.9125	−0.79	10.27	−9.58	−121.6	954
11/02/2016	0.50	0.9708	0.28	9.27	2.66	25.8	951
12/02/2016	0.97	0.9942	−0.61	11.55	−7.07	−87.0	951
15/02/2016	0.22	0.9776	9.44	3.75	32.07	157.8	952
16/02/2016	0.19	0.9874	12.07	2.45	25.39	78.9	960
17/02/2016	0.31	0.9550	9.54	4.48	39.96	201.3	955
18/02/2016	0.16	0.9965	9.57	3.04	29.71	107.1	955
19/02/2016	0.22	0.9936	9.68	4.44	42.93	213.0	958
22/02/2016	0.16	0.9666	6.58	2.84	18.40	78.8	958
23/02/2016	0.17	0.9976	10.42	2.21	18.26	46.1	959
24/02/2016	0.31	0.9935	6.30	4.73	26.75	131.4	952
25/02/2016	0.22	0.9608	10.12	3.82	29.83	141.6	952

[1] The (N_2O) indicates that the values included in the column were obtained using the N_2O tracer gas.

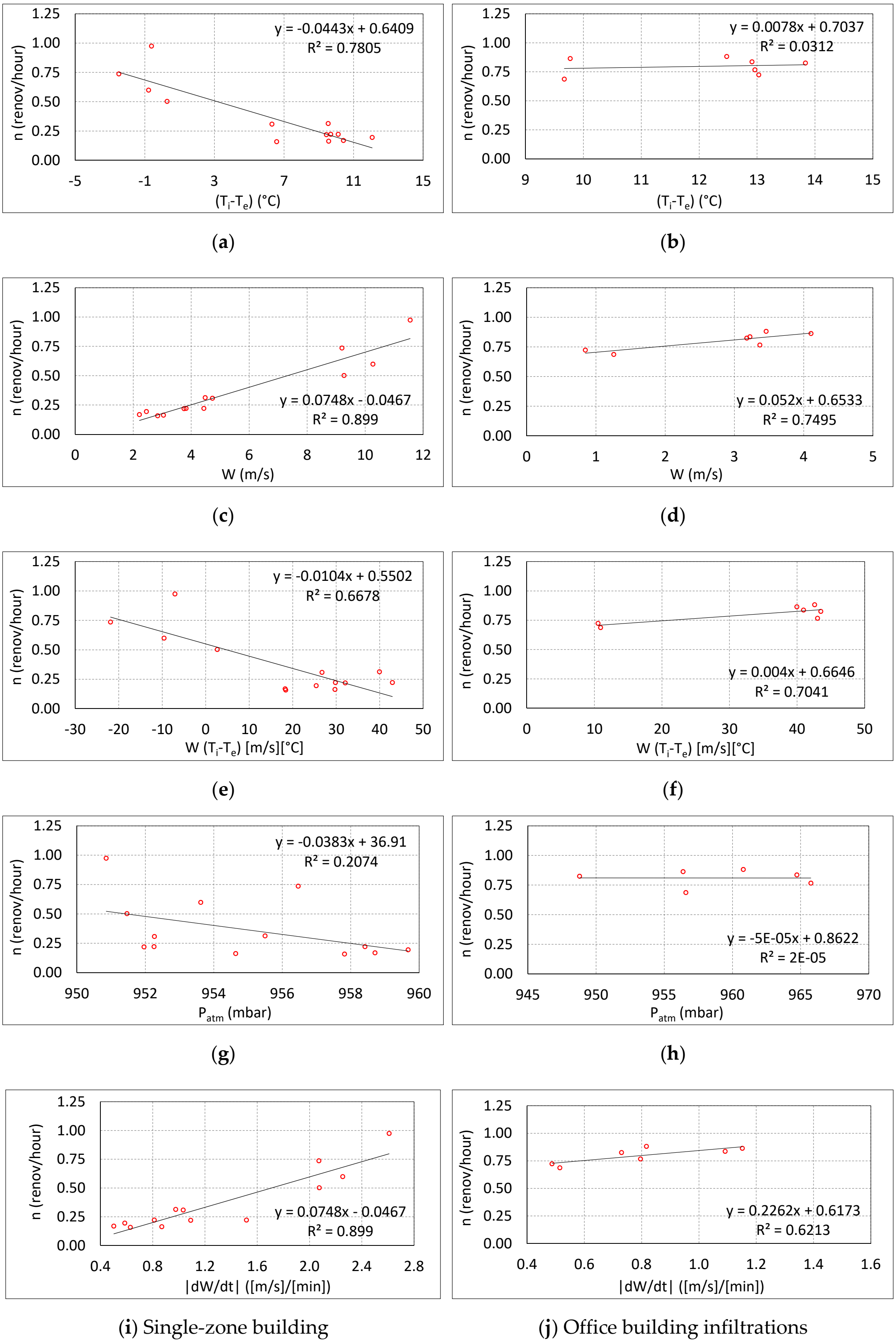
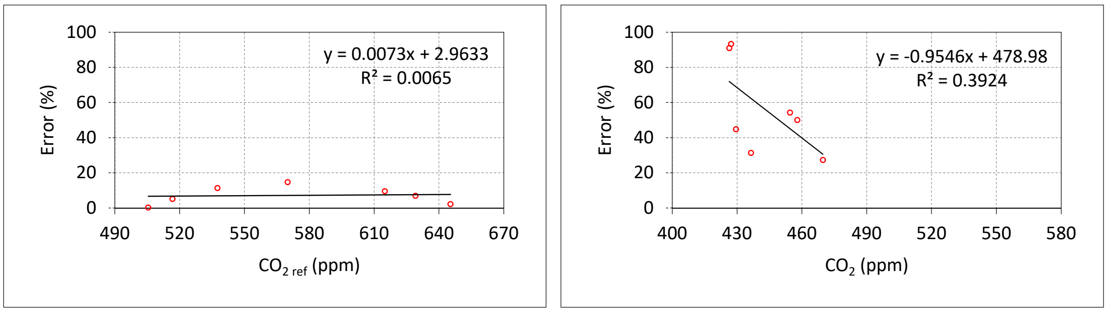


Figure 4. Relations between the air renovations and the climatic variables. Left: single-zone building. Right: Room of the office building. (**a**,**b**) Indoor to outdoor air temperature difference; (**c**,**d**) wind speed; (**e**,**f**) product of the indoor to outdoor air temperature difference and the wind speed; (**g**,**h**) product of the indoor to outdoor air temperature difference and the wind speed raised to two; (**i**,**j**) absolute value of the variation of the wind sped per unit of time.



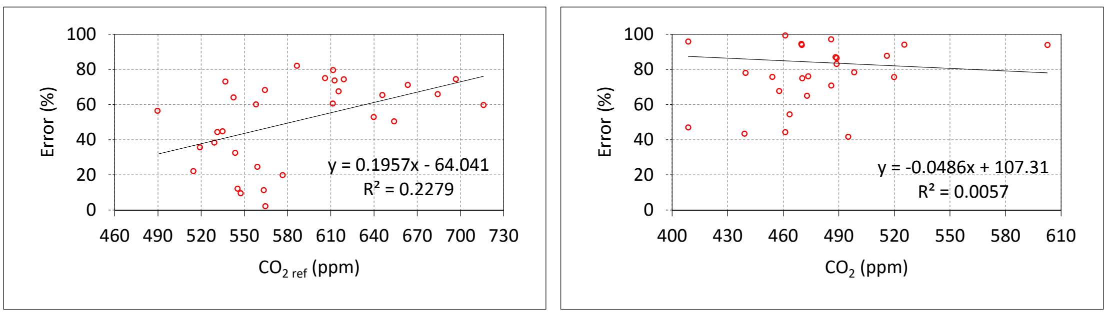
(**a**) (**b**)

Figure 5. Office number 1, analysis of infiltrations. Percentage of error of the results obtained from the Decay method using the metabolic CO_2 concentration and considering as reference the value obtained from the N_2O tracer gas. (**a**) Using the CO_2 reference sensor; (**b**) using the cheaper CO_2 sensor.

3.3.2. Mechanical Ventilation

The results obtained for the studied room are summarised in Tables 4 and 5. Considering the analysis based on N_2O, the air renovation rate (n) presents a large variation. It is between 0.95 and 3.08 renov/hour. Its average is 1.98 renov/hour which is very close to the design value (2 renov/hour), and it standard deviation is 0.59 renov/hour. However, the n value does not show relevant correlation with any of the considered boundary variables. The observed large spread could be caused by the instability of the electricity that powers the mechanical ventilation system that transmits such instability to the ventilation rate. Other effects, such as hysteresis of the mechanical components of the ventilation system could contribute to produce the detected variations. The causes of the detected large spread will be further investigated in future research works.

Large uncertainties are observed for the values obtained using the metabolic CO_2 concentration measured with the wall-mounted sensors (Tables 4 and 5 and Figure 6). These uncertainties are remarkably larger than those observed for the same room without mechanical ventilation (Figure 5). This high uncertainty is attributed the low level of metabolic CO_2 concentration produced by just one user. This issue also leads to large uncertainties in the air renovation rate obtained for the same room without mechanical ventilation using the less accurate sensor (Figure 5b). However, such uncertainty is worsened in the case of mechanical ventilation taking into account that the time interval available for each calculation of the n value is shortened regarding the case of not using mechanical ventilation.



(**a**) (**b**)

Figure 6. Office number 1, tests with mechanical ventilation active. Percentage of error of the results obtained from the Decay method using the metabolic CO_2 concentration and considering as reference the value obtained from the N_2O tracer gas. (**a**) Using the CO_2 reference sensor; (**b**) using the cheaper CO_2 sensor.

Table 3. Office number 1. Experimentally determined air infiltration rates, climate variables and deviations between the results obtained using the metabolic CO_2 concentration and the N_2O tracer gas.

Day	*n* (N_2O) [1] (ren/h)	*n* (CO_2) [1] (ren/h)	*n* (CO_{2_ref}) [1] (ren/h)	r^2 (N_2O) [1] (·)	r^2 (CO_2) [1] (·)	r^2 (CO_{2_ref}) [1] (·)	Ti − Te (°C)	W (m/s)	$W(T_i - T_e)$ [m/s] [°C]	$W^2(T_i - T_e)$ [(m/s)^2] [°C]	P_{atm} (mbar)	$CO_{2ref.max}$ (ppm)	Error (CO_{2_ref}) [1] (%)	CO_{2max} (ppm)	Error (CO_2) [1] (%)
09/02/2017	0.72	0.07	0.72	0.9994	0.0334	0.9639	13.03	0.85	10.5	13.5	800	506	0.2	426	91.0
10/02/2017	0.83	0.57	0.78	0.9994	0.7564	0.9864	13.83	3.18	43.5	161.5	949	517	5.1	436	31.4
14/02/2017	0.88	0.64	0.82	0.9997	0.7520	0.9923	12.47	3.46	42.6	161.7	961	629	6.9	470	27.3
15/02/2017	0.77	0.38	0.78	0.9991	0.7900	0.9909	12.96	3.37	43.0	156.5	966	645	2.2	458	50.1
16/02/2017	0.84	0.38	0.74	0.9996	0.8052	0.9913	12.91	3.22	40.9	149.3	965	538	11.3	454	54.3
21/02/2017	0.86	0.48	0.78	0.9990	0.6157	0.9888	9.77	4.10	40.0	178.0	956	615	9.5	430	44.8
01/03/2017	0.69	0.05	0.59	0.9941	0.0446	0.9677	9.67	1.26	10.9	19.8	957	570	14.7	427	93.3

[1] The (N_2O), (CO_2) and (CO_{2_ref}) indicate that the values included in the column refer to the measurements using the N_2O tracer gas, the CO_2 or the CO_{2_ref} devices respectively.

Table 4. Office number 1, test 1 for each day. Experimentally determined air infiltration rates when the mechanical ventilation is active, climate variables and deviations between the results obtained using the metabolic CO_2 concentration and the N_2O tracer gas.

Day	*n* (N_2O) [1] (ren/h)	*n* (CO_2) [1] (ren/h)	*n* (CO_{2_ref}) [1] (ren/h)	r^2 (N_2O) [1] (·)	r^2 (CO_2) [1] (·)	r^2 (CO_{2_ref}) [1] (·)	Ti − Te (°C)	W (m/s)	$W(T_i - T_e)$ [m/s] [°C]	W2 $(T_i - T_e)$ [(m/s)^2] [°C]	P_{atm} (mbar)	$CO_{2ref.max}$ (ppm)	Error (CO_{2_ref}) [1] (%)	CO_{2max} (ppm)	Error (CO_2) [1] (%)
31/01/2017	2.41	0.41	0.65	0.9983	0.7064	0.9819	2.12	1.06	2.3	3.2	953	537	73	489	83
01/02/2017	2.41	1.10	0.76	0.9982	0.8000	0.9872	2.08	2.19	4.5	11.6	955	564	68	463	54
02/02/2017	2.12	0.26	0.73	0.9963	0.5889	0.9852	6.21	1.64	10.1	18.6	953	646	65	516	88
03/02/2017	2.70	−0.98	0.97	0.9984	0.2534	0.9405	1.97	5.04	9.9	54.5	956	543	64	433	136
07/02/2017	2.61	0.63	1.05	0.9971	0.8246	0.9941	0.30	4.61	0.8	3.7	958	716	60	520	76
08/02/2017	2.45	0.07	0.50	0.9959	0.0427	0.9694	5.74	3.91	22.3	98.9	800	612	80	486	97
09/02/2017	2.50	0.61	0.81	0.9973	0.7653	0.9795	7.63	3.89	29.7	128.6	800	615	68	454	76
10/02/2017	2.31	0.30	0.91	0.9954	0.6379	0.9789	9.50	1.76	16.9	44.5	949	611	61	488	87
13/02/2017	3.08	−0.11	1.23	0.9993	0.0015	0.9823	6.44	3.81	24.5	111.8	947	558	60	436	104
14/02/2017	2.61	0.14	0.68	0.9966	0.2700	0.9487	7.32	2.92	21.4	71.9	959	613	74	470	95
15/02/2017	2.41	0.14	0.69	0.9973	0.2015	0.9894	7.77	4.32	33.6	159.1	964	663	71	525	94
16/02/2017	2.39	−0.04	0.61	0.9959	0.0133	0.9682	9.06	5.74	52.0	323.7	965	619	74	446	102
17/02/2017	1.51	0.33	0.71	0.9965	0.7170	0.9889	9.60	2.07	19.9	50.8	962	640	53	498	78
21/02/2017	2.41	1.34	0.60	0.9935	0.6193	0.9612	8.13	8.48	68.9	605.3	957	606	75	461	44
22/02/2017	2.26	0.54	0.58	0.9955	0.7501	0.9738	5.63	5.94	33.4	207.4	954	697	74	473	76
23/02/2017	1.57	−0.65	0.77	0.9984	0.0542	0.9751	6.17	4.87	29.9	166.5	948	654	51	433	142
24/02/2017	1.54	0.09	0.52	0.9995	0.0588	0.9776	6.92	1.39	9.5	18.8	950	684	66	603	94
02/03/2017	2.64	0.02	0.47	0.9980	0.0014	0.9794	1.47	1.57	2.3	4.4	955	587	82	461	99

[1] The (N_2O), (CO_2) and (CO_{2_ref}) indicate that the values included in the column refer to the measurements using the N_2O tracer gas, the CO_2 or the CO_{2_ref} devices respectively.

Table 5. Office number 1, test 2 for each day. Experimentally determined air infiltration rates when the mechanical ventilation is active, climate variables and deviations between the results obtained the using the metabolic CO_2 concentration and the N_2O tracer gas.

Day	*n* (N_2O) [1] (ren/h)	*n* (CO_2) [1] (ren/h)	*n* (CO_{2_ref}) [1] (ren/h)	r^2 (N_2O) [1] (·)	r^2 (CO_2) [1] (·)	r^2 (CO_{2_ref}) [1] (·)	Ti − Te (°C)	W (m/s)	$W(T_i - T_e)$ [m/s] [°C]	$W^2(T_i - T_e)$ [(m/s)^2] [°C]	P_{atm} (mbar)	$CO_{2ref.max}$ (ppm)	Error (CO_{2_ref}) [1] (%)	CO_{2max} (ppm)	Error (CO_2) [1] (%)
31/01/2017	2.11	0.29	1.42	0.9979	0.7698	0.9911	6.75	2.12	14.1	32.6	954	544	33	489	86
01/02/2017	1.96	−0.29	1.21	0.9949	0.3562	0.9823	5.47	1.11	5.5	8.0	955	529	38	443	115
02/02/2017	2.00	0.12	1.10	0.9960	0.5396	0.9894	6.08	1.03	6.2	7.8	954	535	45	470	94
06/02/2017	2.25	0.56	0.98	0.9949	0.7154	0.9835	2.36	3.37	6.4	24.7	960	490	56	470	75
07/02/2017	1.34	−0.17	0.86	0.9988	0.1874	0.9901	4.10	3.30	13.7	53.2	957	519	36	461	113
08/02/2017	1.33	0.43	1.04	0.9997	0.6881	0.9916	8.91	1.65	14.0	30.0	800	515	22	458	68
13/02/2017	0.95	0.04	0.76	0.9826	0.0970	0.9128	8.90	2.55	22.4	69.2	951	577	20	409	96
17/02/2017	1.22	0.71	1.07	0.9767	0.8458	0.9208	11.91	2.65	31.2	94.4	961	545	12	495	42
20/02/2017	0.95	0.51	1.38	0.9992	0.7741	0.9104	11.29	7.22	81.3	618.8	958	531	44	409	47
22/02/2017	1.12	0.39	0.99	0.9844	0.7994	0.9958	8.21	3.54	29.0	121.8	952	563	11	473	65
23/02/2017	1.42	0.41	1.07	0.9983	0.7682	0.9951	9.87	1.74	16.9	34.1	948	559	25	486	71
24/02/2017	1.36	0.30	1.33	0.9800	0.1849	0.9935	9.48	1.02	9.3	12.4	951	565	2	440	78
02/03/2017	1.46	0.83	1.60	0.9965	0.3075	0.9893	6.54	1.33	7.9	13.2	954	547	9	439	43

[1] The (N_2O), (CO_2) and (CO_{2_ref}) indicate that the values included in the column refer to the measurements using the N_2O tracer gas, the CO_2 or the CO_{2_ref} devices respectively.

4. Conclusions

This section summarises the conclusions regarding the behaviour of the air renovation rate and discusses the effect of this behaviour on the experimental assessment of the Heat Transfer Coefficient (HLC).

The following conclusions are extracted regarding the air renovation rate from the different tests carried out:

- When the mechanical ventilation is not active: Significant correlation between air renovation rate and the wind speed has been observed in both buildings and the Test Cell. The agreement between the values obtained using N_2O and the evolution of metabolic CO_2 increases when the starting value of CO_2 concentration increases.
- When the mechanical ventilation is active: Large variations have been observed among the different values obtained along the test campaign using N_2O tracer gas. However, these values do not show any correlation with any of the considered climate variables. Consequently, the observed spread has been used to estimate an uncertainty of the air renovations rate. The measurements based on CO_2 concentrations do not show good agreement to the values obtained using N_2O tracer gas. This issue will be further investigated, but in principle it is attributed to the low level of CO_2 measured along the analysed test campaign when the mechanical ventilation is active. This explanation is in agreement with previous works carried out regarding the air renovation in the same building [15].

The behaviour observed in the air renovation rate, showing large variability considering infiltrations and also considering mechanical ventilation, contributes to understand the behaviour of the HLC experimentally assessed and its uncertainties. The following text summarises the conclusions extracted from this work and some ideas for further research, regarding the influence of the air renovation rate on the behaviour of the Heat Loss Coefficient (HLC):

- Regarding infiltrations, the dependencies of the n value with the wind speed and its variation per unit of time in absolute value, can explain some variability of the HLC and some uncertainty when it is assumed as a constant value. Further analysis of this wind dependence is an interesting issue regarding future research works that could lead to a wind dependent HTC reducing the uncertainties of this coefficient in experimental assessments.
- The behaviour observed in the n value for the case of mechanical ventilation leads to conclude that the experimental assessment of an HLC assuming n as constant could lead to some degree of uncertainty. The work presented in this paper has not identified any variable that could contribute to model such variability reducing the associated uncertainty. This issue is identified as a relevant topic regarding future research.

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References

1. EBC Executive Committtee. *Strategic Plan 2019–2024. Energy in Buildings and Communities Technology Collaboration Programm*; International Energy Agency: Paris, France, 2019.
2. Tian, W.; Heo, Y.; de Wilde, P.; Li, Z.; Yan, D.; Park, C.S.; Feng, X.; Augenbroe, G. A review of uncertainty analysis in building energy assessment. *Renew. Sustain. Energy Rev.* **2018**, *93*, 285–301. [CrossRef]
3. Kampelis, N.; Gobakis, K.; Vagias, V.; Kolokotsa, D.; Standardi, L.; Isidori, D.; Cristalli, C.; Montagnino, F.M.; Paredes, F.; Muratore, P.; et al. Evaluation of the performance gap in industrial, residential & tertiary near-Zero energy buildings. *Energy Build.* **2017**, *148*, 58–73. [CrossRef]
4. Annex 71 of the Programme "(EBC)" of the IEA on EBC Annex 71. Building Energy Performance Assessment Based on In-Situ Measurements. 2016–2021. Available online: http://www.iea-ebc.org/projects/project?AnnexID=71 (accessed on 4 December 2020).
5. Jiménez, M.J. IEA, EBC annex 58, report of subtask 3, part 1. In *Thermal Performance Characterization Based on Full Scale Testing–Description of the Common Exercises and Physical Guidelines*; Jiménez, M.J., Ed.; KU Leuven: Leuven, Belgium, 2016; ISBN 9789460189876. Available online: http://www.iea-ebc.org/Data/publications/EBC_Annex_58_Final_Report_ST3a.pdf (accessed on 3 November 2020).
6. Marin, M.; Vlase, S.; Paun, M. Considerations on double porosity structure for micropolar bodies. *AIP Adv.* **2015**, *5*, 037113. [CrossRef]
7. Sherman, M.H. On the estimation of multizone ventilation rates from tracer gas measurements. *Build. Environ.* **1989**, *24*, 355–362. [CrossRef]
8. ISO 9972:2015. *Thermal Performance of Buildings–Determination of Air Permeability of Buildings–Fan Pressurization Method*; ISO: Geneva, Switzerland, 2015.
9. Olazo-Gómez, Y.; Herrada, H.; Castaño, S.; Arce, J.; Xamán, J.P.; Jiménez, M.J. Data-based RC dynamic modelling to assessing the in-situ thermal performance of buildings. Analysis of several key aspects in a simplified reference case toward the application at on-board monitoring level. *Energies* **2020**, *13*, 4800. [CrossRef]
10. Díaz-Hernández, H.P.; Torres-Hernández, P.R.; Aguilar-Castro, K.M.; Macias-Melo, E.V.; Jiménez, M.J. Data-based RC dynamic modelling incorporating physical criteria to obtain the HLC of in-use buildings: Application to a case study. *Energies* **2020**, *13*, 313. [CrossRef]
11. Remion, G.; Moujalled, B.; El Mankibi, M. Review of tracer gas-based methods for the characterization of natural ventilation performance: Comparative analysis of their accuracy. *Build. Environ.* **2019**, *160*, 106180. [CrossRef]
12. Carrié, F.R.; Leprince, V. Uncertainties in building pressurisation tests due to steady wind. *Energy Build.* **2016**, *116*, 656–665. [CrossRef]
13. Farmer, D.; Johnston, D.; Miles-Shenton, D. Obtaining the heat loss coefficient of a dwelling using its heating system (integrated coheating). *Energy Build.* **2016**, *117*, 1–10. [CrossRef]
14. Marshall, A.; Fitton, R.; Swan, W.; Farmer, D.; Johnston, D.; Benjaber, M.; Ji, Y. Domestic building fabric performance: Closing the gap between the in situ measured and modelled performance. *Energy Build.* **2017**, *150*, 307–317. [CrossRef]
15. Enríquez, R.; Bravo, D.; Díaz, J.A.; Jiménez, M.J. Mechanical ventilation performance assessment in several office buildings by means of Big Data techniques. In Proceedings of the 36th AIVC Conference "Effective Ventilation in High Performance Buildings", Madrid, Spain, 23–24 September 2015; ISBN 2-930471-45-X.
16. Baker, P.H.; van Dijk, H.A.L. PASLINK and dynamic outdoor testing of building components. *Build. Environ.* **2008**, *43*, 127–128. [CrossRef]
17. Castaño, S.; Guzmán, J.D.; Jiménez, M.J.; Heras, M.R. LECE-UiE3-CIEMAT. In *Report of Subtask 1a: Inventory of Full Scale Test Facilities for Evaluation of Building Energy Performances. IEA EBC Annex 58*; Janssens, A., Ed.; KU Leuven: Leuven, Belgium, 2016; ISBN 9789460189906.
18. Jiménez, M.J.; Porcar, B.; Heras, M.R. Estimation of UA and gA values of building components from outdoor tests in warm and moderate weather conditions. *Solar Energy* **2008**, *82*, 573–587. [CrossRef]
19. Olmedo, R.; Sánchez, M.N.; Enríquez, R.; Jiménez, M.J.; Heras, M.R. ARFRISOL Buildings-UIE3-CIEMAT. In *Report of Subtask 1a: Inventory of Full Scale Test Facilities for Evaluation of Building Energy Performances. IEA EBC Annex 58*; Janssens, A., Ed.; KU Leuven: Leuven, Belgium, 2016; ISBN 9789460189906.