Evaluation of the intrinsic thermal performance of an envelope in hot period.

Outdoor experiment at a 40m³ test cell

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Abstract. Ensuring the proper thermal performance of a building's envelope upon reception is an important stage in the life cycle of the building. Several methods already exist for this purpose, and continue to be improved, such as co-heating, ISABELE, EPILOG, QUB and SEREINE. All these methods follow the common protocol consisting of heating the measured building with an electrical system. These measurement protocols quantify the dynamic evolution of interior and outdoor temperatures, and the thermal power injected into the building. These data are used in calibration algorithms to determine, by an inverse method, a heat loss value. These methods require a difference of a few degrees between the interior and the exterior which can cause in summer periods a risk of damaging the building, as the outside temperature may already be high. The objective of this work is to explore the possibility of determining the intrinsic thermal performance of a building's envelope in the summer period using a cooling hydraulic system. Some encouraging experiments have been done on a square meter scale cell in an indoor environment. The focus of this paper is to test a similar method in an outdoor Passys test cell of $40m^3$ and explore the capacities and limitations of the method at this scale by varying several stress parameters of the enclosure. First, some electrical heating modes are run acting as reference values. Then, a hydraulic system is used to estimate the HLC value and gives comparable results to the electrical mode considering an uncertainty of 2 W/K. Third step is to setup cooling scenario with the hydraulic system. Some of the results are also comparable with the heating mode and some limits are highlighted such as the cooling power limitation to avoid water condensation into the cell. This impact of condensation is then studied and seems to have a limited impact on the results for this experiment.

Keywords. Envelope thermal performance; assessment; performance guarantee; Cooling; Experimentation
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1. Introduction

Ensuring the proper thermal performance of a building's envelope, whether new or renovated, upon its reception is an important step in the life cycle of the building. It allows to quantify the performance gap and to ensure the good consistency between the design phase and the implementation during the construction work, in order to consider possible corrective actions to reduce its environmental impact. Several methods exist for this purpose and continue to be improved such as co-heating(1), ISABELE (2), EPILOG, QUB (3) or SEREINE methods. The objective is to determine the thermal performance of an envelope which can be quantified by the Heat Loss Coefficient (HLC in [W/K]), which is the sum of the heat loss due to infiltration (H_{inf}) and the heat loss due to conduction through the walls (H_{tr}) (towards the exterior and the ground). These values will partly depend on the test conditions including the indoor and outdoor pressure difference and the operative temperature inside, the outside air temperature for H_{inf} and the convective heat transfer coefficient under real conditions for H_{tr}. All these methods have the common point to stress the building over a certain period using a heating system. These protocols measure the dynamic evolution of the indoor temperatures, the thermal power injected into the building and the outdoor conditions. For most of these methods, these data are then used in a calibration algorithm using a RC model to determine, by an inverse method, the model parameters and thus deduce the HLC (Heat Loss Coefficient). These methods require an indoor temperature a few degrees higher than the outside temperature, a gap that is potentially no longer acceptable in summer periods without the risk of damaging the measured building. The aim of the work is consequently to develop a test methodology with a cooling system in order to be able to measure a HLC coefficient even in summer periods.

2. Research Methods

2.1. *Research objective*

The overarching objective of this work is to develop a test methodology with a cooling system in order to be able to measure a HLC coefficient even in summer periods. Some previous work (4) have been done to sketch and test such method at a $1m^3$ indoor cell using a water/air heat exchanger. The test consists of cooling the air inside the cell and measuring the dynamic evolution of the injected cooling power and the temperature inside and outside the cell. The power required to compensate the heat losses with the exterior is then estimated leading to the HLC coefficient of the cell using the SEREINE calibration method. More specifically, the work presented here aims to test this methodology on a larger cell, about $40m^3$ positioned in an outdoor environment. This will need to solve two technical and scientific barriers, the first related to the change of scale and the second to the added perturbations due to solar radiation and day/night temperature variation.

2.2. *Existing methods*

As mentioned in the introduction, several methods exist to determine the proper thermal performance of a building's envelope such as HLC. These tests need an unoccupied building from one to 30 days depending on the methods to estimate a HLC coefficient. First, a blower door test is done to estimate the infiltration flow rate's characteristics of the building. Secondly, the thermal behaviour of the envelope is monitored. For that, a specific thermal stress scenario is set into the building thanks to electric fan coils. During this test, the indoor temperature, the electrical consumption and the weather conditions are dynamically monitored. These data are then used in mathematical models to identify the model parameters and deduce H_{tr} and HLC as shown in **Fig. *1*** from (5)

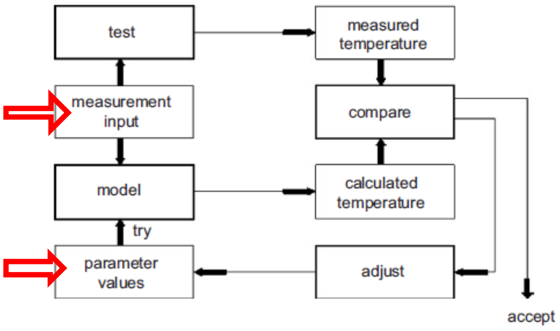

Fig. 1 - Process steps *(5)*

The purpose of the optimization algorithm for the calibration is to find the set of parameters (of the RC model retained) which minimizes the difference between measured interior temperature and the simulated one based on the experimental data (injected power inside and the outside temperature). The algorithm used is taken from the numerical code used in SEREINE method, currently under development. This algorithm is an evolution of the versions used in previous methods (ISABELE (2) and EPILOG), and is partly based on the pySIP uncertainty propagation algorithm (6).

The present analysis consists in calculating by inverse method the HLC of an envelope, from a RC model (7) (8) from the SEREINE tool.

The aim of this work is to validate that the calibration method works with a cooling scenario, allowing to make changes only for the thermal stress of the building and the energy consumption measurement technique.

2.3. *From electric to hydraulic energy source*

One major change in our methodology is to switch from an electrical to a hydraulic thermal source. In order to produce and dissipate cool into the cell, we are using a hydraulic system instead of the conventional electrical fan coils. This implies to change the way to calculate the energy dissipated into the cell. In the existing methods, power sensors measure the electrical consumption of the equipment put into the cell and suppose that the energy consumption is equal to the energy loss by the envelope with a thermal performance ratio of the electrical fan coils and other equipments of 1. The uncertainty of the electrical power sensor used is 2% on the range used. For the hydraulic system, the power injected by the fluid into the cell is estimated thanks to the fluid flow rate, the temperature difference of the fluid entering and leaving the cell as mentioned in equation (1). The energy loss/gain by the envelope (P_{in} [W]) is the sum of energy captured by the fluid (negative) (P_{hydrau}) and the electrical consumption of the fan (P_{fans}), which aims to optimize the heat exchanger's performance and homogenizes the indoor air temperature in the building.

$$P_{hydrau} = \dot{m}_{water} \cdot Cp_{water} \cdot (T_{water-out} - T_{water-in}) \quad (1)$$

$$P_{in} = P_{Hydrau} + P_{fans} \quad (2)$$

With P_{hydrau}, the power released by the fluid inside the cell in [W], $\dot{m}_{water}$ the volume flow rate of water flowing into the heat exchanger in [kg/s], Cp_{water} the thermal capacity of water (fluid used in the thermal bath) in [J/(kg.K], $T_{water-out}$ and $T_{water-in}$ the water temperatures exiting and entering the cell, in [°C or K].

The uncertainty on the hydraulic power is estimated to be:

$$\frac{\Delta P_{hydrau}}{P_{hydrau}} = \sqrt{\left(\frac{\Delta \dot{m}_{eau}}{\dot{m}_{eau}}\right)^2 + \left(\frac{\Delta(\Delta T_{eau})}{\Delta T_{eau}}\right)^2 + \left(\frac{\Delta C_p}{C_p}\right)^2} \quad (3)$$

2.4. *From heating to cooling methods*

Another challenge in this method, which implies to change from a heating method to a cooling method, is the questioning of the condensation. Indeed, bringing cool fluid into a closed cell might generate some condensation phenomena at the cooled pipes surface. If condensation appears in the cell / building, it generates a phase change energy sink. So part of the energy brought by the hydraulic system will be used for phase change (from vapour to liquid) and not to compensate the heat flux through the walls. So either we need to avoid condensation or at least we need to quantify it dynamically.

In previous work (4), the feasibility of this method on a small indoor 1m^3 scale have been demonstrated. Some barriers to change scale to real one and validate the method in outdoor conditions are the interest of this article using the same methodology.

3. Case study

3.1. Experimental cell description / envelope to measure

The test cell used in this study is a Passys cell (**Fig** ***2***) of around 40m3 developed in the project PASLINK (9) and which presents 5 faces highly insulated (~40cm of insulation), and an adaptive facade. In our case, the adaptive facade was south oriented partly glazed (standard double glazing) and poorly insulated woodframe wall for the rest (R~0.5 m^{2}K/W). The opposite face which is one of 5 highly insulated faces separates the cell of a technical room.

Fig 2 – Outside view of a Passys cell

3.2. HVAC system for energy source.

The cooling/heating transmitter is an air/water exchanger placed inside the cell as illustrated in **Fig.** ***3***. The water circulating in this exchanger is cooled or heated by a thermal controlled bath **Fig.** ***4*** with a variable flow pump to set the water flow running through the hydraulic circuit. The heat exchanger is paired to an electric fan, its purpose is to stir the air that runs through the exchanger and to homogenize the interior atmosphere of the cell. The power consumption of the fan is calculated upstream and is taken into account in the overall thermal power that is injected into the experimental cell, considering that the electrical power consumed by the fan is dissipated into heating power. A second ventilator is set to homogenize the indoor air temperature.

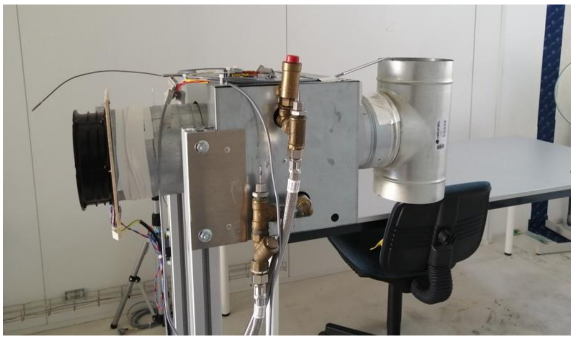

Fig. 3 – Water/Air heat exchanger inside the cell

Fig. 4 - Heating/Cooling systems, left: Generation - Thermal bath, right: View of inside the Passys Cell

3.3. Sensors

The physical quantities measured inside the cell are air, surfaces and water temperatures, the heat fluxes through certain walls, the relative humidity of the air, as well as the water flow rate. A weather station situated on site gives the data for the outdoor temperature and the solar radiation. The setup and position of the sensors is summarized in Table 1. The temperature probes were calibrated upstream of the tests with their complete acquisition chain. The data from the sensors are pre-processed to feed the algorithm presented in the following paragraph. An average indoor air temperature is calculated from the sensors installed.

Tab. 1 - Setup and position of the sensors.

Type of sensors [Unit]	Position	Setup	Nb
Temperature [°C]	Inside Cell – Air	At different points of the cell	11
	Inside cell – Air	Inlet and outlet of heat exchanger	2
	Inside Wall Surface	Center of Each cell face	5
	Outside Cell - Air	Adjacent Room Outdoor	1 1
	Outside Wall Surface		

	Hydraulic loop	Cell Inlet	1
		Cell Outlet	1
Flowmeter **[kg/h]**	Hydraulic loop	Cell Inlet	1
Hygrometer **RH [%]**	Air	Outlet of heat exchanger	1
		Adjacent Room	1
Heat-flux [W/m^2]	Indoor walls	Top/Bottom /Right/Left	4

In the usual methods, electrical resistors are used as heat sources. The dissipated power is then measured directly by monitoring the electrical consumption. One of the challenges in cooling mode is to be able to measure with a sufficient accuracy the thermal power injected into the enclosure. In our case, it is calculated by adding the calorific power supplied by the hydraulic system to the electrical power supplied by the fan. The calorific power is calculated using the water flow rate and the water temperature measurements of the hydraulic circuit taken at the inlet and outlet of the cell [eq (2)].

The power of the fans was calculated before the presented tests by measuring the intensity of the current running through the fan using a multimeter for various voltage values, and gives the following values:

$$P_{fan\_HE} = 42{,}6\,W \;;\; P_{fan\_cel} = 24{,}8\,W$$

3.4. Scenarios setup

Tests were ran between May and December 2021 with different families of scenarios that had been ran with both electrical and hydraulic system.

With the electrical system, the scenarios are a co-heating system and 3 pseudo-random scenarios. The co-heating, which will serve as a reference value, lasts 17 days with a fixed set point temperature at 35°C. During the co-heating, the heating power varies automatically to compensate the indoor/outdoor temperature difference and maintain the indoor set point temperature. Pseudo Random scenario (inspired from SEREINE project and named PSA in this article) consist of sequences with heating source ON and OFF with variable duration from a few minutes to a few hours as shown in **Fig. *5*** for 2 types of PSA (short and long). Pseudo Random scenario test the dynamical behaviour of the building as explained in (5). In this scenario, when heat is ON, the heat power is fixed and is stop only if the temperature limit is reached (35°C) in order to not damage the building/cell.

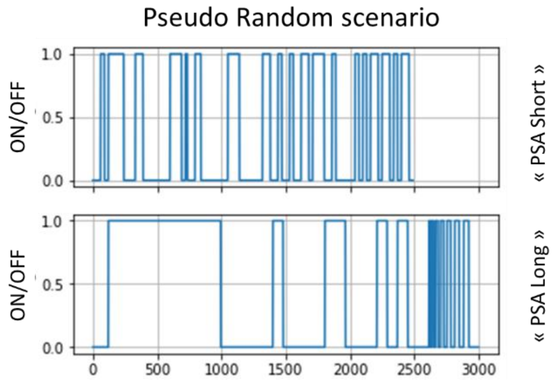

Fig. 5 - Pseudo Random scenario

Tab. 2- Scenario setup

Type	*Mode*	*Set Point*	*Scenario*	*tests nb*	*Exploitable results*
Hydraulic	**Heating**	35 °C	Steady	Hy.1	YES
			PSA short	Hy.7	YES
			PSA long	Hy.17	NO
		30 °C	Steady	Hy.11	YES
		25 °C	PSA long	Hy.8	NO
	Cooling	18 °C	PSA short	Hy.2, Hy.3	NO
		15 °C	Steady	Hy.4, Hy.6	NO
			PSA short	Hy.5	NO
		10 °C	Steady	Hy.9, 10, Hy.12, 13, Hy.14	YES
			Shifting	Hy.15	YES
	Alter-nation	10 - 35 °C	Shifting	Hy.16	YES
Electric	**Heating**	35 °C	Co-heating	El.1	YES
			PSA short	El.2, EL.3	YES
			PSA long	El.4, El.5	YES
		200 W	Steady	El.6	YES

Second family of scenario is using the hydraulic system. For them, two parameters were controlled: the set point temperature of the thermal bath fluid which is then entering the PASSYS cell, and the flow rate of the water getting through the heat exchanger in the Passys cell. Contrary to the electrical scenario, neither the indoor temperature nor the heat flux are controlled in the hydraulic scenario. Three kinds of scenario with the hydraulic system have been tested. Some steady state scenario lasting from 2 to 5 days, both in cooling or heating mode depending of the weather forecasts, some Pseudo Random scenario, following the same spirit as the one with the electrical system and finally scenarios with thermal bath set point temperature shifting from cooling mode during the day to a heating mode during the night.

As illustrated in **Tab.** *2*some of the scenarios were implemented several times in order to verify the repeatability of the experiment.

3.5. Mathematical model used

The mathematical model used in our calibrations is the RC TWTI model from the SEREINE tool (or M2_TmTi model in (7)), where TW indicates the presence of a capacitance associated with two transmittances modelling the envelope and Ti indicates the presence of a capacitance modelling the internal mass. In our case, this internal mass is supposed to model the internal air volume to be cooled. It requires as input data the power supplied, the indoor temperature given by the air temperature sensors, and the equivalent exterior temperatures of the enclosure.

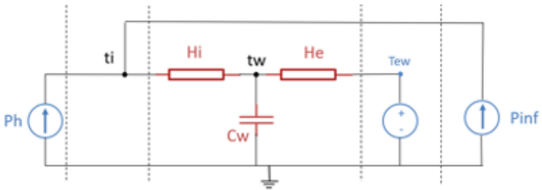

Fig. 6 - RC model used for the calibration.

As far as the exterior temperature is concerned, taking only the outside air temperature around the cell is not enough, because we won't consider the solar radiation on the outside surface of the Passys cell. To take into account the impact of solar radiation into the cell, an equivalent outside temperature $T_{ew-meteo}$ is calculated using meteorological data and surface caracteristics of the test cell.

4. Results

4.1. Passys cell airtightness

As mentioned in paragraph 2.2, in order to be able to separate the impact of infiltration to heat loss, it is important to measure the airtightness of the building. To estimate the infiltration flow rate of the cell, some blower tests have been done and give a Q_{50} value of 138 m^3/h at 50 Pa and an equivalent surface ELA of 0,0026m^2 as mentioned in **Tab.** *3*. Thanks to this last value, we estimate the infiltration flow rate thanks to the model defined by the LBNL model defined by Sherman in (10) depending on the indoor/outdoor temperature difference and the wind velocity, according to equation (4)

$$Q_{inf} = ELA * \sqrt{f_w^2 * v^2 + f_s^2 * |\Delta T|} \ (4)$$

Where Qinf is the infiltration flow rate (m^3/s), fw=0,13 et fs=0,12 m/(s.K$^{1/2}$) are constant coefficients linked to wind and thermal effects. We estimate the thermal loss due to infiltration thanks to the following formula:

$$P_{inf} = Q_{inf} * \rho_{air} * Cp_{air} * \Delta T \ (5)$$

$$H_{inf} = \frac{P_{inf}}{\Delta T} \ (6)$$

Tab. 3: Blower Door results

Estimated quantity	Value
Q_{50} (m^3/h)	138
ELA (m^2)	0,0026

With P_{inf} the power loss due to infiltration in [W], Cp_{air} the thermal capacity of air in [J.kg/K], and ΔT the temperature difference of air between inside and outside the cell. For the Passys cell, we aim to estimate: $H_{inf} = 2{,}3\frac{W}{K}$ considering an average velocity of 5m/s

4.2. H_{tr} theoretical estimation

A first estimation of the Heat Transfer loss by the walls is calculated thanks to the cell specifications (dimensions and material properties) and is summarized in the following graph and table. The H_{tr} is estimated to be greater than 13W/K, regarding that the thermal bridges due to singular points were not fully quantified, and so adding the infiltration loss leads to a HLC greater than 15.3 W/K, which means that the infiltration loss represents a maximum of 15% of the envelope thermal loss.

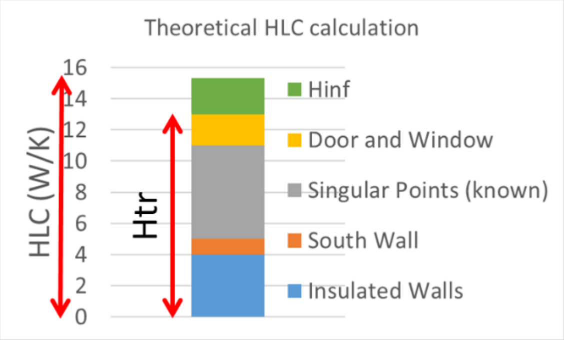

Fig. 7 - HLC theoretical estimation

4.3. Results with an electric scenario

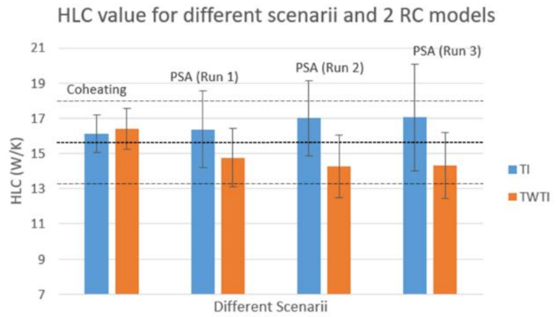

Fig. 8 - Electrical results

Some scenarios have been run with fan coils to get some values with existing methods. A 17 days scenario with a constant temperature at 35°C (named Coheating in the following figure) gives a HLC value estimated to 16.4 W/K with an uncertainty of 1.2 W/K with TWTI RC models from SEREINE method. 3 PSA scenarios with different durations of heating and relaxation mode succession give HLC values between 14 and 17 W/K, all included in a +/-15% range around the estimated theoretical value of 15.3 W/K.

4.4. *Results with a hydraulic scenario*

The **Fig.** ***9*** shows the data monitored for a 3-day scenario, its upper side shows a graph of the evolution of the injected power P_inj and the effective power Ph, received by the cell, which is, in a cooling mode, lower than P_inj because of the heating power released by the electric devices in the cell. The lower graph shows the evolution of the internal air temperature (Ti) and the equivalent outdoor temperature T_{ew-1BC}as mentioned in paragraph 3.5. The power gets stabilized after less than one day around 200 W and the small daily variations are due to the same variations observed in the evolution of the internal temperature, in the second part of the graph. The internal temperature has the same stabilization time and then follows the external temperature but shifted and highly dampened.

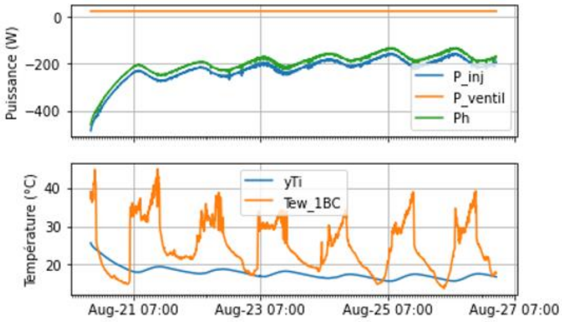

Fig. 9 - Evolution of Power injected and temperatures for a scenario

A series of tests were monitored with the scenario mentioned as "Steady" (section 3.4) , in the cooling mode as well as in the heating mode and the results for a calibration process using the TWTI model (section 3.5) are displayed in **Tab.** ***4***. The values of HLC obtained under the same control temperature, high temperatures (e.g. 35°C) as well as cold ones (e.g. 10°C), and same scenario are repeatable and gathered within the range [14.5, 17.5] W/K, with a global uncertainty lower than 3 W/K. These HLC values were obtained after a stabilization time included between one and four days, because of the cell's volume and the relatively low power injected, depending on the internal temperature and the control one. A comparison of these values with the theoretical one (section 4.2), contained in this range, can validate the model. However, some discrepancies can be observed in the HLC value when the control temperature changes, and even if it can be explained by the uncertainties, a further investigation could lead to a better understanding of the phenomenon.

Tab. 4 - Results with hydraulic mode for both cooling and heating tests

Test nb	Set Point [°C]	HLC [W/K]	ΔHLC [W/K]	Test Duration (Day)
Hy.1	35	14.9	2.8	2.8
Hy.7	35	15.4	1.8	1.9
Hy.9	10	17.1	1.9	5.0
Hy.10	10	17.5	1.5	5.7
Hy.11	30	17.0	1.9	3.2
Hy.12	10	17.3	1.4	6.8
Hy.13	10	15.5	1.0	4.6
Hy.15	10	15.6	1.7	2.1

Another series of tests were lead with Pseudo Random scenarios as mentioned in section 3.4. It was not possible to estimate a correct value of HLC with these scenarios due to the energy injected in the cell was to small to lower the indoor air temperature and to compensate the external gains. Indeed, it is necessary to create a difference of temperature, either positive (for heating method) or negative (for cooling method), between the indoor and outdoor environments, in order to notice the heat gains or losses through the walls. Thus, the energy injected should both be able to compensate the heat losses or gains through the walls but also to cool down the air temperature in the cell at the beginning of the experiment. With the relatively small value of power injected in the cell, the periods in all the PSA tested were not long enough to cool down the cell. Indeed, the modules used in the SEREINE method provide a constant power between 700 W and 2 kW instead of the maximum of 500 W that we observed in these experiments with an hydraulic system and an intermittent operation due the Pseudo random scenario. It can explain the lack of results observed when this kind of scenario in a cooling mode were lead.

An increase of the power injected, by means of lowering control temperature or increasing the waterflow, needs to be explored to check its feasibility.

4.5. *Condensation wonderings*

Working with a cooling method implies to choose between a temperature not too low to avoid condensation in the cell but which limits the heat flux of the heat exchanger or a lower temperature to increase the power generation but this leads to condensation in the cell. As mentioned in paragraph 2.4, it is important to control condensation since this generates a new term in the energy flux equation. So if condensation appears in the cell, a part of the power injected is used for phase change, and need to be quantified to estimate the correct HLC value.

Regarding the low heat flux generated thanks to a water temperature at 15 and 18°C, it has been decided to test the method with a lower temperature (10°C) which generates condensation phenomena. Indeed, with a humidity varying between 8 and 10 g/kg in the cell, a control temperature of 10°C was lower than the dew point temperature, according to the psychrometric chart. During different tests working in the cooling mode, condensation appeared and was observed thanks to pictures captured at a time step of 10 minutes. Two elements rose from this observation:

- some water drops appeared on the pipe all along the test
- during the first hour of each test, a puddle under the inlet pipe closed to its entrance in the cell increased and then started to decrease until it stabilized, which might be due to a probable evaporation, possibly due to the relative higher temperature of the floor.

Following these observations, condensation was neglected, since it was considered to reach a stationary state at the cell's scale, due to the equilibrium between condensation on the entering pipe and evaporation on the floor. Two tests were, then, lead under the same set point temperature and indoor humidity. For one test, the pipes were insulated, preventing from condensation on the pipe. The HLC value was 16,2 ± 2,4 W/K in the insulated case and 17,3 ± 1,4 W/K in the other one. Thus, both results are within the range considered in previous section, validating the previous consideration: in these conditions, condensation can be neglected, since no real discrepancies in the HLC value are noticed.

5. Conclusion

During this work, some experiments have been done to estimate the HLC value of a Passys cell with different thermal stress methods. Two systems were tested: an electrical one thanks to fan coils, and a hydraulic system thanks to a thermal bath coupled to a water to air heat exchanger. Both heating and cooling tests have be tested. The thermal stress scenarios vary from a steady state scenario (a 17 days co-heating test serving as a reference value) to Pseudo Random scenario with sequences of heat sources On/Off varying from a few minutes to a few hours. All these experimental Data were then used in the SEREINE calibration tool to estimate the HLC value.

It has been shown that it is possible to estimate the HLC value of a Passys cell (40m^3 cell in real outdoor condition) in an acceptable range of uncertainty for both electrical and hydraulic system and for both heating and cooling methods. The HLC value of this cell is around 16 W/K, which is too low to be representative of a real size building, but still presents some strong interest in the method development.

Some limitations of the cooling method with this hydraulic system appeared and began to be investigated. The power injected with the hydraulic system used in a cooling mode needed an inlet temperature under the dew point temperature. So, condensation could not be avoided~~was a bit too low if the condensation wants to be avoid~~. However, condensation ~~which appeared with a lower set point temperature~~ seems not to~~to not~~ impact the ability~~capacity~~ to estimate the HLC of the Passys cell.Another limitation is that Pseudo Random scenario which are really promising to reduce the duration of tests with electrical fan coils was not successful in these experiments mainly due to a low energy injected to the cell with the system coupled to its intermittent operation.

Finally, further works need to be investigate to check the feasibility of such a method at a real scale house

6. Acknowledgement

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Data Statement

The datasets generated during and/or analysed during the current study are not available because of time necessary to clean and extract the specific data but the authors will make every reasonable effort to publish them in near future.