Implementation of an innovative hybrid low-energy cooling strategy controlled with a fuzzy logic algorithm in a dwelling: numerical and experimental approaches

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Abstract

Nowadays, in cold and temperate climates, buildings are always more insulated and airtight leading to high heating savings. However, it penalizes a lot the summer thermal comfort and the cooling performance. That is why a current building issue deals with the cooling control and its ability to manage both the summer thermal comfort and the energy savings. Given that, our work proposes an innovative hybrid cooling solution controlled by a fuzzy logic algorithm, combining a passive natural ventilation device with a low-energy active cooling system. The strategy efficiency is demonstrated with a numerical approach and strengthens with an experimental campaign.

Key Innovations

- Hybrid low-energy cooling strategy
- Control with a fuzzy logic algorithm

Practical Implications

The use of the natural ventilation during the night instead of the active low-energy cooling system allows to reduce the cooling needs and to give opportunities of regeneration for the water tank.

Introduction

In cold and temperate climates, the current technologies allow now to reach a good efficiency considering the energy losses. Buildings are highly insulated and their airtightness increases a lot. However, whereas those saving solutions are particularly efficient for heating considerations, they can penalize a lot the summer comfort. Thus, it is necessary to focus on the cooling considerations to be able to guarantee a thermal comfort for the occupants. The main problem resides in the fact that the simpler way to address this issue is to use air-conditioning system. However, it constitutes a significant increase in the global energy consumption. To avoid that, some authors propose intelligent solutions to control hybrid cooling systems combining an active energy-consuming air-conditioning and a passive natural ventilation device (S. J. Emmerich, 2006), (Z. J. Zhai, 2011), (J. Hu, 2014), (Y. Chen, 2019). Our work proposes to go further by associating a natural ventilation device with an innovative low-energy active cooling system for reaching thermal comfort in a dwelling by maintaining a small energy consumption. This latter is composed of a water tank placed on the ground of a crawlspace. It is connected to the indoor environment of a house by a cooling floor. The water contained in the tank is then circulating in the cooling floor when it is activated. This water is refreshed by only two ways: first, naturally by the ground and second, artificially by an additional fan supplying air from the exterior to the surface of the tank. To guarantee the flexibility of the control algorithm, the method chosen is the fuzzy logic. One advantage of this technique resides in the fact that it allows modelling the user behaviour for using a system instead of the system itself. Given that, it requires global concepts to describe approximate variables instead of precise numerical values. It provides then a large flexibility of the control algorithm. Some authors have already shown the efficiency of the fuzzy logic for the ventilation control (A. I. Dounis, 1996), (M. M. Eftekhari, 2003), (R. Z. Homod, 2014). The objective of this article is first to design and to optimize the use of such an innovative hybrid system by employing the numerical approach. Notably, a goal will be to assess the improvement of the low-energy water tank cooling system efficiency thanks to the additional use of a passive cooling strategy. Then, a second part will consist in confirming the system efficiency by an experimental campaigns. First of all, a short presentation of the hybrid cooling system is proposed.

Presentation of the hybrid cooling system

The hybrid solution proposed in this article combines a natural ventilation device and an active low-energy cooling system. More specifically, the natural ventilation is ensured by the coupling of the entrance door placed in the lower part of the dwelling and a skylight positioned in the upper part. Both the door and the skylight can be opened with a 45° angle. This cross configuration is particularly favourable for increasing the airflow thanks to the wind and stack effect. Let us precise that the choice of the entrance door has been done for practical experimental reasons. Security issues could appear and the necessity of a more suitable device would be questioned. However, the goal of this article was mainly to provide a proof of concept.

Figure 1: Scheme of the natural ventilation device
Considering the active low-energy solution, one has proposed to enhance the natural cooling delivered by both the outdoor and the ground temperatures to refresh a water storage. Especially, a water tank with a volume of 3.4 m³ is positioned in the crawlspace of an individual dwelling. The tank is linked to a water cooling circuit located in the floor inside the dwelling. The first principle is to benefit of the fresh temperature of the ground to cool the water in the tank. To increase the water cooling, a fan is then added in the crawlspace and supplies air in the surface of the tank to refresh even more the water contained inside. Previous experiments have shown a major influence of this forced convection on the water cooling. Given that, it has only few influence on the ground temperature. Moreover, during the heating season, the cooling system is not used, the ground is then able to regenerate successfully.

**Numerical approach**

A numerical approach has been chosen to design and optimize the use of the hybrid innovative low-energy cooling solution. To do that, a model of the water temperature in the tank located in the crawlspace has been coupled with a building model developed with the EnergyPlus software (U.S Departement of Energy, 2016).

**Water tank model**

This model is based on the electrical analogy. The Figure 2 presents the structure of the proposed RC model.

The associated equation is given below:

\[
C_{\text{water}} \frac{dT_{\text{tank}}}{dt} = - \frac{T_{\text{tank}} - T_{\text{ground}}}{R_{\text{cond,water,ground}}} - \frac{T_{\text{tank}} - T_{\text{air,CS}}}{R_{\text{cond,water,rad}}} - \frac{R_{\text{hydro}}}{R_{\text{conv}}} \left( \frac{T_{\text{return,floor}} - T_{\text{tank}}}{R_{\text{conv}}} + \frac{T_{\text{air,CS}} - T_{\text{return,floor}}}{R_{\text{hydro}}} \right) + \frac{R_{\text{hydro}}}{R_{\text{conv}}} \left( \frac{T_{\text{air,CS}} - T_{\text{return,air}}}{} \right)
\]

In this equation, \( C_{\text{water}} \) is the water capacity, \( T_{\text{tank}} \) the water tank temperature, \( T_{\text{ground}} \) the ground temperature, \( T_{\text{air,CS}} \) the air temperature in the crawlspace, \( T_{\text{return,floor}} \) the water return floor temperature, \( R_{\text{cond,water,ground}} \) the lower part thermal resistance of the water in the tank, \( R_{\text{cond,water,rad}} \) the upper part thermal resistance of the water in the tank, \( R_{\text{conv}} \) the thermal resistance linked to the start of the supply fan and \( R_{\text{hydro}} \) the thermal resistance linked to the start of the cooling floor. Let us note that the equation members dependent on \( R_{\text{conv}} \) and \( R_{\text{hydro}} \) are not always present in the equation. Indeed, the supply fan is activated only when the water tank temperature is higher than the outdoor temperature. Its airflow is fixed to the constant value of 200 m³/h. In the same manner, the cooling floor is activated only when its temperature setpoint is reached. The water flow in the cooling circuit raises to 1.5 m³/h.

Thanks to a calibration phase through a Particle Swarm Optimization method and a one-month experimental campaign, it was possible to reproduce the behaviour of the water temperature in the tank located in the crawlspace considering the different solicitations (as the crawlspace and ground conditions, supply fan or cooling floor). The Figure 3 shows the results of the model prediction. The red zone represents the learning database.

**Building Energy model**

Our case study is an individual well-insulated dwelling composed of 3 bedrooms, a living room, a kitchen, a bathroom, a WC and a cellar (cf Figure 4). It deals with a single-storey house oriented 15° North. It contains also a crawlspace and a non-heated attic. The kitchen is opened on the living room and it is equipped with a skylight oriented at East for both comfort and lighting functions. The entrance door is positioned in the living room with a South orientation. 1/6 of the entire wall surface is constituted of windows.

![Figure 4: 3D visualization of the case study](image)

Our work was focused on the thermal behaviour of the living room in which the potential of the natural ventilation is maximized thanks to the stack effect by combining the opening of the entrance door and the one of the skylight. Thus, the EnergyPlus software through its nodal mass balance model, the AirFlow Network (AFN) (U.S Departement of Energy, 2016), has been used to model the thermal behaviour and the natural ventilation in the dwelling. To assure conservative results, one has chosen to neglect the wind effect. Finally, only the stack effect is considered for the natural ventilation.
The EnergyPlus model considers also a simple hourly control of the roller blinds. The schedule is given in the Figure 5.

**Figure 5: Blind rollers schedule considered in EnergyPlus**

Moreover, simple dwelling schedules of internal loads extracted from the French regulations (CSTB, 2011) have been considered.

The simulation period laid from May, 1\textsuperscript{st} to September, 30\textsuperscript{th}. The Bordeaux weather file has been used (Meteonorm source). Bordeaux is a town in a south-west of France that presents hot summers and mid-seasons with quite significant daily temperature amplitudes (an average temperature difference between night and day of about 10°C). This aspect is an important point influencing a lot the efficiency of the natural ventilation.

**Cooling control by using the fuzzy logic**

The cooling can operated with both the passive cooling by natural ventilation and the active cooling by the water tank. For that, a fuzzy logic algorithm was developed for regulating the choice between them. The advantage of the fuzzy logic resides in the fact that it does not require a rigorous mathematical model of the phenomena but reproduces more the user behaviour (M. M. Eftekhari, 2003). Thus, three control input parameters have been considered with the indoor temperature, the outdoor temperature and the difference between outdoor and indoor temperature. Each input parameter is described with three membership functions as it is shown in the upper and the lower-left graphs of the Figure 6. The membership function characterizes the probability of the input parameter to belong to a specific “group”. In our case study, three groups for each input parameter have been defined: “low” in blue, “medium” in green and “high” in red. Thus, instead being defined with severe ranges of values, the indoor, outdoor or outdoor-indoor difference temperatures can be either “low” and “medium” or “medium” and “high”. Finally, it allows smooth frontiers and increases the control robustness.

**Figure 6: Description of the membership functions for each input and output parameters**

The output parameter is described similarly. For our case study, the output is the choice between “no cooling”, “passive cooling by the natural ventilation” and “active cooling by the water tank”. The lower-right graph of the Figure 6 corresponds to the “no-cooling” output, the “medium” temperatures to the “passive cooling with natural ventilation” and the “high” temperatures with the “active cooling by the water tank”. Thus, from the different inputs values, an output is deduced and applied to the cooling control in the house. Although the fuzzy logic presents advantages with notably the large flexibility regarding the mathematical model, it requires attention for the determination of the algorithm parameterization. The required fuzzy logic algorithm parameters for each considered temperature are described in the Figure 7.

**Figure 7: Required fuzzy logic algorithm parameters**

In order to enhance the passive cooling by the natural ventilation during the night, different modes for night and day have been proposed with specific fuzzy logic algorithm parameters for the indoor and outdoor temperatures. In a same manner, in order to avoid the cold discomfort, one has defined a cooling and heating mode for the outdoor-indoor difference temperature dependent of the outdoor temperature at each time step. Finally, the following description of the fuzzy logic parameters for each input temperatures can be given:

- **Indoor temperature for the day mode**: \(T_{\text{in}_{\text{day}}}=15°C, T_{\text{in}_{\text{low}}}=19°C, T_{\text{in}_{\text{high}}}=T_{\text{setpoint}_{\text{NV}}} - 1, T_{\text{in}_{\text{huge}}}=T_{\text{setpoint}_{\text{NV}}} + 2\)
- **Indoor temperature for the night mode**: \(T_{\text{in}_{\text{night}}}=12°C, T_{\text{in}_{\text{low}}}=16°C, T_{\text{in}_{\text{high}}}=T_{\text{setpoint}_{\text{NV}}} - 1, T_{\text{in}_{\text{huge}}}=T_{\text{setpoint}_{\text{NV}}} + 2\)
- **Outdoor temperature for the day mode**: \(T_{\text{out}_{\text{day}}}=14°C, T_{\text{out}_{\text{low}}}=16°C, T_{\text{out}_{\text{high}}}=T_{\text{setpoint}_{\text{NV}}} - 3, T_{\text{out}_{\text{huge}}}=T_{\text{setpoint}_{\text{NV}}} + 1\)
- **Outdoor temperature for the night mode**: \(T_{\text{out}_{\text{night}}}=10°C, T_{\text{out}_{\text{low}}}=12°C, T_{\text{out}_{\text{high}}}=T_{\text{setpoint}_{\text{NV}}} - 3, T_{\text{out}_{\text{huge}}}=T_{\text{setpoint}_{\text{NV}}} + 1\)
- **Outdoor-indoor difference temperature for the cooling mode**: \(\Delta T_{\text{out}_{\text{in}_{\text{day}}}}=-20°C, \Delta T_{\text{out}_{\text{in}_{\text{low}}}}=-18°C, \Delta T_{\text{out}_{\text{in}_{\text{high}}}}=-2°C, \Delta T_{\text{out}_{\text{in}_{\text{huge}}}}=0°C\)
Outdoor-indoor difference temperature for the heating mode: \( \Delta T_{\text{out-in}_{\text{hyg}}} = 8^\circ\text{C}, \Delta T_{\text{out-in}_{\text{low}}} = 12^\circ\text{C} \)

As one mentioned before, the heating and cooling modes are dependent on the outdoor temperature at each time step. Thus, a temperature setpoint above which the system switches from the heating to the cooling mode and vice-versa is defined and that for both the day and night mode called respectively \( T_{\text{outminMS}} \) and \( T_{\text{outmax}} \). Moreover, a mid-season mode has also been defined in order to reduce even more the cold discomfort during the mid-season by maintaining the use of a cooling system when it is really needed. Thus, a new setpoint called \( T_{\text{outminMS}} \) is defined for the switch from the cooling mode to the heating mode. On another point, it is required to define the setpoint for the active cooling by the water tank \( T_{\text{setpointAC}} \) but also for the passive cooling by the natural ventilation \( T_{\text{setpointCV}} \). By this way, it provides a cooling control flexibility to the occupant by allowing him to choose between the priority of the active or the passive cooling system. For our case study, one has chosen to enhance the recourse to the natural ventilation. Finally, a list of the adjustment parameters of the hybrid cooling control is summed up in Table 1.

<table>
<thead>
<tr>
<th>Tsetpoint/C</th>
<th>Tsetpoint/V</th>
<th>Tomin/D</th>
<th>Tomin/N</th>
<th>Tomin/MFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>24/25°C</td>
<td>28°C</td>
<td>14°C</td>
<td>12°C</td>
<td>16°C</td>
</tr>
</tbody>
</table>

Coupling numerical model

For the numerical modelling, several models coming from different numerical environments require to be coupled. Notably, as we mentioned before, the dwelling model was done with the EnergyPlus software. The water tank model and the fuzzy logic algorithm were coded in the Python language. More specifically, the fuzzy logic employed the Sci-Kit Fuzzy Python package. The coupling were thus handled also through Python by packaging the EnergyPlus model in a standard FMU (T. Blochwitz, 2011). Finally, the coupled model looks like the Figure 8.

![Figure 8: Scheme of the coupled global model](https://doi.org/10.26868/25222708.2021.30542)

At each time step, the fuzzy logic algorithm is questioned to determine the states of the natural ventilation device and the cooling floor. For that, it requires the indoor temperature \( T_{\text{in}} \), the outdoor temperature \( T_{\text{out}} \) and the outdoor-indoor difference temperature \( \Delta T_{\text{out-in}} \) given by the EnergyPlus model at each time step. As mentioned before, three situations can appear from the control fuzzy logic algorithm:

- When no cooling is required, neither the cooling floor nor the natural ventilation is activated.
- When the natural ventilation is activated, the openings of the entrance door and the skylight are taken into account in the EnergyPlus model via the AFN. It allows then to deduce the indoor temperature \( T_{\text{in}} \) at the next time step and addresses it with the outdoor temperature \( T_{\text{out}} \) and the outdoor-indoor difference temperature \( \Delta T_{\text{out-in}} \) to the fuzzy logic algorithm.
- When the active cooling by the water tank is activated, the water tank temperature \( T_{\text{tank}} \) is deduced from the water tank model by considering the ground temperature \( T_{\text{ground}} \), the air temperature in the crawlspace \( T_{\text{air,CS}} \) and the return floor temperature \( T_{\text{return,flow}} \) extracted from the EnergyPlus model at the previous time step. It is then sent to the EnergyPlus model for calculating the indoor temperature \( T_{\text{in}} \) at the next time step that would be addressed to the fuzzy logic algorithm with the outdoor temperature \( T_{\text{out}} \) and the outdoor-indoor difference temperature \( \Delta T_{\text{out-in}} \).

Numerical results

The objective of the numerical approach was to show the advantages of such a hybrid cooling system by enhancing the use of a passive cooling strategy in term of both energy performance and thermal comfort. More particularly, a focus was done to assess the improvement of the low-energy water tank cooling system efficiency due to the additional use of this passive cooling strategy. Given that, four specific configurations have been compared:

- Alone active low-energy cooling by the water tank with a setpoint of 24°C/ Rollers blinds always closed except for the skylight
- Alone active low-energy cooling by the water tank with a setpoint of 25°C/ Rollers blinds always closed except for the skylight
- Hybrid cooling system with the active low-energy cooling by the water tank with a setpoint of 24°C and the passive cooling by a natural ventilation device/ Rollers blinds control considering the schedule in Figure 5
- Hybrid cooling system with the active low-energy cooling by the water tank with a setpoint of 25°C and the passive cooling by a natural ventilation device/ Rollers blinds control considering the schedule in Figure 5.

Note that the roller blinds controls are not exactly the same between the hybrid and the active configurations with a more penalized schedule for the hybrids regarding the summer comfort.

The Figure 9 presents the distribution of the indoor air temperature in the living room considering the four enounced configurations for the entire simulation period from May, 1st to September, 30th. The active cooling strategy with a setpoint of 24°C is represented in blue, the...
active cooling strategy with a setpoint of 25°C in orange, the hybrid cooling strategy with a setpoint of 24 °C for the active system in green and the hybrid cooling strategy with a setpoint of 25 °C for the active system in red. Despite the less favourable roller blinds control of the hybrid strategies, the figure shows the large decrease of the indoor air temperatures by using the hybrid cooling rather than the active alone. An improvement of the summer thermal seems obvious. Let us state this result by visualizing the temporal variation of the indoor air temperature.

![Figure 9: Distribution of the indoor air temperature in the living room considering the four studied configurations for the entire simulation period](image)

The Figure 10 presents the temporal evolution of the outdoor and indoor air temperatures in the living room for the four enounced configurations from July, 14th to July, 25th. The colour map is the same as the Figure 9 for the indoor air temperatures and the outdoor temperature is represented in violet. Again, one can observe on these curves a significant impact of the additional natural ventilation with a large reduction of the indoor air temperature especially during the night. Remind that the active cooling system is supplied by the water tank positioned in the crawlspace. As mentioned in the section Water tank model, it is cooled naturally with the ground and artificially with a fan supplying air from the exterior to the surface of the closed water tank. Thus, the system requires some periods during the day for which the active cooling system is not used to be able to generate the water tank. By operating natural ventilation, it provides those generating periods and especially during the night. Indeed, on the Figure 10, one can see clearly the high temperature drop appearing during the night due to the natural ventilation. Thus, given the smaller resulting indoor air temperatures, one can conclude on a better summer thermal comfort with the hybrid strategies. However, when comparing the configurations with a setpoint of 24 and 25°C for the active cooling system, a non significant difference is registered. It can be explained by an inability to completely regenerate the water tank. This hypothesis can be supported by the fact that the setpoint for the active system in red.

![Figure 10: Temporal evolution of the outdoor temperature and the indoor air temperatures in the living room considering the four studied configurations during ten days of July](image)

The Figure 11 presents the distribution of the water temperature contained in the tank positioned in the crawlspace. This data is extracted from the water tank model explained before. Once again, the colour map is the same as the Figure 9. As expected, the Figure 11 shows a large decrease of the indoor air temperature for the hybrid strategies coloured in green and red. An interesting point appears here through the fact that the water tank temperature remains almost always under 25°C for the hybrid strategies leading to a quasi-permanent cooling potential of the cooling floor. As it was done for the indoor air temperatures, one proposes to visualize the temporal evolution of those water tank temperatures.

![Figure 11: Distribution of the water tank temperature considering the four studied configurations for the entire simulation period](image)

The Figure 12 presents the temporal evolution of the outdoor temperature and the water tank temperatures considering the four studied configuration from July, 14th to July, 25th. The colour map is the same as the Figure 10. First, one can retrieve the smaller values of the water tank temperatures for the hybrid strategies compared with the active system alone. Second, one can see the periods for which the cooling floor is activated. Indeed, those periods, occurring mainly during the day, show a significant temporal increase of the water tank temperature due to the resulting thermal equilibrium between the living room and the water inside the cooling floor. On the other hand,
one can also observe some periods for which the outdoor temperature is lower than the water tank temperature leading to the activation of the supply fan in the crawlspace and in the same manner, the regeneration of the water tank. During those periods that occur mainly during the night, a significant temporal decrease of the water tank temperature can be observed. This phenomenon is less visible when the active cooling is operating alone because the water regeneration is less efficient when the cooling floor is maintained active on a longer period. Indeed, due to the fact that the indoor temperature remains higher than the setpoint (as it is shown on the Figure 10), the cooling floor does never turn off. Finally, one can remark that the alone active cooling configurations present less efficient regeneration periods leading to a worse cooling effect. To quantify this cooling effect, one propose to visualize the mean power that is generated for each configuration.

The Figure 14 shows the cooling needs considering each studied configurations for the entire simulation period. One can see the large decrease of the cooling needs for the hybrid strategies. It is explained by the fact that the natural ventilation can ensure efficiently the cooling function especially during the night. However, as it was observed before, only few differences appear between the two setpoint case studies.

Finally, the numerical approach allows to highlight the cooling efficiency of the hybrid strategy. Thus, both the thermal comfort and the energy savings have been demonstrated. Moreover, it also showed the quite similar results between the two setpoints of the active cooling by the water tank. Given that, one has chosen to consider a setpoint of 25°C for the experimental campaign. In the following, one proposes to test the hybrid strategy in an experimental campaign and to validate the cooling efficiency obtained with the numerical approach.

**Experimental campaign**

Two experimental campaigns took place in August, September and October 2019 and 2020. To clarify the article, one has chosen to focus on the 2020 campaign.

**Presentation of the experimental campaign**

The campaign took place near Bordeaux in France from August, 1st to October, 15th in 2020. The climate of Bordeaux is characterized by hot summers and soft winters. Bordeaux is located 50 km from the Atlantic Ocean. It is then particularly favourable to the sea breezes. The case study is similar to the individual dwelling described in section Building Energy model. It deals with a single-storey experimental house. The opening employed for the natural ventilation is the entrance door oriented at South and the skylight oriented at East. As it was mentioned before, the house is equipped with a cooling hydraulic floor connected to a water tank positioned in the crawlspace. The setpoint is fixed at 25°C. The other adjustment parameters of the hybrid cooling control are similar to those used for the numerical approach given in the Table 1. No real occupant lives in this house but an internal load has been considered thanks to heated resistors and the roller blinds schedule is similar to the simulation as presented in the Figure 5. For the needs of the experiment, a large amount of sensors have been deployed in the house. All the sensors will not be
described here but a focus will be done on those used for the results presented in the following section. Notably, a thermocouple was positioned in the living room to measure the indoor air temperature. Moreover, two ultrasonic anemometers were placed inside the dwelling in front of the entrance door and near the skylight. By this way, the air orientation and velocity could be registered. Also, a temperature PT100 sensor was placed in the middle of the water tank positioned in the crawlspace and another one on the North face of the house to measure the outdoor temperature.

Experimental campaign results

The Figure 15 presents two graphs registered during about ten days of experiment in August 2020. The upper graph is the temporal evolution of the water tank temperature and the lower part corresponds to the temporal evolution of both the living room (in orange) and the outdoor (in blue) temperatures. Globally, one can observe that the indoor air temperature maintains maximal values around 25°C. Note that it is also true for two days of heat waves registered at the beginning of the period (August, 19th and August, 20th). However, during this period, a higher water tank temperature is visualized. Nevertheless, despite the heat waves, a regeneration occurs during the night. It is observed on the graph through the temporal reduction of the water tank temperature. After this heat waves period, the outdoor temperature reduced a lot leading to a great potential of the natural ventilation and a rare recourse to the cooling floor. Thus, the water tank was able to regenerate and its temperature was decreasing drastically until the following activation of the cooling floor (appearing around August, 26th). Finally, the Figure 15 shows the efficiency of the hybrid strategy both through the thermal comfort and the ability to regenerate the water tank and by this way improve the use of the active low-energy cooling by the water tank.

Concerning the efficiency of a control algorithm, an important aspect resides in the intermittingness of the control. Indeed, to avoid the potential acoustic discomfort and the erosion of the controlled system, it is better to limit the number of state changes. To visualize that for our case study, the Figure 16 presents on the upper part the temporal evolution of the living room, outdoor and water tank temperatures and on the lower part the state of the natural ventilation and the active cooling by the water tank in the time. One can observe that only few intermittencies are registered. Most of the time, they coincide with specific periods for which the outdoor and the indoor temperatures are almost similar. This problem could be easily solved by considering a moving average of the outdoor temperature instead of the instantaneous outdoor temperature. Nevertheless, it would imply a storage of the historical data that would lead to a heavier control solution. For this case study, one has chosen to favour light control algorithm to propose a solution that can be deployed easily and almost everywhere.

Another interesting point is to know the frequency and the moment of the day employing the natural ventilation versus the one employing the cooling floor. For that, the Figure 17 is proposed. It represents radar graphs for both the summer (on the left) and the mid-season (on the right). Each branch of the radar is characterized by one hour of the day from 00h to 23h. The graphs gather the data collected during August for the summer season and September until mid-October for the mid-season. The blue colour represents the use of the natural ventilation and the pink the use of the active cooling by the water tank. Higher the colour surface, higher the frequency of use. Thus, for the summer period, one can see clearly that the natural ventilation is mainly employed during the night, whereas the active cooling is activated only during the day. Moreover, the natural ventilation seems much more often used than the active cooling. To explain that, remind that one adjustment parameter of the hybrid cooling control called $T_{setpointNV}$ was implemented for prioritizing or not the use of the natural ventilation. Thus, higher this parameter, more frequent should be the use of the natural ventilation. For our case study, one has chosen to fix this parameter $T_{setpointNV}$ to the value of 28°C in order to enhance the natural ventilation employment. Finally, the Figure 17 shows that the definition of the $T_{setpointNV}$ parameter seems well-posed given the fact it allows to favour the recourse to the natural ventilation by maintaining a good thermal comfort. For the mid-season, one can observe a totally different behaviour due to the reduction of the outdoor temperature in September and October 2020. Indeed, the active cooling system is never used and the natural ventilation is employed mainly during the day and not anymore during the night when it was the case in summer. It shows that it is important to anticipate an adaptation of the control algorithm between

Figure 15: Temporal evolution of the outdoor and the living room indoor temperature in the lower part and the water tank temperature in the upper part during two weeks of August 2020

Figure 16: Temporal evolution of the outdoor, living room and water temperatures in the upper part and the natural ventilation or active cooling state in the lower part during two weeks of August 2020

Figure 17: Temporal evolution of the outdoor, living room and water temperatures in the mid-season and the natural ventilation or active cooling state in the lower part during two weeks of September and October 2020
the summer and the mid-season. That is why one has implemented a summer mode and a mid-season mode in the control algorithm (cf Table 1) to regulate this aspect in order to avoid the cold discomfort.

Figure 17: Frequency of passive cooling by the natural ventilation and active cooling by the water tank during the summer season and the mid-season of the 2020 experimental campaign.

The Figure 18 shows justly the temporal evolution obtained in the mid-season. As the previous figure, the upper part presents the indoor, outdoor and water tank temperatures and the lower part presents the natural ventilation and active cooling states. As it was observed in the Figure 17, the cooling floor is never used and the natural ventilation is solicited mainly during the day. Moreover, one can also see on the upper graph that the indoor temperature varies around 20°C. It shows then that, thanks to the implementation of the mid-season mode, the control algorithm is able to avoid both hot and cold discomforts.

Figure 18: Temporal evolution of the outdoor, living room and water temperatures in the upper part and the natural ventilation or active cooling state in the lower part during two weeks of October 2020.

Conclusions
A hybrid cooling solution combining a natural ventilation device and an active low-energy cooling floor connected with a water tank located in a crawlspace of a dwelling has been proposed. First, a numerical approach has been presented. It allowed to show the efficiency of the hybrid cooling strategy compared with the alone active cooling system by the water tank considering the thermal aspect and the energy savings. One important result resides in the necessity for the water tank to benefit of efficient regeneration periods that can be provided by the natural ventilation. Second, the results obtained during an experimental campaign in 2020 have been presented. They strengthened the efficiency already deduced from the numerical approach. Moreover, they validated the implementation of the adjustment parameters and the different modes for summer and mid-season proposed in our work to improve the hybrid cooling control. A future work would consist to test this solution in a real occupied environment and to collect the acceptability from the occupants.

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References