IMPACT OF THERMAL MASS ON SUMMER COMFORT IN BUILDING: A NUMERICAL APPROACH LEADING TO A DECISION SUPPORT TOOL

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ABSTRACT

To improve energy efficiency in buildings, airtightness and insulation level have been widely improved in order to lower heating demand in winter but can lead in many cases to overheating in summer. To avoid this summer and mid-season discomfort, thermal mass plays an important role.

The objective of this work is to develop a tool allowing architects and building engineers to better understand and highlight the impact of thermal mass in summer comfort and of some important parameters regulation in heavy buildings thermal behaviour.

A numerical approach has been conducted with the EnergyPlus software on some simple well defined test cases. Specific climate conditions have been built to highlight the thermal mass impact.

In this paper, the effects of night ventilation, shutters regulation and thermal mass quantities are presented on those solicitations.

INTRODUCTION

Due to new expectations on building energy efficiency, people are aware of parameters like insulation level and airtightness but not really about the summer discomfort also created by these parameters. To avoid summer and mid-season discomfort, thermal mass plays an important role if it is well considered from the beginning of the design phase.

The objectives of this work is to develop a tool allowing architects and building engineers to better understand and highlight the impact of thermal mass in summer comfort, and of some important parameters in the heavy buildings thermal behaviour.

This study focuses on summer thermal comfort for individual residential buildings under specific climate conditions. Thanks to the state of the art focused on the role of inertia in summer comfort (and detailed in the first paragraph of this article), the most important parameters which impact the heavy buildings thermal behaviour, have been selected. The second part focused on the model description with

- the definition of the reference case :
    - Geometry
    - Numerical Method
    - Schedules
- the weather solicitations definition
- the values of the selected parameters

The third part is dedicated to the postprocessing definition which helps to highlight the impact of thermal mass on summer comfort and compare different cases. This implies to determine some data postprocessings and characteristic variables (percentage of discomfortable indoor climate time for example) that enable to compare different building conceptions under specific climate solicitations (in terms of average value, period and amplitude). The decision support tool created thanks to this work will be introduced in this part.

Then, some results are presented to quantify the influence of the selected parameters. Thermal mass quantity is first studied, following by night ventilation and shutters regulation. Finally, coupling in the parameters variations is shown. The last part is dedicated to conclusion and perspectives.

STATE OF THE ART

Thermal mass is widely referenced in scientific publications on building physics due to its important and complex role in the building thermal behaviour. It is mainly use as a study parameter, but a large number of publications specifically focus on thermal inertia. In this section, we focus on papers dealing with the role of thermal mass on summer thermal comfort.

On that specific topic, research has been done to quantify the impact of thermal mass on thermal comfort thanks to both numerical and experimental study [Brown, 1990] showed, thanks to a numerical and theoritical study, that increasing from 21 to 201 kg/m² thermal mass of tertiary building could lead to the decrease of the interior temperature from 1 or 2°C. [Balaras, 1996] concludes that thermal inertia is one of the most important parameters for improving thermal comfort conditions as well as for reducing heating and cooling energy demands of buildings. He also underlines the impact of the material properties and especially the thermal effusivity on the thermal mass efficiency.

[Tsilingiridis and al., 1996] showed experimental data (inside and ambient air temperature) made on housings in Athens (Grece) during 37 months in the field of the village-3 project. Housings are opened on south facades and well insulated. In this study case, the evolution of the ambient and inside air temperature showed that well insulated buildings with a high thermal capacity do not need cooling systems.

[Zhou and al., 2011] concludes that night ventilation has three main objectives: improve inside air quality, refresh occupants and building thermal mass. Others researches done in Europe present the interest of coupling thermal mass and night ventilation, as an efficient technique to improve inside thermal conditions and reduce cooling loads in hot, cold and temperate climate [Santamouris and al., 1996 a & b] [Geros and al., 1997] [Flourentzou and al., 1996] [Blondeau and al., 1997] [Givoni, 1998] [Zhou and al., 2008]. Some authors [Lefebvre, 1989] [Neirac, 1989] [Depecker, 1982] [Douzane, 1995] [Sicart, 1984] underline that the potential gain due to night ventilation is closely linked to the building thermal inertia. They also remind that ventilation rate modify the building thermal constant.

[Pfafferott and al., 2005] showed by numerical and experimental study the impact of the climate and the thermal inertia on the inside air temperature of a building cooled by night ventilation.

The review of the state of the art confirms the importance of thermal mass on summer thermal comfort. It guides the selection of a few parameters. Night ventilation rate, thermal mass quantity, building regulation and weather conditions are the parameters we will focus on in a first step.

The work presented here allows to characterize buildings on specific weather files. A reference case has been chosen to highlight the influence of the selected parameters.

MODEL DESCRIPTION

Reference model

The geometry test case used in this paper is based on an experimental low-energy house of the INCAS platform as described in [Spitz and al., 2012], which is a full-scale test facility developed in 2008 by the French National Solar Energy Institute including four experimental houses located in Chambery (France). In this section, the reference model will be first described: geometry, numerical model and scenarii chosen. A focus will then be done on the weather solicitations, and finally Table 1 will summarize the parameters that have been selected for the study and their different values.

Geometry

The house area is a 7.5 m × 8.5 m floor with 2.5m ceiling height over two stories (total of around 100 square meters) with well exposed windows to the south (34% glazed) and is illustrated on Figure 1.

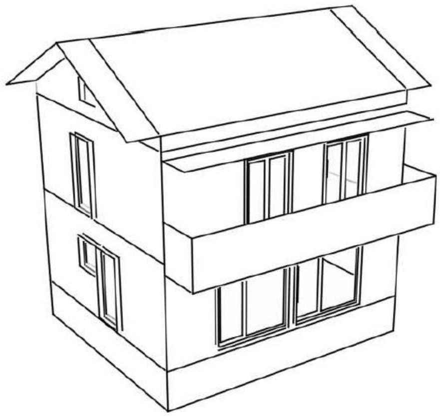

Figure 1: Test case geometry (model)

Numerical model

The house is simulated thanks to the EnergyPlus software with four thermal zones: two heated zones (total of around 250 cubic meters), ground and first floor; two unheated zones, basement and roof space. The outside insulation considered is 20cm glass wool (Average U-value of walls/floor/ceiling : 0.175 W/(m^2.K)). Airflows between zones are not taken into account.

Solar shadings are considered for the south facade (roof eaves and balcony) and windows overhangs for every facades. Shutters are considered: the shutters on the east and west facades are closed any time in order to limit the overheating of the house and obtain workable results.

Thermal bridges treated with a particular attention during the conception and construction phases of the experimental existing houses, are not taken into account in the numerical model because of their very limited impact.

The HVAC model consists in an 80% efficiency recovery system (an electrical resistance and two fans, one for supply and one for return), and has been simplified as a new air flow rate taking into account the heat exchanger efficiency.

Heat convection transfer coefficients were calculated with the TARP algorithm (natural convection based on temperature difference). Conduction through walls is based on the transfer function method.

Schedules

Inside the house, internal loads and occupants were modeled thanks to predefined schedules which are summarized on Figure 2. Four people have been considered as living in the house: they are away from home during the day except at lunch time where two of them come back. Internal loads due to equipment were defined thanks to French regulation and national surveys.

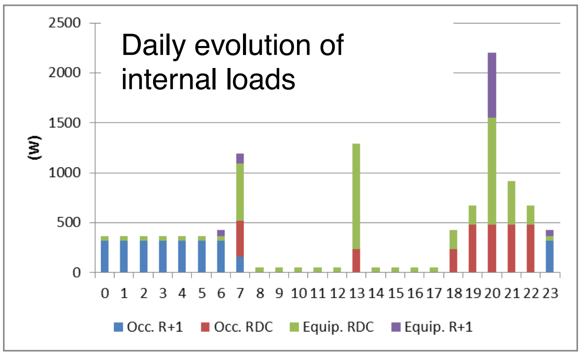

Figure 2: Internal loads scenario

Table 1: Selected parameters

Parameters	Values
Walls thermal mass quantity	Concrete 0, 1, 3, 5, 10, 20 cm, cinderblock 20cm
Slabs thermal mass quantity	Concrete 0, 1, 3, 5, 20 cm
Ventilation rate	Without, 1, 3, 5, 10 vol/h
Shutters	Open, 10, 20, 50%, closed

Weather conditions

This study focuses on summer thermal comfort. The weather file has a key role in highlighting the thermal inertia benefits. Classical weather files are often averages of 10 (or more) years and therefore smooth the impact of thermal mass on building behaviour. Furthermore, when using real weather files, the everyday variations of the weather complicate the results analysis due to the dynamic intrinsic quality of the building inertia (such as time response, decrement factor, phase change). For these reasons, two different weather solicitations have been built: one based on a semi-continental summer day and one on a heat wave period.

Weather Solicitation 1: Semi-continental day

The first weather file chosen is based on measurements done in 2007, 2008 and 2009 during summer in the area of Cadarache city in South East of France. Its characteristics are some regular sunny days with large day/night amplitude (20°C): relatively hot and dry day time (30°C) and quite fresh night (10°C). In the weather file used, the same day is repeated 60 times (during July and August).

Figure 3 shows the temperatures for this weather scenario.

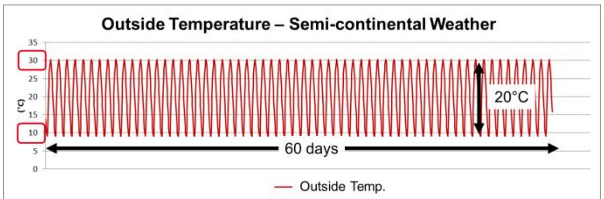

Figure 3: Semi-continental solicitation

Because of its important day/night amplitude (20°C), this weather solicitation will emphasize the coupling of night ventilation with thermal mass on building thermal behaviour.

Crash Test Weather solicitation 2: Heat wave period

The second weather file represents something like a crash test weather file corresponding to a heat wave. Figure 4 shows the temperature changes during the heat wave weather file.

This weather file allows to emphasize the thermal behaviour of different types of buildings during the three different periods of the heat wave:

- Normal behaviour with temperature evolution varying around 20°C +/-5°C,
- Increasing temperature during the heat wave with hot day and night : 35°C during the day and 25°C at night (which will minimize the impact of night ventilation) in order to see different time response of buildings,
- Decreasing temperature after the heat wave with a second time response specific to building type.

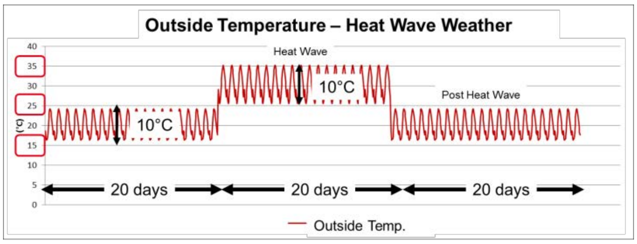

Figure 4: Weather solicitation 2: Crash test

SIMULATION POSTPROCESSINGS

One key point of our study was to determine some postprocessings that could represent the dynamic response of the building and at the same time be understandable by non-thermal specialists (architects, purchasing advisors).

In order to achieve this goal, the defined specifications are:

- Comparing different building conceptions and regulations,
- To have different levels of postprocessings representing the same outputs but with different degrees of complexity.

Outputs, suitable with the two specific climate solicitations applied (semi-continental and heat wave), were developped in that way.

Degree hours of discomfort

To highlight a building comfort, the first focus is set on degree hours of discomfort. To compare the different cases selected, the degree hours of discomfort are set on a colored axis as shown in Figure 5.

$$Degree.hours = \sum_{hourly} (T_{building} - T_{comfort})dt$$

Thanks to French regulation, the comfort temperature is defined at 26°C.

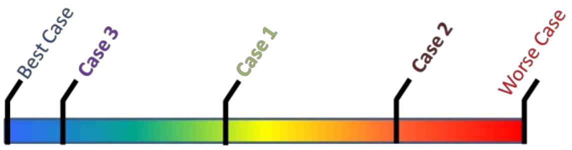

Figure 5: Degree.hours of Discomfort axis

This postprocessing allows an easy comparison between cases but its results remain dependant from the comfort temperature chosen.

Percentage of hours of discomfort

To go further and obtain a more complete overview of the building behaviour, curves representing the percentage of time under or above a certain temperature are plotted. Figure 6 shows three completely different thermal behaviours for the three cases studied. On this example, we can read that the temperature of case 1 is 62% of the time greater than 27°C, for case 2, 4% and for case 3 around 99%. It also appears that the temperature of case 1 is 43% of the time greater than 31°C, for case 3, 4% when case 2 never goes above 28°C. This example shows the importance of a more detailed postprocessing. With a comfort temperature of 27°C, case 3 appears to be the less comfortable building. Actually, case 1 is the least comfortable of the three cases represented here.

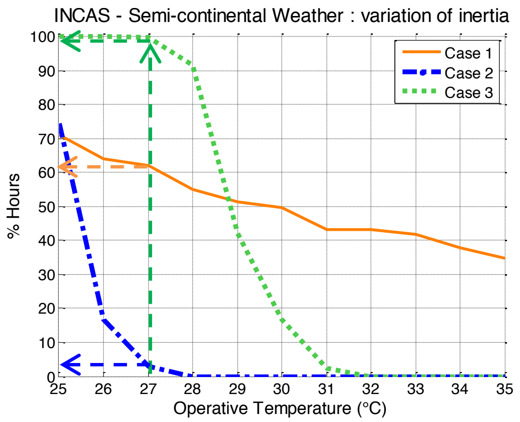

Figure 6: Percentage of hours of discomfort plot

Because of the similarity of models (geometry, occupants, equipments), buildings compared could have trends temperature curves very similar especially for inertial buildings. With the same thermal mass quantity, the position of the curve on the temperature axes will then give information about the best strategies (ventilation rate and shutters for example) to increase summer comfort.

Givoni postprocessing

Another way to compare different cases is the hourly temperature of each studied case set on a Givoni diagram (*Figure* 7). It plots one point every hour on the humid air diagram on which Givoni defined comfortable boxes depending on air velocity. This postprocessing is a good indicator of the building comfort.

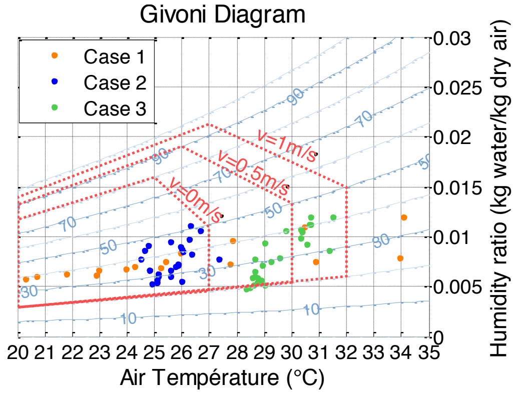

Figure 7: Givoni diagram

Time constant response

Specific postprocessings have been developed for the heat wave climate, in order to show the temperature rise in the building during the heat wave and its decrease afterwards. Figure 8 shows the average temperature evolutions for three cases. It gives an indication[1] on the thermal time constant of buildings and the discomfort level that could exist when heat waves occurred, considering the building thermal mass, shutters and ventilation regulation.

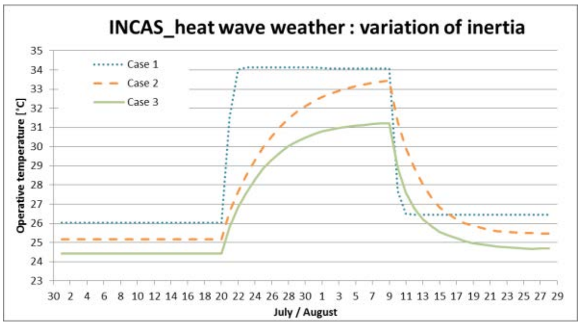

Figure 8: Average temperature evolution

All these postprocessings have been integrated in the decision support tool, which allows three cases comparison. The tool users can visualize easily the impact of inertia and of others parameters (like ventilation rate or shutters regulation) on the inertia and therefore on the building thermal behaviour.

DECISION SUPPORT TOOL

The decision support tool has been developed to reach a non-thermal specialists audience (architects, purchasing advisor), so that it could help them to understand and quantify the impact of thermal inertia on comfort in buildings. The tool has been developed with Matlab, which automatizes both the parametric run of several configurations and the data postprocessings, to point out the results and compare different configurations. The user will be free to

[1] Thermal time constant of buildings can be evaluated by many equations more or less precise.

choose on the user interface showed in *Figure **9***, one to three configurations with free choices for the slab and wall thicknesses, the ventilation rate and the shutters regulation. The climate (semi-continental summer or heat wave) can also be chosen.

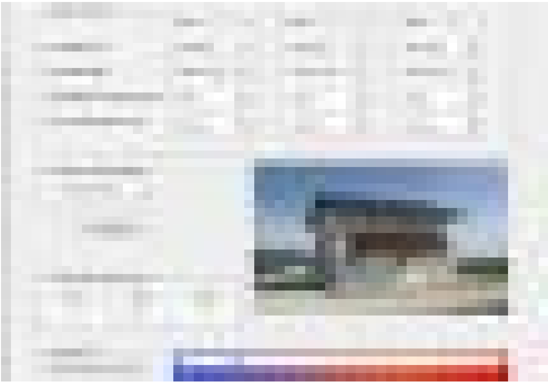

Figure 9: Decision support tool

DISCUSSION AND RESULT ANALYSIS

In this section, some results will be highlighted thanks to the different postprocessings introduced in the previous part. The analysis will focus on the following parameters :

- the impact of the thermal mass quantity
- the ventilation flow rate
- the shutters regulation

To finish this part, some parameter variation couplings will be introduced.

Thermal mass quantity: role of walls and slabs

This study at first aims to understand how the thermal mass would be efficient, and with which thickness: the first centimeters are they really the only effective ones? This study has been carried out for both 'semi-continental' and heat wave weathers in order to verify the thermal mass action for these both solicitations.

Semi-continental weather solicitation

In order to understand the importance of the inertial thickness, we tested the reference model (20cm of exterior insulation, 3vol/h of night ventilation, open shutters) with three configurations of slabs and walls thicknesses: without inertia, 5 and 20cm of concrete.

The thickness variation shows that with 5 cm of concrete for the walls and slabs, the building thermal behaviour is very similar to an inertial building (20cm of concrete). As you can see, the temperature in cases 5 cm and 20 cm of concrete is 95% of the time below 29°C. The discomfort eventually created by temperature between 27°C and 30°C could be solved by a daytime ceiling fan as shown in the Givoni diagram. We can note that overheatings during a typical semi-continental summer day with large temperature amplitude can be avoided with a night ventilation of 3vol/h with only 5 cm of concrete in the slabs and walls. In the next paragraph, the behaviours of the same three cases (0, 5 and 20cm) under heat wave solicitations are studied.

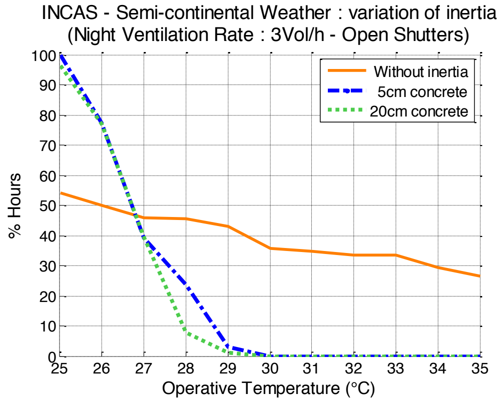

Figure 10: Temperature Building response

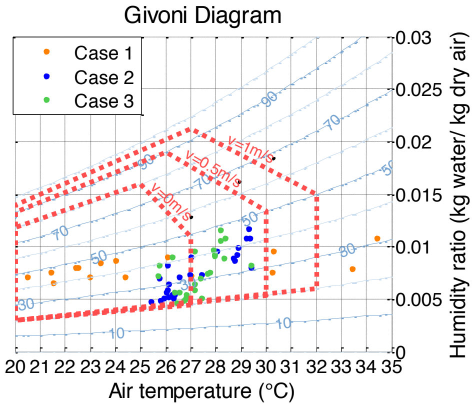

Figure 11: Thermal mass quantity results

Heat wave solicitation

The heat wave solicitation is a good way to highlight the differences of building behaviours. On Figure 12, the three same cases as in the previous section are studied : without inertia, 5 cm and 20 cm of concrete. The building without inertia always records the highest temperatures: before, during and after heat wave; Increase and decrease of temperatures are simultaneous with the weather variations. When an inertial building is studied, the increase and decrease of the outside temperatures have a smaller impact on the building operative temperature and the building time response is longer. At the end of the heat wave, the increases in temperatures are different in the three cases. The case without inertia is 1°C higher than the case with 5 cm of concrete, which is 1°C higher than the case with 20 cm of concrete. This last case does not reach a stationary mode after 20 days of the heat waves.

The simulations on several thicknesses show that as long as there is inertia in the building, summer overheatings are reduced.

The study of the thermal mass quantity highlights that under the semi-continental weather solicitation (with large temperature amplitude), 5 cm of concrete coupled to night ventilation is enough to avoid most of the overheating period (like the case of 20 cm of concrete with an identical regulation), while increasing thermal mass quantity improve the comfort during heat waves. We also note that the post heat-waves period is longer to stabilize within the case of 20 cm in comparison to the 5 cm case.

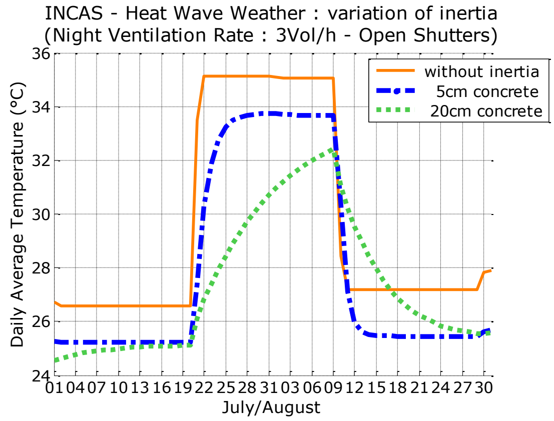

Figure 12: 0, 3, 20cm Thermal mass quantity results

In order to maximize the effect of the thermal mass, some parameters need to be regulated as night ventilation rate and shutters.

Night ventilation rate

The night ventilation rate impact on the inside ambiance of a building depends on its inertia.

<u>*Semi-continental weather solicitation*</u>

Figure 13 shows, on the reference model (20cm of exterior insulation, 20cm of concrete, open shutters), that the night ventilation rate allows a consequent decrease of the operative temperature: when the rate is 1vol/h, the temperature is above 29°C 40% of the time; with a ventilation rate of 10vol/h, the temperature is above 26°C 40% of time. A ventilation rate above 3vol/h does not appear realistic. It also appears that the gap is important between 1 and 3vol/h; Between 3, 5 and 10vol/h, gaps are smaller. It can be conclude then that night ventilation helps to preserve the building comfort and refresh the thermal mass, and that a ventilation rate of 3vol/h would be efficient.

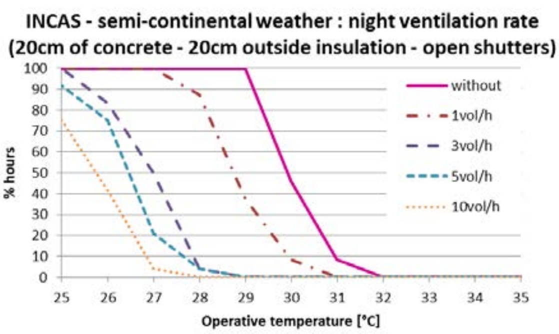

Figure 13: Ventilation Flow rate impact – Semi-continental weather

In case of a 3vol/h ventilation rate, the building will not be comfortable 100% of the time. The discomfort created by temperature between 27°C and 30°C could be solved by a daytime ceiling fan as shown in the Givoni diagram below. Because it is an active way to improve the comfort, air circulation would be less energy efficient, but at least better than air conditioning system.

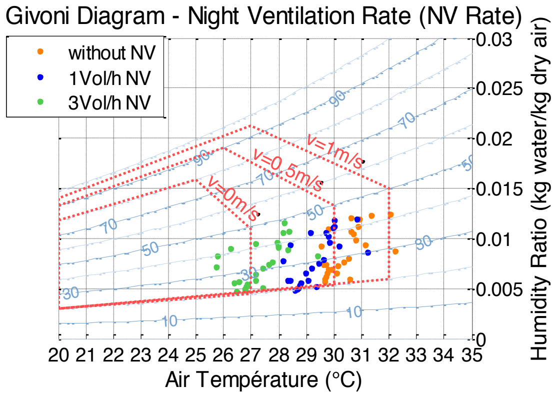

Figure 14: Ventilation Flow rate impact

<u>*Heat wave solicitation*</u>

Because night ventilation is a good way to refresh thermal mass, it appears interesting to study its impact on operative temperatures during heat wave. On Figure 15, an inertial building (20cm concrete) was studied with different ventilation rates: without (case 1), 1vol/h (case 2), 3vol/h (case 3). The building without night ventilation always records the highest temperatures and reaches 34.5°C inside at the end of heat wave. When studied in semi-continental weather, gaps between 0vol/h and 1vol/h, and between 1vol/h and 3vol/h, seemed to be equivalent. Nevertheless, when heat wave occurs, the impact of a 3vol/h ventilation rate increase. In that case, a 3vol/h ventilation rate allows a temperature reduction of more than 2°C.

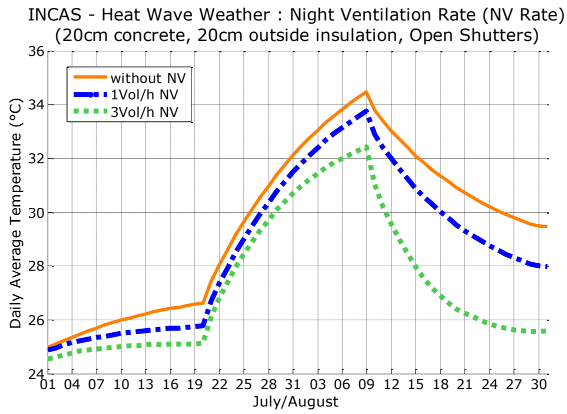

Figure 15: Ventilation Flow rate impact

To conclude, a good ventilation rate regulation seems really important in order to refresh thermal mass and therefore inside ambiance, during heat wave period but also for typical summer temperature.

Shutters

As explained in the model description part, the shutters on the east and west facades are closed any time in order to limit the overheating of the house and obtain workable results.

The following results show the difference of building behaviour with and without shutters on the north and south facades.

Semi-continental weather solicitation

In the case of an insulated heavy construction (20cm of concrete, 20cm of exterior insulation, 3vol/h night ventilation), closing the shutters reduce significantly the operative temperature inside the building: the temperature is above 26°C 85% of the time when the shutters north and south are opened; when closed, the temperature is above 26°C only 20% of the time.

Because it is not realistic to consider all the buildings shutters down during day and night when people are living inside, we made tests with several percentages of shutters openings: 0% (closed), 50% and 100% (opened). Half closing the shutters also enables a significant reduction of overheating: during 40% of the time, the temperature is above 27.5°C when opened, above 26.5°C when 50% opened, and 25.8°C when closed.

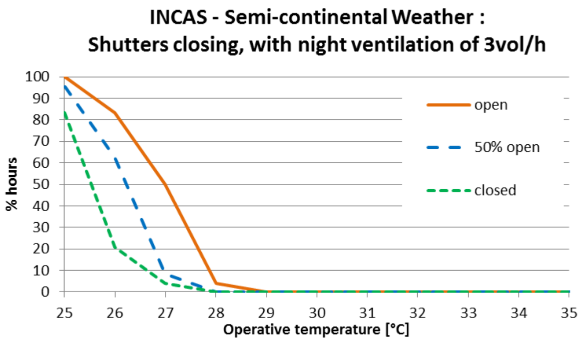

Figure 16: Shutter regulation impact

Night ventilation and shutters combination

The combination of night ventilation rate and shutters opening gives us rules on how to limit the summer discomfort considering the existing thermal mass of the building. Night ventilation is more efficient in order to limit overheatings than shutters closing (that already have a significant impact). The combination of these two factors helps to keep the building temperature under 26°C any time; this would not be possible when shutters are down, and would be true 60% of the time when night ventilation is on (10vol/h).

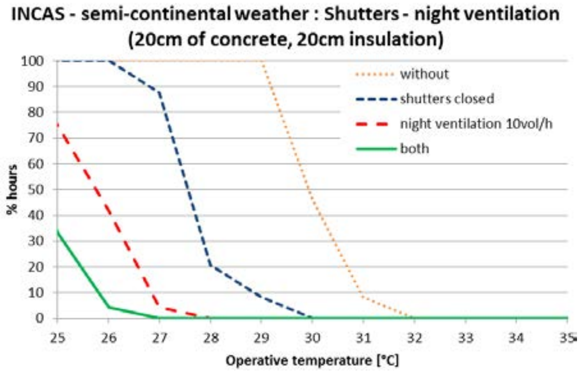

Figure 17: Shutters closing and night ventilation

To conclude, combining night ventilation and shutters closing in an inertial building is interesting in order to increase the summer comfort during typical summer weather. In this configuration, with cool nights, night ventilation is more efficient that shutter regulation.

CONCLUSION

The aim of this study was to better highlight the impact of inertia in buildings. The study based on parameters analysis helped us to better understand the impact of these parameters on the summer inside ambiance of the building: separately or combined. Under the semi-continental summer climate that has been defined in this study, having 3cm of concrete in the slabs and walls is efficient enough to allow a decrease of the internal temperatures in the house. Having a ventilation flow rate of 3vol/h is efficient and create a reduction of about 2°C of the inside operative temperature. Shutter regulation has also been quantified. Half-closing shutters has an interesting impact on the inside ambiance of housing and closing them permit to avoid summer overheating.

In the future, the impact of new parameters could be taken into account as thermal mass position, insulation level, windows ratio and performance, and inside coatings impact. For this last parameter, some experimental validations will be needed to validate the numerical models. It would also be interesting to add tertiary buildings which are very sensible to overheating problems due to their large internal gains during day time. Extend to new hot climates will bring new interesting conclusions as well.

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