THERMAL VULNERABILITY OF RESIDENTIAL HOUSING DUE TO CLIMATE CHANGE IN SUMMER TIME

VULNERABILIDAD TÉRMICA DE VIVIENDAS DEBIDO AL CAMBIO CLIMÁTICO EN EL VERANO

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ABSTRACT

There are more frequent and intense heatwaves in Europe due to climate change. Due to these rare meteorological sequences, the building envelope often fails to provide adequate protection. As we spent most of our time inside buildings, it is necessary to assess the thermal performance of the building during extreme meteorological sequences. Our focus is on determining the principal harmonics of the external temperature that are not damped by the building's envelope during summer time. Therefore, we have developed a methodology to represent the external temperature, which is divide in two zones, a thermal load zone, and a thermal overload zone. The construction of this theoretical external temperature is parametrized using the modal method and the Discrete Cosine Transform. Finally, the methodology is applied to a case study in Paris focusing on the well-known heatwaves, leading to the identification of some common harmonics.

Keywords: heatwave, meteorological sequences, modal method, Discrete Cosine Transform.

RESUMEN

Hay olas de calor más frecuentes e intensas en Europa debido al cambio climático. Debido a estas secuencias meteorológicas poco comunes, la envolvente del edificio a menudo no puede protegernos adecuadamente. Dado que pasamos la mayor parte de nuestro tiempo dentro de edificios, es necesario evaluar el rendimiento térmico del edificio durante secuencias meteorológicas extremas. Nos centramos en determinar los armónicos principales de la temperatura externa que no son atenuados por la envolvente del edificio durante el verano. Por lo tanto, hemos desarrollado una metodología para representar la temperatura externa, que se divide en dos zonas: una zona de carga térmica y una zona de sobrecarga térmica. La construcción de esta temperatura externa teórica se parametriza utilizando el método modal y la Transformada Discreta del Coseno. Finalmente, la metodología se aplica a un estudio de caso en París centrado en las conocidas olas de calor, lo que resulta en la identificación de algunos armónicos comunes.

Palabras clave: olas de calor, secuencias meteorológicas, método modal, Transformada Discreta del Coseno.

1. INTRODUCTION

Due to climate change, there are more frequent and intense heatwaves, which are characterized by high external temperature during both day and night for at least 3 days [1].

The external temperature as a periodic evolution could be considered as the sum of harmonic functions (sinus or cosines), and these harmonics are its components [2].

The envelope of a dwelling plays an important role, since it dampens certain components of the temperature, but not others. The latter are responsible for the increase in indoor temperature and can lead the occupants from a zone of discomfort to a zone of health risk. Our focus lies in identifying these components during heatwaves in a residence in Paris, where each component is associated with a period or pulsation. By identifying them, we could know if a dwelling will be vulnerable to future meteorological sequences that contains those components as predominant.

A representation of a heatwave is proposed to find the not damped harmonics and so its periods. The parameters to characterize this representation are detailed in the methodology, and we use different tools to parametrize it such as : the modal method applied to building thermal [3], and the Discrete Fourier Transform [4].

2. METHODOLOGY

The methodology is developed in three steps.

2.1 Heatwave representation

Firstly, the representation of a heatwave (Fig. 1) is made by using a simplified representation of the external temperature, which is divided into two zones. From t_1 to t_2, we have the thermal load zone which is represented by the average temperature (Ec. (1)), and from t_2 to t_3, the thermal overload zone which is represented by harmonics around the average temperature (Ec. (2)) above the preceding average.

$$U(t) = \bar{U}_{12}, \quad t_1 < t \leq t_2 \qquad (1)$$

$$U(t) = \bar{U}_{23} + \sum_i a_i \cos(\omega_i t), \qquad t_2 < t \leq t_3 \qquad (2)$$

Where U is the external temperature sliding window [K], $\bar{U}$ is the average external temperature in each interval [K], a_i is the amplitude of the harmonic [K], ω_i is a pulsation [Hz] (defined as $2\pi / P_i$, where P_i is the period [s]), and the index i represents the number of harmonics.

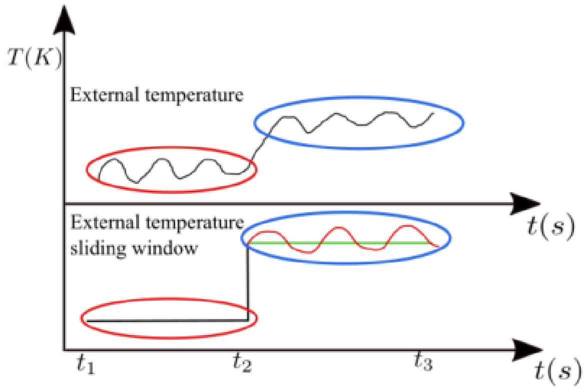

Fig. 1. Simplified representation of a heatwave named sliding window.

Certain parameters must first be identified such as the total duration $(\boldsymbol{t_3 - t_1})$, the duration of each period (see Ec. (1), and (2)), and the pulsations $\boldsymbol{\omega_i}$ of the harmonic functions.

Then, this representation is calculated for the duration found $(\boldsymbol{t_3 - t_1})$ and recalculated for a step time of 1 hour. That means that this simplified external temperature could slide in time, so we named it 'external temperature sliding window'.

Fig. 2 represents the steps taken for the construction of the heatwave representation and the criterion for the determination of the not damped harmonics.

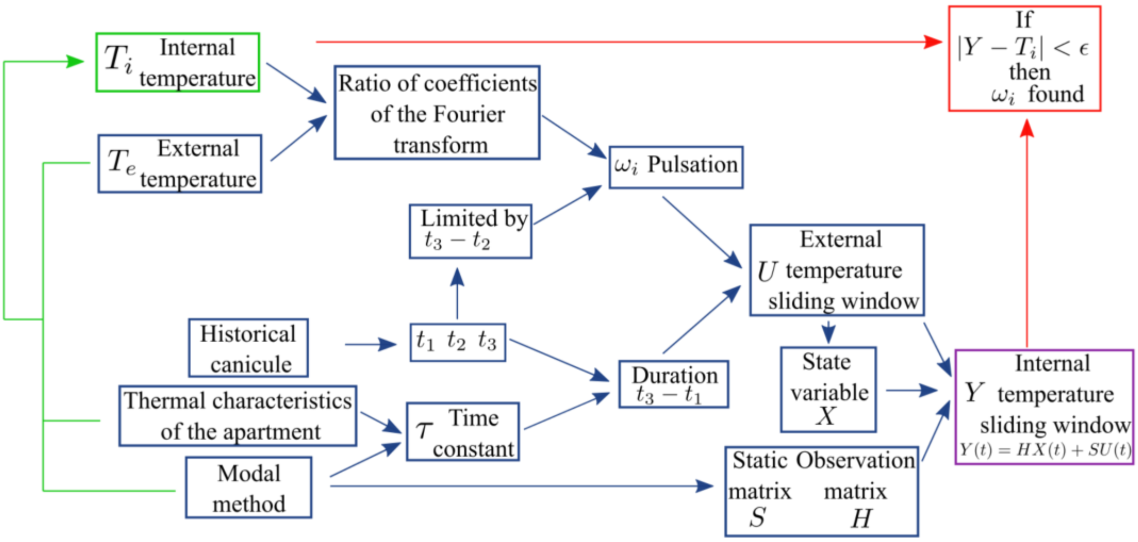

Fig. 2. Steps for constructing a heatwave representation and the criteria for identifying non-damped harmonics.

Where T_i is the internal temperature simulated with a real meteorological sequence [K], T_e is the external temperature [K] (the real meteorological sequence), τ is the thermal time constant of the apartment [s], ω_i is the harmonic pulsation [Hz]. U is the external temperature sliding window [K], Y is the internal temperature sliding window [K], X is modal state variable, S is the static matrix, and H is the observation matrix.

An estimated value of the thermal time constant of the apartment can be defined as the time required for the internal temperature to reach 62.73 % of its steady state value when a step-type external temperature has occurred [5].

By looking at the Eq. (1) and (2), we notice that it does not include the incident radiation. Consequently, the pertinence of using an equivalent external temperature was assessed providing us a good representation of the internal temperature. This proposal allows us to maintain the representation of the heatwave.

Therefore, the external temperature (T_e) is a combined one, called equivalent external temperature. It contains the external temperature and the solar irradiation transmitted by the window. This expression is determined by considering the contribution of thermal fluxes from the outdoor environment to the indoor space.

$$\varphi_{ext-int} = f S_{window} I + U_{window} S_{window}(T_{ext} - T_{int}) + \rho_{air} c_{air} Q_{air}(T_{ext} - T_{int}) \quad (3)$$

where $\varphi_{ext-int}$ is the sum of thermal fluxes that contribute to the indoor environment from the outdoor environment [W], f is the transmittance coefficient of the window [-], S_{window} is the window surface [m^2], I is the incident solar irradiation [W/m^2] in the exposed wall. U_{window} is the overall transmission coefficient of the window [W/m^{2}K], T_{ext} is the external temperature [K], T_{int} is the internal temperature [K], ρ_{air} is the density of the air [kg/m^3], c_{air} is the heat capacity of the air [J/kg K], and Q_{air} is the exchanged volume air per hour [m^3/s].

The first component of the Eq. (3) is the contribution by radiative heat transfer, the second component is the conductive and convective heat transfer contribution, and the last one is the heat flux due to the air flow renovation. As the first component does not have the temperature difference, we rearrange and factorize the Eq. (3).

$$\varphi_{ext-int} = f S_{window} I + (U_{window} S_{window} + \rho_{air} c_{air} Q_{air})(T_{ext} - T_{int}) \quad (4)$$

Introducing the first element, we have:

$$\varphi_{ext-int} = (U_{window} S_{window} + \rho_{air} c_{air} Q_{air})\left(\frac{f S_{window} I}{U_{window} S_{window} + \rho_{air} c_{air} Q_{air}} + T_{ext} - T_{int}\right) \quad (5)$$

The equivalent external temperature results from the sum of the external temperature and weighted solar irradiation.

$$\varphi_{ext-int} = (U_{window} S_{window} + \rho_{air} c_{air} Q_{air})(T_{ext\,eq} - T_{int}) \quad (6)$$

$$T_{ext\,eq} = \frac{f I}{U_{window} + \frac{\rho_{air} c_{air} Q_{air}}{S_{window}}} + T_{ext} \quad (7)$$

The Eq. (7) is used to determine the Eq. (1) and Eq. (2), as we now apply an equivalent external temperature.

Duration of the sliding window. We know that an inertial system reaches 95% of its steady state after a duration of 3 times the main thermal time constant. Consequently, the sliding window duration is taken equal to 3 times the thermal time constant (τ) of the apartment. This allows the apartment to forget anything older than 3 times the thermal time constant with an error of 5%.

We have used the discrete modal method because it allows us to analyze the internal temperature by considering an external temperature in the harmonic form (according to Eq. (1) and (2)). Besides, it facilitates the thermal time constants and specific modal tools to analyze the contribution of eigen modes in the thermal dynamic of the building (spectral index and eigen mode diagrams).

The definition of the time t_2 is important because it limits the duration of the thermal load and overload zones. We have tested three values equals to 1, 1.5 and 2 times the time constant.

Pulsations. We have used the discrete Fourier transform to calculate the Fourier coefficients of a real external temperature (T_e) and the internal temperature (T_i) determined by the modal method. These coefficients once normalized represent the amplitudes of each harmonic component of the temperature.

Then, by comparing their amplitudes for each harmonic (ratio of the amplitude of the internal temperature to the amplitude of the external temperature) and considering a threshold value, we could be able to distinguish the harmonics, which are damped or not by the apartment's envelope.

Consequently, we could select the not damped harmonics as well its pulsations. These pulsations are a reduced number of all pulsations contained in the temperature, so the selected pulsations could help us to create a simplified theoretical external temperature.

External temperature sliding window. Once we define the duration $(t_3 - t_1)$, the intermediate time (t_2), and the pulsations (ω_i), we could be able to parametrize the external temperature in accordance with Eq. (1) and (2).

Internal temperature sliding window. This internal temperature is as well a theoretical one. It is the result of using the discrete modal method and the external temperature sliding window $(U(t))$.

By solving the thermal exchanges between all the nodes with the modal method, we get the Eq. (8) for the internal temperature sliding window:

$$Y(t) = H\,X(t) + S\,U(t) \quad (8)$$

2.2 Criterion of comparison

Secondly, once the sliding window has been defined, the internal temperature sliding window method (Y) is compared with the internal temperature calculated with the modal method for a real meteorological sequence (T_i) (see red box according to Fig. 2) to determine whether the selected pulsations ω_i follow the internal temperature trend in summer time. The internal temperature sliding window (Y) should have a similar behavior to that of the internal temperature (T_i).

As the external temperature sliding window is constructed of two successive parts, where the thermal overload zone is higher in average than the thermal load zone, the internal temperature, obtained after simulation (purple box in Fig. 2), will not be well represented for all the year. However, the internal temperature sliding window will have a similar evolution in summer time in comparison with the internal temperature simulated with a complete meteorological sequence (green box in Fig.2).

2.3 Case study

Finally, the apartment to be studied was identified using the following criteria: top floor, large glass surface, high solar exposure, and low heat loss coefficient.

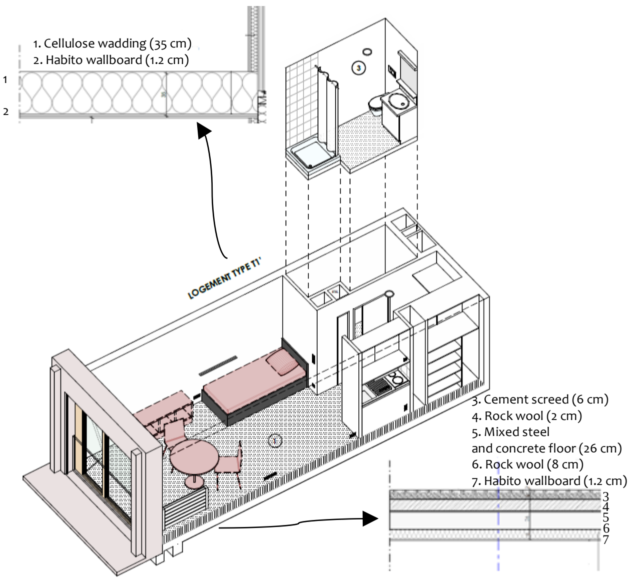

Fig. 3. 3D view of the apartment and dimensions of its main components.

Fig. 3 represents the living area of the apartment as well as the main components of the floor and ceiling. We can notice that this apartment has a significant window area with respect to its opaque wall.

Table 1.
Characteristics of the apartment, Nollet project.

Glass wall surface [m²]	4.14
Opaque wall surface [m²]	1.64
Overall Heat loss coefficient[1] [W/K]	31
Living area [m²]	18.82
Floor number	5 of 5

[1] Calculated for zero air flow renovation.

3. RESULTS AND DISCUSSION

In this section, we are going to present in a first instance the parameters utilized to construct the external temperature sliding windows and in a second instance, the comparison of the two temperatures detailed in the subsection 2.2 applied to the case study for five heatwave sequences: 2003, 2006, 2015, 2018 and 2019.

3.1 Construction of the external temperature sliding window

The first parameter is the time constant. Time constants are calculated with the discrete modal method, and we get as many time constants as the number of nodes in spatial discretization [3]. We listed the first five-time constants because the others are lower than 1 hour and as we have measured data within an hourly space, they can not significantly influence over a one-hour time step.

Table 2.
Five first time constants, Nollet project.

Time constants	Time (h)
τ_1	89.9
τ_2	12.3
τ_3	4.7
τ_4	2.4
τ_5	1.9

After the analysis of spectral index, the first two thermal time constants are always present in each spectral index graph. A spectral index graph shows the contributions associated to all the time constants; it is constructed for one solicitation when the others are not considered. In this case, there are six spectral index graphs as there are only six solicitations (equivalent external temperature and five neighbors' temperatures). By analyzing the spectra index graph, we found that the variations in the internal temperature were more sensitive for the first thermal time constant and therefore it is considered as the most predominant. As a result, we are going to retain the time constant of 89.9 hours, and then the total duration will be $t_3 - t_1 = 3\tau = 270$ hours (approximately 11 days).

The third parameter is the set of pulsations. We manage the Discrete Cosine Transform (DCT) instead of the Discrete Fourier Transform (DFT) because DCT handles real numbers, for its simple analysis of the amplitude spectrum and the rapid convergence of the extremes of the distribution (reduce of the border effect) [6].

Two conditions are stablished to filter the set of pulsations. For the first one, the amplitudes should be higher than 0.2 °C to disregard low amplitudes. For the second condition, the ratio of amplitudes should be higher than 0.44. This arbitrary threshold value was chosen equal to the one used in a spectral analysis applied to the internal and external temperature of an office (Pedregal, 2009). As an example, we have certain values of pulsation that satisfy both conditions for the year 2003.

Table 3.
Periods that meet the condition sorted in decreasing order according to the ratio for the year 2003.

Amplitude		Ratio	Period (days)
Internal temperature [°C]	External temperature [°C]		
21,23	22,72	0,93	0,0
0,98	1,31	0,75	0,5
0,39	0,57	0,69	28,1
0,64	0,99	0,65	121,7
0,62	1,06	0,58	365,0
0,39	0,77	0,51	40,6
0,39	0,78	0,50	19,2
0,73	1,50	0,48	11,1
0,52	1,13	0,46	14,0
0,30	0,65	0,46	12,2

From Tab. 3, we can retain some periods lower than two times the total duration, in other words 6 times the time constant (22 days). The period of 12 hours (0.5 day) is always present in all the evaluated years; however, it will not be taken into consideration in graphics results since our aim is to identify undamped pulsations greater than 1 day. The appearance of the period of 12 hours can be explained by the fact that the equivalent external temperature contains the incident solar irradiation, and the harmonic of 12 hours is predominant in the solar irradiation.

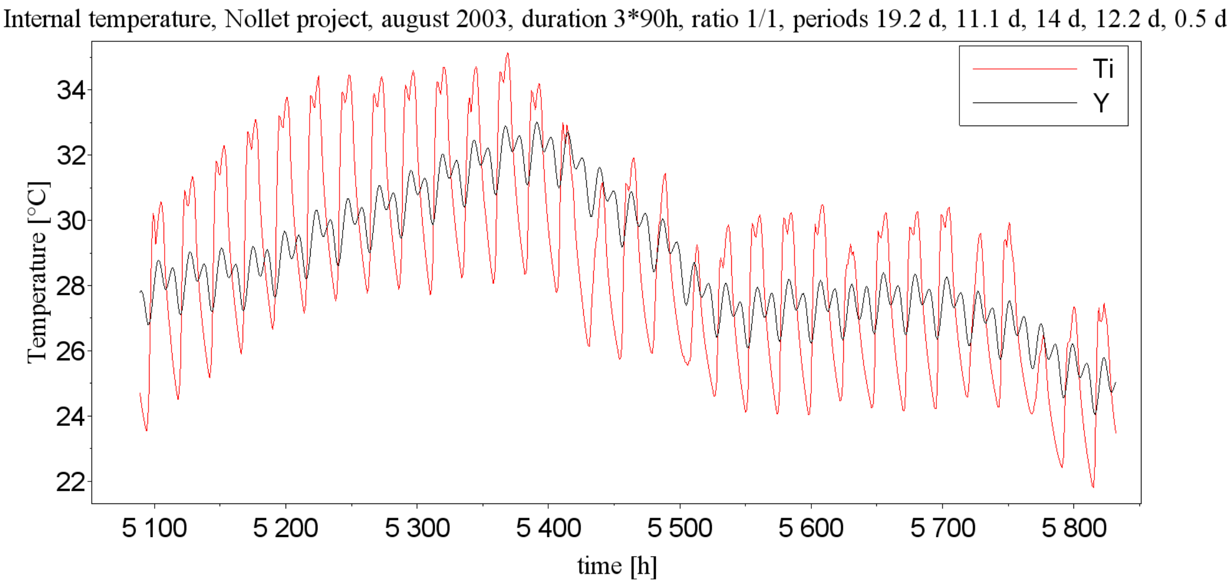

Fig. 4. Internal temperatures in the heatwave of 2003 with five harmonics including the harmonic of 12 hours.

The ratio 1/1 mentioned in the title of the Fig. 4 refers to the relation between the duration of the thermal load zone with respect the duration of overload zone. We have found that the most pertinent value of t_2 to follow the trend of the internal temperature is 1.5 τ, which is half of the duration of external temperature sliding window.

Consequently, the periods selected for the year 2003 are 19.2 days, 11.1 days, 14 days, 12.2 days, and 12 hours. This result will be illustrated in the next section.

With these three parameters, we can construct the reduced external temperature. In the next subsection, we are going to compare and evaluate the choice made of the set of pulsations.

3.2 Comparison of the internal temperatures

The internal temperatures (Y, T_i) are presented in Fig. 5 - 9.

To draw the sliding window the following parameters are calculated. (a) The time constant of the apartment (τ) is used to obtain the total duration $(t_3 - t_1 = 3\tau)$. (b) Different values of t_2.were tested. (c) The DCT applied to the internal and external temperature allows obtaining the periods.

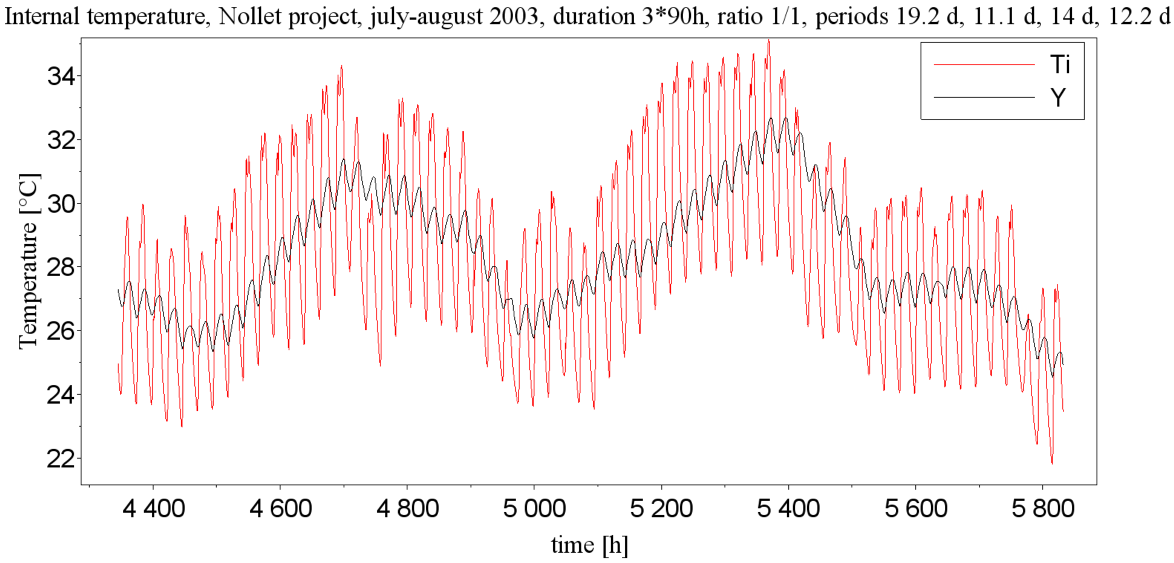

Fig. 5. Internal temperatures in the heatwave of 2003.

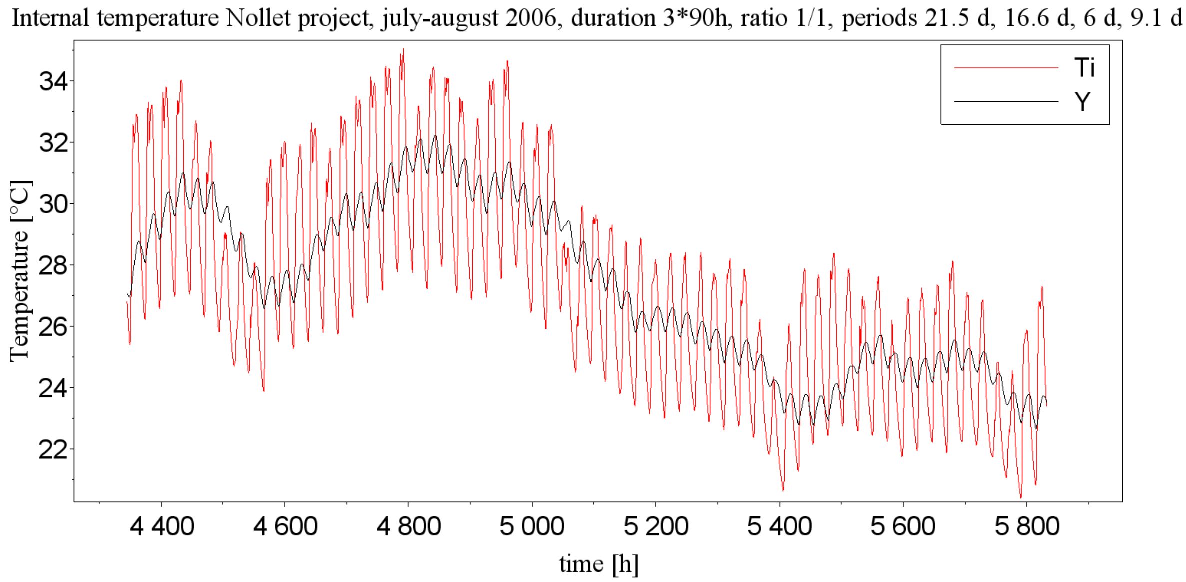

Fig. 6. Internal temperatures in the heatwave of 2006.

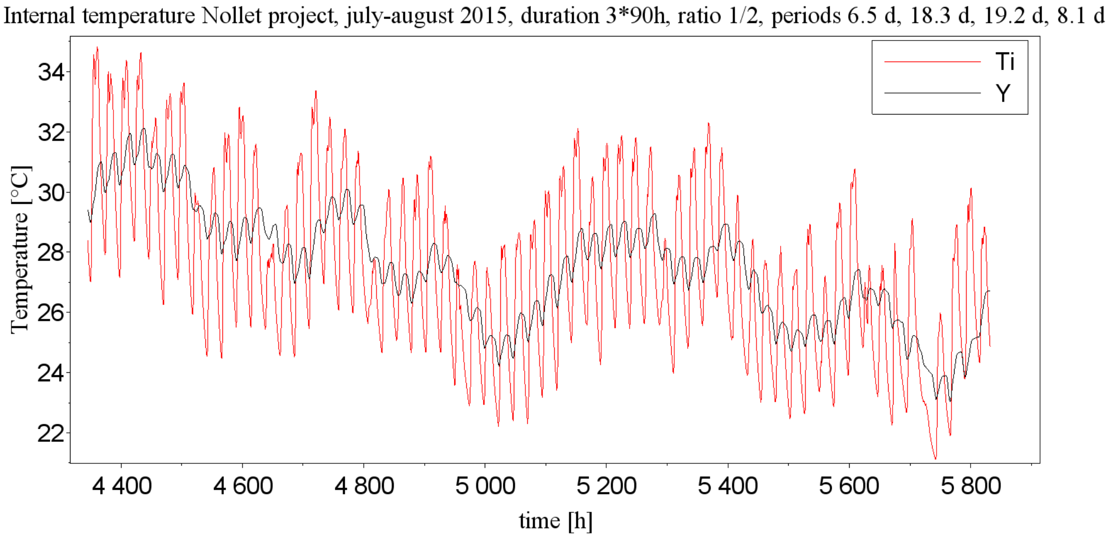

Fig. 7. Internal temperatures in the heatwave of 2015.

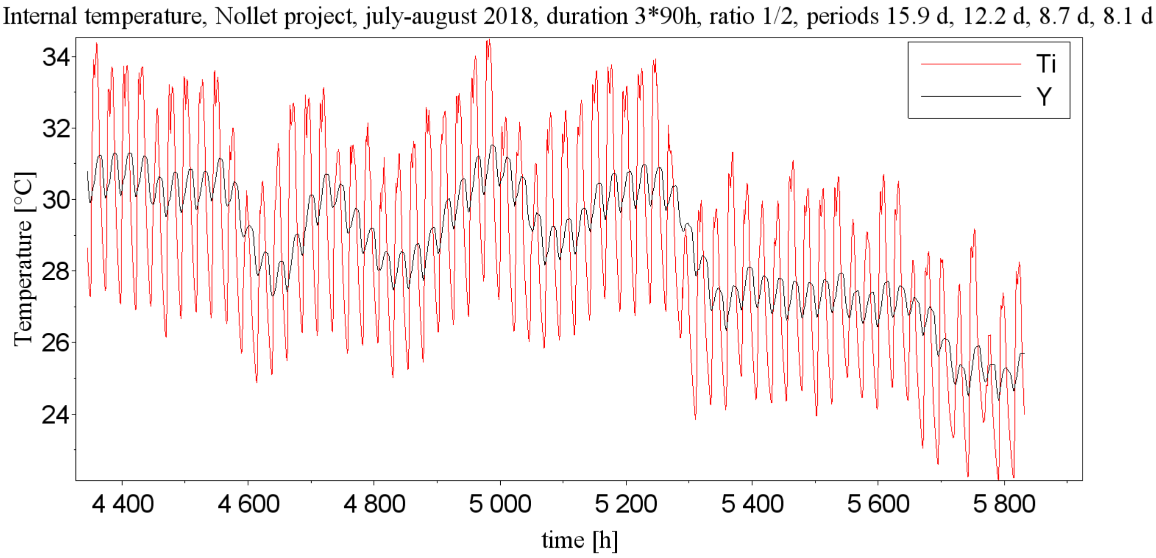

Fig. 8. Internal temperatures in the heatwave of 2018.

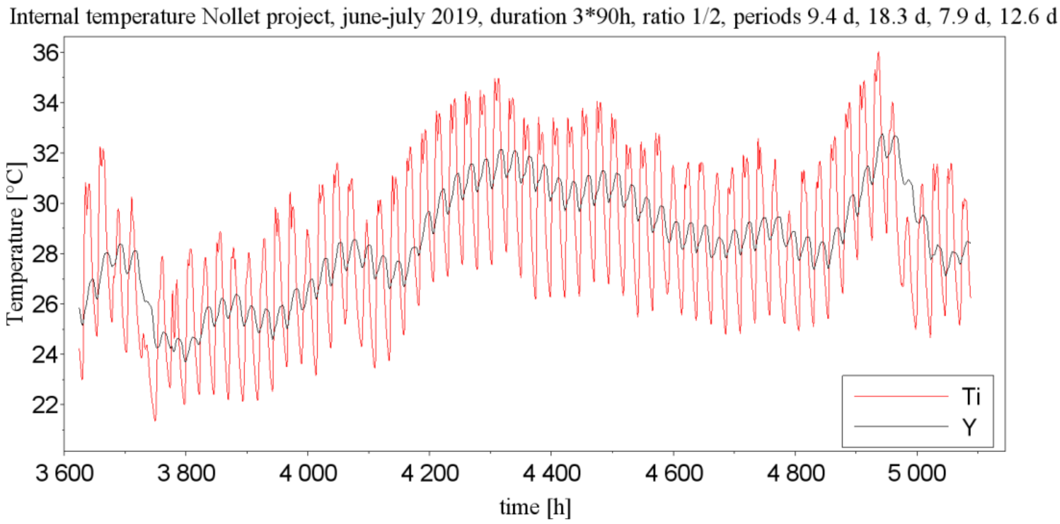

Fig. 9. Internal temperatures in the heatwave of 2019.

The Figures 5 to 9 contain only the first four harmonics in descending order except for the 12-hour period harmonic. The period of 19.2 days appears in 2003 (first position), in 2006 (seventh position), in 2015 (third position). Another period that appears in more than one year is 18.3 days, it appears in 2015 (second position), in 2018 (seventh position), in 2019 (second position).

We observe that the internal temperature sliding window varies with the same trend during the selected period July-August (for 2003, 2006, 2015, 2018), and June-July (for 2019). The maximum and minimum values of the two evolutions are close in time but not in intensity because the composition with four harmonics is not enough to reproduce the amplitude considering all the harmonics (look the amplitudes in Tab. 3). This similarity with the relative representation of the extremums confirms the choice of dominant pulsations of the external climate, which are not damped by the apartment's envelope.

4. CONCLUSIONS

- We can determine that the selected apartment cannot filter certain harmonics. Even though, those harmonics are different from one year to another, by this methodology the periods of those harmonics are encapsulated by twice the total duration of the sliding window.
- Some periods seem to be interesting to explore, such as 19.2 and 18.3 days, since these were observed in at least three heatwaves. The period of 12 hours should also be studied as it is present predominantly in the years evaluated.
- The methodology was applied to a case study in Paris; however, it could be applied to other apartments and meteorological sequences.

PERSPECTIVES

The choice of a complete climate data is primordial, so that we can use the external temperature from the same weather station. In this investigation, the external temperature from Montsouris weather station was used since 2003.

The recalculation of the internal temperature by the modal method should also consider a nocturnal ventilation regime that varies according to the difference of temperature. This will imply a change in the value of the thermal time constant of the apartment.

Instead of making the analysis of the sliding windows per year, it would be interesting to utilize at least 30 consecutive years. By doing this, we can get in one simulation, the amplitudes of the harmonic components of the internal and external temperature.

Further studies will be headed to determine the parameter (t_2) that divide the loading zone from the overload zone by analyzing the average, maximum and minimum external temperature during heatwaves sequences.

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