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Prediction of Thermal Comfort from Operating Temperature and the Predicted Mean Vote / Predicted Percentage Dissatisfied (PMV/PPD) Indices in a Nubian Vault

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Abstract: The building and construction sector has a significant impact on the environment due to its high consumption of energy resources and increasing levels of emissions, and pollution. According to the United Nations Human Settlements Program (UN-HABITAT), the energy used by buildings and construction accounts for more than a third of the final energy consumed in the world and a quarter of greenhouse gas emissions. African countries such as Burkina Faso are concerned in this reality in the field of building. This is why the major issue in the tropic today is the construction of new buildings with high environmental quality and high energy performance. Today's construction choices will have an impact on future generations. The technique and materials of a building contribute to the health, safety and comfort of people. In the present work, the operating temperature and the PMV/PPD indices in a Nubian vault were determined. The operating temperature and the PMV/PPD indices are indicators of thermal comfort. Thus, the knowledge of these indicators allows to appreciate the state of comfort in the Nubian vault. It is in this perspective that the operating temperature will be determined by the adaptive method. The Fanger model is used for the determination of the PMV/PPD indexes. From the state of sensation obtained, acceptable ambient conditions can be defined for an individual in a tropical zone. As an alternative, the most suitable construction type and building materials could be recommended for each type of climate.

Keywords: Operating Temperature, Wall Temperature, PMV Indice, PPD Indice, Thermal Comfort, Adaptive Approach, Analytical Model

1. Introduction

Building with the climate in mind is not new. The history of building with raw earth shows that man has first had to deal with the climate and then, through an intelligent perception of natural phenomena, take advantage of it and provide ingenious answers in each space, adapted to his way of life and his environment. A building, including its structure, lighting, energy production system, etc., must offer the most comfortable interior conditions for human beings. The notion of thermal comfort is closely linked to the energy performance of the building. According to M'Sellem [1], comfort is a global concept including heat, cold, light, noise, landscape, water, greenery, prestige, and others which are elements defining several climatic, aesthetic, and psychological parameters of comfort. Comfort is also the subjective sensation that does not exist in itself. It is only through discomfort that it can be appreciated. In recent years, earthen constructions have emerged as an answer to the problems of thermal (comfort) in buildings, energy demand, and the negative impact of the construction sector on the environment, Zoma [2]. The major issue in tropical climates today is the construction of new buildings with high environmental quality, high energy and thermal performances. To evaluate thermal comfort and to have tools to help the design of buildings, researchers have developed methods to combine climatic parameters such as air temperature, relative humidity, wind speed, etc. The best known and most used of these methods are the predicted mean vote (PMV), the predicted percentage dissatisfied (PPD), the operating temperature, and the bioclimatic diagrams, Halidi [3]. The Fanger method contained in the norm ISO 7730 (2005) [4], and described by the norm ASHRAE 55, analyzed thermal comfort conditions and introduced two of the analytical indices of thermal stress, the "predicted average vote" (PMV) and the "predicted percentage dissatisfied" (PPD), Olesen [5]. Thus, these new parameters are generally used to appreciate thermal comfort. The predicted mean vote (PMV) is the result obtained from an average opinion of a large group of people on the feeling of comfort with reference to a well-defined scale. The predicted percentage dissatisfied (PPD) is the percentage of dissatisfied people given by the PMV. Apart from these parameters, it remains to consider the physiological, psychological, and social aspects, Rabetanetiarimanana and Razanamanampisoa [6]. The study was carried out in a Nubian vault where a measurement campaign was used to determine the air temperature, the temperature of the walls, and the relative humidity of the air. Thus, the knowledge of the operating temperature and the PMV/PPD indices allows the evaluation of the thermal comfort in the Nubian vault. These knowledges have received great interest because it allows achievements which strongly integrate social and cultural development and respect for the environment for a sustainable development perspective.

2. Materials and Methods

To evaluate the thermal comfort in the Nubian vault, we used two different but complementary methods, namely the adaptive method and the analytical method. The building studied is a Nubian vault located in Cassou, a village located seven (07) km from Koudougou, the main town of the Centre-West region of Burkina Faso. The adaptive approach allowed the determination of the operating temperature. As for the analytical approach, it also allowed the determination of the PMV/PPD indices. In the present work, a data logger, J-type thermocouples and a midi logger are used. The temperatures of the indoor air, outdoor air, walls, indoor floor, roof, and indoor relative humidity have been measured during the experiment. The values obtained from this measurement are used to determine the thermal indices such as operating temperature and PMV/PPD indices. Figure 1 represents the geometry building model.

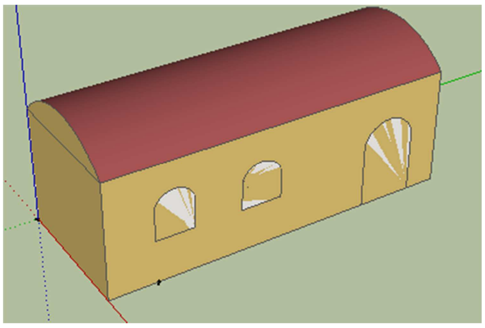

Figure 1. *Building geometry in sketchup.*

2.1. Operating Temperature

According to Jnat [7], the adaptive method takes into account physiological, physical, and psychological factors that have been developed as a result of surveys and studies conducted in the field. This method is based on the fact that the human is an active element in front of his thermal environment. It is an empirical method focused on indoor and outdoor temperatures and based on field surveys in which thermal judgments are measured through questionnaires while the occupants perform their usual activities. The operative temperature is determined from the adaptive approach. The operative temperature is defined as the temperature of an isothermal enclosure in which an occupant exchanges the same amount of heat by radiation and convection as in the enclosure in which he/she is actually located. Mathematically, it is the average of the average radiative temperature and the ambient temperature weighted respectively by the heat transfer coefficients. It is expressed by equation (1):

$$T_{op} = \frac{h_r t_{mr} + h_c t_a}{h_r + h_c} \tag{1}$$

Where T_{op} (°C) is the operating temperature, h_r (W.m^{-2}.K^{-1}) is the radiative transfer coefficient, h_c (W.m^{-2}.K^{-1}) is the convective transfer coefficient, T_{mr} (°C) is the average radiant temperature, T_a (°C) is the ambient temperature.

In a simplified way, a comfort temperature felt also called operating temperature or dry resultant temperature is given by equation (2):

$$T_{op} = \frac{T_a + T_p}{2} \tag{2}$$

With T_{op} (°C) the operating temperature, T_a (°C) the room temperature, T_p (°C) the wall temperature.

This simple relationship applies as long as the air speed does not exceed 0.2 m/s.

The temperature felt by the human body, called "operating temperature", is not the air temperature but an average between the air temperature and that of the walls surrounding the occupant in the building. Equation (3) gives another expression of the operative temperature:

$$t_{op} = at_a + (1-a)t_r ? \tag{3}$$

With t_{op} (°C) the operating temperature, t_r (°C) the radiant temperature, a the air velocity dependent coefficient.

Table 1 summarizes the range of values of the factor. To simulate the operating temperatures of the different zones, TRNSYS 16 proposes another expression of the operating temperature according to equation (4):

$$T_{op} = A_{op} * T_{air} + (1 - A_{op}) * T_{surf} \quad (4)$$

Where A_{op} is the weighting factor, T_{air} (°C) is the air temperature, T_{surf} (°C) is the surface temperature.

Table 1. *Range of values of factor a, Raji [8].*

V (m.s^{-1})	0 -0.2	0.2 – 0.6	0.6 – 1.0
Factor a	0.5	0.6	0.7

To evaluate the thermal environment, Fgaier [9] developed the indices of predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD):

1) The PMV gives the average thermal sensation of individuals in a given thermal environment as it would appear from a statistical study;
2) The PPD is a relation between the PMV and the percentage of dissatisfied people in a given thermal environment.

The results indicate that even in a relatively good thermal environment, the number of dissatisfied people is not zero and remains around 5%. Dear et al. 1994 [10] defined a comfort standard (adaptive standard for naturally ventilated buildings) to evaluate the thermal comfort in buildings. This standard establishes an indoor temperature controlled by the comfort zone varying from 17°C to 22°C when the outdoor air temperature (Text) is below 5°C and from 26°C to 31°C when the outdoor air temperature (Text) reaches 34°C, Dear [11]. The indoor temperature used refers to the resulting dry room temperature (obtained from the air temperature, average wall temperature and air velocity). The upper limit of the Brager comfort zone can be defined by equation (5), Jannot [12].

$$T_{\text{supérieure}} = \left\{ \begin{array}{l} 22°C, if\,(T_{ext} \le 5°C) \\ (9/28)T_{ext} + 20,4°C(5°C \prec T_{ext} \prec 33°C) \\ 31°C, if\,(T_{ext} \ge 33°C) \end{array} \right\} \quad (5)$$

Table 2 gives the sensation and physiological state as a function of effective standard temperature.

Table 2. *Relationship between effective standard temperature and sensation [13].*

Standard Effective temperature (SET)	Sensation	The physiological state of a sedentary person
>37.5	Exceedingly hot	The physiological state of a sedentary person Failure of regulation
34.5 – 37.5	Very hot, very unacceptable	Profuse sweating
30.0 – 34.5	Hot, uncomfortable and unacceptable	Sweating
25.6 – 30.0	Slightly warm, slightly unacceptable	Mild sweating, vasodilation
22.2 – 25.6	Comfortable and affordable	Neutrality
17.5 – 22.2	Slightly cold, slightly unacceptable	Vasoconstriction
14.5 – 17.5	Cold and unacceptable	Slower cooling of the body
10.0 – 14.5	Very cold and unacceptable	Thrills

2.2. Predicted Mean Vote (PMV) and Predicted Percentages of Dissatisfied (PPD)

2.2.1. Predicted Mean Vote (PMV)

The analytical approach makes it possible to determine thermal comfort in terms of physical heat transfers. The model "predicted mean vote" (PMV), is the best known. The model is based on the correlation of the heat balance and the mean comfort vote under given thermal conditions, Carlos [25]. The PMV/PPD indices will be determined using the analytical approach of Fanger. One of the best known thermal indices is the Fanger comfort equation specific to indoor spaces. Fanger [14] experimentally determined the physiological conditions necessary for thermal comfort under homogeneous and stationary thermal conditions. This index expresses the average thermal sensation experienced by a large group of individuals on the ASHRAE thermal sensation scale. Equation (6) gives the expression for PMV.

$$PMV = \left(0.303e^{-0.036M} + 0.028\right)\left[(M - W) - H - E_c - C_{res} - E_{res}\right] \quad (6)$$

Where M is the metabolism (W.m^{-2}), W is the external work (W.m^{-2}), H (W.m^{-2}) is the sensible heat loss (convection and radiation), E_c (W.m^{-2}) is the heat exchanged by skin evaporation, C_{res} (W.m^{-2}) is the heat exchanged by respiratory convection, E_{res} (W.m^{-2}) is the heat exchanged by evaporation related to respiration.

In this equation, the terms H, E_c, C_{res}, and H_{res}, correspond to the heat exchanges between the body and its immediate environment and are calculated with the following equations (7), (8), (9) and (10):

$$H = 3.96.10^{-8} * f_{cl}\left[\left(t_{cl} + 273\right)^4 - \left(t_r + 273\right)^4\right] + f_{cl} * h_c * \left(t_{cl} - t_a\right) \quad (7)$$

Where f_{cl} is the clothing factor, t_{cl} (°C) is the clothing surface temperature, h_c (W.m^{-2}.°C^{-1}) is the convective heat transfer coefficient, t_r (°C) is the average radiation temperature, t_a (°C) is the air temperature, P_{Va} (Pa) is the vapor pressure of this air.

$$E_c = 3.05.10^{-3} * \left[5733 - 6.99\left(M - W\right) p_a\right] + 0.42\left[\left(M - W\right) - 58.15\right] \quad (8)$$

$$C_{res} = 0.0014 * M * \left(34 - t_a\right) \quad (9)$$

$$E_{res} = 1.7.10^{-5} * M * \left(5867 - P_a\right) \quad (10)$$

Where I_P is the plasticity index, I_{cl} (m^2 $K.W^{-1}$) is the clothing resistance, t_a (°C) is the air temperature, t_r (°C) is the mean radiant temperature, V_{ar} ($m.s^{-1}$) is the relative air speed, P_a (Pa) is the partial water vapor, t_{sk} (°C) is the skin temperature established by Fanger.

The main problem in the calculation of the PMV is that the term tcl corresponding to the external temperature of the clothes is a priori unknown. This temperature must be determined by iteration from a thermal equilibrium equation at the building surface. In a steady state, the heat flux transmitted by conduction through the garment at the skin temperature is equal to the sum of the convective and radiative heat exchange with the immediate environment. Equations (11), (12) and (13) are used to determine this temperature.

$$\frac{t_{sk} - t_{cl}}{I_{cl}} = 3.96.10^{-8} * f_{cl} * \left[\left(t_{cl} + 273\right)^4 - \left(t_r + 273\right)^4\right] + f_{cl} * h_c * \left(t_{cl} - t_a\right) \quad (11)$$

Hence, we deduce:

$$t_{cl} = t_{sk} - 3.96.E^{-8} * I_{cl} * f_{cl} * \left[\left(t_{cl} + 273\right)^4 - \left(t_r + 273\right)^4\right] - I_{cl} * f_{cl} * h_c * \left(t_{cl} - t_a\right) \quad (12)$$

where tsk is the skin temperature established by Fanger as:

$$t_{sk} = 35.7 - 0.028\left(M - W\right) \quad (13)$$

With I_{cl} ($m^2.K.W^{-1}$) the resistance of the cladding, f_{cl} the cladding factor, t_a (°C) the air temperature, t_r (°C) the average radiant temperature, t_{cl} (°C) the surface temperature of the garment, h_c ($W.m^{-2}$ K) the convective heat transfer coefficient.

For a PMV between -0.5 and 0.5, thermal comfort is achieved. The studies of Gave [15] and Minane [16] show that an individual living in hot climates or a subject acclimatized in a tropical zone can find acceptable an atmosphere corresponding to a LDC lower than 1.5.

According to the work of Ouattara and al. [17], such a subject could find acceptable in terms of comfort a PMV ≥ 1.5.

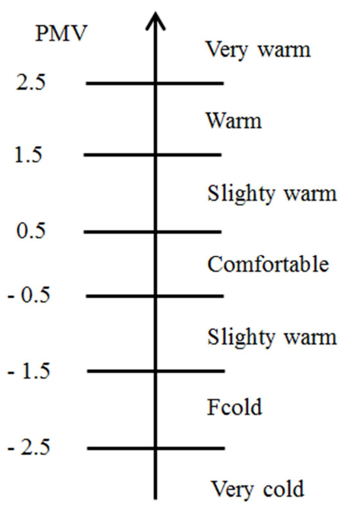

Figure 2. *Values of PMV and sensation according to Fanger [14].*

The evaluation of thermal comfort is described in international standards, in particular the ISO 7730 standard [14]. From this standard, we are able to set the upper temperature limit from which the occupants will be mostly in a situation of discomfort: Temperature limit of discomfort $T_{\_limit}$ = 32°C (Sahelian climate and clothing). Thus, Grosdemouge [18] recommends supplementing this standard by introducing a second indoor temperature limit above which the feeling of discomfort becomes extreme: Temperature limit of extreme discomfort $T_{\_limit}$ = 37°C.

For Dessureault [19], the Equatorial Comfort Index (ECI) is one of the comfort indices that takes into account all climatic parameters such as humidity and air speed. This index varies from -3 to 3 and is defined by the following relationship (equations (14) and (15)):

$$Y = 0.501 ECI - 5.234 \quad (14)$$

With

$$ECI = 0{,}574 T_{ai} + 2{,}033 P_{va} + 1{,}81 * V_i * 0{,}5 + 4{,}2 \quad (15)$$

Where T_{ai} (°C) and P_{Va} (Pa) are respectively the temperature of the indoor air and the vapor pressure of that air, V_i ($m.s^{-1}$) the velocity of the internal ambient air.

Table 3 gives some values of PMV.

Table 3. *Clothing strength values [20].*

Clothing set	I_{cl} (clo)	R_{th} ($m^2K.W^{-1}$)
Shorts + short-sleeved shirt	0.4	0.06
Pants + short-sleeved shirt	0.6	0.09
Pants + short -sleeve shirt + suit jacket	1.0	0.15
Pants + long sleeve shirt + long sleeve sweater	1.0	0.16
Mid-length skirt + short sleeve blouse + tights	0.5	0.08
Mid-length skirt + long sleeve blouse + tights	0.7	0.10
Long skirt + long sleeve blouse + jacket + tights	1.1	0.17

***Table 4.** Metabolic rate for different activity levels related to outdoor practices [21].*

Physical activity	M ($W.m^{-2}$)	M (W)	M (met)
Snooze	45	80	0.8
Sitting - Watching television	60	105	1.0
Standing upright	70	125	1.2
Slow walk	100	180	1.7
Walking at 3.2 km/h (0.9 $m.s^{-1}$)	115	205	2.0
Walking at 4.3 km/h (1.2 $m.s^{-1}$)	150	270	2.6
Walking at 6.4 km/h (1.8 $m.s^{-1}$)	220	400	3.8
Carrying a 50kg load	235	420	4.0
Tinkering/gardering	235 - 280	420 - 500	4.0 – 4.8
Playing basketball	290 - 440	520 - 790	5.0 – 7.6

2.2.2. Predicted Percentage of Dissatisfied (PPD)

The predicted percentage of dissatisfaction (PPD) is an index for assessing thermal discomfort that represents an estimate of the proportion of people who are likely to be too hot or too cold in a given environment. The predicted percentage dissatisfied represents the proportion of people who, when placed in identical conditions, respond that it is cool or cold (-2 to -3 vote) or hot or very hot (+2 to +3 vote). The PPD is expressed as a function of the PMV and has the expression in equation (16):

$$PPD = 100 - 95.\exp(-0.03353 - PMV^4 - 0.2179 PMV^2) \quad (16)$$

It can be seen that no thermal condition can satisfy 100% of the occupants. Even in the most favorable case (LMP = 0), there are still 5% of dissatisfied people. For a LMP equal to +1 or -1 (slightly warm and slightly cool), the PPD will be 27 and 24%. The ISO 7730 standard recommends limiting the PPD to 10%, which is equivalent to limiting the acceptable range of the PMV between -0.5 and + 0.5 [22]. The knowledge of the metabolism, the resistance of the clothing, and the measurements carried out make it possible to determine where the effective operating temperature is in correlation to the optimum comfort level.

According to Olesen & Parsons [23], the PMV index has been established for stationary values of these different variables, but it can be determined with a good approximation when one or more variables fluctuate slightly, provided that their time-weighted averages during the previous hour are considered.

The PMV scale has 7 degrees ranging from -3 (very cold) to +3 (very hot), as shown in Table 5.

***Table 5.** Scale of thermal sensation according to the value of PMV [4].*

-3	-2	-1	0	1	2	3
Cold	Fees	Slightly fresh	neutral	slightly tepid	tepid	hot

3. Results

The operating temperature is determined as the average of the internal air and wall temperatures. The experimental results allow us to obtain figures 3 and 4. They represent respectively the daily profiles of the operative temperature of April 17, 2017 and January 04, 2017 of the studied Nubian vault.

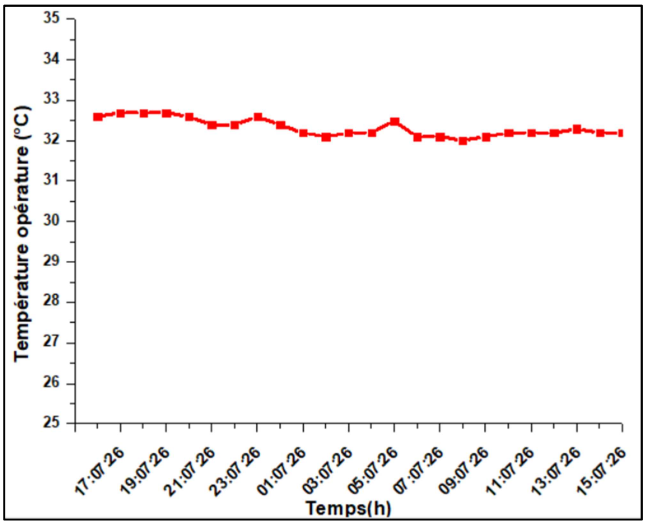

***Figure 3.** Daily operating temperature profile for the day of April 17, 2017.*

It is noted that the operating temperature of the Nubian vault does not vary practically during the day and it oscillates around 32.3°C. The minimum operating temperature 32°C and the maximum operating temperature of 32.5°C. The increase of the outdoor temperature in hot weather leads to an increase in the operating temperature. Thus, adaptive comfort takes into account the radiant temperature, but not the humidity or the air velocity.

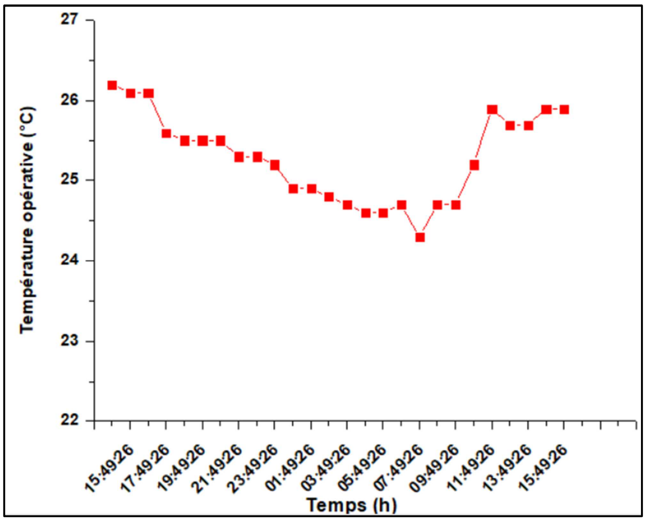

***Figure 4.** Daily operating temperature profile for January 4, 2018.*

During the period from 16h to 7h, the curve decreases and increases from 8h to 15h. This is explained by the fact that the outdoor temperature decreases from around 16h to 8h and increases from around 8h to 15h. The operating temperature being a linear function of the outside temperature, they thus evolve in the same direction. We notice that the operating temperature decreases from 26.3°C to 24.5°C with an average of 25.4°C. The balance of heat is a necessary condition for comfort but it is not sufficient. In the optimal situation (PMV = 0, neither hot nor cold), the dissatisfaction rate is 5% among people with the same thermal, metabolic, and clothing conditions. The dissatisfaction rate increases in the same way if the LMP deviates from 0 towards cold and towards warm.

Figure 5 represents the evolution of LMP and DPP as a function of time for the day of January 18, 2017, in the Nubian Vault.

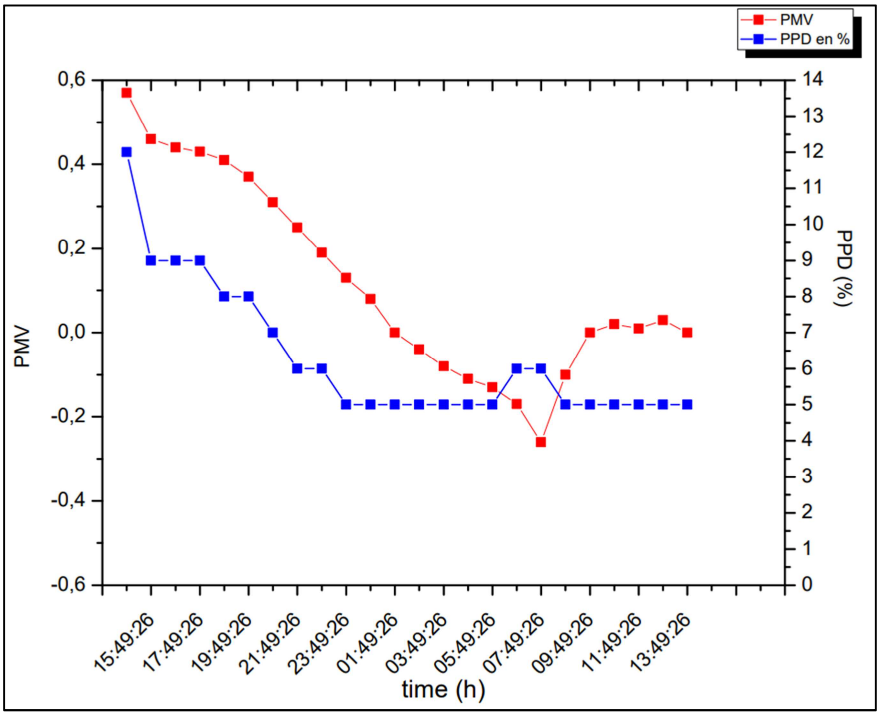

Figure 5. *Daily variation of the VMP and PPD of the Nubian Vault from January 4, 2018.*

It appears from these values that for the whole day, the value of the PMV varies from -0.26 to 0.57 and the PPD from 5% to 12%. Thus, we can say that there is thermal comfort in the room during the day because for Fanger [14], comfort is established for a PMV between -0.5 and 0.5 with a PPD less than 10%. To obtain a thermal comfort situation, it is recommended that the PPD be less than 10%, which corresponds to a PMV between -0.5 and +0.5 as recommended by ISO 7730 [4].

As for Figure 6, it represents the evolution of PMV and PPD as a function of time for the day of 07 April 2017 in the Nubian Vault.

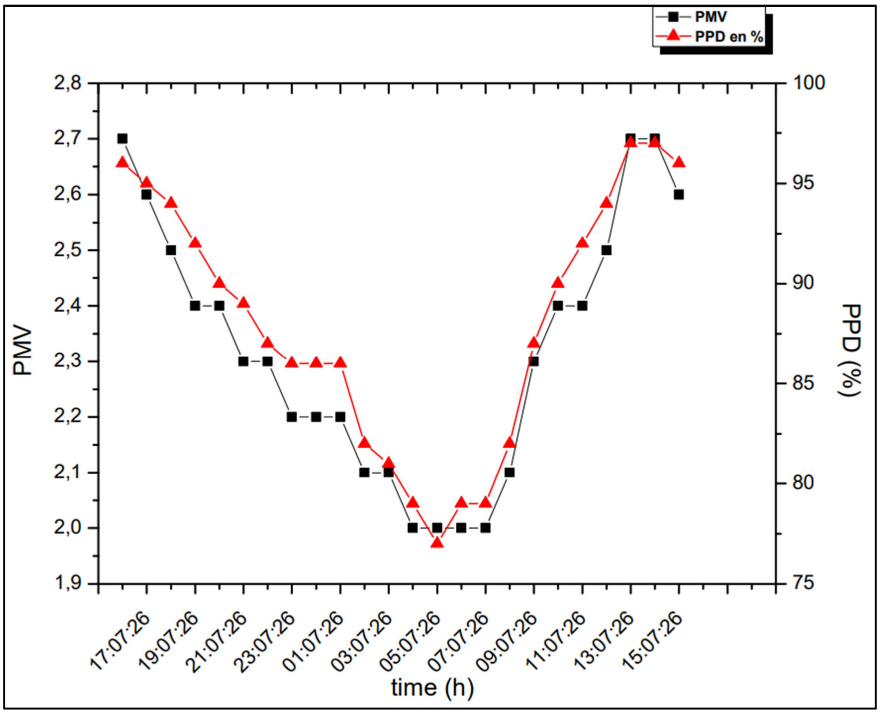

Figure 6. *Evolution of the PMV and PPD of the Nubian Vault as a function of time for the day of April 07, 2018.*

The optimal room temperature is determined when the operating temperature is optimal, corresponding to the PMV = 0.

The values in Figure 6 indicate that the PMV varies from 2 to 2.7 with the PPD varying between 77% and 97% corresponding to a warm comfort state according to the AFNOR [24] and Fanger [14] scale. We note peaks of PMV which correspond to overheating in the building. This leads to discomfort during this period. The relative humidity and mean radiant temperature are within the limits described in ASHRAE Standard 55-2004 [25], in ISO 7730 [4] and by Markov [26].

This overheating is due to the high inertia of the Nubian vault which allows for maintaining a relatively constant indoor temperature throughout the cool period. On the other hand, during hot periods, the inertia allows to the storage of heat during the day and gives it back to the environment at night. However, the part of the heat transmitted could generate periods of discomfort as in the case of the month of April. This high inertia can be used to delay the transmission of heat to the premises during the day and during the night, night ventilation will cool the building. When the outside temperature is low the stored heat loads are evacuated to the outside. Then the thermal comfort zone can be established for a percentage of dissatisfied people.

4. Conclusion

This work allowed us to determine the operating temperature and the PMV/PPD indices. We were interested in the adaptive and analytical approach. Thus, the knowledge of the operative temperature and PMV/PPD indices is an important factor to predict the thermal comfort state in the case of the nubian vault. We found that comfort is achieved during the month of January and it is not achieved in April. This is explained by the fact that the month of April corresponds to the hot period when the outside air temperatures are very high. Therefore, the temperature peak is higher in April. Several indices are used to evaluate a priori the individual thermal sensations according to physical, climatic, and physiological variables. The best-known indices are the thermal indices which are the ambient air temperature, the operating temperature, and the PMV/PPD indices. However, their use remains limited to moderate, stationary, and homogeneous environments, an infinitesimal proportion of cases encountered in the building. The thermal indices and the operating temperature make it possible to predict the state of thermal comfort in the Nubian vault. The values of these parameters obtained show that comfort is relatively achieved in the Nubian vault.

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