# THERMAL INERTIA AND MOISTURE REGULATION OF STRAW BALE BUILDINGS WITH EARTH PLASTERS

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*ABSTRACT: Straw bale buildings and the use of earth for inside plaster cannot be considered as new ways of building. Nevertheless, these building techniques are still poorly widespread in Europe. Beside their low impacts on environment and health, building with straw and earth can lead to low thermal transfer, relatively high thermal inertia and high moisture regulation capacity. The present paper presents simulations results using WUFI Plus software. The software calculates multi zone transient hygrothermal performances of a building. The building introduced in the simulations is the small office building of the young Belgian company Paille-Tech. The different cases show the impacts of heating and ventilation systems with straw bales walls compared to complementary cases where walls are replaced by masonry walls with external or internal insulation with equivalent thermal transmission factor. The results are presented to analyze the evolution of inside comfort conditions (air and surface temperature, humidity and CO2 concentration) and annual energy demand. The influence of the thickness of earth plaster, of the moisture content of straw bales and of the setpoint temperature distribution is further discussed. The paper concludes that strong moisture regulation capacity of straw bale walls could not be linked with a significant increase in comfort feeling. Yet, they can compete with the use of heavy masonry insulated from outside. The paper supports the development of an appropriate use of straw bales and earth plaster in building design aiming building global sustainability and high comfort feeling of inhabitants.*
*Keywords: Straw bale; Earth plaster; Thermal inertia; Moisture regulation; Comfort feeling.*

## INTRODUCTION

Straw bale buildings and the use of earth for inside plaster cannot be considered as new ways of building. Different techniques evolved since the XIX$^{th}$ century [1, 2, 3, 4], but these building techniques are still poorly widespread in Europe. In the last decade, straw bale use in building started to develop increasingly, especially in France, England and Germany. In 2012, there were around 3000 buildings using straw bales for insulation in France (maybe 200 in Belgium). This evolution is linked to the growing importance of sustainable principles in building market. As a matter of fact, beside their low impacts on environment (local production, low embodied energy, carbon storage) and health (no VOC or formaldehyde release), straw bale building can lead to interesting thermal performances (low thermal transfer and high thermal inertia) and high moisture regulation capacity.

The present paper presents simulation results using WUFI Plus software. The software calculates multi zone transient hygrothermal performances of a building. The building introduced in the simulations is the small office building of the young Belgian company Paille-Tech. This work is part of an on-going research project (aPROpaille) that aims to tackle market bottlenecks and to answer requests from end-users in this market area in Belgium.

## METHODOLOGY

The building analyzed in this paper was built by Paille-Tech, a partner of the research project aPROpaille. It is built in a large industrial hall and is thus protected from rain and direct sun. All material data necessary to run the software were obtained through laboratory measurements. Specific sensors were developed to follow temperature and humidity in the straw bale walls and in earth plasters. Inside and outside climate (temperature and humidity of air, inside $CO_2$ concentration) are also monitored, as well as the hygrothermal response of materials.

Different cases are simulated comparing the evolution of inside comfort conditions (air and surface temperature, humidity and $CO_2$ concentration) and annual energy demand. These cases show the impacts of heating and ventilation systems. The results are compared to complementary cases where straw bale walls are replaced by building components classically used in buildings (masonry walls with external or internal insulation) with equivalent thermal transmission factor. The influence of the thickness of earth plaster, of the moisture content of straw bales and of the setpoint temperature distribution is further discussed.

The monitoring was ready to be launched in March 2013, but the blower door test had not yet been performed and the building was still not occupied as it should. The model used in the simulations could thus not be rigorously calibrated and the results are not properly validated. Nevertheless, the analysis of almost twenty cases, compared one to the others, bring interesting information on the specificity of dynamic hygrothermal response of straw bale building depending on the heating and ventilation systems implemented and compared to other type of walls.

## BUILDING MODEL

Fig. 1 gives main dimensions (external) of analyzed building. The small office on the first floor will be monitored (zone 1, 6.3 m²). It will be occupied by one person (+1 computer + lights) from 9am to 1pm and from 2pm to 6pm all week days of the year. The rest of the first floor (zone 2, 20.3 m²) will be occupied at the by three persons (+3 computers + lights) at the same time. Computers (150 W convective) are running with no interruption from 9am to 6pm. The ground floor is used by seven persons for lunch (and reunions) every day of the week from 1pm to 2pm (zone 3, 27.4 m²). In each zone, the light power is 8 W/m². Table 1 gives the profile for inner sources in zone 1. Air tightness of each zone is considered to be 0.024 ACH (equivalent to 0.6 ACH at 50 Pa, interzonal ventilation is neglected).

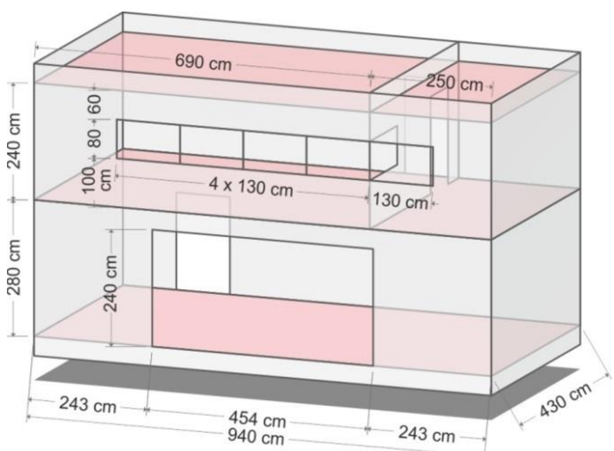


*Figure 1: Main external dimensions of analyzed building.*

Few components are identical in all simulations: the partition wall on the first floor (U= 0.486 W/m²K) is a 16cm plain wood element (nailed) covered on one side with a thin plaster (for air tightness); the intermediate floor (U= 0.45 W/m²K) is also a 16 cm plain wood element (nailed) covered with 4cm of earth concrete and a wood floor of 2.2 cm; windows and doors (U= 1,6 W/m²K) are all double glazed with solid wood frame; the flat roof (U= 0.17 W/m²K) is made of a straw bale (46 cm) covered inside with a thin fiber board (0,9 cm) and outside with a spruce board (2,2 cm); the ground floor (U= 0.21 W/m²K) is made with a straw bale (36 cm) holding on Structural wood fiber panel (open to vapor) of 1,6 cm with an OSB panel inside cover with 5 cm of earth concrete. To keep this paper as short as possible, these building components will not be described thoroughly.

*Table 1: Inner sources in zone 1.*

| Time | Heat conv. [W] | Heat rad. [W] | Mositure [g/h] | $CO_2$ [g/h] |
|---|---|---|---|---|
| 0am | 0 | 0 | 0 | 0 |
| 9am | 270 | 81 | 59 | 36.3 |
| 1pm | 150 | 0 | 0 | 0 |
| 2pm | 270 | 81 | 59 | 36.3 |
| 6pm | 0 | 0 | 0 | 0 |

All simulation cases referred with letter “S” (as “straw”) are defined with the walls that were implemented in this office building (U= 0.134 W/m²K). The other cases, referred with “X” (as “XPS”: extruded polystyrene) or “C” (as “concrete”), are defined to compare the existing building with an equivalent building where exterior walls are replaced by others (with identical thermal transfer coefficient). Table 2 gives thickness (d [cm]) and main parameters (thermal conductivity, λ [W/mK], density, ρ [kg/m³] and vapor diffusion resistance factor μ [-]) of the different exterior walls used in the simulations. Outside layers are given first (the wood cladding is not considered because of a well-ventilated air layer behind the cladding). The data are from producers (*), from WUFI database (**) or from PhD of J. Wihan [5] (***). All other data listed in Table 2 were measured during research aPROpaille.

*Table 2: Building components used in simulations.*

| Material | d [cm] | λ [W/mK] | ρ [kg/m³] | μ [-] |
|---|---|---|---|---|
| **Exterior walls – Type “S”** | | | | |
| Struct. panel | 1.6* | 0.09* | 570* | 11* |
| Straw | 46 | 0.065 | 100 | 2*** |
| Earth plaster | 4 | 1* | 2051 | 18.5 |
| **Exterior walls – Type “X”** | | | | |
| Breeze block | 14 | 0.06** | 1450** | 11* |
| XPS | 21 | 0.03** | 40** | 100/450** |
| Gypsum board | 1.25 | 0.2** | 850 | 8.3** |
| **Exterior walls – Type “C”** | | | | |
| XPS | 21 | 0.03** | 40** | 100/450** |
| Breeze block | 14 | 0.06** | 1450** | 11* |

## SIMULATIONS

Four types of case are defined with straw bale walls ("S"). The first one, written S-1, has no heating and no ventilation system. The second type, written S-2, has no ventilation system, but small heaters (5x1 kW) are introduced in the building: one in zone 1, two in zone 2 and two in zone 3. They start to heat between 8am and 6pm during weekdays if inside temperature falls under 20 °C. The third type, written S-3, has the same heating system (five electric heaters with 1 kW power), combined with an air extraction system renewing, during occupation, 30 m³/h of air per person (no heat or moisture recovery). The last case, case S-4, has a ventilation system (30 m³/h of air per person) with a heat recovery of 85% (no moisture recovery) combined with a heating system equivalent to the previous one (five electric heaters of 1 kW). In all cases, 1 ACH of natural ventilation is considered between 9am and 10am and between 1pm and 2pm.

In the following simulations, cases "X", straw bale walls are replaced by masonry walls made of breeze blocks insulated from inside surface with extruded polystyrene (XPS). Those cases should have low thermal inertia and low moisture regulation capacity. In cases "C" (as concrete), the walls are replaced by masonry walls made of breeze blocks insulated from outside surface with extruded polystyrene. Those cases should have high thermal inertia and average moisture regulation capacity. Case X-1 and C-1 correspond to case S-1; case X-2 and C-2 to S-2; etc.

## RESULTS

Fig. 2 presents the seasonal heating load of zone 1 (6.3 m²) for each case. Cases S-1, X-1 and C-1 do not have any heating system and there is thus no heating load. Winter is of course always the season with the highest heating load for other cases (followed by fall then spring). Low values are obtained by S-2, X-2 and C-2 because there is no heat loss due to ventilation. Results for cases S-4, X-4 and C-4 confirm the significant benefit in terms of heating load when using a heat recovery on ventilation. Despite the equivalent U-value of selected walls, one can observe that heating load is lower for cases "X"; "S" having the highest value. This result will be discussed hereafter.

A yearly value of heating load in zone 1 ("HL") is given per square meter in Table 2. The following data in Table 2 show that $CO_2$ concentration in air reaches (almost every day) unacceptable values in the cases without ventilation, as maximal $CO_2$ concentration ("max$CO_2$") should stay under 1000 ppmv according to Belgian regulation NBN EN 13779 (2007).

Table 2 also give the percentage of hours where inside air temperature is over 28°C (T>28), over 25°C (T>25) or under 16°C (<16). It is interesting to note that no case

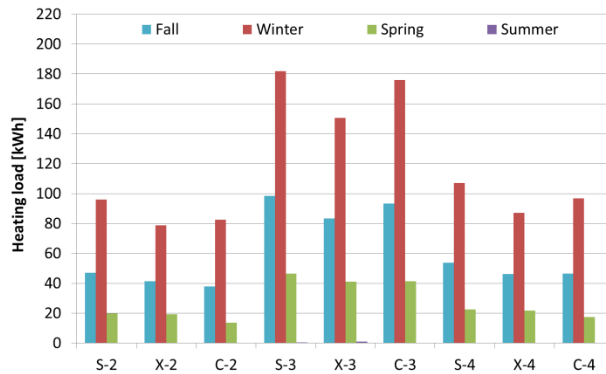


*Figure 2: Heating load of zone 1 (small office at first floor).*

would fit Belgian Passive House specification in terms of overheating where percentage of hours over 28°C should be under 1% and percentage of hours over 25°C should be under 5% (no specification on percentage of hours under 16°C). Results for cases "S" and "C" are rather similar. Cases S-3 and C-3 give the best results. Many hours of overheating (and of temperature under 16°C) are observed in cases "X". Cases S-1, X-1 and C-1 do not have any heating system and there is thus many hours where air temperature is under 16°C.

*Table 2: General results for zone 1.*

| Case | HL [kWh/m²] | max$CO_2$ [ppmv] | T>28 [%] | T>25 [%] | T<16 [%] |
|---|---|---|---|---|---|
| S-1 | 0 | 6534 | 1.1 | 10.9 | 41.9 |
| X-1 | 0 | 6576 | 3.4 | 13.6 | 39.1 |
| C-1 | 0 | 6528 | 0.9 | 13.1 | 39.3 |
| S-2 | 26 | 6546 | 2 | 13.9 | 3.5 |
| X-2 | 22 | 6584 | 4.3 | 16.6 | 8 |
| C-2 | 21 | 6534 | 1.4 | 15.1 | 0.8 |
| S-3 | 52 | 1013 | 0.8 | 8.9 | 8.1 |
| X-3 | 44 | 1015 | 2.1 | 10.4 | 14.3 |
| C-3 | 49 | 1013 | 0.6 | 9.2 | 4.5 |
| S-4 | 29 | 1014 | 2 | 13.5 | 4.5 |
| X-4 | 25 | 1016 | 4.3 | 15.8 | 9.9 |
| C-4 | 26 | 1014 | 1.7 | 14.8 | 1.7 |

Fig. 3 presents maximal and minimal air temperature for each case (in zone 1). One can observe that the difference between maximal and minimal temperature is always higher for cases "X". Minimal temperature is also clearly uncomfortable. Results for cases "S" and "C" are in the same range. The same observation can be made based on Fig. 4 and 5 showing the evolution of surface temperature of analyzed walls in cases S-3, X-3 and C-3, during a typical week in summer and in winter. The decrease in temperature after unheated week-end and the speed to increase temperature again in the morning is a good indicator of thermal inertia of walls. If the surface temperature drops significantly in winter during nights (discrepancy between day and night of 3-

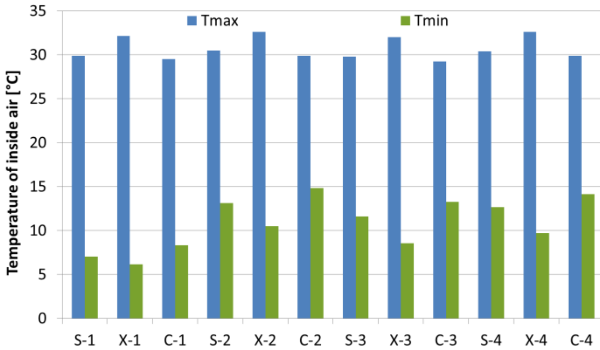


*Figure 3: Maximal and minimal temperature of air.*

4°C) and week-end for case X-3, it is rising fast back in the morning of weekdays (setpoint of 20°C in air is reached at 11am). In summer, the temperature also drops during night and week-end, but a quite high temperature is reached during weekdays (discrepancy between day and night of 3-3.5°C). At the opposite, surface temperature of walls in case C-3 do not vary that much (1-2°C in winter, 1° in summer), but set-point cannot be reached as fast in the morning of weekdays (setpoint in air only at 1pm). Case S-3 has an intermediate behavior: surface temperature of walls is relatively easy to increase (setpoint is reached at 11am) in winter, but do not rise too high in summer (discrepancy between day and night of 1-2°C in winter, 1° in summer).

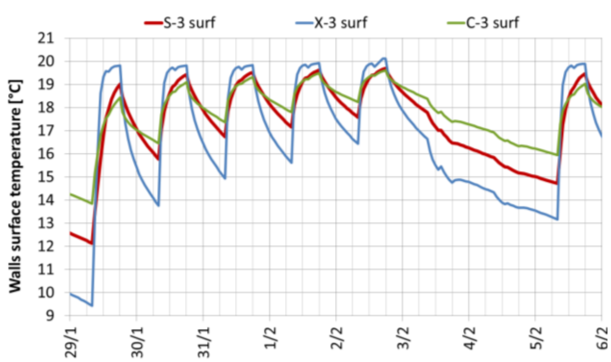


*Figure 4: Evolution of surface temperature in winter.*

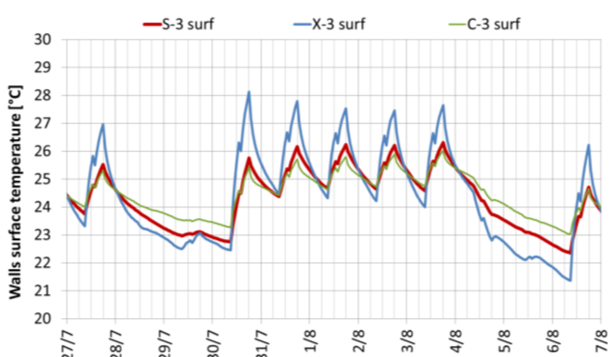


*Figure 5: Evolution of surface temperature in summer.*

Previous research [2] showed the excellent moisture regulation capacity of earth plaster through the characterization of their MBV (moisture buffer value). Nevertheless, this characteristic does not seem to have a significant effect on relative humidity of inside air (zone 1) as Fig. 6 shows, except when no ventilation system is used. This result will be discussed considering moisture transfer through inside surface walls presented in Fig. 7 (positive when going from inside to outside).

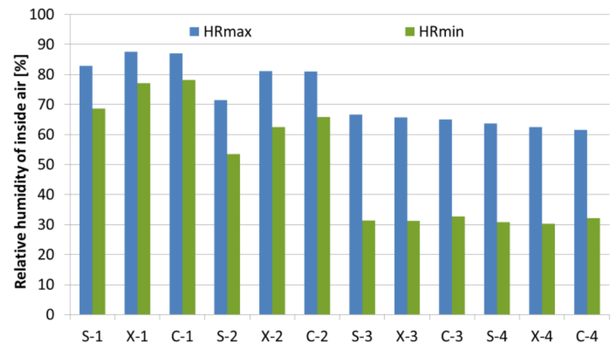


*Figure 6: Maximal and minimal relative humidity of air.*

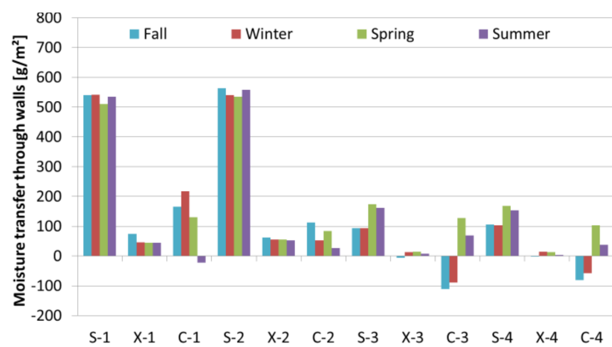


*Figure 7: Moisture transfer through walls.*

## DISCUSSION

This office building was actually built with no heating and no ventilation system. The occupants know they may be too cold and that they will have to ventilate. The monitoring will first be used to calibrate simulation of case 1. As the occupant may install few electric heaters, running at least in winter, the monitoring will then allow calibrating case S-2. A case similar to S-2, introducing a natural ventilation profile (manually by opening windows) where inner space is ventilated during the night, as well as Monday morning and Friday afternoon for 1 hour (1 ACH), was simulated. It did not solve the problem of $CO_2$ concentration (still over 6000 ppmv almost every day) and increased heating demand (43.7 kWh/m²). Based on simulation results, the cases with no ventilation must thus be rejected because of high $CO_2$ concentration in inside air (six case on twelve). Depending on the HVAC system that will be installed, the monitoring will then be used to calibrate the case S-3 or S-4.

Results obtained with straw bale walls were compared to cases where outside walls are replaced by a wall with low thermal inertia, cases "X", or with walls with high thermal inertia, cases "C". Results on the amount of uncomfortable periods (too warm or too cold) and on extreme temperatures provide a good view of what can bring thermal inertia in terms of comfort. Having a high thermal inertia increase comfort, mainly in summer period (reducing overheating) but also during colder period the first hours of weekdays (cold air on mornings). Based on these parameters, it appeared that straw bale walls covered with earth plaster ("S") has a similar response as case "C" and can thus be considered to be walls with high thermal inertia.

Increasing the thickness of earth plaster in cases "S" improves the thermal inertia. Two complementary simulations were defined: case "S-3_8" with 8 cm of earth plaster (instead of 4 cm in case S-3) and "S-3_15" with 15 cm. It showed that the percentage of hour with inside air temperature over 28°C was of 0.45% for case "S-3_8" and 0.13% for case "S-3_15". For temperature over 25°C it was respectively 8.63% and 8.45%, and for temperature under 16°C it was 5.66% and 3%. Earth plaster can thus lead to very high inertia when its thickness is increased.

Another observation concerns results obtained when a heat recovery system in connected to ventilation (cases S-4, X-4 and C-4). It appears that in this choice leads to significant energy savings (23 kWh/m² when compared to case S-3). Unfortunately, it may also lead to an increase of uncomfortable periods if no bypass of the heat exchanger is implemented in warm period. A specific strategy of ventilation should then be developed in these cases.

Despite the equivalent U-value of selected walls "S", "X" and "C", slightly different heating load was observed in corresponding cases. This discrepancy can be explained by their different thermal inertia and by moisture content evolution of materials.

First, complementary simulations (referred as "3_sp"), based on cases S-3, X-3 and C-3, were defined with a constant setpoint temperature of 20°C through the year to show that the effect of thermal inertia on heating load strongly depends on this parameter. Fig. 8 show that, if cases "X" had the lowest heating load in the basic simulations, with this new setpoint schedule, cases "X-3_sp" obtained the same result as case "C-3_sp". High thermal inertia thus leads to higher heating load only with intermittent heating system.

Second, different heating load in corresponding cases can also be linked to moisture content of wall layers. In all simulations, heating load is slightly higher in cases "S" than in other cases. To explain this, the moisture content evolution of each wall layers was analyzed. It appeared that average moisture content of straw bale layer (which is the insulation layer in cases "S") is around 11 kg/m³ (corresponding to equivalent moisture

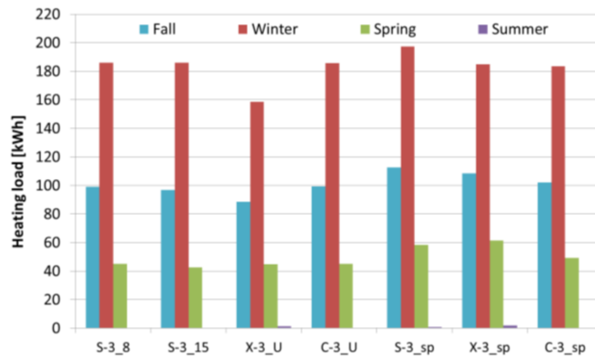

*Figure 8: Heating load of complementary simulations.*

content at 65% of relative humidity). This leads to a thermal conductivity supplement of 12% compared to its value in a dry state (thermal conductivity at 65% is 0.0725 W/mK). In all other cases XPS layer has an average moisture content of 1 kg/m³, leading to no supplement of its thermal conductivity. If U-value of the walls was equivalent when calculated with parameters corresponding to the dry state of the material, transient U-value of cases "S" is actually slightly higher in these conditions than the one of cases "X" and "C". To compare those cases based on an "equivalent thermal transfer coefficient" as announced, their U-value should thus have been set to 0.15 W/m²K (instead of 0.13 W/m²K). Two complementary cases were thus simulated: "X-3_U" and "C-3_U". Fig. 8 presents the heating load obtained for these cases. Case "C-3_U" has a similar heating load as case "S-3" (similar thermal inertia) and it is slightly lower for case "X-3_U" (low thermal inertia).

The last point discussed in this paper is the fact that high moisture transfer through walls observed in cases "S" (Fig. 7) did not lead to significant differences in terms of relative humidity inside the building. This rather surprising result can actually be explained if we consider that inside air contains approximately 8 gr/m³ and outside air 4 gr/m³, and that around 14500 m³ of air is renewed per season. The quantity of moisture extracted through ventilation can therefore be approximated to 70 kg/season. Fig.7 shows that in cases S-3 and S-4, walls are able to remove from inside ambiance around 100 gr/m² of moisture per season. With 25 m² of walls in zone 1, this leads to a moisture flow of 2.5 kg/season. This amount is almost negligible compared to the moisture extracted from ventilation (3.6%).

Is the latent heat effect of this moisture flow through walls significant compared to the heat loss through walls? If we consider that all the moisture transferring through inner surface of walls in winter (94 gr/m² for S-3, 14 gr/m² for X-3 and -89 gr/m² for C-3) is absorbed in porous structure of materials and that this leads to an input of latent heat in corresponding layer, the amount of latent heat given to the walls (0.63 kWh/kg) would be 0.06 kWh/m² for S-3, 0.01 kWh/m² for X-3 and -0.06

kWh/m² for C-3. This amount of energy is almost negligible in comparison to the heat loss in winter through walls of cases S-3, X-3 and C-3: respectively 3.86 kWh/m² (0.16%), 2.98 kWh/m² (0.34%) and 3.5 kWh/m² (-1.71%). This latent heat effect may have a higher impact in specific conditions but this analysis goes beyond the scope of this paper.

## CONCLUSION

The results presented in this paper are not calibrated with monitoring measurements. Yet, they allow comparing different cases one to the others and bring interesting information on the specificity of dynamic hygrothermal response of straw bale walls depending on the heating and ventilation systems implemented and compared to other type of walls.

The results confirm that ventilation level should not be too low to ensure air quality of inside environment (in particular $CO_2$ level). Of course, renewing inside air cost energy, and the use of a heat recovery system is an efficient way to mitigate energy needs (a bypass may be implemented to reduce risk of overheating in warm period).

One thing is to reduce energy needs and the other is to improve comfort. Both are as important. The results show that, in this case (office building unoccupied at night and during week-ends), thermal inertia leads to an increase of heating load but offer a better comfort by reduce uncomfortable periods (too warm or too cold).

Straw bale walls has interesting thermal transfer properties even if the walls must be slightly more thick (here around 50cm) than when using a low thermal conductivity insulation (as extruded polystyrene). In addition, the calculation of U-value should consider that moisture equilibrium in the straw may require using an adapted thermal conductivity. In studied case, transient U-value is considered to be around 0.15 W/m²K, using a thermal conductivity of straw of 0.0725 W/mK (corresponding to the value obtained at 65% of relative humidity).

Straw bale walls covered with earth plaster also have interesting transient behavior in terms of thermal inertia. The simulations showed that the risk of overheating is far under what could happen with heavy masonry insulated from inside and very close to what was observed when simulating heavy masonry insulated from outside. Increasing the thickness of earth plaster (i.e. to 8cm or 15cm instead of 4cm) is a good way to further improve thermal inertia.

Despite the fact that a previous research [2], showed that earth plaster has an excellent moisture buffer value that should lead to a strong moisture regulation capacity of inside ambiance, relative humidity of inside ambiance of studied cases was not significantly different. A simplified calculation showed that the moisture exchange through wall surfaces is negligible compared to the amount of moisture transferred through ventilation. In addition, latent heat that could be linked to this moisture transfer appeared to be negligible when compared to heat flow through walls. Further research is needed to increase to knowledge on moisture regulation and latent heat effects (i.e. under short terms or exceptional solicitations).

As reducing energy needs should not be the only concern of designers, the present paper show that the use of straw bale walls and inside earth plaster combines low heating load with high thermal inertia and thus high comfort in summer and winter. When considering associated environmental impacts of this technique (local production, low embodied energy, high carbon storage, no volatile organic components…) [1, 4], it is easy to believe that this building technique has still a great future in Europe and in any place were man seek to improve global sustainability of buildings and high comfort feeling for inhabitants.

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