Large Scale Measurement Campaign to Assess the Thermal Behaviour of an 18th Century Historic Building in Athens

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ABSTRACT

Historic buildings can present significant thermal energy consumption variations and thus can have a considerable impact in the total energy demand of the building sector in the EU. In order to characterize and quantitatively assess the energy efficiency of a building, real-time monitoring of its thermal behavior, via the collection of detailed information on the thermal properties of the envelope and indoor comfort, is needed. This work presents the results of a real time large-scale monitoring campaign to assess the thermal behaviour of a recently restored two-storey Post Byzantine historic building, located in the centre of Athens. This research implements both qualitative and quantitative analysis, by performing field measurements and real time continuous monitoring of indoor and outdoor air temperature, relative humidity, surface temperature and heat flux values of building components (walls, floors, ceilings and roof), for a full year. The objective was to analyze the obtained results in order to assess the passive thermal behaviour of the building envelope and particularly the thermal properties of the different components, materials and wall systems and correlate them with orientation.

Keywords

Energy efficiency, thermal behaviour, historic building, monitoring, cultural heritage, restoration, masonry and timber-framed walls, sustainability of historic buildings

1. Introduction

Traditional, pre-industrial buildings can provide valuable information regarding the sustainability and climate response to contemporary environmental design [1], [5]. They are considered intrinsically sustainable, since climate and local environmental conditions were taken into account to select their layout and orientation. They were usually built using local materials and most of the time fulfilled long lasting needs [8], [10]. The study of the bioclimatic attributes of traditional buildings has been the focus of significant research efforts during the last decades [2], [3], [5], [9]. The main question was to recognize, assess and exploit the hidden but essential attributes and benefit from them, as they reflect the cultural heritage and identity of a nation [11].

The current study concerns a monument located in the centre of Athens, that represents a rare example of the post Byzantine architecture in Greece (Ottoman period), since it is the only building of its kind still standing in the city area. An extensive, large-scale measurement campaign took place in order to assess the thermal behaviour of the monument in its restored form.

A data acquisition system consisting of several types of sensors as well as instruments for property analysis of the building materials was installed. Data series were collected for a period of one year and were extensively analyzed. External climatic conditions and the microclimate of the surroundings were examined by measurements of temperature, humidity and solar radiation at the building's location.

2. General aspects regarding the traditional post Byzantine architecture in Greece

2.1 Architectural form

The structure under study is an important post-Byzantine monument in Athens. Buildings with similar structural characteristics, i.e. rubble walls on the ground floor and timber-framed walls (or both) on the upper floor, were very common during the Ottoman period in several countries across the Eastern Mediterranean basin and the Balkan area [1], [4], [6].

Structures of this type are found in many areas of the central and northern parts of Greece (Thessaly, Macedonia, Thrace); the majority of them were built before 1850 and although there is substantial variation in size, configuration and regional techniques, the main construction principles are the same. Therefore, monitoring the thermal behaviour of the envelope can deliver conclusions and ideas for future restoration and energy efficiency renewals of such structures focusing on retaining their structural, architectural and thermal characteristics and qualities.

Figure 1. South (left) and north (right) view of the building.

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Residential buildings of that era are characterized by the some common architectural elements. The *hayat*, either as a closed or semi-open space, constituted a vital space for everyday life, as it was used for circulation, resting, cooking and other domestic activities. Frequently, this space extends between the rooms forming a recessed sitting area, called the *eyvan*. The private rooms (*oda*) which are accessed from the *hayat*, were the main living spaces used for sleeping, eating and entertaining. Some types of these buildings possess another closed space used for circulation and gatherings called the *sofa*.

These buildings consist of two or three-storeys. The ground and mezzanine floors are usually built using thick rubble walls, while the upper floor envelope consists of both rubble and timber framed walls, parts of which project, forming the *sahnisi*, a basic structural and morphological element of these traditional buildings (Figure 1). In 3 storey buildings, the ground floor was used for storage, the first floor was usually the winter house, while the last floor was the summer house.

● Air temperature × Heat flux

○ Wall surface temperature + Relative Humidity

Figure 2. Floor plans and locations of sensors

The case study building has two levels. The ground level consists of three rooms, accessed from the yard through an arcade (Figure 2). These spaces have no windows. The upper floor is accessed from an open stair that leads to the open *hayat* which extends to the whole north façade, forming a semi-open transitional space that leads to the two rooms (*oda*) that are positioned symmetrically from the *eyvan,* which extends on the south elevation forming the *sahnisi* (Figure 1, 2). The two rooms are the same in size and configuration. In the east room, two of the walls (east and south) are masonry and the rest are timber framed, while on the west room only the south wall is made of rubble stone. Both rooms have four windows in the long walls and three on each short wall, which are operable with shutters, and an array of non-operable head windows on top of them (Figure 3). In the east room there is a fireplace at the centre of the east wall (Figure 3). The floors and roof are made of wood. The arcade in front of the ground level rooms is characteristic in buildings of this typology that are within the city limits.

Figure 3. Views of west (left) and east (right) rooms.

2.2 Bioclimatic characteristics

Traditional architecture is the product of many years of experience on the continuous repetition of archetypes expressed with many adjustments and variations. The form of the buildings is defined by a combination of factors such as climate, topography, local materials and building technology, along with the social and historic circumstances that define the course of every place.

In pre-industrial buildings the architecture possesses many elements that are directly related to climate. These are either elements, such as shutters, pergolas, size and positioning of windows, head windows etc., or spaces, such as loggias, verandas, hayats etc.

Several elements of the same type of building differ when built within the limits of a city or in the country. In traditional settlements, climate and defence are factors that usually take a more decisive part in the formation of the buildings compared to buildings within cities where the socio-economic and historic circumstances prevail. In traditional settlements their connection and interaction with nature is more direct, they are adjusted to their natural and climatic environment and are constructed with respect to them. Selection of the orientation and position of the buildings on site and the relation to each other, is always made with respect to the most preferable climatic conditions. Their layout is more closed on ground level, since they are situated in open lots in settlements usually not protected from fortification walls. On the other hand, buildings within cities were protected by the city's walls and therefore their layout includes more openings to the yard. Position and orientation of the building on site is mostly affected by its adjacency to main streets or important monuments or the city centre and not by the preferable climatic conditions. This probably explains the fact that in the study building the hayat (main façade) is oriented to the north, adjacent to the yard and the entrance to the property, since Adrianou St. is an important street in the neighbourhood. Usually buildings of this type situated in rural areas orient the lightweight construction with the hayat to the south, which inhibits climatic attributes that contribute to favourable thermal conditions. These are insolation during the winter time and shading during summer.

Measurements in such buildings demonstrate that the lower levels that are surrounded by thick rubble walls and have few openings act as thermal masses, usually exhibiting lower indoor temperatures in summer and higher in winter compared to the external conditions; also they exhibit very small diurnal variations [8], [9]. On the other hand, temperatures on the spaces of the upper floor that are surrounded by the timber framed walls are higher, usually following the external temperatures and diurnal fluctuations with small differences, a fact that is attributed to their exact orientation, size and vast number of openings. The numerous shaded windows on the lightweight construction of the upper floor induce efficient cross-ventilation. The internal temperatures of the upper floor rooms are also affected by the high U-values of the timber roof that has no insulation.

3. Description of structural elements in the case study building

3.1 General Description

The mansion is a two-storey rectangular building, of general dimensions roughly 23.0 x 9.4m with its long side parallel to the east/west axis. The building belonged to a prominent family of Athens (Benizelos mansion) and was initially built during the 17th century. During the next centuries, several interventions changed the original mansion causing important architectural and structural problems [12]. The mansion has been recently (2010) restored to its initial form, retaining many of its structural components (parts of the rubble walls and timber-framed wall structure of the upper floor and timber roof). The restoration project implemented innovative techniques for the structural reinforcement without impairing the original architectural and structural character of the building or the historic qualities that define its cultural value.

3.2 Rubble Walls

The walls on the ground floor (55-60cm thick) and the arcades (35-40cm thick), were initially made of a three leaf rubble masonry with clay mortar. Only two of these walls continue to the upper floor (south and east). The upper floor rubble walls, were covered with plaster and had a lot of openings quite close to each other, reinforced with horizontal timber ties, embedded in 5 levels. During restoration, the rubble walls were consolidated and reinforced using premixed, cement-free, pozzolan-lime grout for the injections, the mortars and the rejoining. Parts of the South wall had to be rebuilt in order to restore the original façade. This was done with the stones found on site from the old wall that had fallen aside and the same type of mortar with the above. The existing timber ties of the upper floor masonry, were either preserved, or reconstructed [12].

3.3 Timber-Framed Walls

The upper floor envelope, consists of a timber colonnade at the main elevation of the mansion and timber frame walls filled with solid bricks and lime mortar (Figure 4). During restoration, reinforcement of the overall behaviour of the timber frame walls was accomplished by the reinforcement of all timber connections and by the reestablishment of the contact between the brick infill and the surrounding timber elements, using premixed, cement-free, pozzolan-lime mortar. A stainless steel mesh was used for reinforcement of the plaster.

Figure 4. Views of timber framed walls.

4. Measuring and assessment methodology

4.1 Design and installation of the data acquisition system

The Data Acquisition System (DAS) was designed to collect and record the necessary data for measurement and characterization of the thermal performance of the envelope and for assessing the overall thermal behaviour of the historic building. In particular, it monitors and records indoor temperature and humidity in the various rooms of the building, temperature distribution and/or heat flux though the walls, floors and roof/ceilings of the building and weather data at the building's exact location. The design of the system also allows the collected data to be used for energy balance calculations for all major surfaces in each thermal zone and for in-situ measurements of the thermal properties of parts of the envelope.

4.2 Physical location of the measurements

Conduction through the walls is a major heat-loss mechanism in the building. Sensors were installed to allow energy balances to be calculated for each major surface in each zone. In order to reduce the measuring locations and the cost of the DAS, sensors were installed only in one (E) of the two identical rooms of the upper floor of the building. In the other room (W) only the indoor temperature is measured to validate the assumption of thermal symmetry of the building.

The locations of surface temperature measurements were selected to lie near the midpoint of the wall surfaces, as far as possible from window frames and the edges of the walls. Indoor temperature and humidity was also measured as near as possible to the centre of every room of the building.

A heat flux sensor is permanently located on the inner surface of the south wall of the ground floor. This wall was chosen for heat flux measurements as it is the largest wall area of the building, exhibiting the maximum total solar gains and has no windows to disturb the one-dimensional heat flow through its mass. Heat flux was also measured occasionally on the inner surface of various walls of the building. Humidity and temperature is also measured inside the attic to allow calculations of heat losses/gains through the roof of the building. The red marks on Fig. 2 indicate the physical location of the measuring devices in the building.

Selection of an appropriate location for the mini weather station is critical in order to obtain accurate meteorological data. The site should be representative of the general area near the building and away from the influence of obstructions. To fulfil these requirements, external temperature measurement sensors were installed near the south wall of the building, and at the open area at the front side (north) of the building. At the south location, where solar radiation is prominent, a radiation shield is used for the temperature measurement.

4.3 Data acquisition system and sensors

The DAS is designed to operate and collect data for long periods to allow seasonal trends and annual totals to be determined. In order to increase the reliability of the system, collected time-series results are stored in an external memory. The schematic diagram of the system is presented in Fig. 5.

An Agilent DAQ device is used for signal processing and logging (Figure 6). The time interval for all the measurements is set to 1 minute. For temperature measurements Micro-BETAchip NTC thermistor probes (MCD 10k3MCD1) are used. The temperature tolerance at 25°C is ±0.2°C. Heat flow through the walls is measured with the use of high sensitivity heat flux sensors of Hukseflux type HFP01 and HFP03 (Figure 6). The relative humidity of the indoor and outdoor environment is measured using Honeywell humidity sensors.

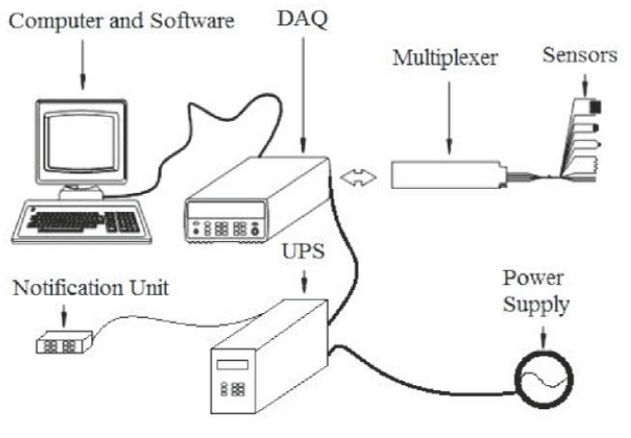

Figure 5. DAS Schematic diagram

Figure 6. DAQ system at ground floor (left) and heat flux sensor on the upper floor (right)

5. Thermal comfort and temperature response analysis

5.1 Microclimate and envelope boundary conditions

Athens is classified as a region having subtropical Mediterranean climate characterized by warm/hot, dry summers and mild/cool, wet winters. According to meteorological data the average high temperature during July (the hottest month of the year) is 33.1°C while the average low temperatures for January (the coldest month) is 6.7°C. Mean daily temperature fluctuations are lower during January (lower than 7°C), whereas they reach 10°C during the summer months. These data are obtained from archives of a permanent weather station at a nearby location. Data collected by the mini weather station installed around the building, generally agree with the above comments showing that the microclimate near the building does not differ from the climate of the wider area.

External humidity values range from 35% to 80% and global solar radiation ranges from 850 W/m^2 in summer months to 500 W/m^2 in winter months. It is observed that temperature at south outdoor spaces is 0°C to 4°C higher than the same temperature at north spaces. The higher differences correspond to midday hours due to high solar radiation values. In the absence of solar radiation no difference is observed.

5.2 Thermal behaviour of the building envelope

Different parts of the building envelope as well as ground, ceiling and roof structures are analyzed in terms of temperature response and heat flux values at diurnal and seasonal basis in order to determine the building's passive thermal behaviour without any active heating or cooling system. External and internal surface temperatures of the massive rubble walls and the lightweight timber-frame walls in respect to external and internal ambient temperature during the year are presented in Figs. 7 and 8 where annual profiles as well as diurnal variations are illustrated. Diurnal analysis is based on a representative time interval of 6 days for both summer and winter season. In order to assess the effect of solar radiation during winter season the selected interval includes three heavily clouded days.

5.2.1 Thermal Behaviour of Rubble Walls

Rubble walls occupy the majority of the area of the south, east and west part of the envelope as well as the north part of the ground floor. The south wall of the ground floor is part of the massive south element of the envelope. With a total area of 27m^2, it is partly exposed to the solar radiation and does not contain any openings.

During the hot summer months, temperatures on its external surface rise up to 40°C, with daily fluctuations of the order of 10°C. Maximum temperatures are observed approximately at 15:00 and are equal to the external air temperature. On the other hand, minimum air temperatures are much lower than the external surface temperatures of the wall. For the same season, the internal surface temperature shows daily variations less than 0.3°C and maximum values approximately 30°C, observed in late morning hours. Inner surface temperatures are constantly higher than the room indoor temperature due to heat gains during the summer months (Figure 7). The heat flow through the inner surface of the wall is higher during the night hours when internal air temperatures reach their minimum values and inner surface temperatures their maximum. It is noted that the temperature of the external surface is constantly higher than that of the internal surface.

During the winter season, the external surface temperature profile follows the variations of the external air temperature with minimum values approximately 8°C and fluctuations up to 10°C. Inner surface temperatures, are stable and slightly lower than the indoor air temperature resulting in low heat losses.

The north wall of the ground floor has two openings, a door and a small window near the ground; the wall is constantly shaded by the arcade. Temperatures on its external surface reach 35°C in summer and 8°C in winter. Daily fluctuations are 3°C and 1°C for summer and winter months respectively. During the summer season, internal surface temperatures exhibit very small daily variations, less than 0.2°C. Generally, during the spring and summer seasons, the internal surface temperatures are lower than the respective external while the opposite is observed in the autumn and winter months. As a result, net heat gains are observed during the summer months and net heat losess during the winter months. Similar to the south wall, maximum values of heat flow are observed during night hours.

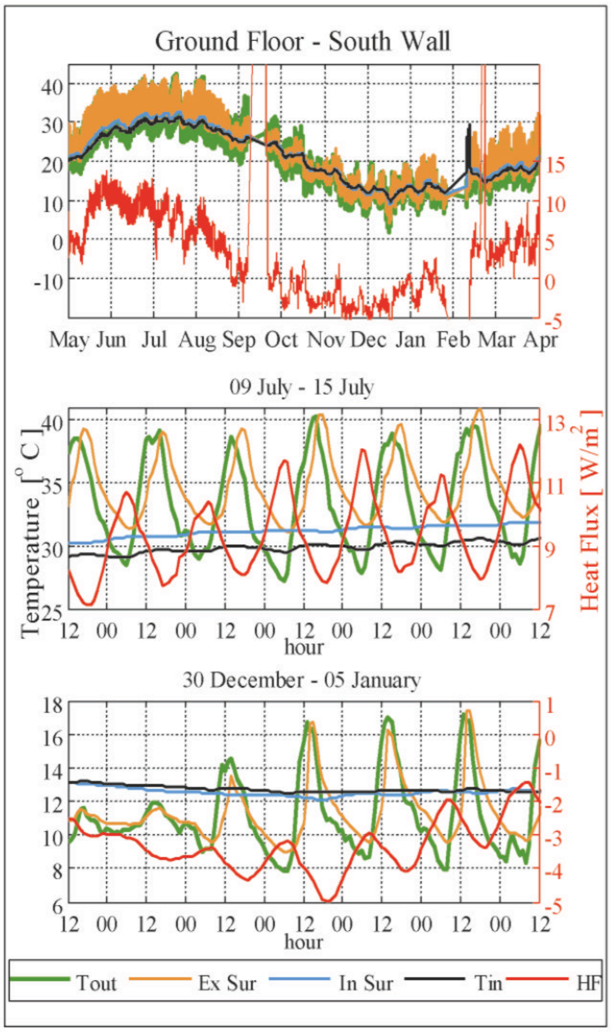

Figure 7. Temperature and heat flux measurements at the southern rubble wall (ground level).

The upper south wall differs from the ground south wall since it is punctured by an array of regular and head windows. Regular windows have a significant size, are operable and equipped with shutters that were closed during the measuring period. Head windows are located on the upper side, which are fixed with no shading devices and enhance daylight. Regarding solar gains, the wall is fully exposed to solar radiation. It is also noted that the upper part of the south wall has minor construction differences compared to the respective lower part (additional 5 cm of internal render at the same total thickness).

External surface temperatures are significantly higher than outdoor temperatures during the midday hours due to the constant exposure to solar radiation. In contrast, during night hours, external surface temperatures follow the outdoor air temperature profile. Regarding the internal surface temperatures, daily fluctuation are small in summer (~0.4°C) and negligible in winter months. Mean values of the internal surface temperatures are also very close to the indoor air temperatures exhibiting higher values during the night and lower during the day. As a result heat gains are observed at night and heat losses during the day.

The majority of the area of the upper-east wall is occupied by windows and the chimney of the fire-place. The wall is exposed to solar radiation from the morning until early midday, where peak temperatures are observed and the sun is at a low angle. During the rest of the day, the external surface temperature is almost identical to that of ambient air. Maximum temperature on the external surface rises up to 47°C during the summer months with daily fluctuations near 15°C, while minimum values are near 7°C with fluctuations of 10°C in the winter season. Internal surface temperatures lie between maximum and minimum values of the external surface during the year and show small daily fluctuations of approximately 0.5°C. The small temperature differences between internal surface and indoor air temperatures result in low values of heat flow that enters the internal space during the night. During the winter season, the time interval when heat losses are observed is limited for a few hours during midday, while for the rest of the day heat gains occur.

5.2.2 Thermal Behaviour of Timber-Framed Walls

The north oriented part of the upper storey envelope is a timber framed wall with two rows of windows. The lower row consists of four operable windows with shutters and the upper of four fixed head windows. External surface temperatures vary from approximately 8°C to 37°C during the year with daily fluctuations of 5°C in the summer and 3°C in the winter months; the daily fluctuations on the internal surface are less than 1.5°C during the entire year (Figure 8). In the summer season, the temperature of the internal surface during the day is always lower than the indoor air temperature, while the opposite occurs at night. As a result, heat gains are observed at night and heat losses during the day. On the other hand, during the winter period, heat losses are generally observed with maximum values during midday hours, especially on sunny days due to the temporary heating of the internal spaces by direct solar gains from the upper row windows of the south wall.

The west oriented timber wall is next to the "sahnisi" and thus exposed to less severe weather conditions than the north wall. Overall, its thermal behaviour is similar to the north timber wall with reduced heat losses/gains and temperature peaks.

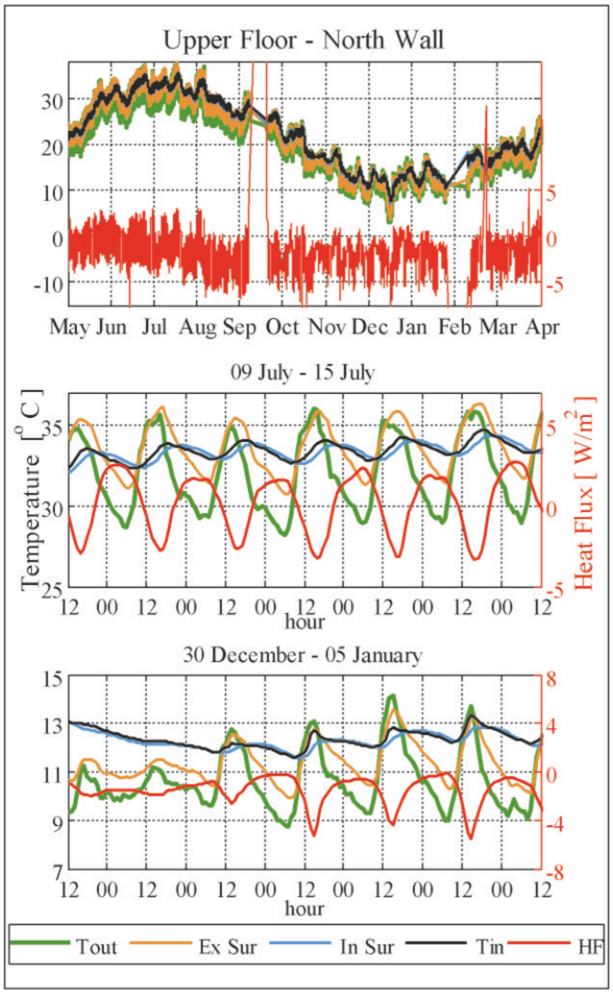

Figure 8. Temperature and heat flux measurements at the northern timber-framed wall (upper level)

5.2.3 Thermal behaviour of floors and ceilings

The behaviour of the floor of the ground level is of particular interest as it constitutes a direct boundary of the room to the ground. As expected, its surface temperature is the most stable in the building, showing the ability to significantly suppress the outdoor temperature variations. Annual temperature values range from 12 °C to 30 °C and daily fluctuations are negligible. In the summer months, it is constantly 2°C less than the indoor temperature and in winter months it is 1°C higher. The floor absorbs significant amounts of excess heat in the summer and makes a major contribution to the heat gains during the winter season.

The ceiling of the ground level, which is the boundary between the ground and upper floor, consists of a 3 cm thick wood layer supported by horizontal wooden beams. During the summer months, when temperatures of the upper floor are 2°C to 4°C higher than the ground floor and the temperature difference between the two surfaces of the ceiling is 1°C, the heat constantly flows towards the ground level. On the other hand, in the winter months, indoor temperatures of the two levels are close and the heat flow changes direction every few days, exhibiting low values (< 2 W/m^2).

The ceiling of the upper floor is made of a 4 cm wood layer, with an additional 5 cm thick layer of XPS insulation. Internal surface temperatures are close to ambient temperatures, resulting in low heat flow values. The presence of the attic on top of the ceiling prevents direct solar gains and suppresses the external temperature variation. The use of XPS insulation, which is attached on the upper surface of the ceiling, significantly reduces the heat gain/losses from the upper east room in comparison to external walls that make a greater contribution to the heat balance of the space. During the summer months, heat gains are observed at night time and heat losses during the day. On the other hand, during the winter season, heat constantly flows towards the outdoor environment.

5.3 Indoor thermal comfort

Thermal comfort of the internal spaces of the building is discussed in relation to internal temperature and humidity. Other parameters such as air movement, clothing, adaptability etc are not taken into account in the present analysis.

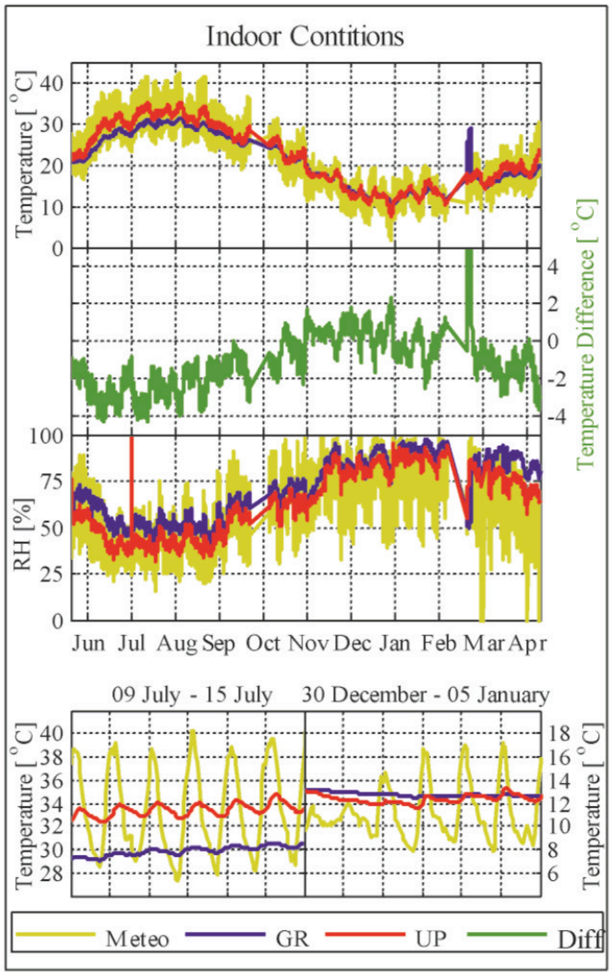

Figure 9. Indoor temperature and relative humidity measurements (ground and upper level)

Figure 9 illustrates the seasonal and daily variations of indoor temperature and humidity on the ground and upper floor at the east part of the building. Annual variation of the temperature in the ground floor ranges approximately from 11°C to 31°C, while in the upper floor it varies from 11°C to 35°C. This fact results in thermal comfort conditions only in the intermediate seasons (May, June, September, and October). In the summer months, the temperature on the upper floor is 4°C higher than that of the ground floor and in the winter period it is 1°C lower.

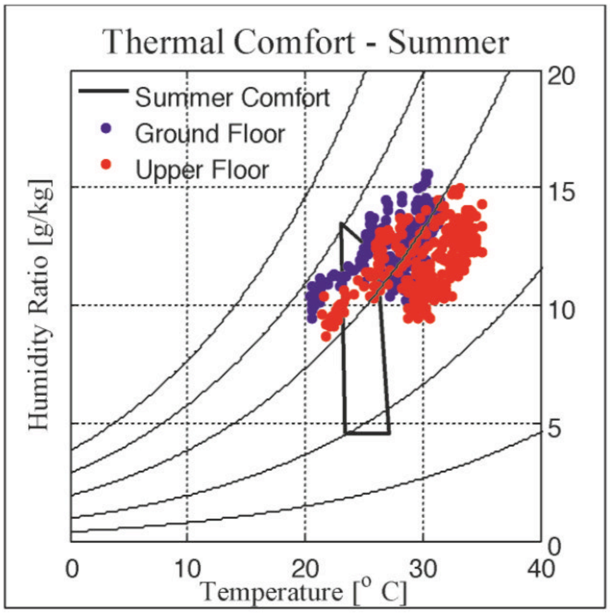

Figure 10. Thermal comfort diagram (summer)

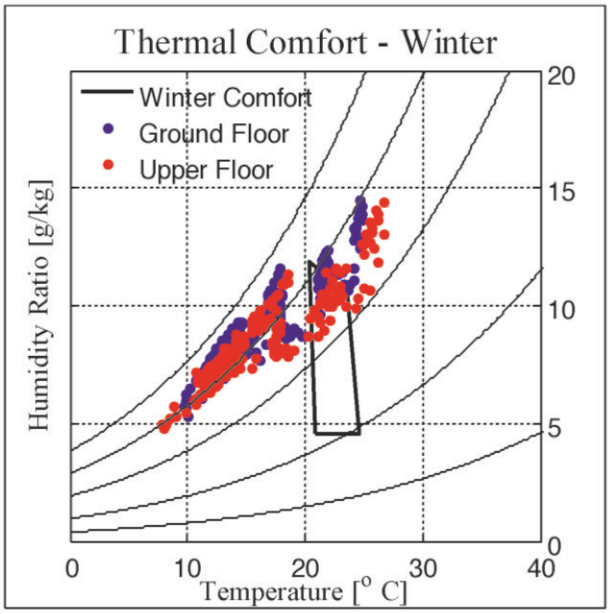

Figure 11. Thermal comfort diagram (winter)

Also, the daily temperature swing is more pronounced in the upper floor, with values of 2°C in comparison to the ground floor, which exhibits temperature swings of approximately 0.5°C. The relative humidity is always higher in the ground spaces due to lower temperatures and the fact that the level of the floor is lower than that of the ground outside.

Thermal comfort diagrams (Figs. 10 and 11) show that the ground floor indoor conditions are closer to the thermal comfort area during the summer period, whereas there are no significant differences during the winter.

6. Concluding Remarks

In this study, the passive thermal behavior of a post byzantine building in Athens was extensively analyzed. A data acquisition system and several sensors were installed in the building in order to examine its thermal response during the year. The fact that the building was restored with the same materials in which it was originally built, has given us the opportunity to simulate its original thermal behaviour. It was found that the configuration and the structure of the envelope are able to provide passive indoor comfort conditions during the intermediate seasons (no heating or cooling devices were operated during the measurement campaign). Measurements reveal that indoor temperatures are strongly affected by the temperature on the internal surface of the walls surrounding the space. Thus, in the ground floor where all the walls are of massive rubble construction either shaded or not, the internal surfaces and indoor spaces exhibit negligible temperature fluctuations during the day. On the upper floor, where part of the envelope consists of medium thermal mass timber framed walls, diurnal temperature swings are more pronounced.

The orientation of the building is of prime importance. It is obvious that if this building had been mirrored towards the east – west axis, then the results may have been different. The hayat would face the south (as discussed in section 2) and thus, would shade south walls and openings while at the same time allow winter sun to enter the rooms. The walls would still collect winter sun and be adequately shaded in summer. The fact that south elevation is completely unshaded results in the high interior temperatures even on the ground floor. The building was not used during the monitoring campaign and all windows and shutters were closed at all times. Therefore, we cannot evaluate the effect of insolation, natural ventilation and internal loads, even though head windows affected somewhat the heat gains and losses in the upper floor rooms. However, we could assume that ground floor rooms would have not been significantly affected, while the upper rooms would profit from the winter sun and users at daytimes. Additionally, the location of the windows on the north-south axis in combination with the north direction of the winds that dominate during the hot summer months would enhance the natural cross-ventilation of the space when the windows are open and shaded in the south wall.

The large-scale measurement campaign carried out allowed an in-depth assessment of the passive thermal behaviour of the historic building. The presented methodology may be applied to a large variety of existing buildings of same typology, both of historical and modern context, aiming to assess their thermal behaviour, for energy efficiency refurbishment purposes.

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