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ИНЖЕЊЕРСКА КОМОРА
СРБИЈЕ

EXPERIMENTAL DETERMINATION OF DYNAMIC PARAMETERS OF HEAT PASSAGE THROUGH THE FACADE WALL OF A WEEKEND COTTAGE ON MOUNTAIN KOPAONIK, SERBIA

Stefan Novčić[1], Diana Vranešević[2], Aleksandra Parezanović[3], Ivana Medarević[4], Radovan Gospavić[5], Goran Todorović[6]

Abstract

In this paper, using a dynamic RC model for heat transfer in a room on the ground floor, the three-time constants of heat transfer that corresponds to the different parts of a weekend cottage on Kopaonik were determined. The model considered the heat accumulation and losses through the facade wall, floor and interior part of the room. The time constant of the wall is the characteristic time for establishing a stationary state of the temperature inside the wall during rapid changes in the external air temperature and it represents a measure of the thermal inertia of the wall. The model was validated by experimental measurements of air temperatures and wall surface temperatures. Measurements were carried out in situ continuously for 21 hours in real conditions in the winter period. Air temperature measurements were made with standalone data loggers. The paper presents the results of the measurements, the parameters and the electrical diagram of the RC model and the results comparing the measured temperatures with the same temperatures obtained by this model. Satisfactory agreements were obtained.

Key words: *heat transfer, RC model, time constant, in-situ temperature measurement*

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1. INTRODUCTION

The measurements and numerical simulations related to the heat transfer through the exterior buildings' envelope are of the enormous practical interest for estimating buildings' thermal performances and energy efficiency [1]. The building's thermal performances are essential regarding the thermal comfort requirements [2]. In the real dynamical conditions, the thermal behavior of the whole building structure depends on different building parts, including the building's exterior envelope, floors, windows, indoor air and different interior structures [3, 4]. The electrical analogy models based on RC circuits have been extensively used in thermal simulations [5, 6]. In this approach, the thermal resistance and thermal capacity of the individual building elements are modelled using the electrical analogy with the electrical circuits consisting of the resistors and capacity elements. In this way, the temperature and heat flux are equivalent to electric voltage and current, respectively. In the literature, this approach is now known as Lumped Parameter Model (LPM) [7].

Ke-Lun He et al. developed an improved unit circuit model for heat transfer in multi-layer insulation materials based on additional nodes in the control volumes on the interfaces between different materials [5]. This approach has been used for the optimization of multi-layer structures to minimize heat losses. The heat transfer model inside a multi-layer wall based on a RC circuit has been validated in a real dynamical regime using experimental data by Jiaojiao Duan et al. [6].

Fraisse et al. have presented a numerical procedure to produce simplified RC circuit models for modelling multi-layer building walls [8]. In this way, the multi-layer planar structure could be modelled with only a few RC elements. The results obtained by the simplified RC model are compared with the reference numerical solution. In the same paper, all heat transfers in the entire building are represented using the electrical analogy and multi-zone building model.

The dynamical heat transfer model based on the electrical analogy with RC circuits and Kron's reduction of graphs has been developed and utilized in building retrofitting applications [9]. This technique is based on Schur's complement of the original Laplacian matrix that corresponds to the graph of the considered electrical circuit. A similar approach has been utilized for the zonal thermal model in a single room by Rivo et.al [10].

In this article, the electrical analogy and simplified RC circuit have been used for modelling of the heat transfer and temperature variation inside a room on the ground floor of a weekend cottage on the mountain Kopaonik during the winter period. The model has included the thermal envelope of the room, the heat losses through the floor and heat capacities of the thermal envelope, floor and the indoor space. Besides this, in-situ measurements of the inside and outside air temperature during 22.33h have been performed. During this period, the heating system has been switched off, and only cooling processes are analyzed. The numerical results obtained by the RC circuit are compared with the experimental data. The selection of the observed object for investigating its thermal properties was based on several pertinent considerations. Firstly, due to the small volume of the object, external temperature variations have a greater impact on the internal temperature and heat losses. Secondly, due to the high altitude and climatic conditions, the variations of the outside air temperature in the winter period are significant. Lastly, the object is isolated and exposed to greater influence of external factors, thereby making it an ideal candidate for this study.

2. DESCRIPTION, THERMAL PARAMETERS OF BUILDING CONSTRUCTION AND EXPERIMENTAL SET-UP

The measurements were taken in a cottage located in Kriva Reka, on the northeastern slope of Kopaonik, Serbia (Figure 1). The cottage is located at an altitude of 1330 meters above sea level, at 43°21'59" north latitude and 20°51'40" east longitude.

Figure 1. Exterior view of the weekend cottage in Kriva Reka, Kopaonik

The base of the outer walls has an overall dimension of 6.85x8.35 m, and the ridge is positioned in the east-west direction. The ground floor plan and vertical section of the weekend cottage with all relevant dimensions are shown in Figure 2. The entrance to the building is from the east cardinal direction. The entrance to the ground floor bedroom is on the left from the corridor, while the bathroom is positioned on the right. The living room is positioned in the front and it’s connected to the dining room and the kitchen. An interior staircase leads from the living room to the hallway in the attic. The attic has two bedrooms with terraces.

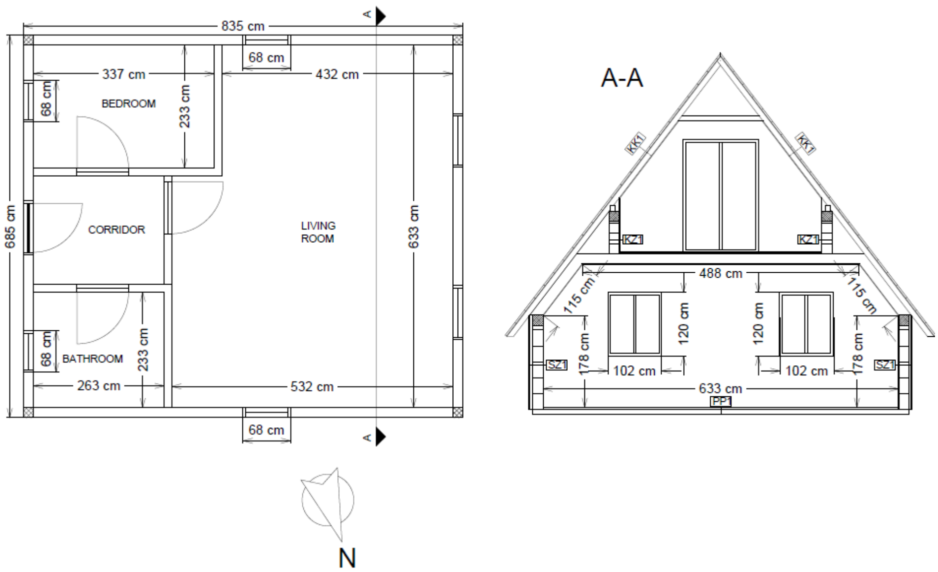


Figure 2. Ground floor plan and vertical section A-A of the weekend cottage

The foundation of the building is on strip foundations, which are connected by reinforced concrete foundation beams. The supporting structure of the building is made of hollow clay blocks with tie columns. The floor construction on the ground floor is a reinforced concrete slab, while the attic floor is a hollow-block floor (Light assembly ceiling). The interior partition walls are also made of hollow clay blocks.

The roof structure is made of wood, while the roof covering is based on bitumen and glass fibers (roof tile - tegola).

The building is heated by a central system with the boiler located in the kitchen area, and radiators are installed throughout all rooms. Radiator dimensions are adapted to the area of every individual room. The exterior joinery (windows) is made of PVC with double glass, while the entrance door to the building is made of aluminium.

Figure 3 shows the "data logger" used to measure the temperature inside and outside the weekend house. The external and internal temperature was measured simultaneously every 5 minutes. The measuring range and the response time of the device to step temperature excitation were from -35 [ºC] to 80 [ºC] and 20 [s], respectively.

Figure 3. Data logger for temperature measurements

Figure 4 shows the temperature measurement accuracy curve. In the measurement range of 5-40 [ºC], the maximum absolute measurement error is less than 1 [ºC] (the minimum at 25 [ºC] is 0.5 [ºC]). The device's sensor is located inside a plastic case that is conveniently designed and allows the internal flow of outside air, which also protects against wind and rain. Two measuring devices were used to measure the temperature.

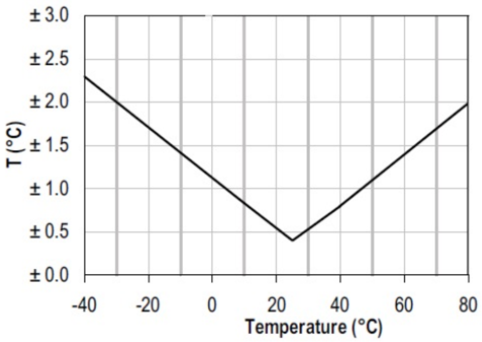


Figure 4. Temperature characteristics of data logger

The internal air temperature was measured in the middle of the living room and the external one under the eaves, in a place protected from the direct influence of the Sun and precipitations (Figure 5).

Figure 5. Positions of the data loggers in the living room and under the eaves

The thermo-physical parameters of considered building components used in the presented model in the section 3 of this paper are given in Tables 1-4.

Table 1. Thermal parameters of the outside façade wall (SZ1- Figure 2)

Material	d_w [cm]	ρ_w [kg/m^3]	λ_w [W/m·K]	c_w [J/kg·K]
Mortar (inside)	1	1900	0.7	1050
Hollow clay block	19	1400	0.61	920
Styrofoam	5	90	0.041	1260
Demit façade (outside)	1	1900	0.7	1050

Table 2. Thermal parameters of the roof above the slope wall (KK1- Figure 2)

Material	d_r [cm]	ρ_r [kg/m^3]	λ_r [W/m·K]	c_r [J/kg·K]
PVC	0.1	1200	0.19	960
Mineral wool	10	30	0.032	840
Wooden beam (10x8 cm) distance 60 cm	10	91	0.044	1727
PVC	0.1	1200	0.19	960
Wooden boards	2	520	0.14	1670
Permeable films	0.1	1000	0.19	1250
Roof tile	0.3	1100	0.17	1050

Table 3. Thermal parameters of the slope wall (attic floor-Figure 2)

Material	d_{sw} [cm]	ρ_{sw} [kg/m^3]	λ_{sw} [W/m·K]	c_{sw} [J/kg·K]
Light assembly ceiling	1	1900	0.7	1050
Styrofoam	19	1400	0.61	920
Mortar (inside)	5	90	0.041	1260

Table 4. Thermal parameters of the floor (PP1-Figure 2)

Material	d_f [cm]	ρ_f [kg/m^3]	λ_f [W/m·K]	c_f [J/kg·K]
Ceramic tails	0.4	2300	1.28	920
Reinforced concrete structure	10	2400	2.04	960

3. PHYSICAL MODEL

The heat transfer inside the ground floor room under dynamic conditions has been analyzed. The thermal model is based on an electrical analogy using a RC circuit and includes the thermal envelope of the considered room with windows, the influence of the floor and the thermal capacity of indoor space. The model can include real variations of the outside temperature. It has been assumed that the heating system during the calculation was turned off.

The presented LMP model is based on the assumptions that all thermo-physical parameters of the building components are constant and that the considered thermal system is linear, also it has been assumed that the indoor air temperature has uniform distribution during the time. Only thermal losses through the outside thermal envelope of the room and floor are considered, while the thermal losses through the ceiling and adjacent rooms are neglected. The thermal capacity of the windows was neglected. The thermal envelope is modelled as a simple equivalent RC circuit that consists of one capacitor and two thermal resistances. Besides this, the heat transfer in all solid building components (i.e. walls) is modelled as a conductive process. The heat transfer due to convection and radiation between air and outer surfaces has been modelled by the heat transfer coefficients in the boundary layers. The thermo-physical parameters of the observed building structures used in the considered thermal model are given in Tables 1-4. The RC circuit used for thermal modelling of the considered dynamical system is shown in Figure 6.

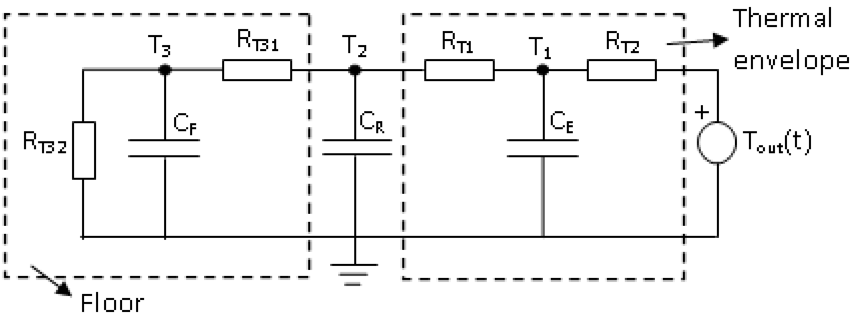


Figure 6. RC circuit used for thermal modelling of the considered dynamical system

The model consists of three parts: thermal envelope, floor and interior space. Interior space is represented by thermal capacity CR. The quantities Tout(t) and T2 in the Figure above represent the time-dependent outside and inside air temperatures, respectively. As mentioned, it has been assumed that indoor temperature is homogeneously distributed.

The thermal envelope includes a façade wall, a slope wall with part of the roof construction above, windows and boundary layers.

The positions and relevant dimensions of the modeled building elements are shown in Figure 2. The boundary layers are included through the inside and outside heat transfer coefficients α1=7.69 [W/m2·K] and α2=25 [W/m2·K], respectively. The constant numerical values for these parameters are adopted according to the Domestic Rulebook on the Energy Efficiency of Buildings [11]. The thermal resistance of the thermal envelope RTE is calculated according to the equivalent electrical scheme shown in Figure 7 and Equation 1.

$$R_{TE} = R_{T\alpha 1} + \left(\frac{1}{R_{Tw}} + \frac{1}{R_{Tsw}} + \frac{1}{R_{Twin}}\right)^{-1} + R_{T\alpha 2}; R_{T\alpha 1,2} = \frac{1}{S_w \cdot \alpha_{1,2}}, \quad (1)$$

where RTw, RTsw and RTwin are thermal resistances of the façade wall, slope wall with part of the roof construction above it and windows, respectively, and RTα1,2 are thermal resistance that corresponds to the inside and outside boundary layer ,respectively, that are calculated according to the above relations. The Sw in the above equation is the effective area of the façade wall which excludes the area of the windows.

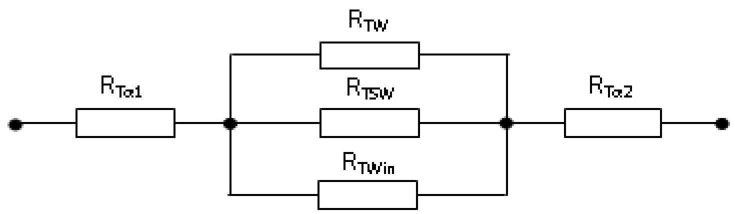


Figure 7. Equivalent electric scheme used to calculate thermal resistance of the thermal envelope used in the model

The thermal resistance of windows is calculated according the next relation:

$$R_{Twin} = \left(S_{glass1} \cdot U_{glass1} + S_{frame1} \cdot U_{frame1} + \cdots\right)^{-1}, \quad (2)$$

where Sglass and Sframes are areas of window glass and frameswhile Uglass and Uframes are U-values for window glass and frames, respectively. In the above relation the summation has to include all windows. The U-values for glass and frames are used according to the Domestic Rulebook on the Energy Efficiency of Buildings [11]. The following U-values of glass and frame are assumed: Uglass =3.0 [W/m2·K] (double glassing 6-8-6 mm) and Uframe =2.2 [W/m2·K] (PVC two-chamber frame).

The areas of window glass and frames for two types of windows used in the considered model are given in Table 5.

Table 5. The areas of window glass and frames

Window type	*Glass area [m²]*	*Frame area [m²]*
Type 1 (front view A-A, Figure 2)	*0.6336*	*0.5904*
Type 2 (side windows)	*0.3483*	*0.4677*

Besides this, the thermal resistance of all building walls and roof construction is calculated according to the Domestic Rulebook on the Energy Efficiency of Buildings [11].

The sum of the thermal resistances RT1 and RT2 used in the model represents the thermal resistance of the thermal envelope in stationary conditions, i.e. RTE = RT1 + RT2. Also it has been assumed that RT1 is the thermal resistance of the façade wall from the inside surface to the middle of the wall. Accordingly, the temperature T1 in Figure 6 is approximately the temperature in the middle of the façade wall. For the layer inside the roof construction that consists of wooden beams and mineral wool (Table 2), the averaged thermal parameters are used, and the same approximation is used for the light assembly ceiling (Table 3). All thermal capacity elements are calculated using the following approximate relation for the thermal capacity of a multi-layer structure:

$$C = S \cdot \sum_{i=1}^{N} d_i \cdot \rho_i \cdot c_i, \quad (3)$$

where C [J/K] is thermal capacity, N is the number of layers, S is the area of the considered structure and d, ρ, and c are thickness, density and specific heat, respectively. In Figure 6 CE, CR and CF are the thermal capacities of the thermal envelope, indoor space (room) and floor, respectively. The thermal resistance of the floor is obtained using the U-value of the floor that is calculated according to ISO 13370 international standard by the following relation:

$$U_f = \frac{2 \cdot \lambda_s}{\pi \cdot B + d_s} \cdot ln\left(\frac{\pi \cdot B}{d_s} + 1\right), \quad (4)$$

where Uf is the U-value of the floor, λs is the thermal conductivity of soil (value 2 [W/mK] is assumed), B is the ratio between the area and half perimeter of the floor, and ds is the effective thickness of building construction [12]. The quantity ds is obtained by the following relation:

$$d_s = w + \lambda_s \cdot \left(R_{se} + R_f + R_{si}\right), \quad (5)$$

where w is the thickness of the building's external wall, Rse is R-value between air and floor, Rf is R-value for floor construction, and Rsi is the R-value between soil and floor construction, for Rse and Rsi the value of 0.17 [m2 ·K/W] is assumed [12]. The overall thermal resistance of the floor is equal to the sum of thermal resistances RT31 and RT32. The ratio RT31/ RT32 is considered as a fitting parameter, and the best agreement with the measurement data is obtained if this ratio is equal to 0.07. This approximately corresponds to the position of the point with temperature T3 in Figure 6 at the interface between tales and concrete inside the floor. All model parameters are listed in Table 6.

Table 6. The model parameters

Parameter	R_{T1} [K/W]	R_{T2} [K/W]	R_{T31} [K/W]	R_{T32} [K/W]
Value	0.00662086	0.0283374	0.00226435	0.0300836
Parameter	C_E [J/K]	C_R [J/K]	C_F [J/K]	
Value	$1.31575 \cdot 10^7$	$8.47332 \cdot 10^5$	$7.60729 \cdot 10^6$	

The air temperature measurements collected during the time period of 21.33 h have been used as time-dependent outside temperature load $T_{out}(t)$ in numerical simulation. During the measurements, the heating system in the building was turned off. The air temperature T_2 for time-dependent loads $T_{out}(t)$ and appropriate initial conditions have been obtained in the complex domain. Utilizing the inverse Laplace transform, the time-dependent room temperature has been obtained in the time domain in the following form:

$$T_2(t) = g * T_{out} + \tau_E \cdot g(t) \cdot T_1(0) + g_1(t) \cdot T_2(0) + g_2(t) \cdot T_3(0);$$

$$g * T_{out} = \int_0^t g(\tau) \cdot T_{out}(t-\tau) \cdot d\tau, \quad (6)$$

where g(t) is the Green function, T1(0), T2(0) , T3(0) are the initial temperatures in the middle of façade wall, inside the room and in the floor construction, respectively. τE is the characteristic time related to the thermal envelope defined as τE = RT2·CE = 103.57 [h]. The initial temperatures used in the simulation had the following values: T1(0) = 16.989 [ºC], T2(0) = 17.5 [ºC], T3(0) = 12.9648 [ºC]. The T2(0) is equal to the initial measurement of the inside air temperature. The values for T1(0) and T3(0) are obtained using the initial measurements for inside and outside air temperatures and assuming the steady-state temperature distribution inside the façade wall and floor at the initial time moment. The functions g1,2 (t) are dimensionless characteristic functions that determine the temperature response to the initial conditions. The integral in the second relation of equations (6) is the convolution integral which determines the influence of time-varying outside temperature loads on the inside temperature variations. In contrast, the last three terms in the first equation represent the response due to the initial conditions. The Green function g(t) has the dimension of reciprocal time, depends only on the thermal characteristics of the observed building structure, and in our case it is given by the following relation:

$$g(t) = g_{01} \cdot exp(-t/\tau_1) + g_{02} \cdot exp(-t/\tau_2) + g_{03} \cdot exp\,(-t/\tau_3), \quad (7)$$

where the numerical values of the constant parameters are listed in the following table.

Table 7. The constant parameters that appear in the Green function

Parameter	*g_{01} [1/h]*	*g_{02} [1/h]*	*g_{03} [1/h]*
Value	*-0.00782131*	*-0.000110488*	*0.0079318*
Parameter	*τ_1 [h]*	*τ_2 [h]*	*τ_3 [h]*
Value	*0.487603*	*4.50222*	*61.1361*

The parameters τ1,2,3 have the dimension of time and represent the characteristic times of the considered building structure. It can be noticed that the last term in the Green functions in equation (7) with parameter τ3 is dominant as other terms decrease much faster. In this way, characteristic time τ3 determines the “thermal inertia” of the whole building structure.

4. RESULTS AND DISCUSSION

In Figure 8, the Green function g(t) multiplied with characteristic time related to thermal envelope τ_E together with functions $g_{1,2}(t)$ are shown. At initial time moment t=0, function $g_1(t)$ must be equal to one due to initial conditions, i.e. at the initial time, the room air temperature T_2 must be equal to $T_2(0)$, on the same time $g_2(0)$ and g(0) must be equal to zero.

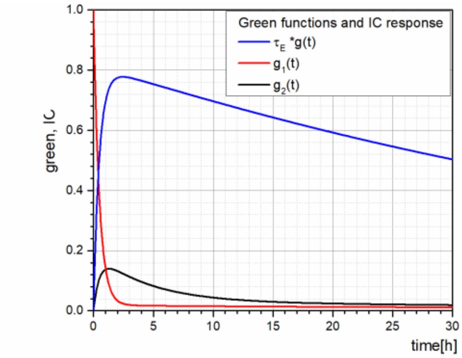
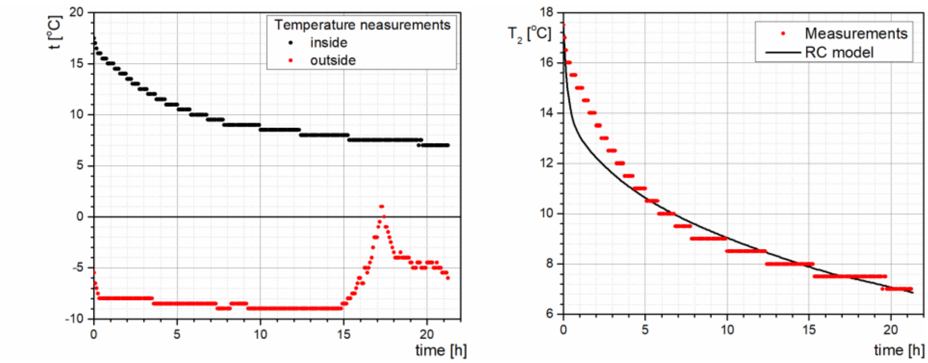


Figure 8. Green function g(t) multiplied with characteristic time τ_E and functions $g_{1,2}(t)$

The convolution integral in equation (6) at the initial moment is equal to zero, which means that the influence of the external temperature loads is not instantaneous. This condition provides that only the third term in equation (6) at the initial time is different from zero and equal to the initial temperature T2(0).



a) b)

Figure 9. a) Inside and outside air temperature measurements, b) comparison between inside air temperature measurements and results from RC model

In Figure 9a are shown the inside and outside air temperature measurements. The temperatures are continuously measured during a time period of 21.33 [h] with a sampling rate of 5 min. It could be noticed that almost all the time during this period, the outside temperature was below 0 [ºC]. As the heating system inside the building was turned off, during this period, the internal temperature continuously decreased from the initial value T2(0)= 17.5 [ºC] to 7 [ºC]. In Figure 9b, the comparison between measured inside air temperature and results obtained by RC simulation have been presented. The maximal deviation of the model prediction from the measurements was 2.09 [ºC] at the time moment equal to 1.16 [h].

5. CONCLUSION

The thermal model for the heat flow in the room on the ground floor of the weekend cottage on Kopaonik under dynamic conditions during the winter period has been developed. The electrical analogy has been used, and an equivalent RC circuit for thermal modelling has been proposed. The model has included all the main parts of the building on the ground floor, including the thermal envelope, floor and interior space of the considered room. The model for the thermal envelope included the façade wall, windows, slope wall and roof construction. All thermal parameters of the models are assumed according to the Domestic Rulebook on the Energy Efficiency of Buildings and to the ISO 13370 international standard [11, 12]. The measured outside time-dependent air temperature has been used as input load. During the measurements, the heating system has been turned off. According to the proposed RC circuit, the inside air temperature has been obtained in the complex domain considering input temperature excitation and initial conditions. The room temperature in the time domain has been obtained using Laplace transformation. The Green function of the system was obtained, and the influence of the external temperature loads has been taken into account through the convolution integral. The three characteristic times, as a measure of "thermal inertia" for the considered system, have been obtained. The characteristic corresponding to the dominant term in the response relation was 61.1361 [h]. The numerical results obtained by the proposed RC circuit have been compared with temperature measurement, and satisfactory agreements are obtained.

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