EVALUATING SEASONAL THERMAL OR COOLING LOADS FOR A HOUSEHOLD IN MUNTENIA, ROMANIA

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Abstract. The purpose of the present paper is to closely simulate thermal behaviour of a family house located in Muntenia region, Romania, throughout the year. The ground floor of the house includes: a living room, a bedroom, a kitchen, a bathroom, the stairs room, all connected to a central hall. At the first floor there are: two bedrooms, a bathroom, the stairs room and the main hall. Thermal gains or losses of the house partitions (walls, windows, ceilings, floors, etc.) are computed based on heat transfer laws and available norms, taking into account thermal inertia of exterior walls and accordingly the thermal transfer delay between interior and exterior elements of the house.

The rest of the heat gains are closely related to house occupancy, lightening and humidity sources, hourly simulated. The results are presented for a full day simulation over the year, comparing each room’s loads with respect to its orientation.

The results are useful in house design phase, for the optimal orientation of the house, corresponding to minimum yearly heating and cooling energy consumption.

Keywords: Seasonal thermal or cooling loads; house design phase; optimal house orientation; minimum heating and cooling energy consumption.

1. INTRODUCTION

Estimation of heat gains and losses is needed in order to evaluate the heating and cooling demand of residential buildings. In the current conditions characterized by dramatic climate changes and galloping energy price rises, reducing energy consumption required to ensure thermal comfort in residential buildings, becomes an essential step in the design phase of new buildings.

A feasibility study regarding a solar house with partial energy autonomy, located in Banat region, Romania is presented in [1]. The authors conclude that during the winter the solar input can supply 30–40 % of thermal energy needed to meet the comfort of the house, while, during the summertime, the solar input can fulfil completely the energy demand of the house.

The potential energy savings using cool roof coatings in residential buildings in various climatic conditions worldwide have been simulated and evaluated in [2]. A parametric analysis was also carried out in order to estimate the impact of solar reflectance and insulation on cooling and heating loads as well as peak cooling loads. The results show that increasing the roof solar reflectance reduces cooling loads by 18–93% and peak cooling demand in air-conditioned buildings by 11–27%. They have concluded that the application of cool roof coatings is an effective, minimal cost and easy to use technique that contributes to the energy efficiency and the thermal comfort of buildings.

The influence of opening windows and doors on the natural ventilation rate of a residential building was studied in [3]. The authors have stressed the importance of openings and exterior-to-interior air temperature difference on the air exchange rates.

The influence of climate change under future climate scenarios on the heating and cooling demands for four sample office buildings in Vienna, Austria, was studied in [4]. The authors have concluded that the influence of decreasing the internal load for energy efficient IT equipment and artificial lightening is more important on the net energy demand than that of a changing climate. The main conclusion was that the internal load is the most important factor influencing the cooling demand.

The heating and cooling load variations caused by the interior and exterior shading devices and different window material combinations were quantitatively investigated in [5] under Korean climatic condition. The sensitivity analysis was performed to evaluate the effect of the different slat reflectance and window type. They have performed the heat balance analysis in detail by breaking down heat transfer mechanisms taking place around the shading device and window using the robust building simulation software Energy Plus. They have concluded that the solar transmittance was the main factor for the cooling load increase and heating load reduction with the elevated slat reflectance in case of the exterior blind and the infrared heat gain from the blind and convective heat gains from the gap air and blind were the main factor for the cooling load decrease and the heating load increase at the higher slat reflectance in case of the interior blind.

A few features of building envelope that intensively affect summer internal microclimate in low energy building have been analysed in [6]. Dynamic thermal simulations of building model were conducted in Energy Plus software. The authors have concluded that a very effective measure against overheating, that requires a relatively small amount of conventional energy is night cooling or intense cooling of a massive enclosure during the night and that even very thick layers of thermal insulation of the building external shell, typical for zero energy buildings, do not intensify overheating duration.

An interactive software application intended for calculation of the heat demand for family housing based on current trends on the global scale in this area and some results of studies that have been conducted using this program are presented in [7]. The computing software allows users to perform studies in selecting components of the building envelope and the successful completion of thermal power analysis of single family housing, by calculating the thermal load or thermal capacity required for heating and domestic hot water.

From the above information one may notice that there is a major concern for estimating heating and cooling demand based on climatic conditions, the structural characteristics of buildings and their orientation relative to the cardinal points, in order to minimize the energy consumption of the building.

The proposed paper is intended to describe the thermal behaviour of a residential 2-storeys building during the whole year of operation, to analyse the contribution of each building element (wall, window, door, ceiling, etc.) to the total heat gain or loss, also to analyse the rooms from the same point of view, for the considered built environment. A comparison is provided between working and weekend days, based on inside occupancies activity. The two seasonal simulations (for winter and summer, respectively), a constant inside temperature of 25ºC is considered.

2. HOUSEHOLD DESCRIPTION

The studied house is located near the city of Bucharest, Romania at 44.25ºN latitude.

The property with ground floor and first floor (Fig. 1), intended for a four-person family (husband, wife and two children) and the facade is oriented southwards. The total built surface of the house is 104.47 m^2.

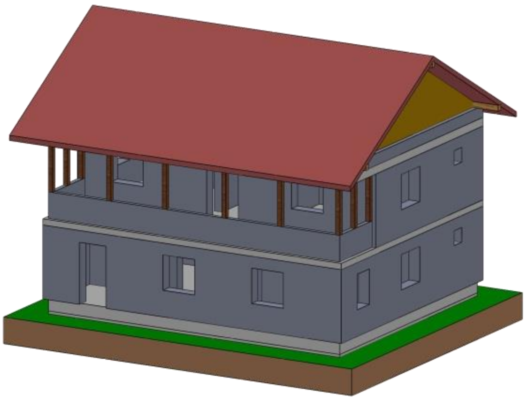

Fig. 1. Single family house, SE view.

The ground floor takes the idea of a central shared and distribution space (1 - hall with an area of 19.13 m^2), around which the living rooms are situated (2 - living room of 13.58 m^2 and 3 - bedroom of 13.7 m^2) and utilities (4 - kitchen - 7.76 m^2, 5 - bathroom - 9.74 m^2 and 6 - staircases - 9.74 m^2).

The entire ground floor is elevated on a concrete base of 52 cm. The first floor preserves the same conformation as the ground floor: 7- central hall with an area of 12.17 m^2 provides access to the two bedrooms (8 and 9), each of 13.7 m^2, 10 - bathroom (9.74 m^2) and 11 - staircases (9.74 m^2), as well as the terrace which extends along the entire length of the house. The total deployed living area of the housing is 137.70 m^2.

The thermal insulation of the house is made of brick walls 25 cm thick, plastered on both sides with 5 cm polystyrene next to concrete elements, corresponding to actual standards. External wall insulation is supplemented with a layer of 10 cm polystyrene.

Table 1. *The structure of the construction elements*

No	**Naming and abbreviation**	**Structure, from outside to inside**	**δ [cm]**
1	Exterior wall, PE	exterior coating	0,5
		expanded polystyrene (as insulation)	10
		interior mortar coating	3
		autoclaved aerated concrete brickwork	25
		interior mortar coating	2
2	Interior wall, PI	interior mortar coating	2
		autoclaved aerated concrete brickwork	25
		interior mortar coating	2
3	Slab over the ground floor, PPS	wood flooring	2
		dig leveling	5
		extruded polystyrene	10
		reinforced concrete	15
		gravel	10
		soil	10
4	Ceiling above the ground floor, PPP	wood flooring	2
		dig leveling	5
		reinforced concrete	12
		interior mortar coating	2
5	Mansard ceiling, PPE	dig leveling	5
		extruded polystyrene	10
		reinforced concrete	12
		interior mortar coating	2
6	Exterior window, FE	PVC profile with 5 rooms, 24 mm standard insulating glass	7
7	Exterior door, UE	Metallic, insulated with polyurethane foam	8.7
8	Interior door, UI	Solid wood	2

The structure of the construction elements used to build the house is summarized in table 1.

3. ENERGY GAINS AND LOSSES

The thermal or refrigeration load is equal to the sum of external and internal loads:

$$\dot{Q}_T = \dot{Q}_E + \dot{Q}_I\,. \tag{1}$$

The heat rates entering the system (i.e. the building) are considered positive, while heat rates exiting the system are considered negative. According to this sign convention, a positive value represents the cooling demand, while a negative value represents the heating demand.

3.1. External load

The heat gains and losses are computed according to standard norms [12], [13].

The external load due to heat exchanges between the building and exterior air, through exterior and interior building elements (walls, doors, windows, roofs, basements) is calculated using the equation [12]:

$$\dot{Q}_E = \dot{Q}_{PE} + \dot{Q}_{FE} + \dot{Q}_{PI} . \qquad (2)$$

The heat flux which enters the room through construction elements with thermal inertia, $\dot{Q}_{PE}$, depends on the structure of the construction elements, on the air temperature and on the damping coefficient of the heat flux.

According to [12], the following relationship is used:

$$\dot{Q}_{PE} = k \cdot A\left(T_{ES_m} - T_i\right) +$$
$$+\alpha_i \cdot A\left(T_{ES} - T_{ES_m}\right) \cdot \eta. \qquad (3)$$

The global coefficient of heat transfer is computed as:

$$k = \frac{1}{\frac{1}{\alpha_i} + \frac{1}{\alpha_e} + \sum\frac{\delta}{\lambda}} . \qquad (3')$$

The sunny exterior air temperature T_{ES} is:

$$T_{ES} = T_E + I_{Tt} \cdot \alpha/\alpha_e. \qquad (4)$$

The exterior air temperature t_E, is measured and reported by **Error! Reference source not found.**, solar irradiation on a horizontal plane I_T and on a tilted plane I_{Tt} is computed using Hottel and Woertz model applied at 44.25 N latitude in clear sky conditions **Error! Reference source not found.-Error! Reference source not found.**.

The calculated values of T_{ES} are time shifted compared to the heat contributions calculated with a period of time called phase shift, ε which depends upon the structure of the construction element:

$$\varepsilon = \tan^{-1}\frac{\mathrm{Im}(\beta_T)}{\mathrm{Re}(\beta_T)}, \qquad (5)$$

in which the complex number, β_T, has the expression:

$$\beta_T = e^{\sqrt{i}\sum_1^n Rs}\frac{s_1 + \frac{\alpha_i}{\sqrt{i}}}{s_1 + U_1} + \frac{s_2 + U_1}{s_2 + U_2} + ..$$
$$+\frac{s_n + U_{n-1}}{s_n + U_n}\frac{\alpha_e + U_n\sqrt{i}}{\alpha_e}, \qquad (6)$$

where $U_n = s_n \cdot M_n^{fin}$,
$M^{fin} = \frac{sh\left(R \cdot s\sqrt{i}\right) + M^{in}ch\left(R \cdot s\sqrt{i}\right)}{ch\left(R \cdot s\sqrt{i}\right) + M^{in}sh\left(R \cdot s\sqrt{i}\right)}$, and $M^{in} = \frac{\alpha_i}{s\sqrt{i}}$.

The daily mean sunny exterior air temperature is computed in the same manner as T_{ES}: $T_{ESm} = T_{Em} + I_{Ttm} \cdot \alpha/\alpha_e$.

The damping coefficient of the thermal flux, η depends on the structure of the construction elements.

For a structure of n layers, with no intermediate air layer, η can be determined as it follows:

$$\frac{1}{\eta} = |\beta_T|. \qquad (7)$$

For the exterior wall structure specified in table 1, η = 0.0041 and ε = 11.7942 hours and, for the ceiling, η = 0.0116, ε = 6.7618 hours.

Heat flux entered through windows, $\dot{Q}_{FE}$, is the sum of two components:

$$\dot{Q}_{FE} = \dot{Q}_{solar} + \dot{Q}_{termal}. \qquad (8)$$

Heat flux due to direct radiation, I_D and diffuse, I_B, can be calculated based on the equation:

$$\dot{Q}_{solar} = c_1 \cdot c_2 \cdot c_3 \cdot m \cdot \left(A_{GS} \cdot I_B + A_{G\,t} \cdot I_D\right). (9)$$

Heat flux due to the temperature difference between inside and outside, $\dot{Q}_{termal}$ can be determined using the relationship:

$$\dot{Q}_{termal} = k_G A_{Gt}\left(T_{ESG} - T_i\right). \qquad (10)$$

Heat flux entered through interior building elements, $\dot{Q}_{PI}$, is calculated based on the equation:

$$\dot{Q}_{PI} = k_R A_R\left(t_R - t_i\right), \qquad (11)$$

where the subscript R refers to the studied interior element.

The temperature difference $\left(t_R - t_i\right)$ is computed as **Error! Reference source not found.**: $t_R - t_i = 2°C$ if the wall of the next room is N-W, N or N-E oriented; $t_R - t_i = 3°C$ if the wall of the next room is E oriented; $t_R - t_i = 4°C$ if the wall of the next room is S-E, S or S-W oriented; $t_R - t_i = 5°C$ if the wall of the next room is W oriented.

The global coefficient of heat transfer, k_R, is computed by applying eq. (3’) using α_i instead of α_e.

4. COOLING AND THERMAL LOADS

4.1. Internal load

The internal load considers sensible and latent heat rates corresponding to perspiration and exhalation of occupants, humidity sources, heat gains from electronic equipment, appliances and artificial lightening [9].

Therefore, the internal load, $\dot{Q}_I$, consists of three components:

$$\dot{Q}_I = \dot{Q}_H + \dot{Q}_W + \dot{Q}_{LS}\,. \tag{12}$$

The total (sensible and latent) heat gain due to occupants activity is computed as:

$$\dot{Q}_H = \dot{q}_H \cdot n_H. \tag{13}$$

The heat gain due to humidity sources is:

$$\dot{Q}_W = \dot{m}_W \cdot h_W = \left(\dot{q}_W \cdot n_H + \sum \dot{m}_{W_i}\right) \cdot h_W \tag{14}$$

The heat gain due to artificial lightening:

$$\dot{Q}_{LS} = a \cdot n_{LS} \cdot P_{LS}. \tag{15}$$

The number of occupants and the periods of operation for light sources were estimated as time-dependent considering that the building is occupied by a family of four and the simulation is done for working days. Different time periods for winter and summer activities are considered, as one can notice reflected in Results section.

5. RESULTS AND DISCUSSIONS

The results are represented graphically in Figs. 2-5.

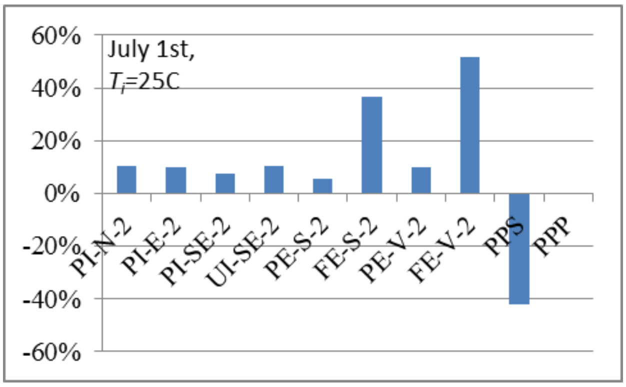

Fig. 2. Thermal contribution of each structural element of room no 2 to the total thermal load.

The negative value emphasized in Fig. 2 of the heat gain through the slab over the ground floor (PPS) is actually a heat loss from the room to the ground. As shown in Fig. 2, the highest heat gains occur through the two windows of the studied room, followed by the exterior wall West oriented. Naturally, the exterior wall South oriented has the lowest contribution to the room heat gain as it almost never sees the sun.

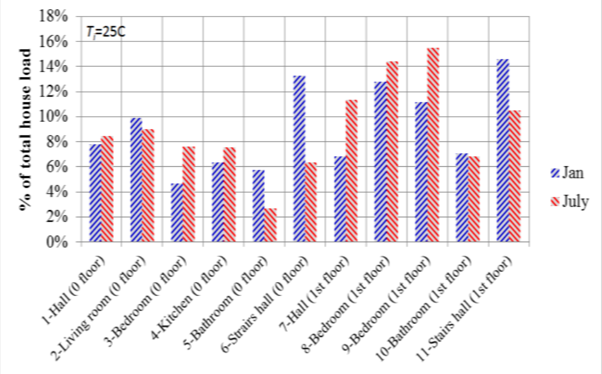

Fig. 3. Thermal contribution of each room to the total thermal load of the house, considering losses in January and heat gains in July.

Fig. 3 shows the contribution of each room to the total heat exchange with the external environment in winter (blue bars), compared to summer (red bars). One can observe that in six of the rooms the heat gains on July is greater than the heat losses from January and in three of the rooms the situation is reversed.

Heat gains are equal to heat losses only for two of the rooms: downstairs hallway and first floor bathroom. The greatest differences between heat losses and gains are recorded in the staircases downstairs and upstairs hallway.

The highest heat gain occurs in the Eastern upstairs bedroom (15%) and the highest heat loss occurs at the first floor stairway.

As one may notice, both in winter and summer, the first floor rooms contribute with the highest losses, respectively gains to the total energy demand.

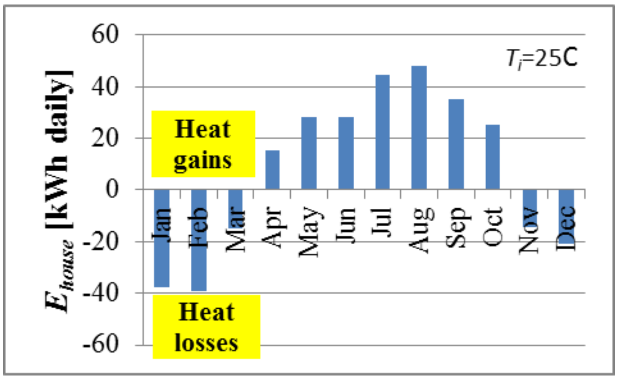

Fig. 4. Total household heat exchange expressed in kWh (daily energy exchanged between the house and the environment), over a calendar year.

Results presented in Fig. 4 emphasise the energy required to maintain 25ºC inside the house, during winter (downward part of the graph) and in summer (upper part). As noticed, cooling is required in summer, from April to October, while heating is needed from November to March. The cooling required energy is much higher than the energy consumed daily for heating. The two peaks are relatively closed to 40 kWh/day.

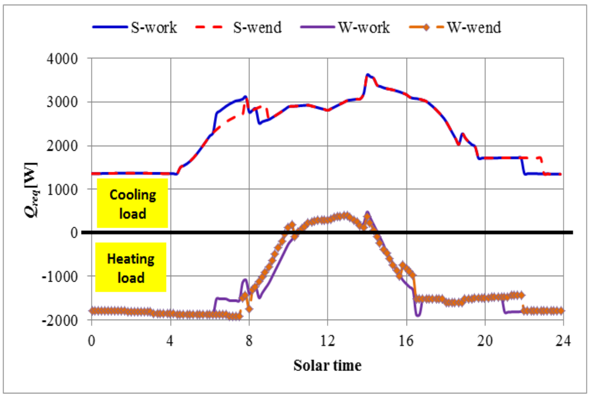

Fig. 5. Total energy demand (thermal<0, refrigeration>0); comparison between summer and winter regimes, working days and weekends.

Total refrigeration requirements of the building in summer time time-dependent, as can be observed in Fig. 5. From 9 pm or 11 pm (depending on day type, working or weekend) to 4 am, the refrigeration demand is constant and equal to about 1.2 kW as no sun strikes the house. From 4 am, the refrigeration demand increases continuously to the maximum value of 3.5 kW at 2 pm, then it drops until 8 o'clock in the evening. The difference between working ("work") and weekend ("wend") days are due to occupants' activity inside the house.

The heating demand during winter time is constant and equal to about 2 kW between 9 pm or 11 pm to 6 am, so it is more important than the cooling one in summer. During the rest of the day, the heat demand varies: between 8 and 10 it drops from 2 kW to zero and between 10 am – 2 pm it becomes positive (central heating can be turned off) and then increases to about 2kW between 2 and 9 pm.

Table 2. *Daily and monthly energy exchanged between the house and the environment.*

	Jan	Feb	Mar	Apr	May	Jun
*E*_day [kWh]	-37.67	-38.96	-14.72	15.22	28.43	27.41
*E*_month [kWh]	-1167.6	-1090.9	-412.10	426.1	796.1	795.40

	Jul	Aug	Sep	Oct	Nov	Dec
*E*_day [kWh]	44.84	47.99	35.40	25.44	-14.16	-20.95
*E*_month [kWh]	1255.4	1343.7	991.11	712.4	-396.5	-586.7

From table 2 it can be noticed that peak load months are February with a daily heat loss of 39 kWh, respectively August with a heat gain of 48 kWh per day.

4. CONCLUSIONS

The mathematical model consists of equations of heat transfer applied to the constructive elements with thermal inertia (exterior walls) and without thermal inertia (windows etc.) and it was used to simulate the thermal behaviour of a single-family house, located near the city of Bucharest, throughout the year.

During the summer, most of the heat flux (40%) penetrates the house from the outside through the windows. Maximum heat gain depends on the orientation of windows and solar time. In the bedrooms with windows facing east, the heat gain has a maximum at around 8 am, in the hall on the ground floor and kitchen (with windows facing south) peak is reached at lunch, while in rooms with windows facing the west (living room and bedroom upstairs) peak is reached at 4 pm.

During the winter, heat losses from the house to the outside environment at night are almost constant and variable during the day, with a minimum at noon.

For one and the same room, heat exchange with the external environment differs in the summer compared to winter. In most of the rooms, the heat gain during summer time is greater than the heat loss in winter time. Bathrooms at the ground floor and staircases are an exception.

During a calendar year, the maximum heat gain of 48 kWh per day, is recorded in August, while the maximum heat loss of 39 kWh daily, occurs in February.

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NOMENCLATURE

- a [%] - a simultaneous coefficient showing the percent of lights on;
- A [m^2] - the surface area of the construction element;
- A_{GS} [m^2] - sunny glass surface depends on the position of the sun and on the constructive elements of the window; (in this study, A_{GS} was considered to be equal to the total glass one A_{Gt}, considering no shading on window surface);
- c_1 - quality coefficient of the window ($c_1 = 0.9$ for double glazed window);
- c_2 – coefficient of window shielding ($c_2 = 0.6$ for light colored interior blinds, $c_2 = 0.6$ for metallic windows, according to **Error! Reference source not found.**);
- c_3 – the ratio between the area of the glass and the total window area;
- $h_W = 2500 + 1.88 \cdot t_I$ [Jkg^{-1}] - the water vapor enthalpy at t_I;
- $i = \sqrt{-1}$ - the imaginary unit;
- I_{Tt} [W/m^2] - the solar irradiation;
- I_{Ttm} [W/m^2]- the mean solar irradiation;
- k [Wm^{-2}K^{-1}] - the global coefficient of heat transfer;
- k_G [Wm^{-2}K^{-1}] - the global coefficient of heat transfer, k_G=2.56 Wm^{-2}K^{-1};
- m - heat accumulation coefficient depending on hourly values **Error! Reference source not found.**;
- $\sum \dot{m}_{W_i}$ - the total amount of water vapors absorbed or condensed on different elements inside the room;
- n_H - the number of occupants inside a room;
- n_{LS} - the number of light sources;
- P_{LS} - the power of each light source (60 W for bulbs);
- $\dot{Q}_E$ [W] – total heat rate penetrating the building from the outside due to solar radiation;
- $\dot{Q}_I$ [W] - total internal heat rate released inside the building by perspiration and exhalation of occupants, humidity sources, electronic equipment, artificial lightening etc.;
- $\dot{Q}_{PE}$ [W] - the heat flux penetrating the room through construction elements with thermal inertia (exterior walls, terrace, roof);
- $\dot{Q}_{FE}$ [W] - the heat flux which penetrates the room through building elements without thermal inertia (windows);
- $\dot{Q}_{PI}$ [W] - the heat flux penetrating the room through interior construction elements;
- $\dot{Q}_H$ [W] - the total (sensible and latent) heat gain due to occupants activity;
- $\dot{Q}_W$ [W] - the heat gain due to humidity sources;
- $\dot{Q}_{LS}$ [W] - the heat gain due to artificial lightening;
- $\dot{q}_H = 368$ kJ hr^{-1} (102 W) corresponding to the average metabolic rate of an adult male at rest;
- $\dot{q}_W = 0.0632$ [kg humidity hr^{-1}] - the average amount of water vapors eliminated by human respiration and perspiration;
- $R = \frac{\delta}{\lambda}$ [Wm^{-2}K^{-1}] - thermal resistance of the layer;
- $s = 8.5 \cdot 10^{-3}\sqrt{\delta \rho c_p}$ [Wm^{-2}K^{-1}] - the thermal assimilation coefficient of the material;
- t_I [°C] - interior air temperature;
- T_E [K] - the effective temperature of the exterior air;
- T_{Em} [K] - the effective mean temperature of the exterior air;
- T_{ESG} [K] – equivalent computational temperature of the outdoor sunny air;, ($T_{ESG} = T_E + 2A_{Gt}(1 - A_{Gt}) \cdot I_{Tt}/\alpha_E$ for double glazed windows);
- T_i [K] – the indoor air temperature;
- T_{ESm} [K] - the daily mean sunny exterior air temperature;
- T_{ES} [K] - the sunny exterior air temperature.

Greek symbols:

- α - the solar energy absorption coefficient for the wall exterior coating (for plastered walls: $\alpha = 0.91$);

- α_i [W/(m^{2}K)] - the interior convection heat transfer coefficient;
- α_e [W/(m^{2}K)] - the exterior convection heat transfer coefficient;
- δ [m] - the wall thickness for the wall structure specified in table 1;
- λ [Wm^{-1}K^{-1}] - thermal conductivity for the wall structure specified in table 1;
- η - damping coefficient.

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[12] Romanian norm STAS 6648/1-82 Calculul aporturilor de căldură din exterior (Norm for computing heat gains from exterior, in Romanian language).

[13] Romanian norm STAS 1907/1-90 Calculul necesarului de căldură. Prescripţii de calcul (Norm for computing heat demand. Calculus prescriptions, in Romanian language).