Thermal Energy Efficiency Analysis for Residential Buildings

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***Abstract*—The paper presents an interactive software application, for the calculus of the heat flux demand in residential houses, based on international trends, standards and specifications in the fields of thermal energy in buildings. These types of calculations are considerable useful in the context of the large and constant interest on the subjects of energy conservation, reduction of polluting emissions and use on large scale of renewable energies. In order to reach the objective of the research, the heat flux demand was parameterized to identify each influence on the thermal energy consumption and costs. The development of the mathematical model had the aim to allow the minimization of the heat losses into the environment and to choose the correct thermal power for the residential houses heating devices. By the use of PHP language, the mathematical model has been transposed into a client-server application. The interactive software system has been validated through a case study and the obtained results were consistent and relevant. Based on the results it was possible to extract key conclusions about the parameters that contribute to the heat losses.**

***Keywords*—Energy efficiency, heating demand, residential building.**

I. Introduction

The concern of energy conservation, the reduction of green house gases and sustainability was continuously growing in last years [1]. The concept of green building has been introduced, and refers the practice of increasing the efficiency with which buildings and their sites use and harvest energy, water, and materials, and reducing building impacts on human health and on environment, through better design, construction, operation, maintenance, and removal [2].

In the green building concept, an important issue is the energy efficiency. An energy efficient house is a building that provides a high level of thermal comfort without over reliance on artificial heating and/or cooling. The economical strategy of sustainable development imposes the promotion of global energy efficiency and the rational use of thermal energy in buildings, the major energy consumer, globally speaking.

In Romania, there were inherited from the communism a huge amount of home buildings that are heating by a central system (a thermal power station that is use to heat more than one buildings of flats with four to ten floors - for example in a building with ten floors there are sixty-four apartments with two or three rooms). The heat is distributed towards and around the building through ducts (hot air) or pipes (hot water). Since 2000, many flats owners renovated their apartments, getting insulated walls, changing windows and installing individual heating system that use natural gases as fuel. Note that, according to the Association for the Study of Peak Oil & Gas the natural gases will be depleting in sixty-six years [3]. In Romania, the standard of residential building construction was redefined in 2006 by the government, the new regulations being imposed through Minister Decree No. 729 [4].

Starting from the national [4] and international trends [5-8] in development of environmental performance of new and existing home buildings, an interactive system for assisting the calculation of home energy efficiency has been created and validated, and its performances are presented.

II. Material and Method

A. Mathematical Model

According to [9], the total heat flux losses through a building (Φ) is given by the formula:

$$\Phi = \Phi_1 + \Phi_2 + \Phi_3 \quad (1)$$

where Φ_1 = the heat flux losses through transmission, Φ_2 = the heat flux losses through ventilation, and Φ_3 = the heat flux needed for preparing the domestic hot water.

The heat flux lost through transmission is distributed between the walls, the floor, the ceiling and the windows. According to these, the formula of the Φ_1 is:

$$\Phi_1 = \Phi_{1.1} + \Phi_{1.2} + \Phi_{1.3} + \Phi_{1.4} + \Phi_{1.5} \quad (2)$$

where $\Phi_{k.j}$ = heat flux losses through: walls ($\Phi_{1.1}$), ceiling ($\Phi_{1.2}$), windows ($\Phi_{1.3}$), main floor ($\Phi_{1.4}$), and basement ($\Phi_{1.5}$).

The heat flux losses through ventilation depend directly by the global insulation of the building in conformity with formula:

$$\Phi_2 = \varepsilon \cdot \Phi_1 \quad (3)$$

where ε = a coefficient correlated with the global insulation of the building. This coefficient is assumed equal with 0.7 for buildings without insulation, 0.8 for buildings with minimal insulation, 0.9 for buildings with good insulation, and 1 for buildings with very good insulation (buildings with low energy consumption, passive buildings regarding the energy consumption).

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The heat flux needed for preparing the domestic hot water depend on the following parameters: number of persons (n), the working time per day of water heating system (τ - seconds), the volume of hot water needed per person per day (V - m^3), water density ($\rho \approx 1000$ kg/m^3), the specific heat of water (c_p = 4.186 kJ/kgK), the imposed temperature of hot water (t_{Wi} - K), and the assumed temperature of the external cold water (t_{We} - K). The heat flux needed for preparing the domestic hot water is given by the formula:

$$\Phi_3 = n \cdot \rho \cdot V \cdot c_p \cdot (t_{Wi} - t_{We})/\tau \quad (4)$$

The expression of heat fluxes lost through walls ($\Phi_{1.1}$), ceiling ($\Phi_{1.2}$), windows ($\Phi_{1.3}$), main floor ($\Phi_{1.4}$), and basement ($\Phi_{1.5}$) must be reported to the total surface of the house ($S_{1.i}$ taking into consideration only those elements that are connected with the outside), according to the global heat transfer coefficient ($k_{1.i}$), temperature from the outside of the building (t_{out}), temperature from the inside of the building (t_{int}), soil temperature (t_{sol}) and the temperature of the basement (t_{sub}). The generic formula of the heat fluxes lost through transmission become

$$\Phi_{1.i} = S_{1.i} \cdot k_i \cdot (t_1 - t_0) \quad (5)$$

where: $t_1 = t_{int}$ (i = 1..5), $t_0 = t_{out}$ (i = 1..3), $t_0 = t_{sol}$ (i = 4), $t_0 = t_{sub}$ (i = 5).

The heat transfer coefficient is a function of the convective heat transfer from inside ($\alpha_{1.i.1}$) and from the outside ($\alpha_{1.i.2}$), heating conductivity ($\lambda_{1.i.1}$ - for the main structure, and $\lambda_{1.i.2}$ - for the insulation structure). The formula is:

$$k_{1.i}^{-1} = \alpha_{1.i.1}^{-1} + \alpha_{1.i.2}^{-1} + \delta_{1.i.1}/\lambda_{1.i.1} + \delta_{1.i.2}/\lambda_{1.i.2} \quad (6)$$

The assumed value of the inside convective heating transfer was considered equal with 8 W/m^{2}K (corresponding to normal natural convection conditions); for the outside convective heat transfer coefficient was assumed a value of 25 W/m^{2}K (corresponding to the most unfavourable conditions). In the case of the main floor, the heat transfer coefficient has a specific value for the outside and other value for the inside. It was considered that the outside convective heat transfer coefficient for the main floor ($\alpha_{1.i.2}^{-1}$) is infinite for a building without basement.

B. Construction Parameters

It has been considered that the energy efficiency of a building, according to the above described formulas, depends on the environment parameters, the nature of the construction materials of the house (insulation and main structure of walls, floor, ceiling) and of windows type.

The assumed characteristics for the construction materials of the main structure for walls, floor and ceiling are presented in Table I. The global heat transfer coefficients assumed for different types of windows are indicated in Table II.

The roof temperature was calculated according to the roof type: $t_{roof} = t_{out}$ (for terrace roof), $t_{roof} = t_{out}$ + 5°C (for normal un-insulated roof), and $t_{roof} = (t_{out} + t_{int})/2$ (for well-insulated roof).

TABLE I.
HEAT CONDUCTIVITY ASSUMED FOR DIFFERENT MAIN MATERIALS OF THE STRUCTURE

Resistance structure	Conductivity [W/mK]
Concrete	1.45
Brick	0.90
Autoclaved Cellular Concrete	0.40
Plated wood	0.10
Beech/oak wood	0.37
Pine/fir wood	0.28
Stone	2.90

TABLE II.
ASSUMED HEAT TRANSFER COEFFICIENT ACCORDING WITH WINDOWS TYPE

Window material	Coefficient [W/m^{2}K]
Triple-pane Kr insulated glass	0.5
Triple-pane insulated glass	0.8
Low- Emission insulated glass	1.1
Single-pane insulated glass	1.4
Double glass	2.0
Simple glass	2.5

C. Implementation Method

The PHP language (Hypertext Preprocessor) [10] has been used as method for implementation of the mathematical model on heat flux requirement for domestic house buildings. The PHP language has the unique distinction of being an open-source scripting language that allows creation of interactive and/or dynamical applications. PHP allows integration of C, Pascal, Basic, and Perl programming languages syntaxes. The connection with a MySQL databases is easy, and proved to be a real solution in creation of interactive applications [11-13]. Modular programming and graphical implementation are possible with PHP [14].

D. System Validation

The system validation was performed through analysis of the energy efficiency of a new building. Starting from the supposition that a field of 2300m^2 is available in Alba Iulia County, Romania, a residential building has been designed and the characteristics of the energy efficiency were analyzed.

The considered environmental conditions were as follows:

÷ The wind speed: up to 40 km/h;

÷ The relative humidity: could vary from 60% to 90%;

÷ The distribution of raining water: could not be considering homogenous, some variations existing according with the season and the calendaristic month. The average in the last year was considered (equal with 714 mm).

The characteristics for the experimental designed residential building are presented in Table III.

The total perimeter of the building was equal with 58 m, the house being designed for a family with four members.

TABLE III.
DIMENSIONS OF THE HOME AND ROOMS SURFACES

Room	Surface (m^2)
Kitchen	27.5
Living room	36
Bathroom	9
Bathroom	7
Matrimonial bedroom	21.25
Bedroom	10.5
Bedroom	10.5
Vestibule	10
Lobby	8.25
Total surface	140

III. RESULTS

The application designed for assisting the users in analysis of the heat flux requirement for a residential building has developed and is available online at the following URL:

http://vl.academicdirect.org/molecular_dynamics/heating_buildings/

Four programs have been designed and implemented. The *form.php* program allows the user to introduce the characteristics of the environment and of the building according to personal desires and/or own building (see Fig. 1).

Based on the mathematical model presented in Material and Method section, a total number of twenty-five functions were implemented and stored in *func.php* file. The *func.php* computes and displays the heat losses through windows, the heat losses through walls, and the global heat losses by transmission.

The parameters calculated and displayed by the program are graphically represented by the use of two types of diagrams:

÷ First type represents the variance of one parameter depending on one component (for example the total heat transfer associated with chosen type of window).

÷ Second type of diagram represents the dependences between multiple parameters (for example the dependence between flows of the heat losses necessary to warm up the water according to the number of persons, the temperature, and the volume of hot water). In the second type of the diagram representations, the user can choose the parameter on the X-axis and Y-axes, the number of colour used for graphic displaying, etc.

According to the chosen parameters (see Fig. 1), the program calculates and display:

1. The heat losses through windows (see Fig. 2). Plot the heat losses through windows according to windows type (see Fig. 3), and the relative heat losses through transmission according to window type (Fig. 4);
2. The dependences between heat losses through wall and thickness and type of the resistance and insulation layers (see Fig. 5). The calculated values can be graphically represented (see Fig. 6);
3. The dependence between flows heat losses through transmission and the chosen type of the resistance material (see Fig. 7). The obtained values can be graphically represented (see Fig. 8);

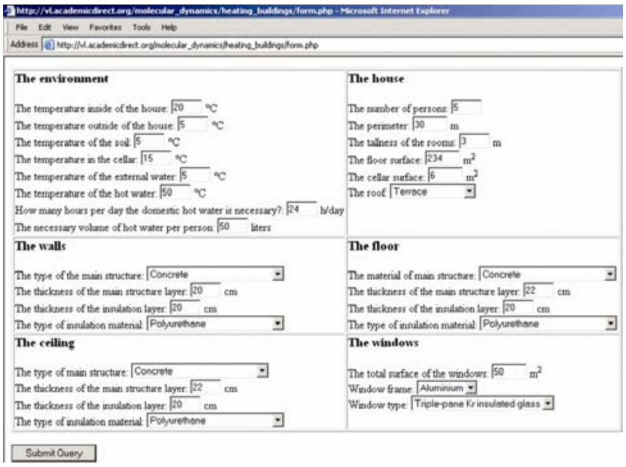
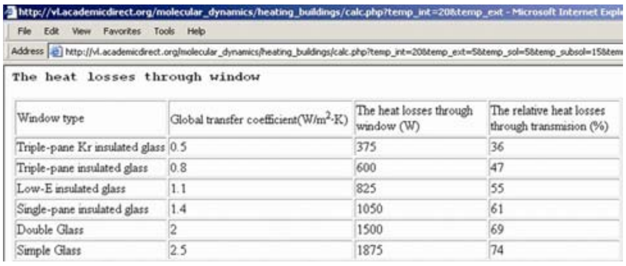


Fig.1. Main interface of the energy efficiency program.


The heat losses through window

Window type	Global transfer coefficient($W/m^2 \cdot K$)	The heat losses through window (W)	The relative heat losses through transmission (%)
Triple-pane Kr insulated glass	0.5	375	36
Triple-pane insulated glass	0.8	600	47
Low-E insulated glass	1.1	825	55
Single-pane insulated glass	1.4	1050	61
Double Glass	2	1500	69
Simple Glass	2.5	1875	74

Fig. 2. Characteristics of the heat losses through windows and transmission according to windows type.

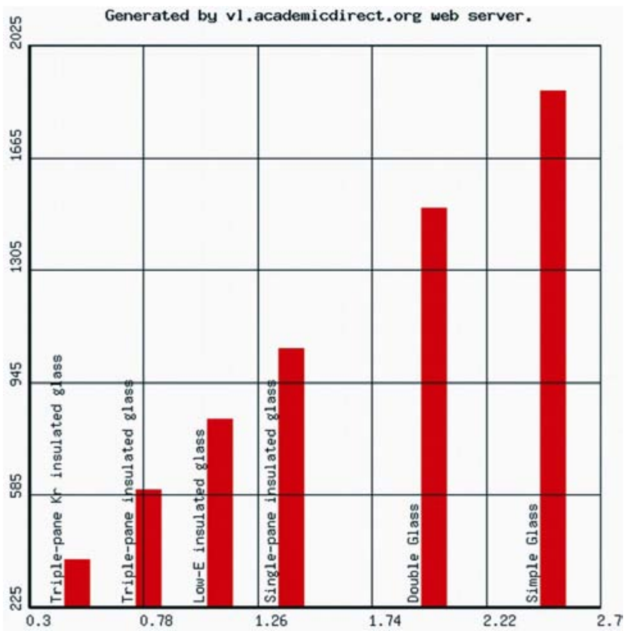


Fig. 3. Distribution of heat losses through windows according to their type.

4. Plot the dependence between flows heat losses necessary to warm up the water according to the number of persons, and the temperature and the volume of hot water (see Fig. 9).

According to the standard values presented in Material and Method section, the program is able to compute the heat losses through walls and allows users to define the variables on the X-axis and Y-axis in graphical representations (see Fig. 5).

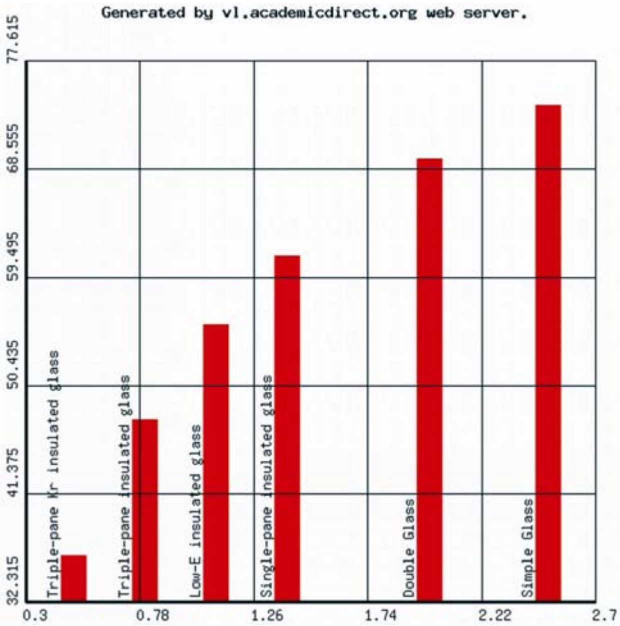


Fig. 4. Relative heat losses through transmission according with windows type.

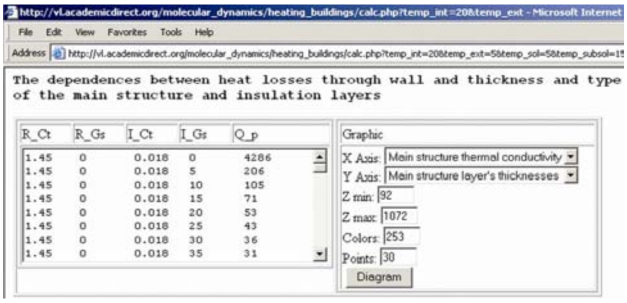


Fig. 5. Computed values of the heat losses through walls according with thickness and type of the resistance and insulation layers.

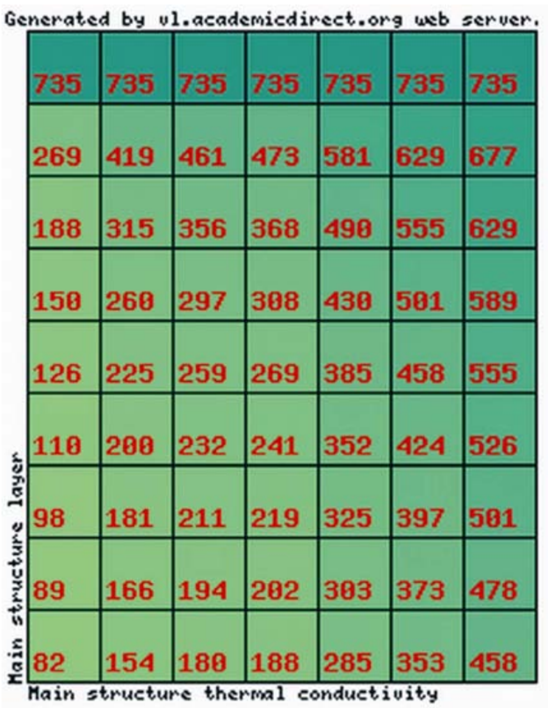


Fig. 6. Heat losses through walls according with the main structure layer and thermal conductivity.

The results that represent the main structure layer versus the main structure thermal conductivity are shown in Fig. 6. In this figure the red numbers represent the values of the heat losses through walls, on the dark green background the highest values of the mains structure layer, respectively of the main structure thermal conductivity, and on the light green the lowest values for the same parameters.

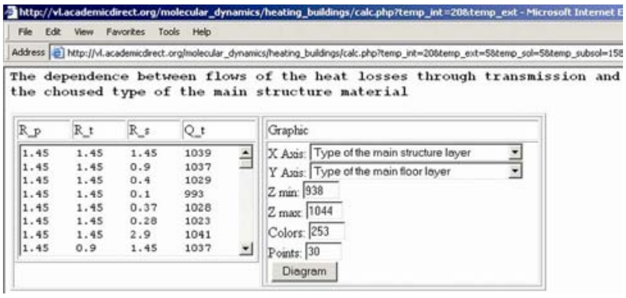


Fig. 7. Dependence between flows of the heat losses through transmission and the chosen type of the resistance material.

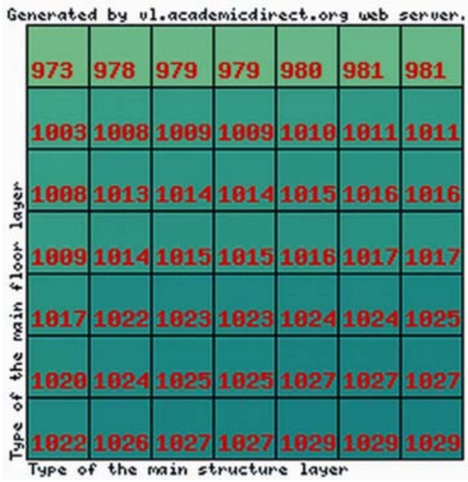


Fig. 8. Dependence between flows of the heat losses through transmission according to the type of the main floor layer and structure.

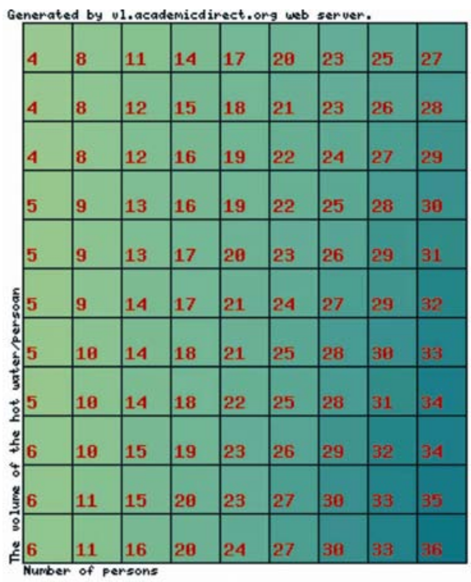


Fig. 9. Dependence between flows of the heat losses necessary to warm up the water according to the number of persons, and the volume of hot water.

IV. Discussion

Different researchers developed different software able to calculate the heating and/or cooling energy according to the type of the windows, for analysis of the window thermal and optical performances [15], or for comparing the environmental performance of houses at the design stage (BASIX [16], ACTHERS [17], LEED® [18]). These software's were created in order to assist the architects in process of designing buildings and/or owners which desire to improve their houses in order to reduce the energetic consumption, to increase the thermal comfort and to decrease daily thermal energy costs.

The aim of the presented research was reached. The application for assisting calculation of residential buildings integrates into a friendly interface the calculations useful in analysis of the heat flux requirements.

The evaluation of the developed application can be done through analyzing its advantages (noted with + sign) and disadvantages (noted with - sign) as followed:

÷ + Interaction with the users: the users can choose his/her own residential building parameters

÷ + Assisting calculation of coefficients and heat losses: according to the input data, the application compute and display in a real time a number of twenty-four coefficients

÷ + Interactivity: the user is free to choose the graphical representation of the interest parameters

÷ + Accessibility: the access is free and the application can be use at any hour (the use of the application is not restricted by any timetable)

÷ + Multi-tasking: the application can be use simultaneously with other applications

÷ + Multi-user: the application can be use simultaneously by more than one user

÷ + Updating: the updating of the application is an effortless process, and can be done in real time and as many time as it is consider being opportune

÷ - The use of application requires minimum computers skills (opening a program, browsing, etc.)

÷ - There are not included into application any financial estimations;

÷ - There are not included into application any evaluation of the construction (such as strength structure calculations, etc);

÷ - The application can be use just by the user that had a computer connected to the Internet.

The usefulness of the application is obvious. In a development country, such as Romania for example, where the daily costs for living is sometimes greater comparing with the family monthly income, the attention of the citizens is straight on decreasing the costs of day-by-day living. Created application give the possibility to analyze and compare the heat losses flux through windows, walls, main floor, ceiling, roof and to estimate the heat flow necessary to warm up the water according with the main structure and insulation materials, type of windows, total surface of the building, etc.

Analyzing the results of the proposed building for the chosen parameters (see Fig. 1) it can be observed that, as it was expected, the lowest value for the global transfer coefficient was obtained for the triple-pane Kr insulated glass and the highest value for the simple glass windows. Each parameter calculated by the application has its usefulness. A detailed analysis of the parameters usefulness can be found in a previous reported paper [19].

The proposed application, even if it does not offer the ideal solution for build and/or renovate a residential building, it offers important information about the thermal energy efficiency. The plans of application development include creation of modules to allow financial estimations, the total annual energy and its cost including the cost of cooling the house and electrical costs.

V. Conclusion

The presented software application can be considered very useful in the computer assisted analysis of buildings, it calculates the components of the heat flux demands and it allows important observations about the parameters that influence the heat flux losses.

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