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THE HEAT BALANCE FOR EXTERNAL COMPOSITE WALLS

Abstract

One of the first steps in reducing energy consumption for heating and cooling buildings is developing of thermal insulation envelope of building. Nowadays contemporary walls have constructions composed from different layers – which make composite structures. We have developed model of the heat balance and based on that model simulation that could analyze and determine the heat balance and temperature distribution inside the buildings in dependence from external conditions and temperature distribution inside the walls and on their boundaries between different layers. All cases represents passive isolation, where the heat balance depend only on materials characteristics, on their heat transfer coefficients, thermal conductance properties and thickness of used materials. For various combinations of today available construction and insulating materials, we have calculated the overall coefficients of heat transmission. Our calculations confirm advantage of usage hollow bricks instead solid bricks, and placing insulation layers on the outer side of walls. Furthermore, those simulations will serve as test for the wider project of the dynamic heat flow experiments in general structures and among them in nanostructures as well.

Keywords: the heat balance equation, composite walls, passive isolation.

ТОПЛОТНИ БАЛАНС ЗА СПОЉАШЊЕ КОМПОЗИТНЕ ЗИДОВЕ

Сажетак

Један од првих корака у смањењу потрошње енергије за загријавање и хлађење зграда је развој топлотне изолације код омотача зграде. Данашњи савремени зидови имају конструкцију која је сачињена од различитих слојева – који чине структуру композита. Развили смо модел топлотног баланса и на основу тог модела симулацију која анализира и одређује топлотн баланс и температурну дистрибуцију унутар зграда у зависности од спољашњих услова и температурне дистрибуције унутар зидова и на граничним слојевима између различитих слојева. Сви случајеви представљају пасивну изолацију, гдје топлотни баланс зависи само од карактеристика материјала, од коефицијената пролаза топлоте, топлотне проводности и дебљине кориштених материјала. За различите комбинације конструктивних и изолационих материјала, који су данас доступни, израчунали смо укупне коефицијенте пролаза топлоте. Наши прорачуни потврђују предност кориштења шупљих умјесто пуних цигли, као и потребу постављања изолационих материјала на спољашњој страин зидова. Надаље, симулације ће служити као тест за шири пројекат експеримената динамике топлотног протока, како у структурама у општем случају, такои у наноструктурама.

Кључне ријечи: једначина топлотног баланса, композитни зидови, пасивна изолација.

1. INTRODUCTION

Until the end of the twentieth century, not much attention was paid to the thermal properties of the outer walls. The walls were mostly built according to the old empirical rules, and in our country, the general rule was that thickness of the outer wall must be 1.5 solid bricks[1]. If the wall was not sufficiently thermally insulated, the rooms were heated more, and as energy sources (wood, coal, electricity, and gas) were not expensive, the thermal properties of the walls were not relevant for sizing the outer walls. Due to the energy crisis, the need to save energy for the heating has become very relevant [2]. The average building in Serbia and the Republic of Srpska consumes 200 to 280 kWh/m2 of energy per year, standard insulated below 100 kWh/m2, while modern low-energy houses consume 40 kWh/m2, and passive 15 kWh/m2 and less. In recent years, the debate on the importance of energy savings has intensified, due to the need to reduce CO2 emissions into the atmosphere, which is considered one of the main causes of the current problem - global warming. In addition, there are very important hygienic and health reasons, due to which this phenomenon is given great attention. For example, when heat is dissipated in large quantities, the surface of the wall becomes damp (corners of the room) and mold forms. Molds cause allergic effects and emit toxins [3], which is very harmful to human health.

Thermal insulation of buildings has multiple consequences [4]. It should provide the comfort of the interior space - not only in terms of providing optimal temperature, but also in terms of also calming unpleasant air currents that occur due to temperature differences (from the facade wall to the interior and from the floor to the ceiling). Then, it should provide more permanent protection - after the basic investment and installation, to perform its role for a longer period, without requiring additional maintenance and power costs, unlike air conditioning systems. Thermal insulation has a dual role - depending on where the building is located, the season or time of day, it protects it from winter or heat, doing so 24 hours per day, through the whole year. Finally, thermal insulation should ensure energy efficiency - to contribute in reduction of the cost of energy used, but also to have a positive impact on the environment. After the construction of a thermally insulated house, the savings in energy consumption can be over 60%, so the primary investment pay off in a few years. However, efforts are still being made to find ways and new materials to increase efficiency and reduce investment costs. The motive for researching these problems lies in finding optimization methods and software solutions that will provide a clear analysis of different combinations of commercially available insulation materials, as well as their thicknesses, depending on microclimatic conditions and economic parameters. The goal is to recommend an adequate solution for the construction of walls in buildings – especially civil engineering (max. 1 to 2 floors), which are most common and numerous in villages and peripheral areas of larger settlements and cities.

Additionally, but not least, is the fact that the minimization and introduction of nanostructures in building materials is becoming a reality. In addition to a large number of questions about the potential hygienic and health danger of embedding nanoparticles in buildings, there is a real need to incorporate nanostructures into materials, because nanostructures showed completely different properties when compared to the same substances made in macro sizes. In addition to the necessary experiments in real conditions, it is necessary to analyze and previously develop computer simulations of heat flow through such structures. Finally, after complete elaboration and test-verification, this software could be used to test the thermodynamic and hydrological properties of new materials, based on modern nanostructures.

2. HEAT CONDUCTION

Three basic ways of heat transfer are known [3,5-9]. First is conduction, where heat transfer occurs from one body to another in the direction of heat flux movement, i.e. from a place of higher temperature to a place of lower temperature. The second way is by heat flow (convection), which takes place through the movement of individual parts of the body or the environment in which the bodies are located. The third way of heat transfer is by radiation, which is carried out by electromagnetic waves. Although all three mentioned ways of heat transfer can take place at the same time, one of them is always dominant. In construction, the dominant one is conduction and in this case –we talk about the conduction of heat through the wall.

However, there are many real cases in which radiative processes, and especially convective processes (which are especially related to the processes of heat convection in the air layers), not only cannot be ignored – but also become dominant. These cases are especially important for phenomena that are closely related to the condensation of water vapor on the walls. In this paper, however, we will limit ourselves to heat conduction, with the intention of including other processes in further research.

2.1. PHYSICS BACKGROUND OF HEAT CONDUCTION

The solution to this problem comes down to considering the flow of heat through a conductive rod placed between two heat reservoirs located at temperatures T_1 and T_2, as shown in Figure 1.

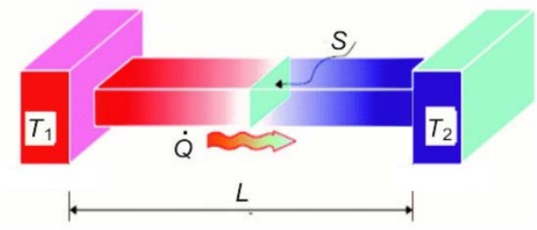

Figure 1. *Heat conduction through the conductive rod between two reservoirs at temperatures: T1>T2*

It has been established that the amount of heat exchanged in a unit of time (heat transfer rate) is a function (difference) of the temperature of the given heat reservoirs, geometry and other relevant properties of the conducting rod:

$$\dot{Q} \equiv \frac{dQ}{dt} = -\lambda\, S\, \frac{dT}{dx} = K\, x\, S\, \frac{dT}{dx}, \tag{1}$$

where λ is the coefficient of thermal conductivity, and K is the coefficient of heat transfer - an important property of insulating materials. For simplicity, the heat transfer rate per unit area is defined – as follows:

$$\dot{q} \equiv \frac{\dot{Q}}{S} = -\lambda \frac{dT}{dx} \tag{2}$$

and is called the heat flux per unit time in [W/m^2]. This is a one-dimensional form of Fourier's law of thermal conductivity [6-9]. It should be emphasized that Fourier's law in the general form is the equation expressed in vector form that shows the heat transfer in real 3D conditions. However, of special interest is the heat flow normally to the wall surface (heat lost or heat gain), so in this case the use of a one-dimensional Fourier's law equation is justified.

2.2. STATIONARY QUASI-ONE-DIMENSIONAL HEAT CONDUCTION

Suppose that we have a thin layer of thickness dx within the isothermal surface (Figure 2).

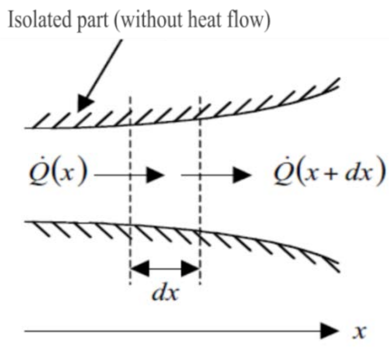

Figure 2. *Stationary heat conduction through the homogeneous material normally to the isothermal surface*

As the process is stationary [6-9], the input rate of heat transfer must be equal to the output rate. Therefore, the rate of heat transfer that passes through a layer of thickness dx can be given as a sum of power series:

$$\dot{Q}(x + dx) = \dot{Q}(x) + \left.\frac{d\dot{Q}}{dx}\right|_x dx + \frac{1}{2!}\left.\frac{d^2\dot{Q}}{dx^2}\right|_x (dx)^2 + \cdots \tag{3}$$

Neglecting the members of the higher ranks, and comparing with the initial definition, it follows:

$$S\frac{d\lambda}{dx}\frac{dT}{dx} + \lambda\frac{dS}{dx}\frac{dT}{dx} + S\lambda\frac{d^2T}{dx^2} = 0. \tag{4}$$

This equation describes the temperature field for quasi-one-dimensional stationary thermal conduction. It was analyzed in the case of a homogeneous material, and this was necessary for further analysis of a single-layer flat homogeneous wall, and later for a multi-layer one.

2.3. HEAT CONDUCTION THROUGH A SINGLE LAYERED WALL

The derived equation can now be applied to the calculation of heat conduction through a flat homogeneous wall shown in Figure 3. The direction of heat transfer (positive x-axis) is normal to the isothermal surface [5-9]. The cross section is not a function of x, i.e. S = const., and the coefficient of thermal conductivity λ is constant (in a very real case, it still depends poorly on temperature and is affected by air humidity and pore dimensions, so these phenomena must be included in the calculation), so equation (4) reduces on:

$$\frac{d^2T}{dx^2} = 0 \;\rightarrow\; T(x) = a\,x + b. \tag{5}$$

This equation describes the temperature field of a single-layer wall. There are two integration constants: *a* and *b*, which are determined from the initial boundary conditions: $T(0) = T_1$ and $T(L) = T_2$: $a = \frac{T_2 - T_1}{L}$; $b = T_1$.Finally, the temperature field of this simple wall is described by the expression:

$$T(x) = T_1 + (T_2 - T_1)\frac{x}{L}. \tag{6}$$

Thus, the quasi-stationary temperature profile through a flat single-layer wall is linear, as in Figure 3.

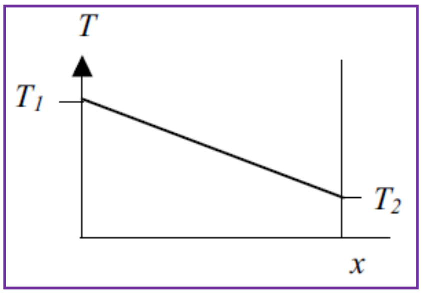

Figure 3. *Temperature profile through the plane wall*

For the heat flux in a unit of time, defined by expression (2), taking into account that *S* = const and that it can be assumed that *λ* = const., we obtain:

$$\dot{q} = -(T_2 - T_1)\frac{\lambda}{L} = \text{const}. \tag{7}$$

Therefore, normally through a flat homogeneous wall, the change in temperature is a linear function of the distance from the beginning of the wall, and the heat flux in a unit of time is constant.

2.4. HEAT CONDUCTION THROUGH A MULTILAYERED WALL

We will now consider heat transfer through a wall consisting of parallel vertical layers. Each individual layer represents a different and particular material with a certain thickness (Figure 4).

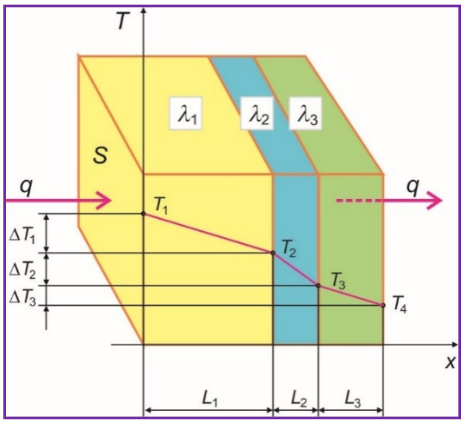

Figure 4. *Heat conduction through multilayer wall*

Taking into account equations (6) and (7), the amount of heat that passes through each layer can be determined individually [10-13]. As the heat flux of a single-layer wall is a constant quantity, it will be the same through each of the wall layers. After defining the boundary conditions, the following follows:

$$\begin{gathered} Q_1(T_2) = Q_2(T_2); \\ Q_2(T_3) = Q_3(T_3); \\ \vdots \\ Q_{n\text{-}1}(T_n) = Q_n(T_n); \end{gathered} \tag{8}$$

and replacing them in equation (7), after integrating expression (6) – a system of equations is obtained that describes the amount of heat in individual layers:

- for the 1st layer

$$Q_1 = \frac{\lambda_1}{L_1}(T_1\text{-}T_2)S_1 t\,, \tag{9a}$$

- for the 2nd layer

$$Q_2 = \frac{\lambda_2}{L_2}(T_2\text{-}T_3)S_2 t\,, \tag{9b}$$

- for the nth layer

$$Q_n = \frac{\lambda_n}{L_n}(T_{n\text{-}1}\text{-}T_n)S_n t\,. \tag{9c}$$

These relations represent the application of Fourier's law to multilayer walls. If heat passes through a system consisting of several layers of material arranged in parallel – next to each other, in the case of stationary conduction [6-9], the same amount of heat per unit time passes through each layer, ie:

$$\dot{Q} = \frac{\lambda_1}{L_1}S_1\Delta T_1 = \frac{\lambda_2}{L_2}S_2\Delta T_2 = \frac{\lambda_3}{L_3}S_3\Delta T_3 = \cdots \tag{10}$$

As all these surfaces are (approximately) equal, i.e. $S_1 = S_2 = S_3 = \cdots \equiv S$, and if from (10) are expressed:

$$S\,\Delta T_1 = \dot{Q}\frac{L_1}{\lambda_1};\;\; S\,\Delta T_2 = \dot{Q}\frac{L_2}{\lambda_2};\;\; S\,\Delta T_3 = \dot{Q}\frac{L_3}{\lambda_3};\;\; \cdots$$

and when we all these terms summarize, we get:

$$S\,(\Delta T_1 + \Delta T_2 + \Delta T_3 + \cdots) = \dot{Q}\left(\frac{L_1}{\lambda_1} + \frac{L_2}{\lambda_2} + \frac{L_3}{\lambda_3} + \cdots\right). \tag{11}$$

The sum of temperature differences through the layers is equal to the temperature difference between the two outer layers of the complex system, i.e. $\dot{Q} = \text{-}\lambda S\frac{dT}{dx}$ On the other hand, based on the definition of the heat transfer coefficient from (1), it follows:

$$\frac{L_1}{\lambda_1} + \frac{L_2}{\lambda_2} + \frac{L_3}{\lambda_3} + \cdots = \frac{1}{K_1} + \frac{1}{K_2} + \frac{1}{K_3} + \cdots \equiv \frac{1}{K_U}, \tag{12}$$

where KU is the total (effective) heat transfer coefficient of the complex system, which is also expressed in [W/(m2 °C) ≡ W/(m2K)].Based on expressions (10) to (12), the expression of heat current - the amount of heat in a unit of time, a complex system - a multilayer wall, is given in the following form:

$$\dot{Q} = K_U\, S\, \Delta T. \tag{13}$$

This is one of the most important quantities that evaluates the energy efficiency of the wall, and heat transfer through the whole building (when considering the whole building as complex unity) [10-13].We have calculated the heat transfer coefficients of individual layers based on standard data (given in following data tables). Thermal conductivity coefficients of observed (and used) materials are known, and we vary their required thicknesses, and the wall surface sizes, according to specification of the building design, while the largest temperature differences are set in relation to the geographical position and orientation of the object.

3. EXTERNAL WALL INSULATION

Today, a large number of insulating materials are used. Depending on the degree of insulation, an appropriate combination of materials can be chosen [1,4,8-15]. This section will present several possible combinations and consider their applicability in the light of energy efficiency. From the external walls are also required thermal stability, i.e. characteristic (or property) that the wall in the summer retains the relevant temperature stability on its inner surface. If a ventilated air layer is provided in the wall cladding on the outside, it is not necessary to check the thermal stability. This air layer also serves to remove water vapor from thermal insulation materials (Figure 5). The calculated values for such an assembly are given in Table 1 and graphically presented in Figure 6.

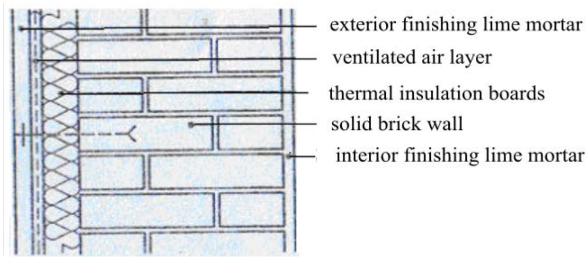

Figure 5. *The cross section of the constructions for the external insulation for the air-layer*

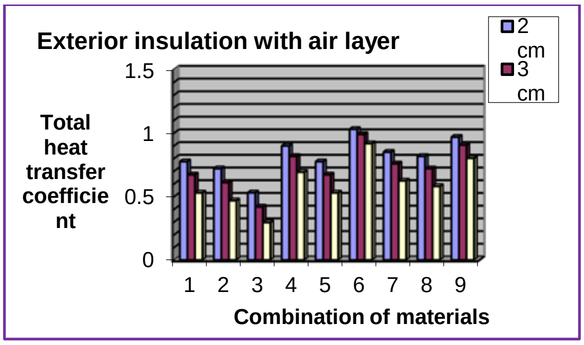

Figure 6. *The total coefficient Ku in dependence of the layer combination (Table 1) and thickness of thermo-insulating material (given in legend)*

Table 1.The total transfer coefficient for various compounds of the material; calculated for the combination of two lime mortar with an air interlayer, solid brick facade and thermo-insulation material (from [15])

The # of combination	Material		The heat conductance	The heat transfer coefficient $K = \lambda/L$ [W/(m^2 °C)] Insulation thickness L 0.02 m	0.03 m	0.05 m	Insulation thickness L	The heat transfer coefficient $K = \lambda/L$ [W/(m^2 °C)] L = 0.02 m	L = 0.03 m	L = 0.06 m
	Lime mortar 2 cm		0.85				42.50			
	Layer of air 1 cm		0.02				2.30			
1.	Insulation thickness L plate of:	Styrofoam-expanded polystyrene	0.04	2.5	1.67	1.0		0.77	0.67	**0.53**
2.		Cork	0.03	2.0	1.33	0.8		0.72	**0.61**	**0.47**
3.		Polyurethane	0.02	1.0	0.67	0.4		0.53	**0.42**	**0.29**
4.		Stitched straw	0.09	4.5	3.00	1.8		0.90	0.82	0.69
5.		Stitched reed	0.05	2.5	1.67	1.0		0.77	0.67	**0.53**
6.		Durisol	0.25	12.5	8.33	5.0		1.30	0.99	0.92
7.		Expanded perlite	0.07	3.5	2.33	1.4		0.85	0.76	0.63
8.		Honeycomb plastic	0.06	3.0	2.00	1.2		0.82	0.72	**0.58**
9.		Mineral wool	0.14	7.0	4.67	2.8		0.97	0.90	0.80
	Solid brick 25 cm		0.61				2.44			

As can be easily seen from Table 1 and the graph in Figure 6, the total wall thickness does not exceed 35 cm. Judging by these values, the air layer contributes greatly to the thermal insulation of a given assembly. It is noticed that the combination 3 gives the lowest value of the total coefficient of heat transfer, therefore it provides the best thermal insulation. Combinations 1 and 2, as well as 5 and 8 also give very good results. Lately, hollow blocks are used more, partly because masonry is faster, buildings are lighter, and because of the need to save thermal energy (regulations for thermal protection are stricter, so the thickness of external walls built of solid brick would increase significantly).Table 2 will give the same combination of materials as Table 1, only with hollow brick. A graphical representation of these results is given in Figure 7.

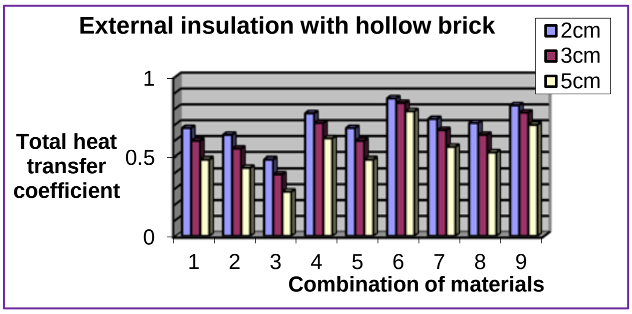

Figure 7. *The total coefficient Ku in dependence of the layer combination (Table 2)and thickness of thermo-insulating material (given in legend)*

Table 2.The total transfer coefficient for various compounds of the material; calculated for the combination of two lime mortar with an air interlayer, hollow brick and thermo-insulation material (from [15])

The # of combina...	Material	The heat condu...	The heat transfer coefficient $K = \lambda/L$ [W/(m^2 °C)]	The heat transfer coefficient

				Insulation thickness *L*			Insulation thickness *L*	$K = \lambda / L$ [W/(m² °C)]		
				0.02 m	0.03 m	0.05 m		*L* = 0.02 m	*L* = 0.03 m	*L* = 0.05 m
	Lime mortar 2 cm		0.85				42.5			
	Layer of air 1 cm		0.02				2.3			
1.	Insulation thickness *L* plate of:	Styrofoam-expanded polystyrene	0.04	2.5	1.67	1.0		0.68	**0.60**	**0.48**
2.		Cork	0.03	2.0	1.33	0.8		0.63	**0.55**	**0.43**
3.		Polyurethane	0.02	1.0	0.67	0.4		**0.48**	**0.39**	**0.28**
4.		Stitched straw	0.09	4.5	3.00	1.8		0.77	0.71	**0.61**
5.		Stitched reed	0.05	2.5	1.67	1.0		0.68	**0.60**	**0.48**
6.		Durisol	0.25	12.5	8.33	5.0		0.86	0.84	0.78
7.		Expanded perlite	0.07	3.5	2.33	1.4		0.73	0.66	**0.56**
8.		Honeycomb plastic	0.06	3.0	2.00	1.2		0.71	0.63	**0.52**
9.		Mineral wool	0.14	7.0	4.67	2.8		0.82	0.77	0.70
	Hollow brick 25 cm		0.42				1.7			

It can be seen from Table 2 and Figure 7 that the maximum wall thickness is 35 cm, but very good insulation was obtained even with a total wall thickness of 32 cm. It can be noticed that the best insulation is provided by the combination with a 5 cm thick polyurethane board, given under no.5. 2 cm thick Durisol plate provides the weakest protection. It can be noticed that approximately the same value of the total coefficient heat transfer is given by the combination of 5 cm thick expanded polystyrene, cork and reed. The combination with 2 cm thick polyurethane provides almost the same protection. The 5 cm thick straw or mineral wool joint provides similar protection as the combination of reed, expanded perlite or 3 cm thick honeycomb plastic. Comparing the results from Tables 1 and 2, as well as the graphs from Figures 6 and 7, it is noticeable that better protection is obtained with each combination when hollow is used instead of solid brick.

4. CONCLUSIONS

In this paper, we have calculated heat conduction coefficients through different walls. The advantages and necessity of installing thermal insulation are stated and examples of several combinations for two ways of passive insulation are given and analyzed. Only thermal insulation of the wall was considered. Numerous thermal insulation materials are presented and the value of the total heat transfer coefficient for a large number of combinations is given. It was stated that it is more adequate to install the outer insulation than the inner one, because the insulating shell does not break, which avoids the formation of "thermal bridges" and the protection becomes more complete. The results obtained when calculating the total heat transfer coefficient speak for themselves. It is clear that leaving an air layer not only regulates the removal of water vapor from thermal insulation materials, but also provides better protection. It has been shown that the use of hollow bricks in combination with an air layer provides the best insulation. There are several other reasons why is more convenient to use hollow bricks instead of solid bricks. The disadvantage of this construction in relation to the external insulation is that the walls are very thick, for example 40 or 45 cm, although this thickness can be reduced to 32 cm and meets the minimum of energy requirements.

The next important result of the simulations is yet to come. The test simulation proved to be accurate because it confirmed the well-known results and facts about the importance of installing insulation layers, the use of air layers inside walls and finally the use of composite structures. The next phase of research will include the use of very thin insulation layers and simulation of heat flow through these structures, when made in the form of composite layers or superlattices. In that sense, previous research and developed simulations have a test or control function.

ACKNOWLEDGEMENT

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