THERMAL INSULATION EFFECTS ON ENERGY EFFICIENCY OF BUILDING STRUCTURES

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ABSTRACT

Abstract: This paper presents the use of Finite Element Method for heat transfer analysis. Connections wall-beam-floor structure with different positions of the thermal insulation have been analyzed and conclusions about energy efficiency and energy loss are made.

Keywords: heat transfer, numerical analysis, finite elements, thermal insulation, energy efficiency.

1 INTRODUCTION

Energy consumption is significantly greater today than in the past decades as lifestyle changes have resulted in more consumption of energy. Now more than ever, we must find a way to build homes and buildings with greater energy efficiency. The Building Codes and state regulations require new houses to achieve energy-efficiency goals. Therefore, it is important to use materials and well-established building technology that will help a building to use less energy over its lifetime.

Taking into consideration life cycles with respect to thinking and acting is the basis of sustainable building. The more energy-efficient a building is and the less energy it uses within the useful life, the more important its construction, the choice and processing of materials are.

Planners and architects who want to create buildings in a sustainable way are confronted with the following questions: How recyclable are the materials used during the process of construction? How much primary energy is spent in the building? How big is the carbon footprint? Are the environmental impacts considered in planning through the whole life cycle and are they revealed correspondingly? When does a decision for a more ecological option pay for itself? Every building is unique and needs an individual analysis to illustrate the environmental impact and sustainability performance as well as to identify optimisation potentials.

2 FINITE ELEMENT METHOD FOR HEAT TRANSFER ANALYSIS

The governing differential equation of heat transfer in conduction is [3],[5]:

$$\frac{\partial}{\partial x}(\lambda_x \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(\lambda_y \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z}(\lambda_z \frac{\partial T}{\partial z}) = \rho c \frac{\partial T}{\partial t} \quad (1)$$

where: λ_x, λ_y, λ_z are thermal conductivities (temperature dependent); ρ is a density of the material (temperature dependant); c is a specific heat (temperature dependent).

The boundary conditions can be modeled in terms of both convective and radiative heat transfer mechanisms. The heat flow caused by convection is:

$$q_c = h_c(T_z - T_f) \quad (2)$$

where: h_c is coefficient of convection; T_z is the temperature on the boundary of the element; T_f is the temperature of the fluid around the element.

The heat flow caused by radiation is:

$$q_r = V\varepsilon\sigma_c(T_{z,a}{}^4 - T_{f,a}{}^4) = h_r(T_z - T_f) \tag{3}$$

$$h_r = V\varepsilon\sigma_c\left(T_{z,a}^2 + T_{f,a}^2\right)\left(T_{z,a} + T_{f,a}\right) \tag{4}$$

where: h_r is a coefficient of radiation (temperature dependant); V is a radiation view factor (recommended $V = 1.0$); ε is a resultant coefficient of emission $\varepsilon = \varepsilon_f \varepsilon_z$; $\sigma_c = 5.67 \cdot 10^{-8}$ is Stefan-Boltzmann constant; $T_{z,a}$ is the absolute temperature of the surface; $T_{f,a}$ is the absolute temperature of the fluid.

Using a typical Galerkin finite element approach Equation (1) assumes the form:

$$\int_V N^T \left[\lambda_x \frac{\partial^2 T}{\partial x^2} + \lambda_y \frac{\partial^2 T}{\partial y^2} + \lambda_z \frac{\partial^2 T}{\partial z^2} - \rho c \frac{\partial T}{\partial t} \right] dV = 0 \tag{5}$$

where the approximation field function is expressed in terms of the interpolation function as:

$$T = N \times T_e \tag{6}$$

Integration of Equation (6) by parts yields:

$$\int_V \left(\left[\frac{\partial N}{\partial x}\right]^T \lambda_x \frac{\partial T}{\partial x} + \left[\frac{\partial N}{\partial y}\right]^T \lambda_y \frac{\partial T}{\partial y} + \left[\frac{\partial N}{\partial z}\right]^T \lambda_z \frac{\partial T}{\partial z} \right) dV - \tag{7}$$

$$- \int_S N^T \left(\lambda_x l_x \frac{\partial T}{\partial x} + \lambda_y l_y \frac{\partial T}{\partial y} + \lambda_z l_z \frac{\partial T}{\partial z} \right) ds + \int_V \rho c N^T T dV = 0$$

where:

$$q = q_c + q_r = (h_c + h_r)\ (T_z - T_f) \tag{8}$$

Finally, the governing equation takes the form:

$$C\dot{T} + (K_1 + K_2)T + RT = P \tag{9}$$

$$C = \int_V \rho c N^T N dV \tag{10}$$

$$K_1 = \int_V B^T D B dV \tag{11}$$

$$K_2 = \int_S h_c N^T N dS \tag{12}$$

$$R = \int_S h_r N^T N dS \tag{13}$$

$$P = \int_S h_c T_f N^T dS + \int_S h_r T_f N^T dS \tag{14}$$

where: C is a heat capacity matrix (temperature dependent); K_1 is the conductivity matrix (temperature dependent); K_2 is the convective matrix; R is the radiative matrix (temperature dependent); P is the external heat flow vector (caused by convection and radiation on the surface of the element and is temperature dependent); $\dot{T}$ is the vector of temperature derivatives; T is the vector of unknown temperatures in the nodal points of the element. If the heat capacity of the material is taken under consideration and if thermal load is time dependant the problem becomes transient and an iterative procedure has to be used for solving the Equation (9). In a small time interval we assumed that the time derivative of the temperature is constant

$$\dot{T}_t = \dot{T}_{t+\Delta t} = \frac{T_{t+\Delta t} - T_t}{\Delta t} \tag{15}$$

Summarizing Equation (9) for time t and $t + \Delta t$ and assuming that the capacity matrix in small time interval is constant: $C_t = C_{t+\Delta t}$, heat flow equation becomes:

$$\left[K_{t+\Delta t} + \frac{2}{\Delta t} C_t \right] T_{t+\Delta t} = \left[-K_t + \frac{2}{\Delta t} C_t \right] T_t + P_{t+\Delta t} + P_t \tag{16}$$

Equation (16) together with the initial and boundary conditions completely solves the problem. Taking the radiation into account makes the problem nonlinear. This problem is solved by involving new iterative procedure in every time step.

Problem becomes nonlinear too, when temperature dependent physical properties of the materials are assumed. In that case, the conductivity and capacity matrix are defined at the beginning of each time step based on the temperature from the previous time step.

3 THERMAL INSULATION AND ENERGY EFFICIENCY OF STRUCTURS

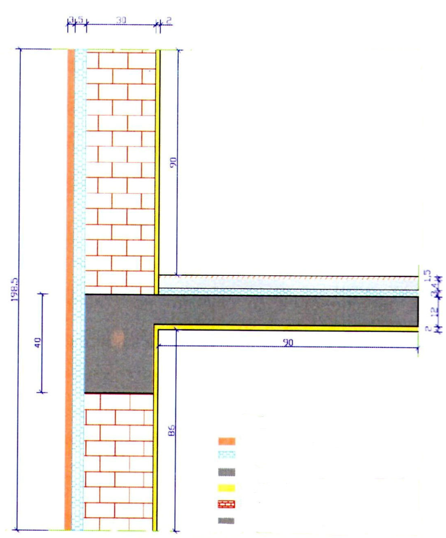

Figure 1-a. Vertical section - outside insulation.

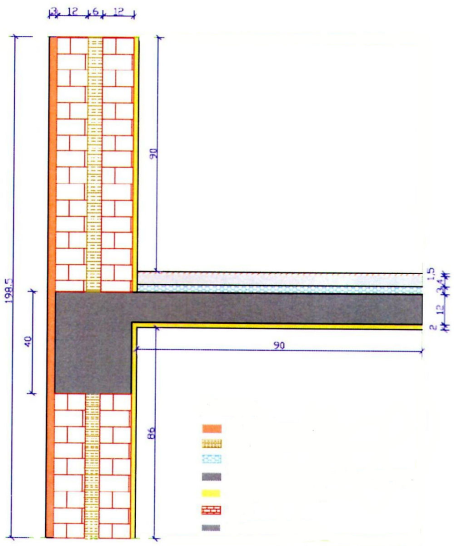

Figure 1-b. Vertical section - insulation in the middle.

In order to elaborate the use of the numerical method presented in this paper and to make some conclusions about the influence of the position of the thermal insulation on the energy efficiency of structures, a part of a building between two floors, together with the outer envelope and the connection wall-beam-floor structure (fig.1) have been analyzed. Numerical 2D analysis has been performed by using the computer program TERMIKA [2].

Four models have been analyzed: non-insulated all, outside wall insulation with 5cm styrofoam (Fig. 1a), insulation in the middle of the wall with 6 cm rock wood (Fig.1b) and inside wall insulation with 5 cm styrofoam. Analyzed structure comprises: brick wall (d=30 cm, except in the case with insulation in the middle when d=24 cm), reinforced concrete beam 30/40cm and floor structure (reinforced concrete floor slab d=12 cm, EPS d=3 cm, cement screed d=4 cm and parquet d=1.5 cm). The interior temperature in the upper room is T_{upper}=+20°C (for air moisture of 50%, the critical condensation point is 9.3°C), while in the lower room is T_{lower}=10°C (for air moisture of 50%, the critical condensation point is 0.1°C). The exterior temperature is assumed to be $T_{exterior}$=-15°C.

For each example, the analysis has been performed for two cases. First, a stationary analysis has been performed when the air temperatures in the rooms and the exterior temperature are constants. The aim was to define the influence of the thermal insulation on the formation of the temperature profile in the structure, as well as the possibility of appearance of thermal bridges, but in this case the data for the energy loss trough the building envelope is not available, so the real effect of the thermal insulation on the energy efficiency of building structures can't be defined. The capacity and the time duration of the heating source necessary to maintain constant temperature conditions on both floors are not defined either.

The temperature distribution results obtained by the steady state analysis (presented on the Figures 2a, 3a, 4a and 5a) are close to the results obtained by R-value calculations, but only for the sections fare from the connection wall-beam-floor structure, where the heat transfer is one-dimensional. Temperature distribution for the cross section fare from the connection wall-beam-floor structure, for the case of insulation in the middle of the wall, is presented on Fig.6. These results are obtained by numerical steady state analysis, but the R-value calculations [1], [4] are almost the same.

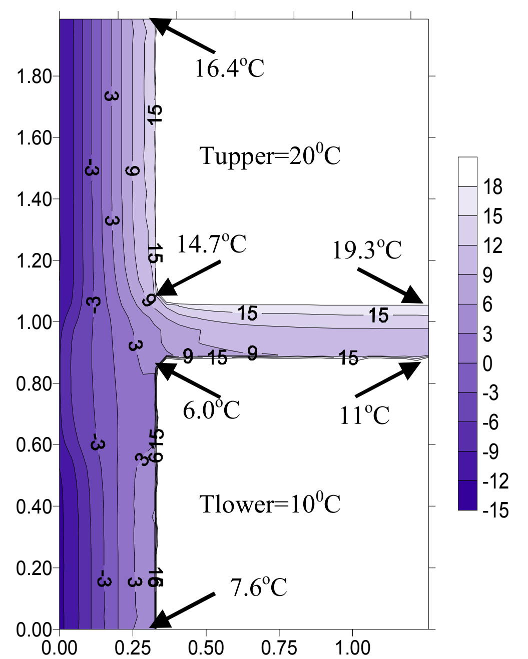

Figure 2-a. Isotherms for non-insulated wall - constant thermal conditions (T_{upper}=20°C, T_{lower}=10°C).

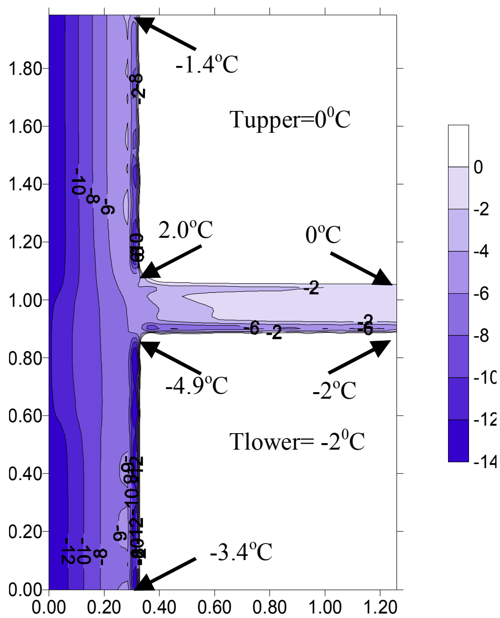

Figure 2-b. Isotherms for non-insulated wall - time t=140h, after finished cooling of the structure (heating off).

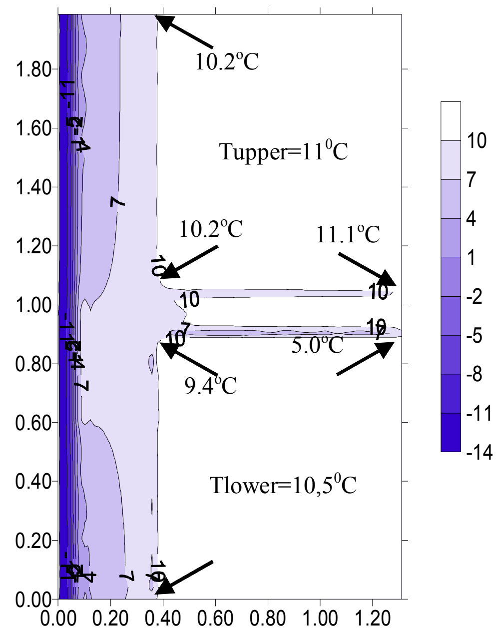

Figure 3-b. Isotherms in case of outside insulation- time t=168h, finished structure cooling (heating off).

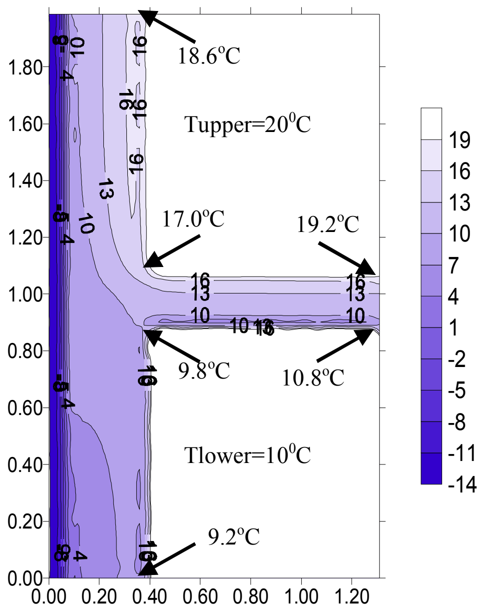

Figure 3-a. Isotherms in case of outside insulation-constant thermal conditions (T_{upper}=20°C, T_{lower}= 10°C).

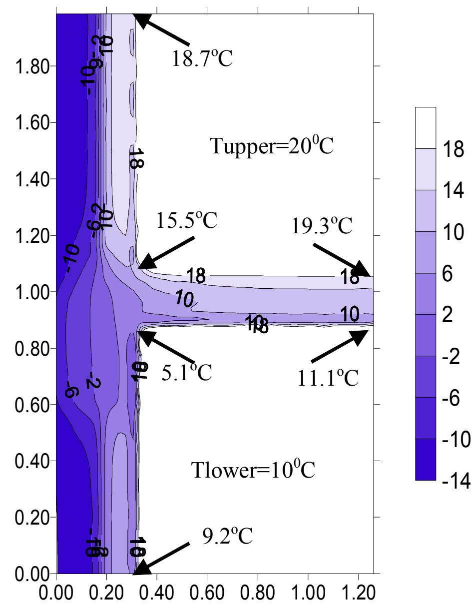

Figure 4-a. Isotherms in case of middle insulation-constant thermal conditions (T_{upper}=20°C, T_{lower}= 10°C).

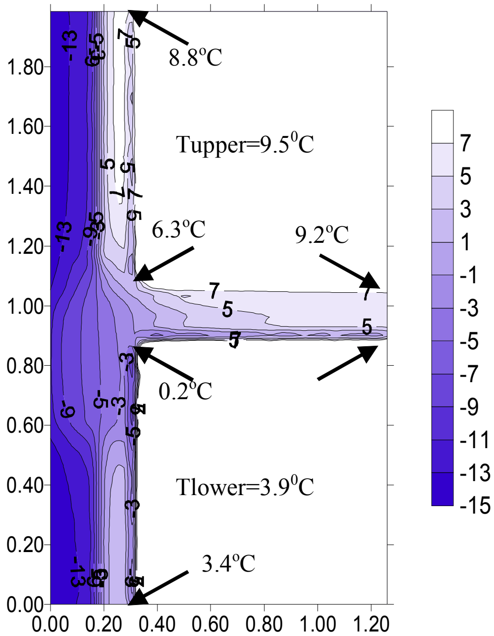

Figure 4-b. Isotherms in case of middle insulation- time t=106h, finished structure cooling (heating off).

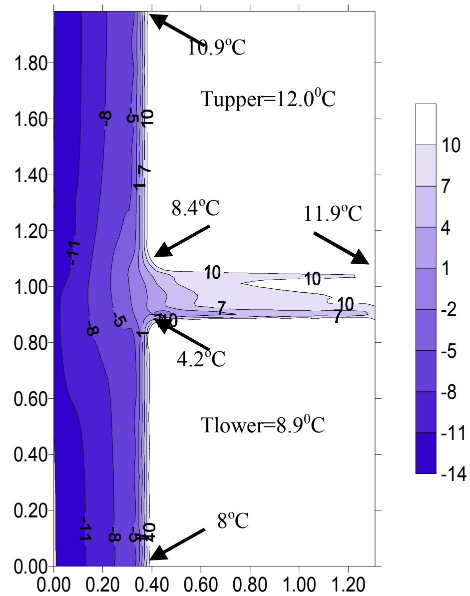

Figure 5-b. Isotherms in case of inside insulation- time t=94h, finished structure cooling (heating off).

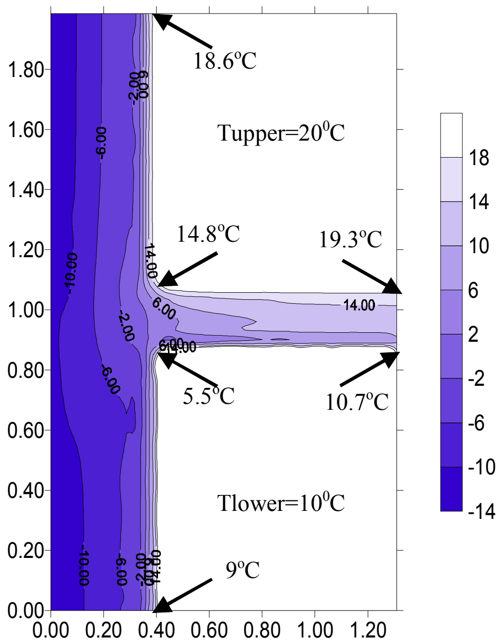

Figure 5-a. Isotherms in case of inside insulation-constant thermal conditions (Tupper=20oC, Tlower= 10oC).

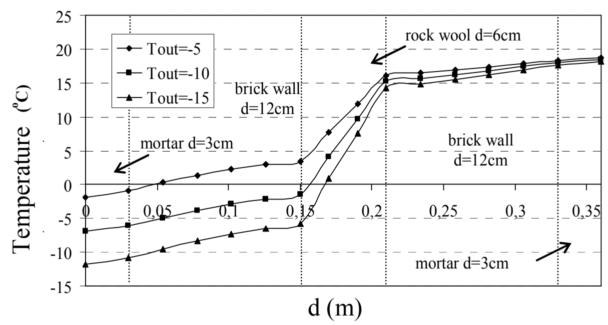

Figure 6. Graphical presentation of temperature flow when the insulation is in the middle of the wall, for the cross section distanced from the connection wall-beam-floor structure.

Furthermore, another analysis has been performed from the moment when the heating in the rooms is set off and cooling begins. The analysis lasts up to the moment of finished cooling, when the steady state is obtained (Figures 2b, 3b, 4b and 5b).

The influence of the thermal insulation on the cooling time and level of the final temperature in the rooms has been compared for all different cases. Some of the results of the performed analysis are presented in Figure 7.

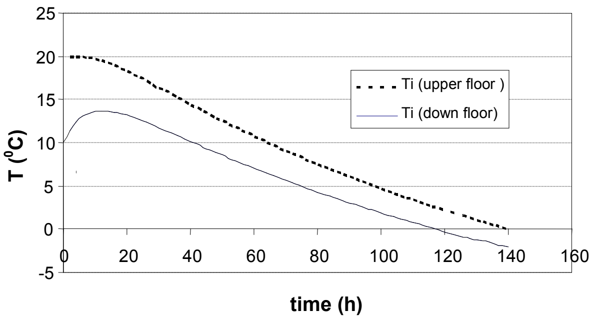

Figure 7-a. Time-temperature diagram for wall without insulation.

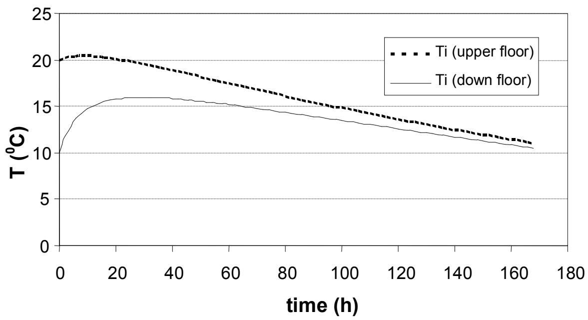

Figure 7-b. Time-temperature diagram for wall with outside insulation.

Comparison of the time needed for cooling of the upper room depending on the location of the thermal insulation is given in Figure 8.

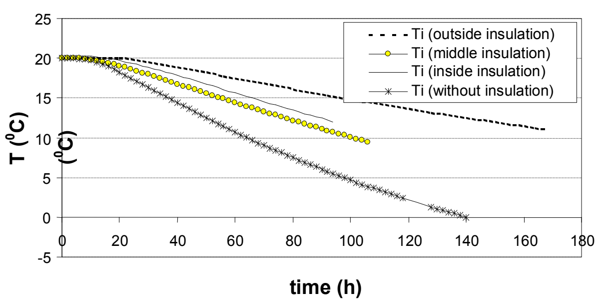

Figure 8. Comparison of the time needed for cooling of the upper room depending on the insulation location

The analysis in winter conditions presents that the best way for insulation is placing the insulation material on the outside of the wall. Thermal bridges appearance is avoided at the connection wall-beam-floor structure. In all other cases, thermal bridge appears in that part of the structure.

The steady state analysis shows that the surface temperature in the upper room in the sections distanced from the connection wall-beam-floor structure is high for all cases of insulation. The difference in the temperature appears in the internal angle, which represents the influence of the thermal bridge.

The insulation and its location obviously influence the time and the level of the room cooling, see fig. 8. The longest time for cooling of the structure, when the heating is off, was obtained for the case of outside insulation (t=168h), that means in this case the energy loss is the least and the time for cooling to same temperature is almost twice longer than for the case when the insulation is inside (t=96h). In case without insulation, the energy loss has the biggest value. The time for cooling to same temperature is almost three times less than for the case with outside insulation (t=60h).

4 CONCLUSION

If we want to take under consideration all parameters that influence the energy efficiency of buildings and to calculate the real energy loss, the whole structure has to be analyzed. Numerical procedures based on Finite element method, or Boundary element method solves this problem with sufficient accuracy.

Thermal insulation placed on the exterior side of the wall is absolutely the best case; it avoids appearance of thermal bridges, provides the longest time for cooling of the buildings when the heating is off and the highest temperatures in the rooms when the cooling is finished.

Energy efficiency end energy loss from buildings are not always treated adequately, although the consequences are well known. All insulated building components need to be designed and built in a way to work as an integral system, which will provide continuous barrier of the heat transfer through the building envelope. In order to obtain the maximal potential of the used materials and measures, coordination of the civil engineers and architects is necessary in all design phases.

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