Original scientific paper *

SIMULATION OF THE INSULATION PROPERTIES BY MODIFICATION OF THE TROMBE WALL

Jovan Šetrajčić[1], Siniša Vučenović[2], Nikola Vojnović[3], Dušan Ilić[3]

[1]Academy of Sciences and Arts of the Republic of Srpska, B&H;

[2]University of Banja Luka, Faculty of Natural Sciences and Mathematics, B&H

[3]University of Novi Sad, Faculty of Technical Sciences, Serbia

Abstract. *Energy efficiency of residential and commercial buildings is becoming an increasingly important issue today. Among the many ways to reduce energy losses and leakage in heating or cooling buildings, one of the best is to improve building insulation. In the present paper, a model of active insulation of buildings using a special form of Trombe wall is proposed. The experimental conditions of different combinations of currently used insulation layers in combination with load-bearing walls and the use of Trombe walls are numerically simulated for realistic temperature conditions and for the non-stationary regime of heat conduction. In addition, we willcalculate the internal temperature of the buildings and the thermal inertia in this combined thermal building envelope.*

Key words: *Trombe wall, Non-stationary heat conduction, Numerical simulation, Energy efficiency of buildings*

1. INTRODUCTION

One of the best ways to minimize energy (heat) losses in buildings is the combination of solar architecture with the variant of the so-called Trombe walls, the type of wall proposed by Féilix Trombe in the 1960s. As he demonstrated [1, 2], it could be an excellent source of additional heat energy, with a share of up to 20% of the total heating load at the annual level. Yet, the Trombe wall concept has weaknesses that come into play in summer, when the additional heat load must be removed from the buildings, requiring extra energy. Possible resolutions to this problem are ideas that use what is known as controlled or active insulation [3-5], including various shading devices (removing methods) and bridging methods. The former encloses mechanisms that

physically move the outer insulating panels in selected directions but are relatively complex and expensive (both to install and maintain) and have a shorter life span. Thus, in this paper, we will study the bridging method schematically shown in Fig. 1.
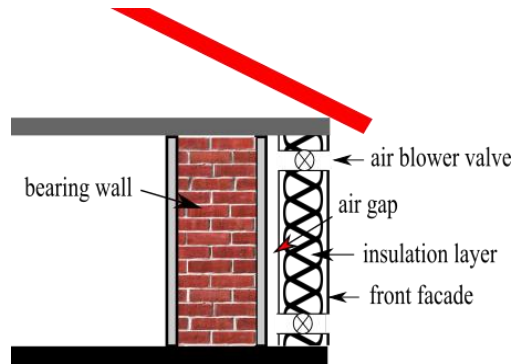

Fig. 1 Trombe wall with bridging method

Active insulation with the bridged method is based on the air gap with trapped air between the load-bearing wall of the building and the insulation layer (front façade). Openings with fan valves can be automatically opened or closed at the top and bottom. When both valves are closed, the insulation becomes passive. This way, the shortcomings of the classic Trombe walls, especially in high heat, can be avoided.

This research started with the idea of developing a software package capable of testing insulation materials (by type and thickness) used on exterior walls. Basically, it is much more cost effective to test current and new insulation materials that will appear in the future using software instead of experimenting. This paper presents such a software package with the results of testing two currently widely used materials.

To begin, we will have to define the physical process of non-stationary heat transfer through exterior walls: from the outside to the inside of the building or vice versa, depending on which part of the wall has a higher temperature. Next, we will present the basic specifications of the created software.

2. PROCESSES AND SIMULATION OF UNSTEADY HEAT CONDUCTION

2.1 Physics of heat transport

We aim to simulate the temperature behavior in buildings while varying the type of insulation and building envelope. For that cause, we constantly use the same (and extreme) outdoor temperatures but under non-stationary conditions (outdoor temperatures are not constant and change continuously over time). Here, the temperature depends on the spatial coordinates as well as on the time, i.e. $T=f(x,y,z,t)$. The temperature dependence in space-time can be depicted using a model of partial difference equations derived from formulating the energy (heat) balance through the building wall.

To make things easier, we consider heat transfer along one dimension (x-direction), assuming no heat sources and with constant values for density ρ, specific heat c, and heat conductance λ. The incident heat is [6, 7]:

$$Q_{in} = -\lambda \frac{\partial T}{\partial x} S \tag{1}$$

and the heat leaving the layer of wall with thickness dx is $Q_{out}=Q_{in}+dQ$, where:

$$-dQ = d\left(-\lambda \frac{\partial T}{\partial x} S\right) = -\lambda d\left(\frac{\partial T}{\partial x} S\right) = -\lambda \frac{\partial^2 T}{\partial x^2} dxS \tag{2}$$

represents the heat change. It is obvious that the heat change must be negative, which is a consequence of the Second principle of thermodynamics. Some of the heat is being accumulated in the wall:

$$\frac{dmc\Delta T}{\Delta t} = \rho c \frac{\partial T}{\partial t} dV = \rho c \frac{\partial T}{\partial t} Sdx \tag{3}$$

When we write the heat balance, considering equations (1-3), we obtain:

$$a \frac{\partial^2 T}{\partial x^2} = \frac{\partial T}{\partial t} \tag{4}$$

where $a=\lambda/\rho \cdot c_p$ is the thermal diffusivity and this value is set by the type and arrangement of the wall. As one can see, equation (4) is a partial differential equation (which is of the second order by space coordinates and of the first order by the time) and to solve it we must set up at least two boundary conditions by space (for $x=0$ and $x=L$) and one initial time condition, i.e. for $t=0$ we must know the initial temperature spatial dispersion throughout the x-axis $T(x=0)=f(x)$.

2.2 Software and simulation setup

The space consisting of the interior insulation and a multi-layer wall is divided into 50 non-overlapping cells, with the cell size of 1 cm, and considered as a 1D system. It was assumed that the cell size is small enough to ignore the inhomogeneity of the material and consider the cell structure homogeneous. During the current iteration, a time interval of 30 minutes is simulated. One iteration yields the calculated temperature profile at a given time step. If higher accuracy is desired, it is possible to reduce the time and space step. However, this would affect the calculation speed and increase the simulation time. Given initial conditions, the temperature profile through a flat wall is obtained by solving the differential equation (4).

The outdoor temperature is approximated by a sinusoidal curve with a period of 24 h. The initial temperature is 20ºC in all room points, and an amplitude of ±10ºC is assumed. It is possible to define the duration of the simulation in hours. It is also recommended to choose a longer time interval for the simulation (longer than e.g. 24 hours), so that clear temperature trend curves can be monitored during the simulation. In the results, an interval of 96 hours (four days) is assumed, with a time step of 30 minutes.

In all simulations, the heating effect is observed, i.e., air is blown in. The air temperature is higher than the temperature of the interior (room). The incident heat is accumulated in the load-bearing wall (and the insulation), and further transferred to the interior by thermal conduction.

Let us first apply finite difference schemes: (i) a forward difference scheme for the time derivative $\partial T/\partial t$ and (ii) a central difference formula for the second order partial derivative $\partial^2 T/\partial x^2$, and these schemes are as follows:

$$T' = \frac{T(x, t+\Delta t) - T(x,t)}{\Delta t}$$

(5)

$$T'' = \frac{T(x+\Delta x, t) - 2T(x,t) + T(x-\Delta x, t)}{(\Delta x)^2}$$

(6)

Integrating equations (5) and (6) into (4) yields the following equations:

$$\frac{T(x, t+\Delta t) - T(x,t)}{\Delta t} = a\frac{T(x+\Delta x, t) - 2T(x,t) + T(x-\Delta x, t)}{(\Delta x)^2}$$

(7)

$$T(x, t+\Delta t) = T(x,t) + \frac{a\Delta t}{(\Delta x)^2}\left[T(x+\Delta x, t) - 2T(x,t) + T(x-\Delta x, t)\right]$$

(8)

With the help of the PDE and the boundary conditions, the temperature value T could be calculated at any time, for example from Fig. (1) ($t=k$, $x=l$):

$$T_l^{k+1} = T_l^k + \frac{a_l\Delta t}{(\Delta x)^2}\left[T_{l+1}^k - 2T_l^k + T_{l-1}^k\right]$$

(9)

where the following notation is adopted $T_l^k = T(x,t)$. The boundary conditions: T_i^k, $i=1,...,L$, are set to value t_0. For every time t_k:
(i) the boundary condition T_L^k is calculated as $T_L^k = t_0 + t_{amp}\,sin\left(\frac{2\pi}{T}t_k\right)$, $t_k = t_{k-1} + \Delta t$
and (ii) $T_0^{k+1} = T_1^{k+1}$, where T_1^{k+1} is calculated using (9).

The values $\Delta t=0.05$, and $\Delta T/x^2=0.5$ are adopted. The heat diffusion coefficient $a_l=a_l(x)$ is a space variable since the different materials in the wall are considered.

In the software, it is possible to set (i) the combination of materials of the load-bearing walls, (ii) the type of insulation, (iii) the thickness of the layers, and (iv) the thermal diffusivity of each layer. Finally, once the simulation is completed, the developed software also provides a graphical representation of the change, which allows a clear representation of the heat transfer of the interior. This approach allows one to consider the temperature changes through the wall in relation to the external temperature changes.

In the developed software (Fig. 2), the number of combinations (wall layers) is set by parameter i_x and the total length (expressed in cell number) by parameter i_y. The thicknesses of the sandwich wall layers are set using the matrix d_{layer}, while the coefficients of the sandwich layers (interior air, load-bearing wall and insulation) are set in the matrix k_{layer}. The time step expressed in minutes is adjusted through the scalar dt, where the selected value is 0.05 (Fig. 3). This step represents a time step of 30 minutes, while the duration of the simulation is set by the scalar t_{tot}. As mentioned before, for this case $t_{tot} = 96$. The current time is set by the scalar t, where after each iteration the current time is increased by the time offset dt.
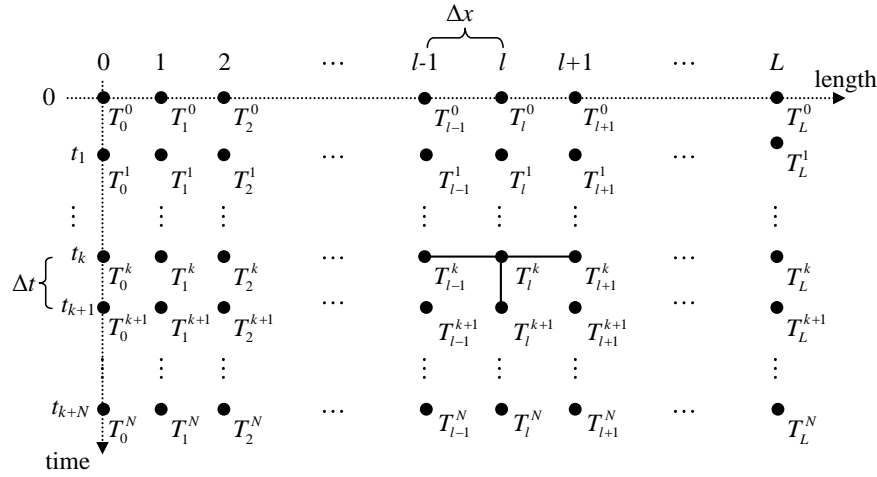
Fig. 2 PDF calculation scheme

```
nfreq=1     % an avi file records every nfreq-th slide

t=0;


% thermal conduction linear model

% the number of combinations of cells in the horizontal
% and vertical direction
ix=2
iy=50
% sandwich layer thicknesses: air, wall and outside
dsloj=[11, 2, 25, 12; 11, 2, 25, 12; 11, 2, 25, 12, ;]
% sandwich layer coefficients: air, wall and outside
ksloj=[1, 0.671, 0.492, 0.714;...
     1, 0.671, 0.402, 0.714; 1, 0.671, 0.632, 0.714;]

dubina=50    % layer depth in cm

dt=0.05    % time step in hours
ttot=96     % simulation duration in hours
period=24

% 1- heating, 0- balance, -1- cooling
xx=0

% Initial depth temperature - annual average
to=20
tamp=10     %10 surface temperature amplitude

LRC=10       % value lambda/ro x C
rad=0.0   % calculated proportion from the inside
sirx=1   % x and y axis width in cm
siry=1

aviobj = VideoWriter(' sandwich024unins.avi');
```

Fig. 3 Part of the software code implemented in the MATLAB 2022 software package in which the basic arrays for heat conduction calculations are initialized.

Video simulations are recorded using the built-in VideoWriter library, Fig. 4. Before the simulation, a lazer matrix is defined, into which the total length of the space and the number of planes are integrated (and in which the type and thickness of each layer is taken into account). The total length is 50 pixels, where one pixel represents one centimeter. Moreover, the initial values (initial conditions) are defined by the matrices *tt* and *ttold*, after which the following calculations are performed in the software, Fig. 4a: (i) definition of the irradiation conditions, (ii) heat transfer through the insulation, the wall and finally the indoor air premises. After each iteration, a plot of temperature versus time is drawn using the built-in plot function, Fig. 4b, and recorded in the specified .avi file.

```
% Calulation part
ii=0
while t<ttot

Definition of irradition condition

    for k=1:ix

        tt(k,iy)=to+xx*tamp+tamp*sin(2*pi*t/period);

        % gornji osvetljeni sloj
        tt(k,iy+1)=to+xx*tamp+tamp*sin(2*pi*t/period);
    end


    % heating conductance
    for k=1:ix

        for l=2:iy-1
        tt(k,l)= ttold(k,l)-konst(k)*sloj(k,l)*(2*ttold(k,l)
                -ttold(k,l-1)-ttold(k,l+1));
        end
        % definition of internal heat dissipation
        tt(k,1)=tt(k,2);
    end

    % ACTIVE ISOLATION

    bbb=sin(2*pi*t/period);

    for j=1:ix

        if bbb>0

            for k=dsloj(j,1)+dsloj(j,2)+dsloj(j,3)+1:iy
                tt(j, k)=tt(j, iy);
            end
        end
    end

    % Air
    for k=1:ix

        for l=1:dsloj(k,1)-3
            tt(k,l)= tt(k,dsloj(k,1));
        end
    end
```

```
    for k=1:ix

        aaa=ymin+(k-1)*15;

        rectangle('Position',[0,aaa,dsloj(k,1),15],...
        'FaceColor',[0, 1, 1]);

        rectangle('Position',[dsloj(k,1),aaa,...
        dsloj(k,2),15],...
        'FaceColor',[1, 0, 1]);

        rectangle('Position',[dsloj(k,1)+dsloj(k,2),...
        aaa,dsloj(k,3),15],'FaceColor',[1, 1, 0]);

        rectangle('Position',[dsloj(k,1)+dsloj(k,2)+…
        dsloj(k,3),aaa,dsloj(k,4),15],'FaceColor',[0, 1,
        0]);
    end

    str = num2str(ksloj);
    text(2,ymax-5,str);

    xlabel('Thickness (cm)')
    ylabel(' temperature (C)')

    str = num2str(t);
    title(str)
    x=0:(dubina/iy):dubina;

    hold on
    h = plot(x,tt);

    pause(0.1)
    frame = getframe(gcf);
    writeVideo(aviobj,frame);

    t=t+dt
end
```

Fig. 4 Part of the software code implemented in the MATLAB 2022 software package: (a) calculation of heat transfer through the surfaces of different layers; (b) recording the temperature distributions for the wall and the temperature profile.

The simulation can also be performed with the cooling effect, i.e. the given insulation model can be applied in both cases. For each simulation, the number of material combinations, i.e. the number of layers in the construction, and the thickness of these layers are determined separately. At the end of the simulation, the temperature change of the interior is determined in relation to the external temperature changes.

3. RESULTS OF SIMULATIONS

3.1 Non-insulated wall

The first wall observed is a non-insulated wall, consisting of a load-bearing wall, which can be made in three variants: Solid brick (a), hollow brick (b) and porous brick (c). In the non-insulated walls, there is a 2 cm thick lime mortar on both sides of the load-bearing wall. The results of the simulation are shown in Fig. 5. From the results one can see that the temperature inside the object has remained almost the same and the value is slightly above 20ºC.
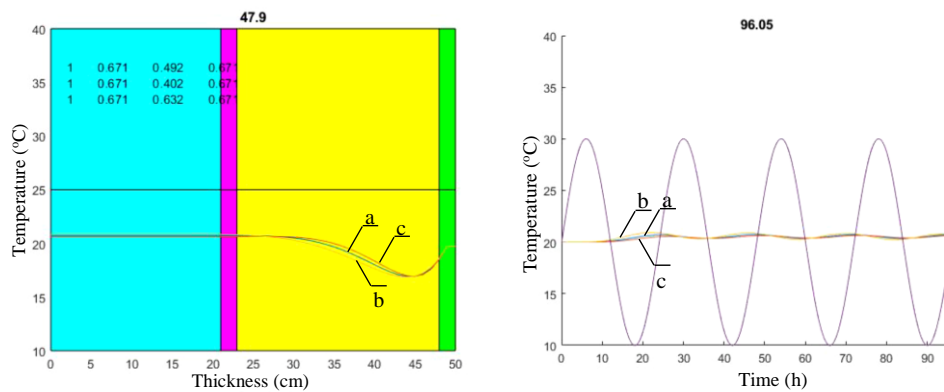

Fig. 5 Temperature distribution for a non-isolated wall in one moment of simulation (at 47.9 hour) with solid (a), hollow (b) and porous (c) brick and with 2 cm lime mortar on both side of the wall (left) and temperature profile distribution through the wall for the whole 96 hour time period (right)

2.3 Influence of type of insulation

In simulating the heat transfer in an insulated wall, we limited ourselves to the two types of insulation commonly used today: stone wool and Styrofoam (XPS - expanded polystyrene), both with a thickness of 12 cm. A 2 cm thick lime mortar remained on the inside. The objective was to determine what influence the insulation material applied to the outside of the wall would have. The results of these simulations are shown in Figs. 6 and 7. One can notice that the insulation material has a significant influence on the internal temperature, which increases slightly during the simulation period of 96 hours, when compared to the temperature profile of a non-insulated wall during the same period.
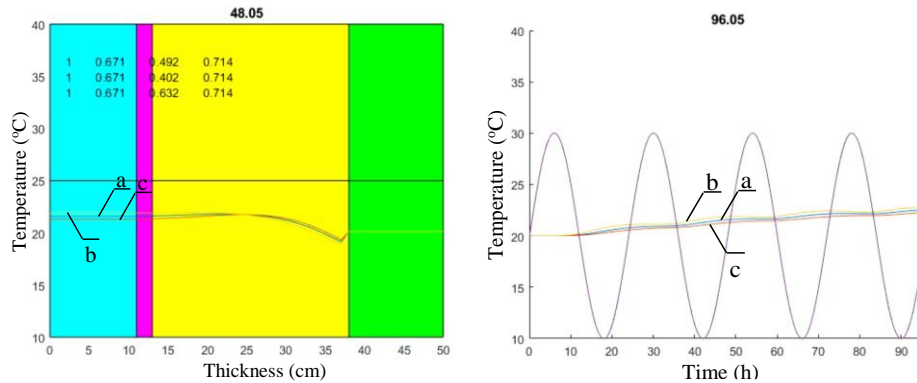
Fig. 6 Temperature distribution for an insulated wall with the stone wool at a random moment of simulation (at 48.05 hour) with solid (a), hollow (b) and porous (c) brick (left) and temperature profile in the wall for the whole 96 hour time period (right)
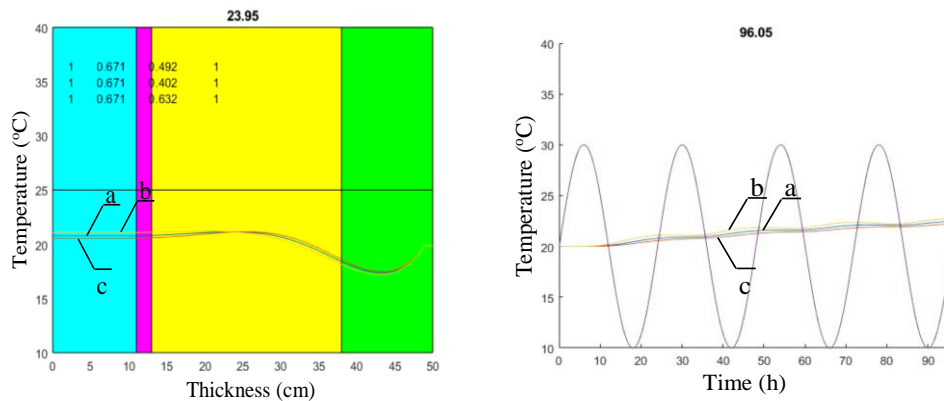

Fig. 7 Temperature distribution for an insulated wall with the Styrofoam (XPS - expanded polystyrene) at a random moment of simulation (at 23.95 hour) with solid (a), hollow (b) and porous (c) brick (left) and temperature profile in the wall for the whole 96 hour time period (right)

An uninsulated wall will heat up and cool down at the same rate - which will ultimately result in the fact that the average temperature remains the same (~20ºC). Herewith, it should be noticed that the type of load-bearing wall does not play a major role in the modified Trombe wall, because there is no significant difference between the 3 types of load-bearing wall. Also, regarding the type of used insulation material, there is no significant difference in thermal characteristics between stone wool and Styrofoam. The question is, how can this type of wall be used in the summer months? The proposed answer to this question is in the "smart" use of the above introduced bridging method of the modified Trombe wall, regarding the use of ventilation openings at night - when the temperature is lower, and closing them during the day - when the temperature is higher. Thus, the modified Trombe wall can be used successfully in all-weather periods.

5. ANALYSIS AND DISCUSSION OF RESULTS

At the outset of this section, it should be emphasized that the simulation shown here predicts a "heating mode" of operation of the Trombe wall, in the sense that the outer portion of the wall, which employs the bridging method, is structurally designed to heat the inner wall. In the case of an uninsulated wall, the average initial temperature of 20ºC remains almost at the same value during the simulation, while in the case of an insulated wall, the internal temperature increases slightly during the simulation. This is explained by the fact that an insulated wall cools down less at lower temperatures and thus retains heat inside the building. However, in all cases it is assumed that the heat accumulates mainly in the load-bearing wall, which has the highest values for heat capacity, much higher compared to the values of the insulation materials.

An uninsulated wall heats up and cools down at the same rate - which ultimately results in the average temperature remaining the same (~20ºC). It should be noted that the type of load-bearing wall does not play a major role in the modified Trombe wall, as there is no significant difference between the 3 types of load-bearing walls. Also, regarding the tested types of insulation materials used today, there is no significant difference in thermal properties between stone wool and Styrofoam. The question is how this type of wall should be used in the summer months. The proposed answer to this question lies in the "intelligent" use of the bridging method of the modified Trombe wall presented above, by using the ventilation openings at night - when the temperature is lower, and closing them during the day - when the temperature is higher. In this way, the modified Trombe wall can be successfully used in all-weather periods.

5. CONCLUSION

Our primary goal in this paper was to create a simulation that can be easily tested on today's most commonly used insulation materials. In this respect, we have presented the model of a modified Trombe wall transformed using a bridging method, with the basic idea that heat transfer (to or from the wall) is aided and abetted by airflow (heat convention) to the bearing wall and by heat conduction to the interior air. This is accomplished through the vents on the top and bottom of the wall, with a control considered "intelligent," i.e., automated and determined depending on the indoor and outdoor air temperature. With this modification, we proved through the simulations that undesirable properties of the Trombe wall can be reduced in high heat when extra energy is needed to cool the building walls. We have observed extreme sinusoidal temperature variations in outdoor temperatures, and our simulations have shown the following:

- The decisive factor for the increase in internal temperature remains the insulating layer of the building envelope. For materials with lower heat diffusion coefficients, the increase in internal temperatures is more pronounced.
- The type of load-bearing wall does not significantly affect the thermal properties of the modified Trombe wall. The load-bearing walls remain the most extensive heat reservoir (with the highest heat storage) since they are made of materials with the highest specific thermal properties.
- Trombe walls with all kinds of different combinations of load-bearing walls and insulating envelopes clearly and obviously show a passive thermal effect.

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