NUMERICAL INVESTIGATIONS OF HEAT TRANSFER IN A TROMBE'S WALL

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Introduction

Many solutions have been proposed to save energy for heating in passive solar systems such as direct gains, attached sunspace, Trombe's wall [1,2,3,4] and so on.

The paper presents numerical model of a building with passive solar system, in particular, direct or indirect. Exemplary results obtained by means of this model in climatic conditions of Poznan are presented.

1. Problem formulation

The problem under consideration is heat transfer in a building with passive solar system in the form of Trombe's wall with gravitational air flow and direct gains.

The mathematical model of a building constitutes the systems of partial differential equations which describe heat conduction in material layers, the equations of heat balance for the rooms of building and equations describing a flow and heat transfer in Trombe's wall air-gap.

System of model equations is completed by boundary and initial conditions systems.

The following main assumptions have been made:

- walls forming the enclosure are discussed as multilayered plane walls,
- air temperature is assumed to be equal in a room space,
- heat conduction in material layers is considered as being one-dimensional, disregarding corners, thermal bridges and window framings,
- heat transfer on internal surfaces of the walls takes place with constant heat convection coefficients,
- heat convection coefficients on external surfaces of the walls are wind speed functions,

- transmittance coefficient for glazing depends on sun's position,
- air flow inside Trombe's wall air-gap is considered as gravitational resulting from density difference,
- climatic factors: external air temperature and solar radiation in the form of average hourly courses for two kinds of day: solar and cloudy, for each month are given.

The aim of this paper is therefore to present a numerical model based on finite difference method [5,6,7,8,9], which is able to calculate the thermal behaviour of a building with indirect and direct passive solar systems, in particular ventilation efficiency of Trombe's wall with gravitational air flow inside its air-gap.

The presented method can be used also for analysing of thermal balance components for buildings equipped with passive solar system and conventional heating system.

2. Accepted numerical model of a building with passive solar system

To solve a model of a building with passive solar system (PSS) implicit finite difference method has been used.

Schematic model of a fragment of building enclosure with PSS based on quantization method is shown in Fig. 1.

The building is considered as a set of rooms characterized by different appropriation and maintenance, connected by walls of different construction.

Construction of a numerical model of building includes calculation of distribution of temperatures in all walls forming the enclosure, composition of system of energy balance equations for nodes representative of rooms and its solution.
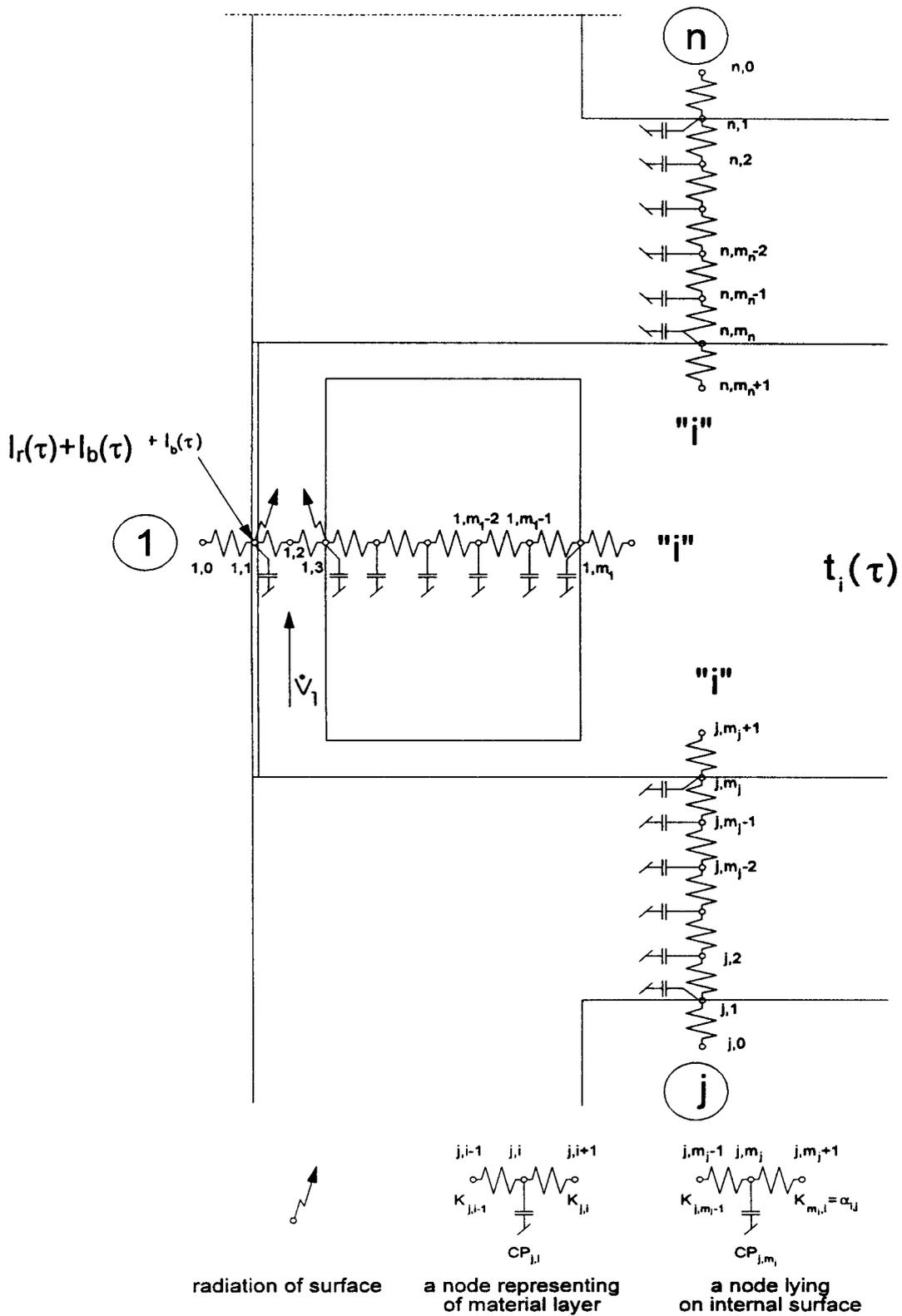
Fig. 1. Schematic diagram of a building enclosure with passive solar system based on quantization method.

Numerical model of individual room composed of "n" walls, in which a structure of each wall is represented by "m_j" nodes, constitutes a system of energy balance equations.

The number of equations for individual room is equal:

$$N = \sum_{j=1}^{j=n} m_j + 1 \qquad (1)$$

Temperatures in all nodes of walls (except nodes "j,0", in which temperature results from boundary conditions) are unknowns in a system of equations.

With reference to Fig. 1 energy balance equations for characteristic nodes are as follows:

- for a node representative of material layer

$$K_{j,i-1}(X_{j,i-1} - X_{j,i}) + K_{j,i}(X_{j,i+1} - X_{j,i}) =$$
$$= \frac{CP_{j,i}}{Dt}(X_{j,i} - T_{j,i}) \qquad (2)$$

- for a node representative of a glazing of Trombe's wall

$$\alpha_e(X_e - X_{1,1}) + \alpha_{CON\,1,1}(X_{1,2} - X_{1,1}) + \alpha_{RAD\,1,3} \cdot$$
$$\cdot (X_{1,3} - X_{1,1}) + a_1(I_r + I_b) = \frac{CP_{1,1}}{\Delta\tau}(X_{1,1} - T_{1,1}) \qquad (3)$$

- for a node representative of air-gap in Trombe's wall

$$\alpha_{CON\,1,2}(X_{1,1} - X_{1,2}) + \alpha_{CON\,2,3}(X_{1,3} - X_{1,2}) +$$
$$+ \dot{V}_1\rho c_p(X_i - X_{1,2}) = \frac{CP_{1,2}}{\Delta\tau}(X_{1,2} - T_{1,2}) \qquad (4)$$

- for a node lying on absorptive surface of accumulating material layer in Trombe's wall

$$\alpha_{CON\,2,3}(X_{1,2} - X_{1,3}) + K_{3,4}(X_{1,4} - X_{1,3}) +$$
$$+ \alpha_{RAD\,3,1}(X_{1,1} - X_{1,3}) + a_3(\tau_\alpha)(I_r + I_b) = \qquad (5)$$
$$= \frac{CP_{1,3}}{\Delta\tau}(X_{1,3} - T_{1,3})$$

- for a node lying on internal surface of walls that form enclosure of a room

$$K_{j,m_j-1}(X_{j,m_j-1} - X_{j,m_j}) + K_{j,m_j}(X_i - X_{j,m_j}) =$$
$$= \frac{CP_{j,m_j}}{\Delta\tau}(X_{j,m_j} - T_{j,m_j}) \qquad (6)$$

- for a node representative of an air in the room

$$\sum_{j=1}^{j=n} K_{j,m_j}(X_{j,m_j-1} - X_{j,m_j})A_{i,j} + \dot{Q}_H(\tau) +$$
$$+ n(\tau)c_p\rho V(X_e - X_i) = \frac{c_p\rho V}{\Delta\tau}(X_i - T_i) \qquad (7)$$

List of the most important symbols used in the equations:

a - absorption coefficient,
A - internal area [m²],
c - specific heat capacity of air [Jkg⁻¹K⁻¹],
CP - thermal capacity [Jm⁻³K⁻¹],
J - solar radiation [Wm⁻²],
K - thermal conductivity [Wm⁻²K⁻¹],
n - ventilation rate [s],
$\dot{Q}$ - heat flow [W],
T - actual temperature in a node (at the beginning of time interval) [°C],
X - forecast temperature in a node (at the end of time interval) [°C],
V - ventilated volume [m³],
$\dot{V}_1$ - volumetric air change rate in Trombe's wall [m³s⁻¹],
ρ - density [kgm⁻³],
α - surface film conductance [Wm⁻²K⁻¹],
Δτ - interval of the time [s],
(τ_α) - transmittance of solar radiation.

List of subscripts :

b - direct,
CON - convection,
e - external,
H - heating,
i - number of a node, internal,
j - number of a wall (1-Trombe's wall),
m - number of material layers,
r - diffuse,
RAD - radiation,
s - solar,
w - window.

The system of equations of energy balances ought to be solved for each wall in every step of time. The system of equations which binds all the equations systems for walls forming the enclosure of individual room is the system of equations of thermal balance for nodes representative of an air in single rooms (7).

Convective heat transfer coefficients for surfaces forming an air-gap are given by Barra [1]

$$Nu = 4.35 \, Gr^{0.22} \qquad (9)$$

where Nu - Nusselt number,
   Gr - Grashoff number.

For convection on external surfaces the following expression was used:

$$\alpha_e = 5.7 + 3.8 \, w \qquad (10)$$

with w - wind velocity [ms^{-1}].

Standard generalized transmittance of solar radiation through glazing is given in the form of formula:

$$\tau_\alpha = \alpha_1 \alpha_2 \alpha_3 (\tau_\alpha)_s \qquad (11)$$

where $\alpha_1, \alpha_2, \alpha_3$ are correction coefficient and $(\tau_\alpha)_s$ depends on sun's position.

Volumetric air change rate in Trombe's wall depends on the total pressure drop throughout the air-gap and the gravitational pressure resulting from density difference, according to the expression :

$$h \Delta \rho g = \Delta p_c \qquad (12)$$

where :

   h - height of an air-gap [m],
   $\Delta \rho$ - density difference [kgm^{-3}],
   g - acceleration of gravity [ms^{-1}],
   Δp_c - total pressure drop throughout the air-gap [Pa].

Total pressure drop throughout the air-gap is composed of pressure losses caused by frictional resistance and pressure losses caused by local resistances.

Coefficient of internal friction is calculated from equations given by Hagen-Pouisseuille (for laminar flow) and by Colebrook-White (for turbulent flow).

The above procedure gives temperature distributions in all elements forming the building in every time step of simulation period.

3. Model of external climate

The model of external climate for Poznan was elaborated in the form of Average Reference Year [10] on the ground of meteorological data from ten years period.

Basic data relating to external temperature for Average Reference Year for Poznan are shown in Fig. 2.

Accepted courses of direct radiation falling on surface perpendicular to sun beam are presented in Fig. 3 and courses of diffuse radiation are presented in Fig. 4. Data of ARY were stored in a disk file.

4. Results of modelling

The room with south orientated Trombe's wall double glazing was taken as a model for calculation. The volume of the room is 40m^3.
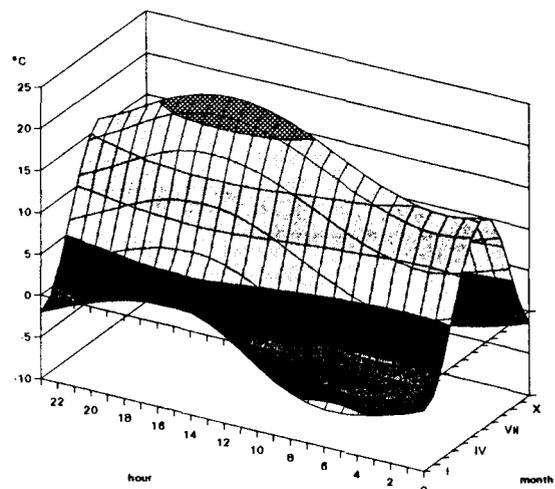

Fig. 2. Accepted courses of external temperature in ARY of Poznan.
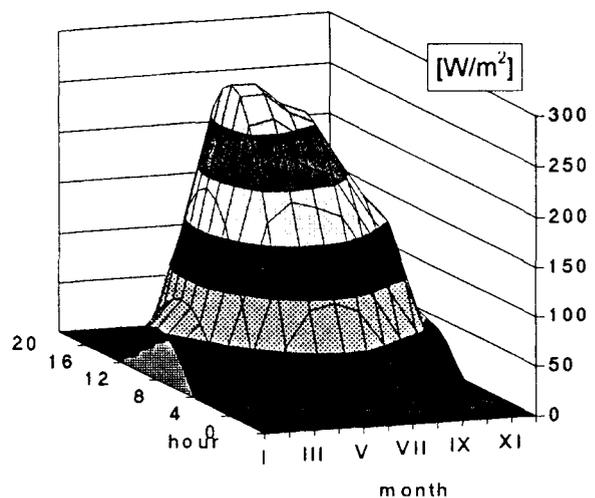

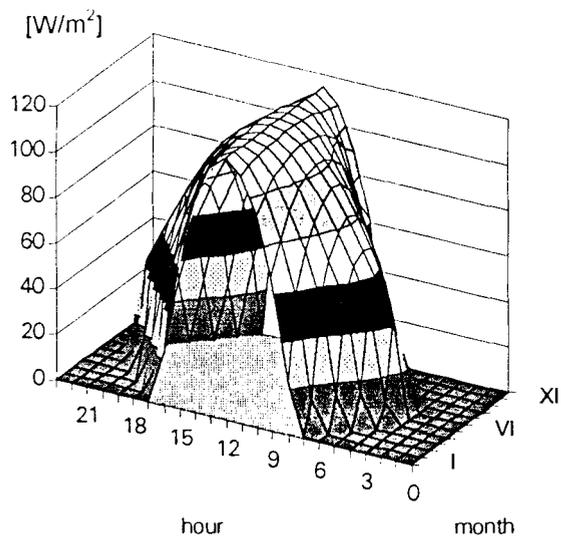Fig. 3. Accepted courses of direct radiation for Poznan.

Fig. 4. Accepted courses of diffuse radiation for Poznan.

Construction of Trombe's wall is as follows: single or double glazing, an air-gap 0.15m thickness, brick work accumulating layer 0.25m thickness.

The second external wall is east orientated and is composed of 0.24m cellular concrete, 0.04m foamed polystyrene, 0.04m air-gap and 0.12m brickwork (overall heat transfer coefficient k = $0.44 W/m^{-2}K^{-1}$). This wall has double-glazed window.

The floor and the ceiling are situated between heated rooms. They have overall heat transfer coefficient k = $1.37 W/m^{-2}K^{-1}$).

The air change rate n = 0.5 h^{-1}. The target of calculations was analysis of variability of volumetric air change rate through the air-gap of Trombe's wall in Average Reference Year of Poznan as well as analysis of variability of thermal balance components in this period. Calculations were done for Average Reference Year for Poznan for sunny and cloudy days with defined occurence frequency. The following assumption has been made - the used room is equipped with direct and indirect passive solar system and conventional heater with thermoregulator which secures 20°C - given internal air temperature.

Two kinds of air flow regulation through the air-gap of Trombe's wall are considered :

- case A - outflow of the air to room comes after the temperature of incoming air raises above the required temperature t_{in} > 20°C

- case B - outflow of the air to room comes after the temperature of incoming air contains in specified interval 20°C < t_{in} < 24°C

Exemplary results in the form of variability of air change rate and thermal balance for the room with double glazing Trombe's wall are shown in the Fig. 5. Courses of variability of volumetric air change through the air-gap of Trombe's wall $\dot{V}_{mean}$ and $\dot{V}_{max}$ in Average Reference Year of Poznan are presented in Fig. 5. Courses of ventilation heat gains issuing to application of Trombe's wall $\dot{Q}_{v\,mean}$ and $\dot{Q}_{v\,max}$ are shown in Fig. 6. The course of maximal internal temperature t imax in the room with Trombe's wall without shading devices are shown in Fig. 7. Courses of characteristic heat fluxes $\dot{Q}_{overall}$ for Trombe's wall and required heating output for the room $\dot{Q}_{Hmean}$ and $\dot{Q}_{Hmax}$ are presented in Fig. 8. Infiltration losses $\dot{Q}_{inf}$ and transmission losses through east orientated external wall $\dot{Q}_{Ewall}$ and window $\dot{Q}_{wind}$ are shown in Fig. 9.
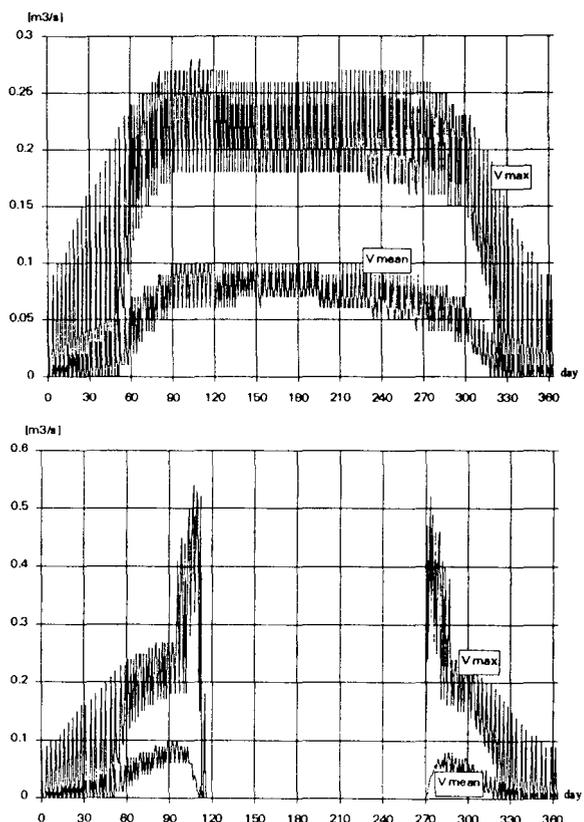

Fig. 5. Variability of volumetric air change rate through the air-gap of Trombe's wall in ARY of Poznan - case A and case B.
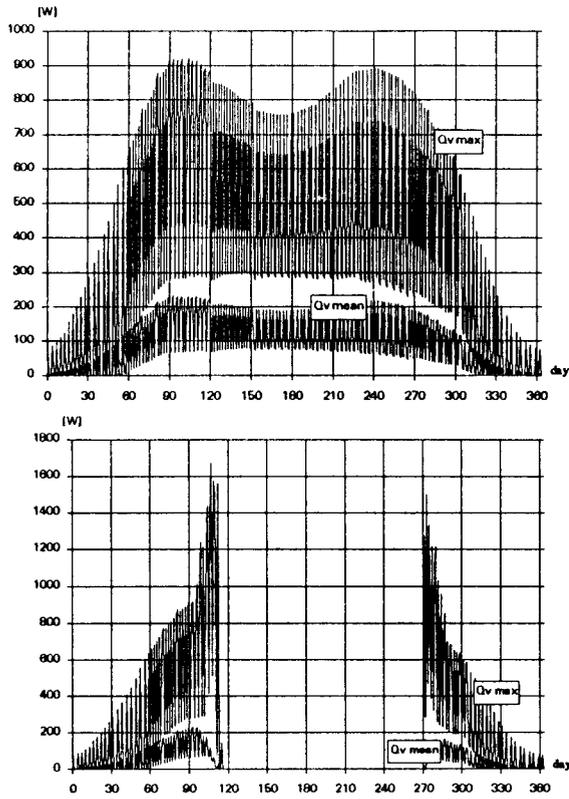
Fig. 6. Variability of ventilation heat gains for Trombe's wall in ARY of Poznan - case A and case B.
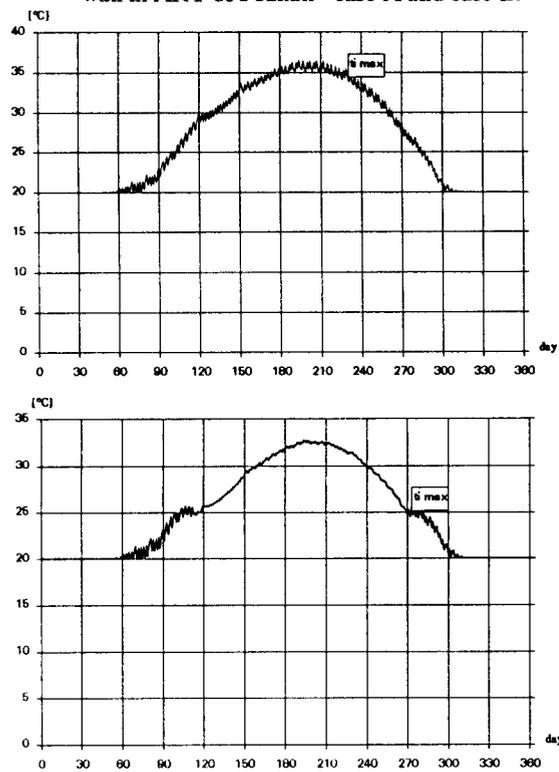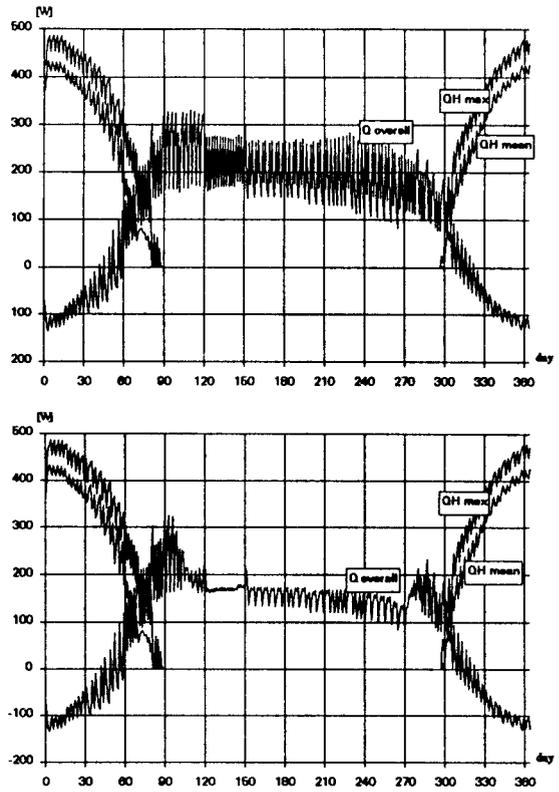
Fig. 8. Variability of heat flux for Trombe's wall and required heating output for the room with indirect passive solar system in ARY of Poznan- case A and case B.

Fig. 7. Maximal internal air temperatures in the room with Trombe's wall in ARY of Poznan - case A and case B.
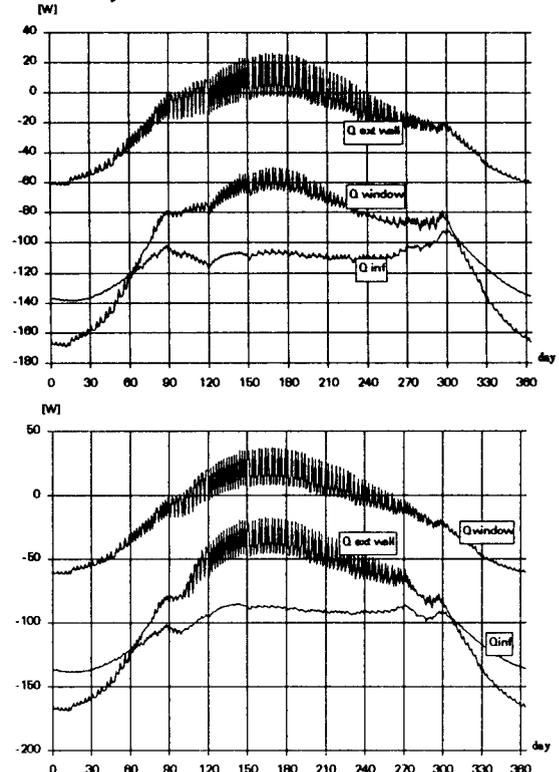
Fig. 9. Variability of transmission and ventilation losses for the room with Trombe's wall in ARY of Poznan - case A and case B.

5. Conclusions

Trombe's wall is the source of room overheating in summer months, independently of kind of air flow regulation method. It has to be equipped with shading devices.

The presented algorithms and elaborated computer program can be applied to other investigations of thermal behaviour of heated buildings with passive solar systems, among other things, ventilation efficiency of Trombe's wall with gravitational air flow inside its air-gap.

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SKAITINIS ŠILUMOS PERDAVIMO TROMBE'S SIENOJE TYRIMAS

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Santrauka

Straipsnyje nagrinėjama, kaip taikyti baigtinių skirtumų metodą šilumos perdavimo modeliui sukurti pastatams, kurie naudojasi pasyviąja saulės sistema, ypač tiesiogine ar netiesiogine. Pateiktieji algoritmai bei skaičiavimo programa gali būti taikomi šiluminės pusiausvyros elementams tirti nurodyto tipo pastatuose, be to, nustatyti ir vėdinimo efektyvumui Trombe's sienoje, pasižyminčioje savitakiu oro srautu vidinėmis tuštumomis.

Straipsnyje pateikiamas Poznanės lauko klimato modelis, pagrįstas vidutiniais metų duomenimis. Pateikti ir Poznanės klimato sąlygoms būdingi pavyzdiniai rezultatai, susiję su šiluminės pusiausvyros elementais patalpoje su pasyviąja saulės sistema. Įvertintas ir oro kaitos greitis Trombe's sienoje su savitakiu oro srautu, susidarančiu dėl tankio skirtumų.

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