HEAT AND MOISTURE TRANSFER IN THE SELECTED PARTITIONS OF A COMPLEX STRUCTURE

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Received: 6.05.2014; Revised: 10.08.2014; Accepted: 25.08.2014

Abstract

The paper presents authors' analysis of mechanically modified polystyrene plates. It provides selected research results included in the work [6]: i.e. determining basic heat-dampness parameters of tested insulating material: heat conductivity coefficient and steam diffusion coefficient. The main element is testing of heat and moisture phenomena in natural weather conditions: measurement of temperature and moisture in partition plane, measurement of heat flow density. Obtained results [6] have been used to validate, proposed by the author, mathematical model of the associated phenomena of heat and moisture transportation in partitions of complex structure.

Streszczenie

W artykule przedstawiono analizę modyfikowanych mechanicznie płyt styropianowych. Przedstawia on wybrane wyniki badań zawarte w pracy [6]: czyli określenie podstawowych parametrów cieplno-wilgotnościowych badanego materiału izolacyjnego: współczynnik przewodzenia ciepła oraz współczynnik dyfuzji pary wodnej. Głównym elementem jest badanie zjawisk cieplnych i wilgotnościowych w naturalnych warunkach atmosferycznych: pomiar temperatury i wilgotności w płaszczyźnie przegrody, pomiar gęstości strumienia ciepła. Uzyskane wyniki [6] zostały wykorzystane do walidacji zaproponowanego przez autora modelu matematycznego powiązanych zjawisk transportu ciepła i wilgoci w przegrodach o złożonej strukturze.

Keywords: **Vapour diffusion coefficient; Heat conductivity factor; Perforated polystyrene.**

1. INTRODUCTION

One of main causes bringing about the decrease of a functional value and durability of constructional bulkheads is the dampness of materials, from which these bulkheads were made.

In case of usage of styrofoam as an insulating material in the walls of insulated buildings we may be concerned about appearance of vapour condensation in the plane of bulkhead. Low steam permeability is in such cases an obstacle during the setting process of a newly erected wall, or it is the cause of humidity increase in case of insulating of a wall erected some time ago. One of possible structure modifications of the rigid material such as the styrofoam was the implementation of its modification by drilling the holes in styrofoam plates. The justification of a diameter's selection, the spacing and inclination of the holes as well as their influence on thermal and diffusional features in reference to vapour were presented in monograph [6]. The scope of initial studies included the measurement of a steam transport's factor, the measurement of a heat conductivity, the thermographic control of the bulkhead insulated by the solid and perforated styrofoam as well as the simulation of thermal-moisture phenomena in the bulkheads being analysed.

The essential studies were conducted in Solar Energy Utilization Laboratory located in Architectural Engineering Faculty. Two types of a wall configuration were analysed in the studies. The supporting structure of the wall was the common element. The first bulkhead was insulated with the use of a base material – type 15EPS-70-040 solid styrofoam – and was separated from the other part of the layout by the tar board divider. The second bulkhead was insulated with the material of a modified structure – the styrofoam with 5 mm diameter perforation holes. The record of the temperature and relative humidity of external and internal air was conducted, along with the record of temperature and relative humidity on the border of a particular bulkhead layers. The parameters of external climate were recorded by the Kombi weather station. Within a framework of the studies the mathematical model of an associated transport processes was verified. Moreover, the chosen thermal-moisture parameters of the wall layouts were specified. These were as follows: heat infiltration factor U, dimensionless internal surface temperature fRsi, the vapour flow. From the conducted studies as well as from the computer simulations by the usage of accepted heat and mass floatation process model the following conclusions were drawn:

1) the mechanical modifications made in solid styrofoam plates increase the steam permeability of the insulating material. They allow simultaneously to preserve the satisfactory value of thermal conductivity,
2) the usage of plates in typical ETICS [13] (External Thermal Insulation Composite System) solutions may cause the dampness of the façade layer and may affect the durability of the whole solution.

2. CHARACTERISTIC OF TESTED PARTITIONS

Deliberations presented in the paper are the result of the research on insulating material of modified structure which have been widely presented in the work [6]. The tested material is expanded polystyrene 15EPS-070-040 [12]. Perforations were made in basic material parallel to the heat and moisture flow direction. Material prepared in this way was subject to both preliminary testing [6] as well as testing in the partition installed in the experiment and test stand [6]. Preliminary testing included determining of a heat conductivity coefficient and vapour diffusion coefficient for various types of perforation (Fig. 1, Fig. 2).

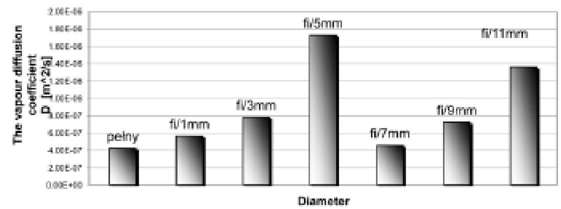

Figure 1.
Values of a vapour diffusion coefficient for various types of perforation [6]

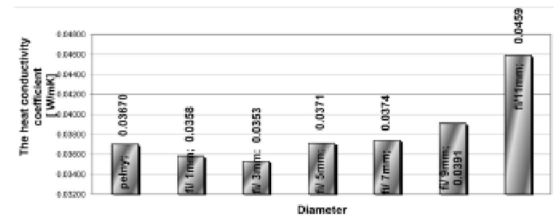

Figure 2.
Values of a heat conductivity coefficient for various types of perforation [6]

The object of the further analysis of this phenomenon the mathematical model of the flow in the analysed bulkheads was worked out, based on the Jacob's empirical dependences [3]. During the little intensive heat exchange we observe the pure conductivity, and after the presence of convection currents the conductivity and convection is encompassed by the equivalent heat conductivity factor λ_r. The relationship of the λ_r/λ factors (λ – air lambda) is characterized by the increase of intensivity of heat exchange caused by the free convection in relation to the pure heat conductivity. For the analysed apertures their dimensions such as thickness and height were taken into account. In the description of the phenomena the Jacob's empirical dependences were put into use [3], [6].

The researches show [6], that with the thickness of air aperture to 8 mm the convection is not present and we have to deal with the pure heat conductivity (it is proved by the shown calculations results). This fact can explain the decrease of the heat conductivity value, and in consequence the heat's flow value. The closed air aperture acts as the insulator. For the diameters ranging from ø7 mm to ø11 mm we observe the appearance of movement in the aperture, what probably causes the increase of the heat conductivity. Additionally the heat's flow due to radiation and the surface radiation characteristics adjoining to the sample are affecting the research results. That is why the feature of heat's flow incorrectly called heat conductivity, calculated from determined formulas and results of heat's flow, difference of temperatures and sample dimensions measurements – should be called the heat exchange factor.

The simulation of the steam diffusion phenomena through the analysed wall arrangements which are characterized by their discontinuity in the styrofoam layer confirms the fact, that the apertures and holes in the styrofoam layer considerably increase the possibility of the vapour flow, changing the moisture potential of the whole bulkhead. It is derived from the further analysis, that the places of intensive vapour flow due to difference in partial pressures may contribute to the weakness of the plaster's layer to the basis. Due to the thermal-moisture phenomena the emerging tensions may cause the damage to the elevation layer, what in turn may cause bigger moisture penetration deep into particular layers of the bulkhead.

Two types of partitions were analysed for which heat and moisture processes analyses were carried out (Fig. 3., Fig. 4) and they comprised of measurements of heat flow density as well as temperature and moisture distribution in selected zones of a partition. They were accompanied by measurements of surrounding parameters (weather station of Kombi type). Parameters were recorded continually, however, only some measurement periods were chosen for analysis. The analysis of the measured parameters enabled answer to the question whether employed method of testing in actual weather conditions, adequately reveals course of transport phenomena in the examined wall systems and their nature for two partitions of different structure [6].

The tests analysed two wall systems [6]. The common element was a load-bearing structure consisting of structural clay tiles. The first partition has been insulated with basic material – solid polystyrene 15EPS–70-040 and isolated from the remaining part of the system with the use of separator made of tarboard (Fig. 4). The second partition has been insulated with the material of modified structure – polystyrene with 5mm perforation of the low diffusion resistance coefficient $\mu=8$ and heat conductivity coefficient (declared value) $\lambda = 0.04$ [W/mK] [6] (Fig. 4).

Figure 3.
View of testing stand in the Faculty of Building Processes:
1 – partition with slab "okalux"
2 – partition with transparent insulation,
3 – analysed multilayer partition insulated in the first part with solid material and in the second part with perforated material

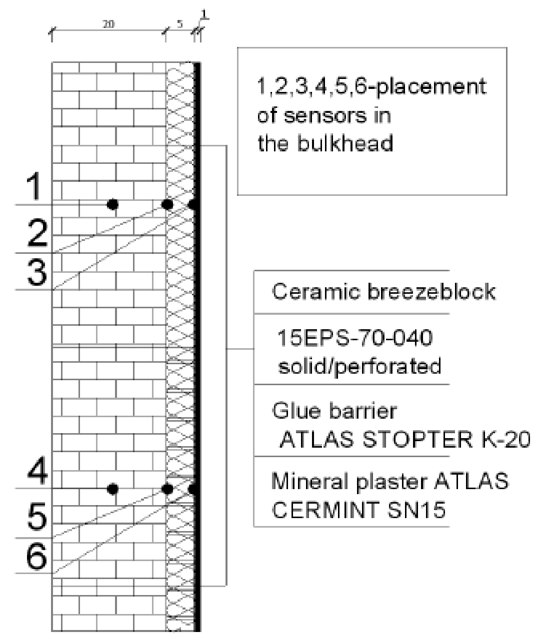

Figure 4.
Diagram of analysed partitions and distribution of sensors in their planes

First part of partition number 3 consists of the following layers:

- wall made of 20 cm thick hollow bricks,
- thermal insulation (5 cm thickness) made of polystyrene 15EPS-70-040,
- reinforcing layer made of mortar applied on mesh,
- prime,
- plaster.

Second part of partition number 3 (separated from the first one with separator made of tarboard) consists of the following layers:

- wall made of 20 cm thick hollow bricks,
- thermal insulation made of 5 cm thick perforated polystyrene (of 5 mm diameter openings, made on the 20 mm x 20 mm mesh on the typical polistyrene board 50 x 100 cm) 15EPS-70-040,
- the other layers as above.

3. TESTS RESULTS AND ANALYSIS

The testing has been carried out since 2007 until now. One of the measurement cycles dated 2008 was taken into account. There were constant heat-moisture conditions in the room whereas the temperature outside was about 0°C. The chamber was continually moistened and heated. The aim of the teasing was measurement of the parameters: temperature and moisture content in the partition, in the natural conditions. The analysis of the measured dimensions will enable answer to the question: what is the impact of the employed mechanical modification of polystyrene plates, in relation to solid material, on the processes of heat and moisture transportation in a partition? Figs. 5, 6 below show results of tests recorded every hour, in 7-day testing: a diagram of dampness and temperature changeability in particular layers/laminations of the partition insulated with the use of solid and perforated material.

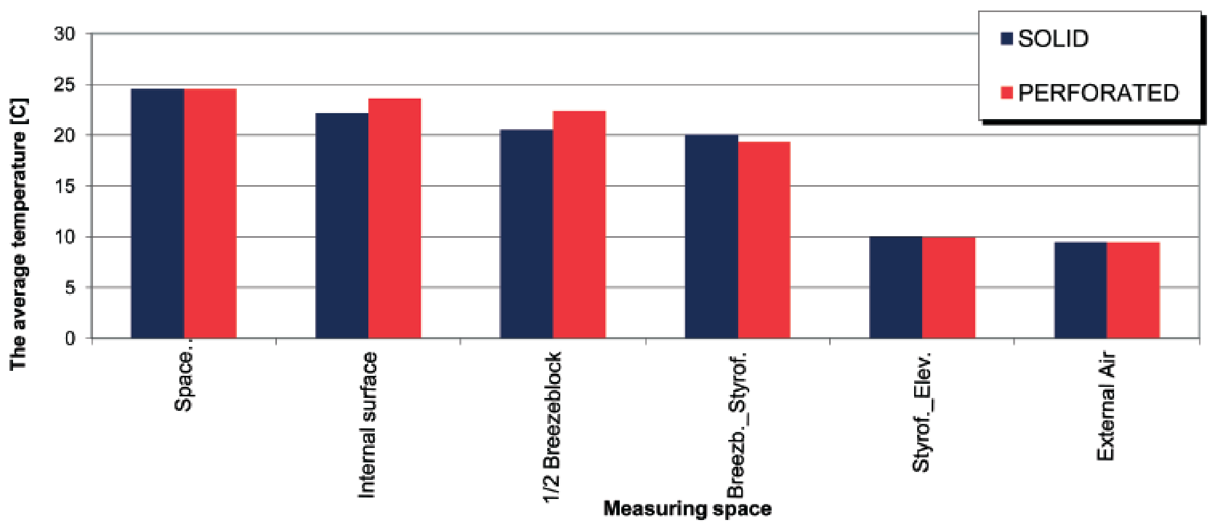

Figure 5.
Change of temperature (mean values of a given cycle) for tested partitions

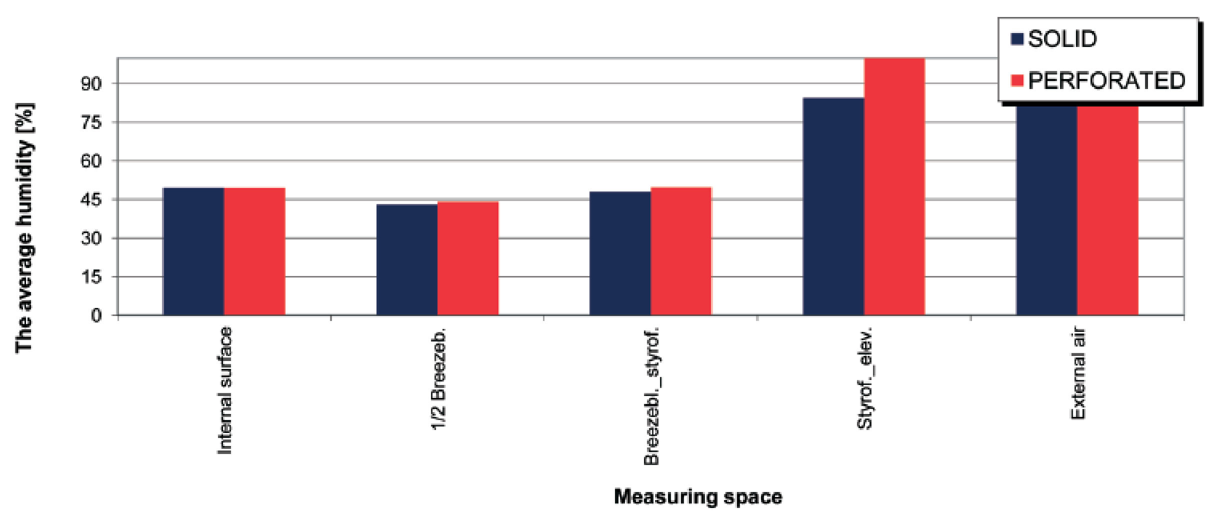

Figure 6.
Change of humidity (mean values of a given cycle) for tested partition

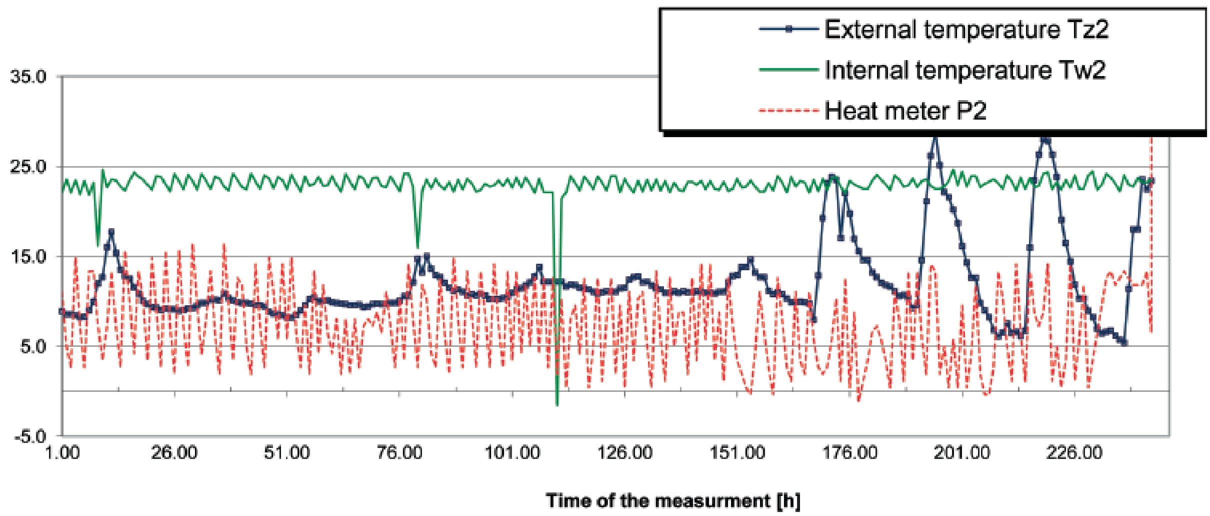

Figure 7.
The example of measurements: heat temperatures and densities for partition insulated with perforated material P2

Diagrams showing distribution of relative temperature and humidity in the partition (Fig. 5, Fig. 6) have been made based on average values of relative temperature and humidity of an environment surrounding a partition.

For temperature distribution in "solid" partition planes we note falling tendency towards external environment and for "perforated" partition sudden increase has been observed in a hollow brick plane.

In case of a partition insulated with perforated material the temperature in a hollow brick goes up; it may be caused by little content of humidity in this partition in relation to solid partition. Moreover, it may result from better insulation capacity of the whole partition. Observed tendency of changes of analysed dimensions takes place also in other testing periods.

For all analysed testing periods (autumn-winter period), despite relatively low temperatures outside, the temperature of the internal surface of both partitions increases by around 12÷15°C; however, it needs to be noted that for internal surface of a perforated wall the surface temperature is higher by 0.7÷1.6°C than for a solid wall.

Analysing a period with long-lasting rainfalls, substantial dampness has been noted for a partition insulated with perforated material reaching a hollow brick plane. Rain water influenced by wind and due to capillary lifting penetrates a partition and at the same time it is transferred through leaks (perforations).

During the measurement of the temperature and relative humidity, parallel measurement of heat flow density was introduced to get heat characteristic of a partition expressed by means of heat transmission coefficient U [3], [10], [11]. Based on the readings from the test bench (Fig. 7) [6] and calculations the following U coefficient values were obtained: for wall insulated with solid material U = 0.76 [W/m^{2}K], for wall insulated with perforated material U = 0.61 [W/m^{2}K].

In case of perforated material fall of the value of heat flow transmitted through the partition was noted as well as smaller value of heat transmission coefficient amounting to 0.15 [W/m^{2}K] in relation to the partition insulated with solid material. To explain fall of the value of thermal transition of an insulating material, and in consequence heat transmission coefficient characterizing the whole partition, mathematical model has been prepared showing transmission in analysed gaps based on Jacob's empirical dependencies [3], [6]. Perforations made in the polystyrene plate (closed in the wall system) and air in them play the role of insulation, having good impact on partition's thermal capacity.

Values of the vapour density have been obtained based on earlier results of temperatures and humidity, based on which saturation pressure as well as partial pressure have been determined. Fig. 8 shows the results of the analyses [6].

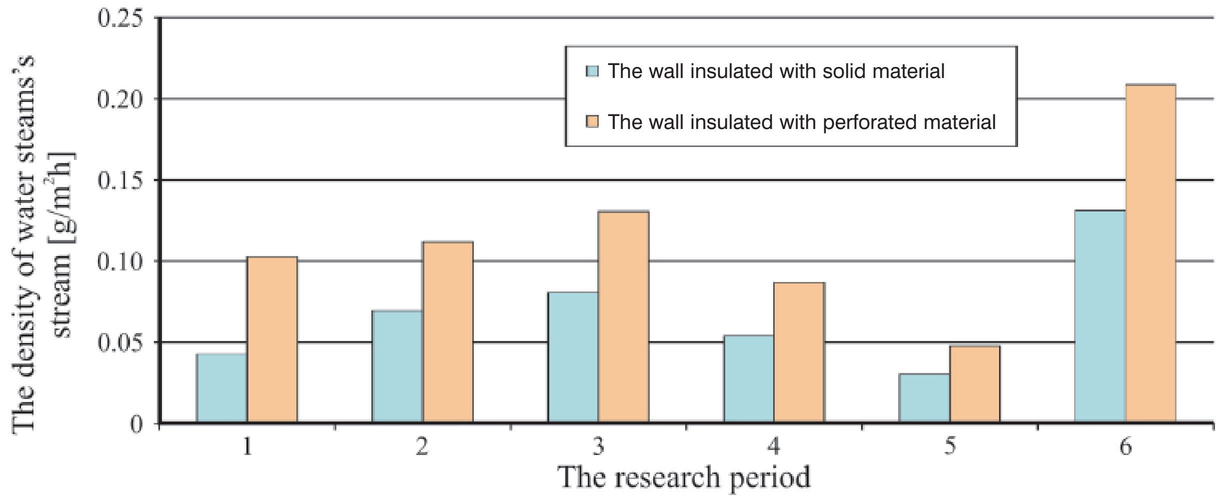

Figure 8.
Change of the vapour flow density for particular testing periods

Wall insulated with solid material characterizes with smaller permeability of the vapour than wall insulated with perforated material. It results from substantial differences in values of factor of vapour diffusion or in other words vapour permeability coefficient (δ), which for perforated polystyrene has got the value of $89.6x10^{-6}$ [g/(mhPa)], and for solid polystyrene $26.8x10^{-6}$ [g/(mhPa)]. Differences observed for various testing cycles vary from 35% to 55% in the value of vapour flow density [6].

4. ATTEMPT OF MATHEMATICAL DESCRIPTION OF TRANSPORTATION PHENOMENA

4.1. General model equations

Employed mathematical model takes into account all heat-humidity phenomena that take place in a building or its partitions. In case of transportation phenomena it comprises of both diffusion as well as capillary transportation of the vapour [1], [4]. Software computational algorithm is based on a system of differential equation describing heat-humidity transportation [6]:

- transport of heat (1); transport of mass (2)

$$\rho_0 c_m(T,\Theta)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(\lambda(T,\Theta)\frac{\partial T}{\partial x}) - L(T)\frac{\partial}{\partial x}(j_v) \quad (1)$$

$$\frac{\partial \Theta}{\partial t} = -\frac{\partial}{\partial x}(\frac{j}{\rho_l}) \quad (2)$$

where:

T – temperature [°C],

L – heat of vaporization [J/kg],

ρ_o – material density [kg/m^3],

c_m – specific heat [J/(kgK],

λ - material heat conductivity [W/mK],

Θ - moisture volumetric content [m^3/m^3],

j_v – vapour flow [kg/(m^{2}s)],

t – time [s],

ρ – mass density [kg/m^3],

x – distance into wall [m].

Equation (1) differs from Fourier's equation for transient heat flow by an added convective transport term (due to moisture diffusion associated with evaporation and condensation of water in the pores of the medium) and by a dependence on the moisture content (so that it is coupled to eqn. (2)). The driving forces for convective transport are the temperature and moisture gradients. The vapour flow and total flow (vapour plus liquid) are expressed in terms of transport coefficients, D, associated with the thermal and moisture gradients. According to Philip and DeVries (1957), the equations are:

$$\frac{j_v}{\rho_l} = -D_{T,V}(T,\Theta)\frac{\partial T}{\partial x} - D_{\Theta,V}(T,\Theta)\frac{\partial \Theta}{\partial x} \quad (3)$$

$$\frac{j}{\rho_l} = -D_T(T,\Theta)\frac{\partial T}{\partial x} - D_{\Theta}(T,\Theta)\frac{\partial \Theta}{\partial x} \quad (4)$$

where:
t – time [s],
j_v – vapour flow [kg/m^{2}s],
j – vapour plus liquid flow [kg/m^{2}s],
$D_{T,V}$ – vapour phase transport coefficient associated with a temperature gradient [m^2/sK],
$D_{\Theta V}$ – vapour phase transport coefficient associated with a moisture gradient [m^2/s],
D_T – mass (liquid plus vapour) transport coefficient associated with a temperature gradient [m^2/sK],
D_Θ – mass transport coefficient associated with a moisture gradient [m^2/s],
Subscripts: v – vapour, l – liquid.

Note that the model does not take into account the gravity influence on the transfer of liquid water through the walls; this effect is very small compared to the capillary effect, especially for microporous materials.

The simulation includes calculations done based on the presented model as well as for selected variants of this model: Table 1.

Table 1.
Examined models

Submodel	Employed simplifications
0	original model
1	D_Θ, D_T, D_{TV}, $D_{\Theta V}$, c_m, λ=const
2	V_Θ (moisture gradient), V_T (temperature gradient)= 0
3	V_Θ, V_T = 0 oraz D_Θ, D_T, c_m, λ=const
*	Simulation results are available for selected models.

Own climate data base was created for simulation based on the measurements obtained at test stand. Additionally results obtained based on Typical Meteorological Year for Gliwice have been presented. Both external as well as internal climate have got impact on the partition surface through so called boundary layer. The layer reflects occurrence of heat resistance and moisture resistance on the surface depending on the method of transfer. Due to the little resistance value of transfer on the surface, in comparison to resistance in particular layers of a partition, averaging values of convection coefficients were assumed in the simulation. The impact of solar radiation was taken into account by means of absorption coefficient dependent on colour and type of surface. The calculations employed the value of 0.4 for white plaster.

4.2. The results of computer simulations

Selected climate parameters have been analysed – air humidity and temperature outside having an essential impact on heat and humidity characteristics of the partitions. Preliminary statistical analysis was carried out for a subject climate parameter (Fig. 9, Fig. 10). Based on the analysis of tests results (Fig. 9, Fig. 10) it can be stated that average values of the air temperature in particular planes of the partition determined based on the presented models, are partly contained in confidence intervals limits, determined for measurement data. Constant tendency of the analysed parameter change has been observed which may confirm authenticity of "certain behaviours" in a partition e.g. temperature drop at the contact of polystyrene and façade which results from the humidity increase in this plane. In case of the change of temperature distribution in the partition, second and third models (Model 2, 3), based on the assumption that V_Θ, V_T = 0 and D_Θ, D_T, c_m, λ=const, turned out to be close to the actual conditions. However, for each case differences can be noted as to the temperature values within the range of 0-4°C. While analysing the tests results it can be noted that average values of humidity in particular planes of the partition appointed based on presented models do not fall within the confidence limits appointed for measurement data. In case of humidity distribution second model based on the simplification V_Θ, V_T = 0 is closest to the actual conditions. It has also been observed that the increase of humidity takes place in the layer polystyrene-façade in each of the presented cases. Moreover, it was assumed in the simulation that the partitions are initially dry. Differences in values that have been noted may result from the employed physical properties of other materials partition is made of (hollow brick, plaster) which were selected based on the available material data (literature, manufacturer's data). What is more incomplete knowledge of the environment impact on the measurement procedure, inaccurate known values of constant and other parameters outsourced and used in procedures of data transmission and application, cause results discrepancies.

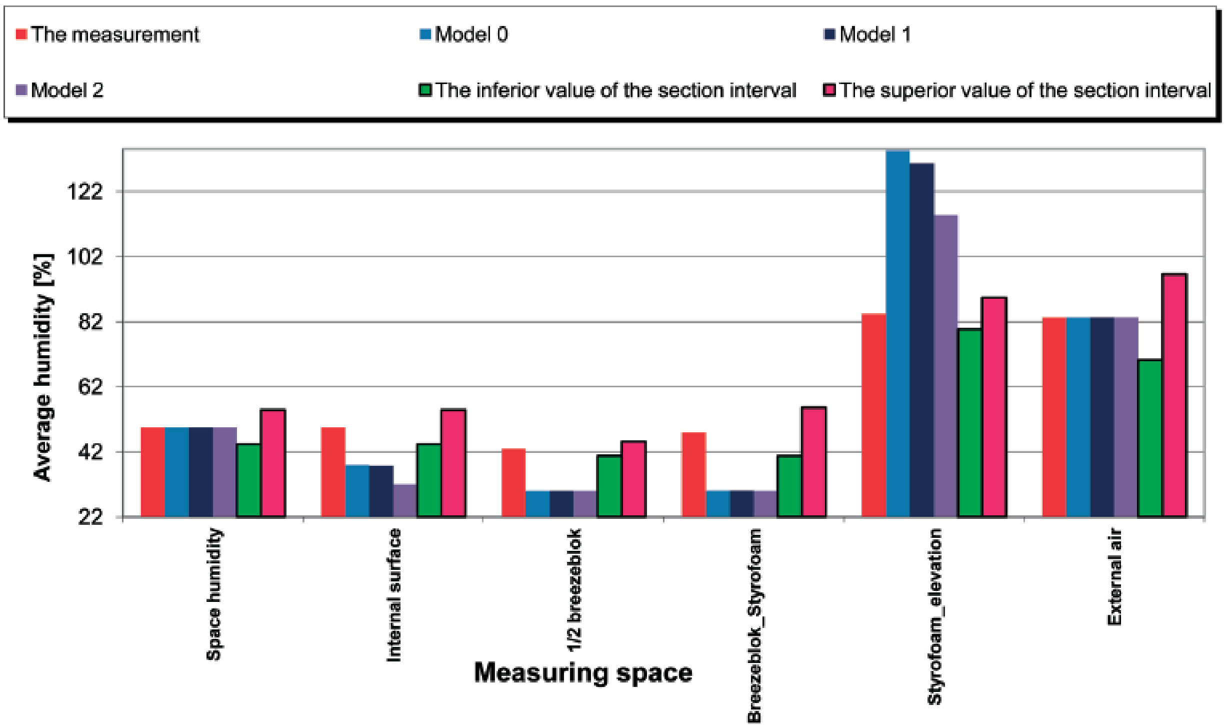

Figure 9.
The course of humidity distribution in the selected plains of the partition in 6 periods

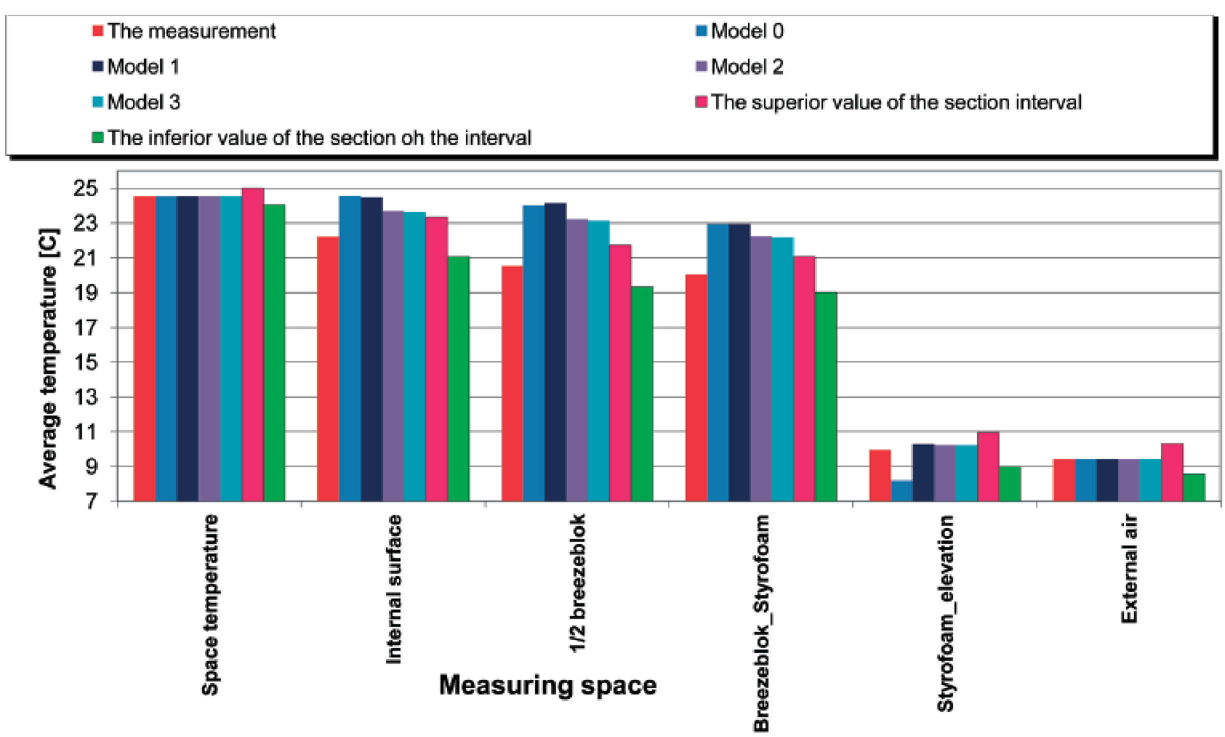

Figure 10.
The course of temperature distribution in the selected plains of the partition in 6 periods

Statistical analysis has been carried out for obtained value of the heat flow density. The results were presented with the use of STATISTICA software (Fig. 11, Fig. 12). Time series was analysed to check whether the subject series includes trend or fluctuations. Data was filtrated – random noise was eliminated as a random element is represented by stochastic process, i.e. sequence of independent random variables of the same probability distributions in the form of white noise i.e. of finite variations and finite averages (Fig. 11). The intention was to eliminate potential disturbance related to great thermal inertia of the heat meters which caused that a graph is "jagged", with particular devices of research set.

In addition to the proposed equations in mathematical model, the heat flow was also determined by means of a simple Fourier's equation (Fig. 12).

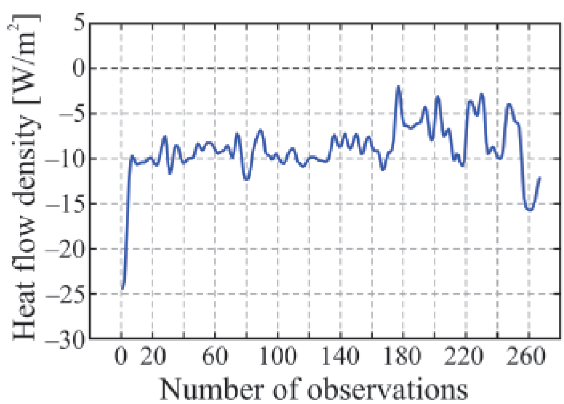

Figure 11.
Filtration of the obtained values of heat flow density

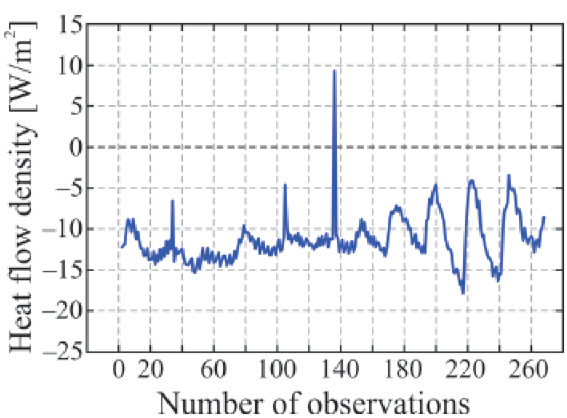

Figure 12.
Heat flow described by means of Fourier equation

Comparison was made between obtained models of heat flow and the values of heat flow density obtained based on the measurement at test stand in period 6 (Fig. 13, Fig. 14). Models obtained based on TMY (Typical Meteorological Year) as well as climatic data obtained from weather station at test stand in period 6 were compared.

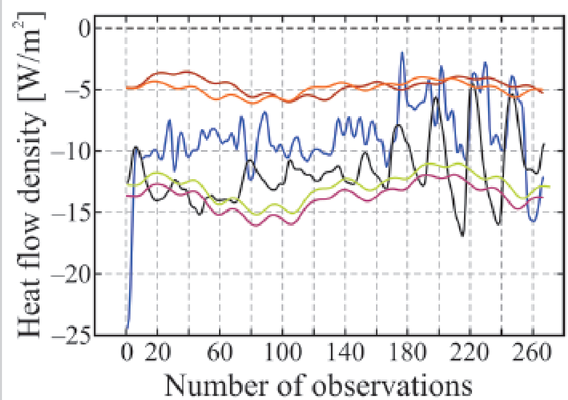

Figure 13.
Comparison of mathematical models with the measurement results. Models obtained based on TMY 6 (indications in the picture: orange colour – model_0; brown colour – model_1; green colour – model_2; violet colour – model_3; blue colour – the measurement of heat density; black colour – heat density calculated from Fourier equation)

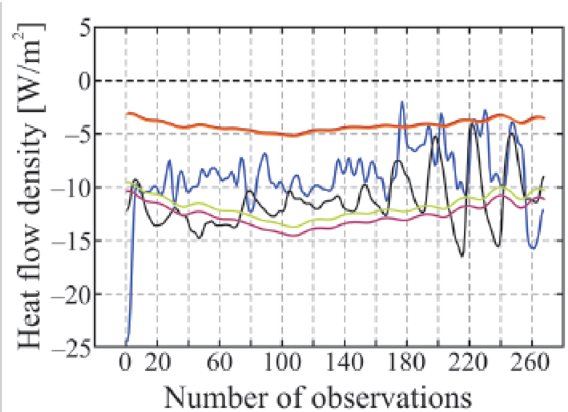

Figure 14.
Comparison of mathematical models with the measurement results. Models obtained based on the data in period 6 (indications in the picture: orange colour – model_0; brown colour – model_1(these two curves are congruent); green colour – model_2; violet colour – model_3; blue colour – the measurement of heat density; black colour – heat density calculated from Fourier equation)

Figures 13, 14 show results of simulations presenting different models of heat flow used in the software. Additionally, the heat flow obtained based on Fourier's equation solution has been presented. All the models were related to the dimension measured during measurement cycle no. 6. Analysing graphs (Figs. 13, 14) substantial differences in the presented models of heat flow, obtained based on climatic data TMY (Typical Meteorological Year) and measured at test stand in period 6, can be noted. The use of climate parameters being average-multiannual dimensions in the simulation significantly overestimates the values of heat flow density within the range of 0-6 W/m^2.

Current readings of the climate parameters during measurement enabled more accurate modelling of flow phenomena in the analysed partition. Discrepancy between the value of heat flow density and presented models (models 0-3) has been reduced, which concurrently allows more exact and careful adjustment of the model to tested reality (Fig. 14). However, as it turns out, the model which fully shows tendency of changes in heat flowing through the partition is based on the simple Fourier's equation. Therefore, it can be stated that for the evaluation of transport phenomena we can use models based on simple assumptions (Fourier's equation, Fick's equation) which enable determination of the tendency as well as scope of heat-humidity changes in the partition. Models based on Typical Meteorological Year should be used to estimate phenomena and not to verify or evaluate them.

5. SUMMARY

Applied perforations of the polystyrene plates in the form of mesh of openings parallel to heat flow and mass substantially improved its steam permeability preserving at the same time its original thermal properties.

Wall insulated with material in the form of mechanically modified plates showed greater steam permeability in relation to the wall insulated with solid material. During the testing substantial increase of moisture in façade layer has been observed.

The layer, in case of the change of weather conditions outside (precipitations), characterized with water flow through plaster layer towards the middle of the wall through perforations. This phenomena did not occur in the wall insulated with solid material. Mechanical modifications (perforations) made a typical diffusion bridge. Therefore, application of this solution can be recognized as the right one in case of a cavity walls. In typical ETICS (External Thermal Insulation Composite System) system proposed solution has got adverse impact on the plaster hardness causing substantial increase of its moisture content. Such a dampness is a factor that favours occurrence of damage but first and foremost reduces its durability. Increase of dampness in this layer is also confirmed by computer simulations showing at the same time the scale of the phenomenon. Additionally, proposed method of the measurement and results based on it, obtained in any place of the partition, may be used to work out heat-humidity assumptions and determine application areas for particular materials and partitions. Employed measurement technique enables determination of real impact of the dampness on heat flow in the partition.

Overall heat-transfer coefficient for insulated wall, determined based on the heat flux density testing, is smaller and within 20% in relation to the coefficient characteristic for solid wall. Perforations made in polystyrene plate (closed in the wall setting) and air in them play the role of an insulator which has got favourable impact on the overall heat-transfer coefficient in the partition. Thermovision testing performed for the partitions did not show the differences in the temperature areas on the external surfaces for both walls insulated with solid as well as perforated polystyrene walls.

The subject raised within this paper has got great practical meaning, especially in times when power certificates are required for buildings and the most favourable thermal-moisture solutions for external partitions are searched for. However, application of new materials and technologies requires full recognition of very important physical conditions that occur during the coupled phenomena of heat and mass flow.

ACKNOWLEDGEMENTS

The paper is elaborated on the base of monograph [6] and is published with the permission of Wydawnictwo Politechniki Śląskiej.

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