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IMPACT OF ENVELOPE STRUCTURE ON THE SOLUTIONS OF THERMAL INSULATION FROM THE INSIDE

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Abstract

The article presents chosen issues related to the heat insulation of complex structure walls. Subjects covered in this study are building partitions that had been constructed in the so called "Prussian wall" technique and are located in the Upper Silesia region. Their technical condition as well as usable state are not satisfactory, especially in the light of thermal protection. One way of increasing their standard is insulating partitions. In case of historical monuments or rich architectural facades, typical insulation methods (the ETICS system) will not apply. Thus, the solution is to insulate external walls on the inside surface. This, however, causes moisture content difficulties, which means that steam diffusing through partition undergoes the process of condensation.

The authors suggest their own solutions to the problem of insulating diverse external partitions and base them on the research conducted in situ. They use The School of Music in Gliwice as an example. The measurement results obtained here were used in "heat-water content" modeling of walls for which WUFI 2D programme was applied. As shown in numerical analysis, the thickness and the sort of insulating layer have a key impact on the partition water content including wooden elements of construction. In case of walls that are 25 cm thick, the water content in the wall itself and wooden elements increased alongside the insulation material thickness, but it did not excess the permissible level, otherwise wood degradation would ensue. For "Prussian walls" that are 12 cm thick and insulated on the inside we observe exceeding the level of 20% water content, which is critical for wood durability.

These results present elementary problems that occur when buildings with "Prussian walls" construction undergo thermo insulation. Restoration process must be a compromise between the need to retain the historical aspect of a building and the need to bring them to modern heat and usability standards. On the basis of numerical analysis, possible solutions, which meet these criteria, have been proposed.

Keywords: Prussian wall; Insulation from inside; Water content.

1. INTRODUCTION

Legal requirements applicable in Poland in the field of thermal protection have an impact on the introduction of procedures involving the design process of new buildings but also the maintenance and exploitation of the existing ones [1]. In newly designed buildings, ensuring proper insulation of building envelopes together with energy efficiency required nowadays is possible due to a suitable application of modern technologies and materials in the design process. With respect to buildings covered by conservation protection, the insulation is applied from the inside of buildings [2, 3, 4]. Such solutions enforce the application of more advanced design methods which take into account the character of the building and its exploitation manner [5, 6, 7]. The use of thermal insulation materials on the internal side is not appropriate in view of building physics, for example due to condensation risk of the diffusing water vapor. Modern material solutions allow to effectively improve the thermal condition of building envelopes through internal insulation, provided that the existing condition is subjected to correctly carried out calculations preceded by detailed analyzes, taking into account the actual conditions of external climate or conditions involving the use of rooms [8, 9, 10]. An individual approach for such solutions should be adopted for buildings with inhomogeneous wall construction, e.g. walls made as a wooden frame with a brick filling, the so-called Prussian walls. Such structures were used at the turn of the 19th and 20th centuries also in the present areas of Upper Silesia [11, 12].

The objective of this publication is to present some selected elements of thermal diagnostics of historic buildings. In the form of a short review, the authors present the selected in-situ tests which were conducted for the building in question and its elements, i.e.: measuring surface moisture of the wall, its mass humidity, defining capillary absorption, thermographic diagnosis. Such a form of hygrothermal assessment before the start of thermal insulation works allows to optimize the selected thickness and the type of thermal insulation material.

Basing on the modeling in the WUFI 2D program, water content in the selected wall elements was predicted, depending on the type and thickness of the insulation material.

Also selected details of wall connections were presented, treated in this work as thermal bridges for which linear heat transfer coefficient and the risk of surface condensation were determined

2. DESIGN METHODOLOGY OF THER-MAL INSULATION FROM THE INSIDE

2.1. Analyzed envelopes

The subject of the authors' research involves timberframed wall structures with a ceramic brick filling, referred to as Prussian wall. An example of such a half-timbered structure is the building of the existing State Music School, dated the beginning of the 20th century, located in Gliwice (Fig. 1). The frame structure was applied in the walls of the first floor, and the ground floor was made entirely of a brick wall. The rooms on the first floor contain a library and music rooms for students to practice.

The structure of the envelopes made in Prussian wall technology in Silesia depended on where they were placed in the building. Residential and utility floors of multi-family buildings and public utility buildings (further floors) were made with the thickness of one brick. The timber frame (the most commonly used cross-sections of studs: 12/12 cm - 16/16 cm) visible from the façade's side was filled with bricks and covered from the inside with a layer of bricks laid flat. The thickness of the envelope was approx. 25 cm. In unused attics or staircases, the walls were made with the thickness of 1/2 brick (12 cm). The fields within the wooden frame were left as brickwork structure or they were covered with layered plaster, often textured.

Due to the historic character of many buildings, thermal insulation must be placed from the inside. Such a solution is not efficient in view of building physics. High thermal resistance of thermal insulation brings about a significant drop in the temperature of the wall from the inside and increases the risk of interstitial condensation of the diffusing water vapor. The research shows that with the mass moisture of wood at the level of over 20%, being persistent over longer time periods, there is a risk of biological corrosion [13, 14]. The extent of such moisture significantly increases insulation thickness [12, 13]. It is assumed that in the climatic conditions of Poland, the insulation thickness should not exceed 8 cm. The optimal thickness is 3 cm [13, 14].



Prussian wall in the building of State Music School in Gliwice [11]

2.2. Classification of insulation methods from the inside

When using interior wall insulation, we can choose three main solution concepts (Fig. 2):

• Insulation from the inside, preventing the development of condensation.

The literature [15] recommends that the value of the diffusively equivalent air layer thickness sd of the thermal insulation or the applied vapor barrier



a) Capillary-active method

b) Method with vapour barrier

Figure 2.

Selected insulation methods from the inside for the Prussian wall [16] (1 – summer vapor diffusion flux, 2 – winter vapor diffusion flux, 3 – flux of slanting rain)



Figure 3.

Moistening with lashing rain and drying-out of the non-insulated Prussian wall

should exceed 1500 m.

• Insulation from the inside, minimizing the development of condensation (Fig. 2a)

The standard DIN 4108-3 [15] permits the use of diffusion resistance materials for which the diffusively equivalent air layer thickness s_d is contained between 0.5 and 1500 m. Such large variation in the value of s_d affects ambiguously the assessments involving the suitability of the applied thermal insulation.

• Insulation from the inside, permitting the development of condensation, with provided justification or proof that the condensate formed during the unfavorable period evaporates during the calculation year (Fig. 2b)

DIN 4108-3 [15] permits the use of materials for which diffusively equivalent air layer thickness s_d is lower than 0.5 m. The thermal insulation materials

used in such solutions are capillary-active and enable the developed condensate to accumulate in the material structure, without deterioration of their physical properties.

The systems with vapor barrier from the inside prove most effective in buildings with high humidity. Since the diffusion of water vapor through the surface is completely blocked, possibly the highest efficiency of the ventilation system should be ensured.

The envelopes in the Prussian wall system are characteristic of the presence of gaps between the frame and the adjacent elements, allowing the penetration of rainwater into the wall (Fig. 3). Studies have shown [17] that it can penetrate the wall to the depth of 20 cm. Such a phenomenon was described by Kozakiewicz [18], who also pointed to the aging processes and slow losses in the cross-section of wooden elements. CIVIL ENGINEERIN

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The properties of external wall coatings in terms of rain protection are defined by their water absorption coefficients, equivalently thick layer of air s_d and the product of both these quantities C_{RP} [17].

Initially, the suggested C_{RP} value was to be 0.1 [kg/m·h^{0.5}] [19]. However, most products and materials were not able to meet such criteria, and therefore the value was increased to 0.2 [kg/m·h^{0.5}].

For envelopes insulated from the inside, WTA guidelines recommend that C_{RP} should not be higher than 0.1 [kg/m·h^{0.5}] with the W_w value not higher than 0.2 [kg/m²·h^{0.5}] and s_d lower than 1 m [17].

The explained earlier limit values and requirements for W_w and s_d refer to water-resistant plaster and paint systems as defined in part 3 of the standard DIN 4108 [15].

In 2009, the document WTA - Merkblatt 6-4 2009-05 [20] has been published in which selected issues concerning the design of thermal insulation from the inside were presented. Such solutions lead to coolingout of the structural part of the wall, and hence they reduce the drying-out process of the existing structure. The presented procedure allows, in a simplified way, to estimate the correctness of the choice of a material solution, in terms of water absorption of the existing envelope and its outer layer. The first element of the procedure is to determine the impact of rain on the outer coating of the wall, i.e. to determine its water absorption expressed in W_w [kg / m² h^{0.5}]. If there is sufficient protection against rain in accordance with DIN 4108 [15], (part 3), it is usually sufficient. If the condition is not met, the following diagram is applied (Fig. 4) [20].

However, the diagram – methodology [20] can only



Minimum requirements involving thermal insulation layer, depending on the thermal resistance of insulation for substrates characterized by different capillary activity [20]

be applied if:

the existing rain protection of the façade is efficient, the existing external wall has the thermal resistance of at least R≥0.39 [(m² K)/W]; the normal climate prevails in the room, according to the definition given in WTA [20]; the average annual temperature of outside air exceeds 7°C, and the improvement of resistance ΔR should not exceed 2.5 or 2.0 [(m² K)/W]. If one of these requirements is not met, detailed analyzes and calculations are required.

2.3. Material tests of wall elements

The envelopes insulated from the inside require a detailed assessment of their interaction with additionally designed thermal insulation layers in terms of durability of the entire structure.



Figure 5.

a) Making opencasts and collecting material for the wall from the room side; b) Measurement of surface humidity; c) Measurement of water absorbency of the wall

The preparation of project documentation should be preceded by a thorough examination of the building and its elements. The authors made a number of research studies for the investigated building. Some of them are presented in this work. Basing on the said studies, and in accordance with the recommendations presented in section 2.2, the material for thermal insulation of the walls was selected.

- identification of material structure of the envelope, including the made opencasts; measurement of the thickness of the existing layers (Fig. 5a),
- measurement of surface moisture using non-invasive methods; close to ceramic walls of the thickness above 51 cm, measurement of mass humidity by collecting samples from the outcast (Fig. 5b),

The measurements were made in three opencasts, at three heights, after the removal of plaster off the brickwork. The measured surface humidity was the highest close to the flooring, and it decreased with the height. On the façade, damage to the bricks was identified, which is characteristic of progressing capillary action. The strongest damage was observed by the ground and up to the height of about 150 cm. The measurements confirmed the diminishing level of moisture (17% by the ground, 2.5% at the height of 175 cm). Also brick brittleness and discolorations were found. The lowest bricks were chipped. At moistened places, biological growth was visible. Similar damage occurred in the zone near the ground on the remaining façades.

• determination of capillary absorbency of the wall (Fig. 5c)

The determination of capillary absorbency of the wall was carried out using the Karsten tube [21, 22].

The research was conducted for the front façade. The measurement was carried out for the wall part of the wall. The study used 4 Karsten samples in two measuring series.

The measurement defined the extent of water penetration in the plane of brickwork. The measurement results for the brickwork are 5-7.3 (kg/m²h^{0.5}).

• determination of the material type of wall layers and the adoption of physical properties using the available data.

It is often impossible to determine all material parameters required in the assessment. This is due to restricted sampling possibility of materials (in the case of historic buildings, etc.) and research costs. For this reason literature data is applied in the modeling process of transfer phenomena in the envelope. • inventory of sensitive areas – linear thermal bridges (Fig. 6), made using a thermal imaging camera. The contact places of wood and brick surfaces as well as the areas around the studs make up a zone of heat flux density disturbances, which may adversely affect the durability of mortar in these parts of the envelopes and cause penetration of rainwater into the wall.

Climatic conditions during measurements

During the tests, both the outside air temperature and the temperature inside the building were measured before and in the course of the tests.

Measurement performed: December 18, 2014.

Outside ambient temperature, $t_e: 5.5^{\circ}C \div 5.0^{\circ}C$

The temperature inside the building, $t_i: 20.0^{\circ}C \div 22.0^{\circ}C$

Thermovision measurements were performed at a temperature difference, $\Delta t = 14.5 \div 17.0$ K.

During 72 hours preceding thermal measurements of the building, favorable weather conditions prevailed:

- outdoor air temperature during the day: 7°C÷8°C;
- outside air temperature during the night: 4°C÷5.5°C;
- during the day the predominant proportion of scattered solar radiation, no/occasionally occurring direct radiation;

The obtained temperature difference between external and internal air (about 15 K) meets the requirements of the PN-EN 13187 standard – the minimum temperature difference at the level of Δt_{min} > 10 K. Thermovision tests were conducted from 7 pm to 9 pm.

Analysis of the obtained thermograms showed no gaps or cracks at places where wooden elements got into contact with the wall for the investigated building.

On the basis of the carried out research and visual inspection of building elements, following the design recommendations for thermal insulation of external walls, light cellular concrete was selected. The thickness of the thermal insulation material was adopted in the following variants: 3, 6, 8 cm. For comparison, the modeling results for a wall insulated with polyurethane foam of the thickness of 3, 6, 8 cm have been presented. The parameters of the material are presented in Table 1.



Figure 6.

Thermogram made from the outside of the building in Gliwice

3. RESEARCH RESULTS AND THEIR ANALYSIS

3.1. Employed assumptions

The modeling tests were carried out on the basis of hygrothermal simulations for transient boundary conditions, using the software WUFI 2D. [23] From the described physical principles of heat and moisture transport a closed differential equation system can be developed with which the moisture behaviour of multi-layered building components can be calculated under natural climatic boundary conditions. Since it is a non-linear equation system whose coefficients are greatly dependent on the potentials, an analytical solution is not possible. Described in detail below is the derivation of the coupled equation system and the numerical solution technique which forms the basis for the computer program called WUFI [23]. For non-stationary flows and conditions of two-dimensional heat transport and mass equations, they have the form:

• heat transport (eq. 1):

$$\frac{\partial H}{\partial \vartheta} \cdot \frac{\partial \vartheta}{\partial t} = \nabla \cdot (\lambda \nabla \vartheta) + h_{\nu} \nabla \cdot (\delta_{p} \nabla (\varphi p_{sat})) \quad (1)$$

$$\frac{dw}{d\varphi} \cdot \frac{\partial\varphi}{\partial t} = \nabla (D_{\varphi} \nabla \varphi + \delta_p \nabla (\varphi p_{sat}))$$
(2)

where

 $dH/d\theta$ – heat storage capacity of the moist building material [J/m³K],

 $dw/d\varphi$ – moisture storage capacity of the building material [kg/m³],

 λ – thermal conductivity of the moist building material [W/m·K],

 D_{φ} – liquid conduction coefficient of the building material [kg/m·s],

 δ_p – water vapour permeability of the building material [kg/m·s·Pa],

 h_v – evaporation enthalpy of the water [J/kg],

 p_{sat} – water vapour saturation pressure [Pa],

 ϑ – temperature [°C],

 φ – relative humidity [-]

The program has its own material database comprising basic types of building products. Some specific information involving physical features of the envelope components was supplemented basing on measurements. Simulation tests were carried out for Prussian wall envelope – a building envelope with a brick filling 25 cm thick, covered with a lime-cement plaster 2 cm thick, 14/14 cm wood studs, the interior covered with lime plaster, 2 cm thick, insulated from the inside with light cellular concrete blocks of the thickness 3, 6, 8 cm.

Material parameters were adopted from the WUFI database: for historical bricks and hardwood. The distance between the studs was determined on the basis of inventory measurements of the building.

The initial moisture content of the materials was accepted as for the equilibrium state. The parameters of the indoor climate were determined as for average-humidity living quarters based on the standard EN 15026:2007. External climate conditions for the area of Upper Silesia (from the meteorological station in Katowice), were determined using outside temperatures, air humidity, atmospheric precipitation and insulation. For the northern wall, the influence of the slanting rain was taken into account (according to the most frequent wind direction for the region of Silesia). A three-year period of hygrothermal simulations was adopted.

Table 1.

Summarized data accepted for analysis

No	Material/Layer	R.H. [-]	μ[-]	$\lambda[W/m \cdot K]$	ρ [kg/m ³]
1	Wood	0.8	200	0.13	650
2	Solid Brick; historical	0.8	15	0.60	1800
3	Lightweight concrete	0.8	4	0.04	115
4	Polyurethane plates	0.8	90	0.022	44

The results of the calculations made in the WUFI program are presented in a graphic form. The changes in the water content $[kg/m^3]$ (Figs. 7÷13) in the selected planes of the insulated envelope were determined.



Figure 7.

Total water content in the envelope (25 cm) insulated with lightweight cellular concrete (markings: 30–30 mm insulator; 60–60 mm insulator; 80–80 mm insulator)



Figure 8.

Changes of water content over time in a layer of the wooden frame stud in the wall insulated with lightweight cellular concrete (markings: 30–30 mm insulator; 60–60 mm insulator; 80–80 mm insulator)



Changes of water content over time in a layer of the brickwork (25 cm) insulated with lightweight cellular concrete (markings: 30–30 mm insulator; 60–60 mm insulator; 80–80 mm insulator)



Figure 10.

Total water content in the envelope (25 cm) insulated with polyurethane panels (markings: 30–30 mm insulator; 60–60 mm insulator; 80–80 mm insulator)



Figure 11.

Changes of water content over time in a layer of the wooden frame stud in the wall with polyurethane panels (markings: 30–30 mm insulator; 60–60 mm insulator; 80–80 mm insulator)



In the presented case (Figs. $7\div12$), the analysis of the proposed solution did not confirm the accumulation of moisture inside the envelope for a given calculation period. Both the application of porous concrete materials (Figs. 7, 8, 9) and barriers in the form of polyurethane panels (Figs. 10, 11, 12) did not raise the water content of the envelope. It should be mentioned that the envelope modeling was carried out assuming full tightness of the external wall (its facade layer). The graphs demonstrate (Figs. 8, 11) that the water content in the cross-section of wooden element exceeds 100 kg/m³ and shows a downward tendency drving out to the level of \sim 75 kg/m³. With respect to the biodegradation of wood, the moisture content in wood should not exceed 20% of the volumetric weight. Slightly higher values are permitted for a period of 6 months.

Fig. 13 presents changes of water content in the particular layers of the 12 cm-thick walls insulated with 8 cm-thick thermal insulation material (lightweight cellular concrete). Water content in wooden elements exceeds 20% (\sim 130 kg/m³ in the winter season). In the summer season, the level of water content drops to 90 kg/m³. We must add that such a situation becomes disturbing with heavy rainfall. Rainwater can penetrate to the depth of about 20 cm [13, 14, 17] and can extensively dampen the envelope, resulting in the degradation of its elements. In such a situation the insulating material itself (light cellular concrete) loses its insulation qualities since the pores are filled up with water.



One of the criteria needed to ensure an effective design of thermal insulation from the inside is the efficient elimination of thermal bridges. As part of the carried out analysis, an exemplary thermal bridge was presented in the form of Prussian wall corner (Figs. 14, 15). The assumptions given in Table 2 were adopted for the calculations. The modeling of joints was made in accordance with the principles of ISO 10211: 2017 [24].

- Linear coefficient of thermal coupling L^{2D} [W/ (m·K)]
- · Linear heat transfer coefficient, determining addi-

(both branches)						
	Non-insulated wall	Insulated wall (8 cm thick)				
U [W/m ² K)]	1.57	0.34				
$L_i^{2D}[W/m{\cdot}K]^*$	4.4250	0.8673				
${L_e}^{2D}[W/m{\cdot}K]^*$	4.4250	0.8673				
$\psi_i [W/m {\cdot} K]^*$	0.3304	-0.1846				
$\psi_{iwall} \left[W/m \cdot K \right]$	0.1652	-0.0923				
$\psi_e [W/m {\cdot} K]^*$	-0.5048	0.0465				
ψewall [W/m·K]	-0.2740	0.0233				
f _{Rsi} [-]	0.54	0.81				

 Table 2.

 Summary of results (*values calculated for the whole bridge (both branches)



Summary of calculation results for the corner of Prussian wall without thermal insulation (a, b – distribution of isotherms, c – distribution of heat flux density)



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tional heat losses resulting from the presence of linear thermal bridges ψ [W/(m·K)],

• Temperature factor, determined on the basis of the minimum temperature on the envelope surface at the place of thermal bridge f_{Rsi} [-] ISO 13788:2012 [25].

The following qualities were accepted as boundary conditions: temperature of outdoor air t_e : -20°C, temperature of indoor air t_i : +20°C, thermal surface coefficients $h_e = 25 \ [W/(m^2K)]$, $h_i = 7.69 \ [W/(m^2K)]$, for calculations f_{Rsi} : $h_i = 4 \ [W/m^2K]$ was assumed.

The research results are presented for a 25 cm-thick wall with the 8 cm-thick thermal insulation.

The obtained results (Tab. 2) demonstrate that there is a risk of surface condensation and mold growth for the non-insulated wall. The value of the temperature factor f_{Rsi} is lower than the permissible value of 0.72 [1]. For the thermally insulated wall the risk is eliminated, but we can observe a high impact of external temperatures on the structural part of the wall (masonry).

4. CONCLUSIONS

Successful renovation works carried out in buildings depend on a number of factors. The following are considered the most important: proper identification of the condition of existing objects, taking into account the techniques, technologies and materials used in them, correct identification of the humidity level of selected fragments of walls and connections. The existing Prussian wall buildings have very low thermal insulation of the external envelopes. Due to their historic character, it is necessary to preserve the original elevation, characteristic of this type of construction. Therefore, thermal insulation must be applied on the inside of the external walls. Such a solution brings about specific moisture problems, consisting in internal condensation of water vapor diffusing through the envelope.

In the paper, two extreme solutions for insulation have been proposed i.e. allowing the passage of water vapor (light cellular concrete) and a solution based on polyurethane panels which limit this flow. The aim of the paper is to assess the moisture condition of the walls after the insulation because of different vapourdiffusion features and the complex structure of the partitions. Numerical analyses have shown that both insulating materials do not adversely affect the moisture condition of the partitions, assuming, however, full water tightness (joining the bolts, pillars with the wall part) and eliminating rain water migration into the wall.

As shown by the calculations, the thickness of the insulation layer has a significant impact on the moisture of envelope, including wooden structural frames:

- in the case of 25 cm-thick walls, water content in the masonry and in wooden elements was rising with the thickness of the insulating material, but it did not exceed the permissible value, after which the wood would have been subjected to degradation hazard (regardless of the type of insulation material),
- for Prussian walls 12 cm thick insulated from the inside, we can observe that the mass humidity critical for wood durability, which is 20%, is surpassed.

For such cases, a solution in the form of intelligent vapor barrier with variable diffusion resistance is proposed [13, 14]. The diffusion of water vapor is sufficiently limited, while the envelope in high moisture conditions can also dry out into the interior of the building.

In the pre-design analyses for this building, the designer proposed material solutions referred to in the paper. The authors, however, focused solely on the hygrothermal analysis of the walls based only on these materials.

The selection of the arrangement of individual filling layers must allow for the issues of heat and mass transfer. It cannot lead to internal accumulation of moisture or any other phenomena that cause the destruction of material or structure. At all times the proposed solutions must ensure safe use of rooms with proper (for specific use) internal climate parameters.

Walls with wooden elements are subject to individual rules involving their shape or construction process, due to possible development of biological corrosion. It is unacceptable to permit water stagnation to develop, without ensuring drainage and drying-out facilities of the material.

For the works carried out in historic buildings, in line with the conservation doctrine, the principle of reversibility of undertaken actions applies. Newly introduced elements cannot damage historical fragments of the objects.

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